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COMPARISON
OF
MAJOR FORGING SYSTEMS

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FOREWORD

This Final Technical Report covers all work performed under Contract F33615-67-C-1109 from 1 November 1966 through 22 February 1971. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force. It was released by the authors in May, 1971 for publication and is designated internally as TRW ER-7201-6.

This contract with TRW Inc., Cleveland, Ohio, was initiated under Manufacturing Methods Project 9-120, "Comparison of Major Forging Systems". It was accomplished under the technical supervision of Mr. L. C. Polley of the Materials Processing Branch (LTP), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

C. R. Cook, Section Manager, Materials Development Department, TRW Equipment, was responsible for program management at TRW Inc. F. N. Lake was engineer in charge and D. J. Moracz was associate engineer in charge throughout the program. Subcontractors and equipment items employed were: Ladish Co., hammer and mechanical press; Cameron Iron Works, hydraulic press; Precision Metal Products, CEFF-type HERF Machine; and Aluminum Co. of America, hydraulic press. The following subcontractor personnel deserve specific acknowledgment for their contributions in monitoring accurate technical communication and in providing excellent subcontract reports; Aluminum Co. of America - G. C. Holme, Cameron Iron Works, Inc., P. E. Kadlecek, Ladish Company - G. D. Willison & C. Sobol, Precision Metal Products - E. J. Breznyak.

This technical report has been reviewed and is approved.

H. A. Johnson
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ABSTRACT

A program to compare forging equipment effectiveness in providing superior structural forgings of advanced aerospace materials has been successfully completed. Comparisons of precision, quality, properties, and costs have been made after evaluation of representative, rectangular, rib and web structural forgings produced to essentially common shapes with different forging equipment. The program was divided by equipment size into separate efforts involving intermediate size and large forgings.

An "H" section, leading edge fin rib was employed as a target component enveloped by intermediate size forgings produced of a high strength steel (D6ac), a titanium alloy (Ti 6Al-4V), and a nickel-base alloy (Inconel 718). Subcontractors and equipment items employed were: Ladish Company, hammer and mechanical press; Cameron Iron Works, hydraulic press; and Precision Metal Products, CEFF-type HERF machine. Results of TRW dimensional evaluation revealed little difference in overall tolerance levels maintained during production of the forgings. Section thinness characteristics were, however, considerably different. The CEFF machine forgings were thinnest by design, and the hydraulic press forgings were thickest because the die closure rate was too slow to prevent excessive chilling of the forgings. Forging quality features relative to defects and uniformity of macro- and microstructural characteristics were also considerably different. Program results in this regard have conclusively demonstrated the importance of equipment closure mode and rate in maintaining a uniform, metallurgically correct workpiece temperature profile during deformation. Mechanical property levels of the three materials were not significantly different as a function of the equipment which produced the forgings.

An "H" section fuselage bulkhead with cross ribs was the target shape which was enveloped by large forgings of the D6ac and the Ti 6Al-4V materials. The Ladish Company (125,000 MKG counterblow hammer) and Alcoa (50,000 ton hydraulic press) designed and successfully produced the bulkhead forgings. Results of TRW evaluation indicated that overall control of dimensional tolerances was similar in both instances, but that the hammer forgings were considerably lighter in weight and thinner in section. Relative to quality, the macro- and microstructural features of the hammer forgings were more uniform, but the degree of thinness and detail achieved by the hammer also resulted in the onset of a "lapping" tendency in the titanium alloy forgings at rib-web fillet radii formed by the upper die. As with the smaller forgings, mechanical testing did not reveal significant differences in property levels between the bulkhead forgings produced by the different machines.

In general, hammers and hydraulic presses are both cost effective in forging oversize structurals to the variety of shapes, sizes, and materials in the low to medium quantity requirements typical of aerospace applications. However, due to chilling by the dies, higher temperature die systems must be used with typical hydraulic presses to achieve the same degree of detail and quality which can be obtained using conventional, economical dies in a hammer. Mechanical presses and HERF machines are more limited in application to structurals because of more limited control in die closure characteristics.

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I INTRODUCTION

This final report documents results of activities conducted by the Materials Development Department, TRW Equipment, TRW Inc., under Air Force Contract F33615-67-C-1109.

A wealth of literature describing impression die forging* of structural shapes of advanced aerospace materials has been printed in recent years. This has been well summarized in a large manual(1)** and three books(2-4). A large, very recent report(5) also includes description of comprehensive theoretical and experimental studies of the mechanics of the impression die forging process in general. However, in spite of this advanced state-of-the-art, one area of forging technology had been relatively untouched prior to the program described in this report. Presumably due to the low procurement quantities of aerospace structurals of a single design and material, definitive value analyses of the forgings produced versus the equipment employed in producing them had not been performed. The objective of this "Comparison of Major Forging Systems" program, therefore, has been to more closely define the influence of the forging equipment on the precision, quality, mechanical properties, and costs of representative structural shapes produced from advanced aerospace materials; e.g., high strength steels, titanium alloys, and nickel-base alloys.

The above objective has been accomplished by TRW evaluation and comparison of rectangular "H" section forgings produced to essentially common shapes by recognized commercial forgers employing different equipment types. Forgings representing an intermediate size structural component were produced from alloys chosen from the three materials groups by: 1) a conventional steam drop hammer, 2) a hydraulic forging press, 3) a crankshaft-type mechanical forging press, and 4) a pneumo-mechanical HERF (high energy rate forging) machine. A parallel effort involved forgings representing a large size structural component produced by massive forging hammer and hydraulic press equipment. This effort resulted in production of high strength steel and titanium alloys forgings which were evaluated with primary emphasis on comparison of the latter.

The program has necessarily been conducted as three separate, successive efforts. The first involved TRW definition of the shapes, materials, and techniques which would result in comparisons most representative of aerospace structural forging needs. Tooling was prepared and the forgings were produced by the commercial forgers under subcontract during the second effort, with TRW performing monitoring activities. The forgings were then evaluated and compared by TRW during the third effort. Results of the three efforts are presented in Section III through VII of the report which follow the program summary. A general discussion of program results, and conclusions and recommendations are provided in report Sections VIII and IX, respectively.

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* Sometimes termed "closed-die" forging. This report follows the terminology defined by the Forging Industry Association.

** References are listed at the end of this report.

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II SUMMARY

The program conducted under Contract F33615-67-C-1109 to compare forging equipment effectiveness in providing superior structural forgings of advanced aerospace materials has been successfully completed. Comparisons of precision, quality, mechanical properties, and costs have been made after evaluation of representative, rectangular, rib and web structural forgings produced to essentially common shapes with different forging equipment. The program was divided by forging size (and thereby equipment size) into separate production and evaluation efforts involving intermediate size and large forgings, summarized below.

Intermediate Size Forgings

A leading edge rib design from the fin (vertical stablizer) of a supersonic military aircraft was selected as the target shape for the intermediate size forgings to envelop. The forging materials selected were a high strength alloy steel (D6ac), an alpha-beta titanium alloy (Ti 6Al-4V), and a nickel-base alloy (Inconel 718). Equipment and subcontractor selections were: 12,000 pound steam drop hammer, Ladish Company; 6000 ton hydraulic press, Cameron Iron Works, Inc.; 4000 ton mechanical press, Ladish Company; and 400,000 foot-pound CEFF-type HERF machine, Precision Metal Products Div., Macrodyne-Chatillon Corp.

Although working to a common subcontract work statement, each forging source designed and manufactured different tooling to illustrate the particular features of the individual machine types. During initial die try-outs, none of the forgings filled at the corners and the intermediate shape dies for all four efforts required extensive modification. After the sequential dies were properly developed, the hammer forgings were produced essentially without incident. The hydraulic press employed, however, proved to be too slow to achieve its target forging thinness without overloading the dies. Production of the forgings with the mechanical press indicated that inflexible machine closure characteristics can result in excessive flash losses during early operations with dies of conventional design. Forgings from the CEFF machine were produced to the most difficult (thinnest, most detailed) design of the four and, after completion of the required steel and titanium alloy forgings, die failure was experienced during production of the Inconel 718 forgings.

Evaluation of the dimensional characteristics of fin rib forgings from the four machine types did not reveal truly significant superiority of one type over the others from the standpoint of control of tolerances. The CEFF machine forgings were, as mentioned, thinner and most closely detailed in terms of minimum excess metal. Forging quality features relative to defects and uniformity of macro- and microstructural characteristics were considerably different among the forgings. Program results in this regard have well illustrated the importance of equipment closure mode and rate and of die temperature in maintaining a uniform, metallurgically correct workpiece temperature profile throughout deformation, particularly with the titanium alloy and the nickel-base alloy. From this point of view, the hammer forgings were superior. After sectioning of test specimen samples,

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machining to a common size, and heat treatment; mechanical property levels of the three materials were not significantly different as a function of the equipment which produced the forgings.

Equipment, tooling, and production costs have been generally approached in view of the limited "forging cost-forging quantity" relationships developed during the program and due to the inability to bring accounting factors to common status among the subcontractors. In general, hammers and hydraulic presses in this size range are both cost effective in forging the variety of shapes, sizes, and materials in the low to medium quantity requirements typical of airframe structural components. However, more costly, higher temperature die systems and/or other means of reducing workpiece chilling by the dies is a requirement for typical hydraulic presses if forging detail and quality levels in high temperature materials which can be attained by current hammer forging techniques with conventional dies are desired. Mechanical presses and HERF machines are more limited in application to structurals because of the limited variability in the closure characteristics which they provide.

Large Forgings

An internal fuselage bulkhead design from a second supersonic military aircraft was selected as the shape target for envelopment by the large forgings. Materials selections were the D6ac high strength steel and the Ti 6Al-4V titanium alloy. Mechanical presses and HERF machines are also limited in size in comparison to hammers and hydraulic presses. Equipment selection for the large forging comparisons, therefore, included only the 125,000 MKG counterblow hammer owned by the Ladish Company, the largest hammer in the world; and the 50,000 ton hydraulic press operated by the Aluminum Company of America (Alcoa), one of only two hydraulic presses with this force rating in the U.S.

Although preforming of the D6ac material was accomplished without incident, both sources experienced cracking difficulties in preparing preforms of the Ti 6Al-4V alloy to the thinnesses targeted. The dies employed in the large machines, however, did not require modification, and die failures did not occur during forging of the large bulkhead. The hammer dies were designed to provide thinner forgings.

As with the smaller forgings, evaluation of dimensional inspection results from the large bulkhead forgings did not indicate that either of the two large machines afforded significantly superior control of tolerances. The principal dimensional difference was that the hammer forgings were considerably lighter and thinner. Upon arriving at this degree of thinness, however, the Ti 6Al-4V forgings produced with the counterblow hammer exhibited the beginnings of a "lapping" tendency in rib-web fillet radii. This was attributed to a die shift condition coupled with the degree of forging design detail attempted, and can be considered the limiting factor in hammer forging of such structurals. The thicker forgings from the large press contained no defect indications, but were characterized by greater variation in microstructure from section to section and from surface to surface, indicating a less uniform thermal environment during deformation. Again, after sectioning of specimen samples, machining to a common size, and heat

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treatment; mechanical test results did not indicate significant superiority of materials forged by either of the two large machines.

Analysis of structural forging costs suggests that tooling costs are similar for the large machines if conventional dies are employed, and that higher costs associated with depreciating the higher purchase price of a large press tend to be offset by higher production costs in operating a large hammer.

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III PROGRAM SELECTIONS AND FORMULATION

The objective of initial program activities was to define: 1) characteristic structural component configurations, 2) alloys of greatest interest within each of the three materials groups, and 3) forging and evaluation techniques which would result in comparisons most representative of aerospace structural forging needs. This was accomplished through TRW review of information derived primarily from an intensive, interview-type survey of the aerospace, the commercial forging, and the forging equipment industries. The selections which were made following this survey relative to specific shapes, materials, equipment, and techniques are discussed below.

A. Structural Components

Program survey results indicated that complex "H" section components of supersonic aircraft should be employed as forging design targets for evaluation of the relative capabilities of the different forging equipment types in intermediate and large sizes. Further, it was recommended that the components be sized to allow forging designs to closely envelop each structural shape.

The components selected, Figures 1 and 2, typify advanced aircraft requirements for thin rib-and-web shapes with contoured rib sidewalls which must support aerodynamic surfaces. The plan area of the Figure 1 component (50 square inches) allowed consideration of a maximum average unit loading on the dies of approximately eighty tons per square inch at a total force of 4000 tons. Thus, none of the intermediate size equipment items available to the program, as explained subsequently, were compromised by lack of ability to achieve the unit load requirements reported during the survey as necessary to produce highly detailed nickel-base alloy forgings. It is apparent, of course, that selection of both components involved limitations in plan areas to accommodate forging to the degree of detail desired in the material class requiring the highest unit loads.

The "size difficulty factor" was emphasized to a greater degree in selection of the large component illustrated in Figure 2. The plan area (approximately 1635 square inches overall and 1265 inches with the central area removed) was selected to allow a maximum average unit die loading of approximately forty tons per square inch during the final operations with a 50,000 ton press after the central area was removed. Since survey results indicated that large forgings are produced with lower unit loadings and since degrees of detail and tolerances which are practical in small and intermediate size forgings cannot be economically duplicated in large sizes(6-8), this value was considered adequate for production of large titanium alloy forgings meeting program objectives.

B. Materials

Materials selections for the intermediate size and the large forgings were also in accordance with needs for advanced aircraft structural materials as expressed by the aerospace industry during the survey. Specific selections were as follows:

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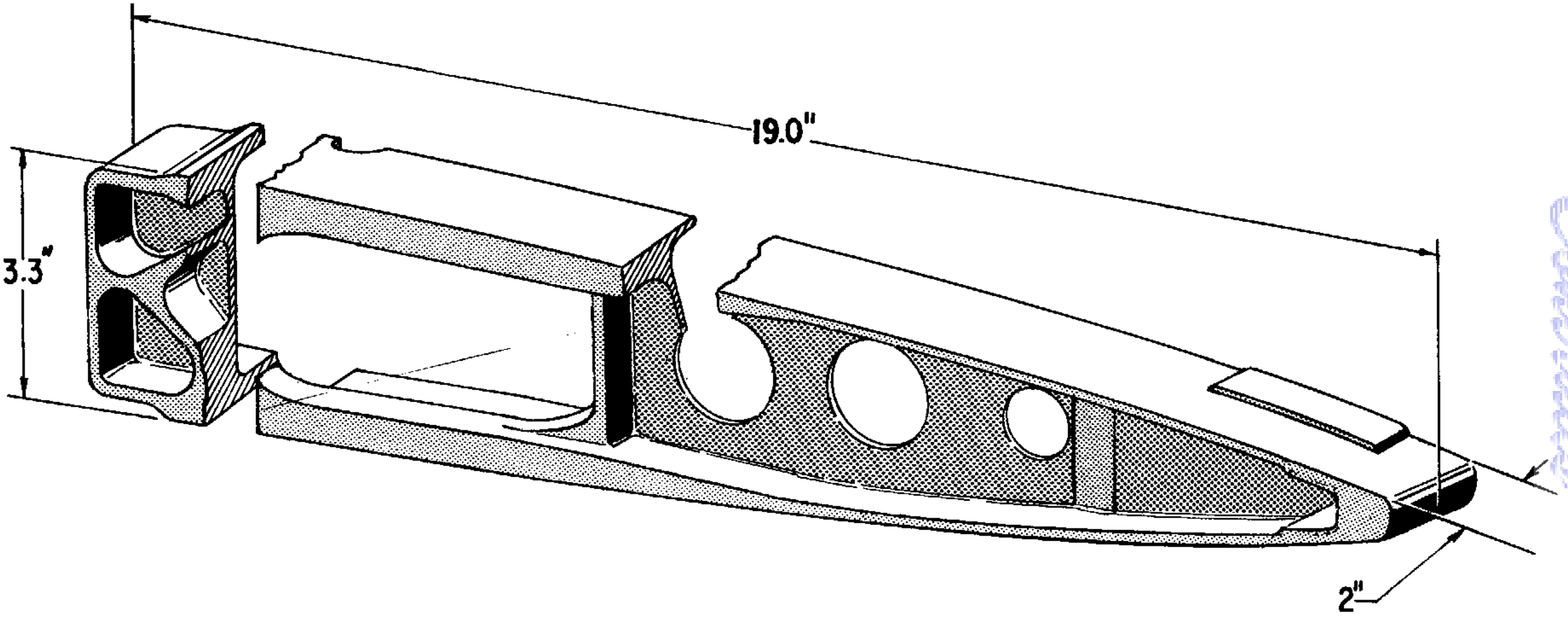

Figure 1. Leading Edge Fin Rib for F-104 Aircraft. Selected as Target Shape for Intermediate Size Forgings to Envelop.

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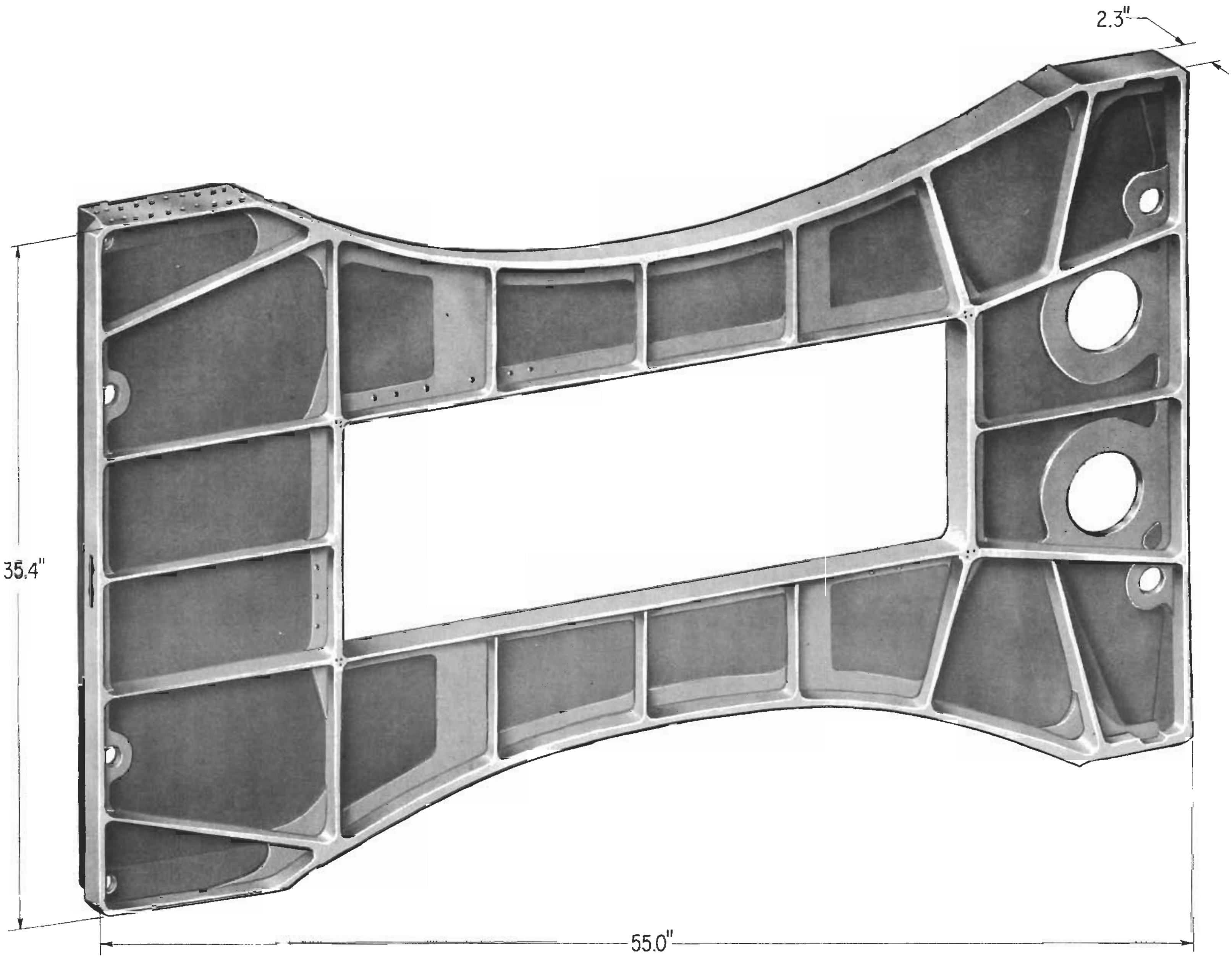

Figure 2. Fuselage Bulkhead for F-111 Aircraft. Selected as Target Shape for Large Forgings to Envelop.

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Intermediate Size Forgings

High Strength Steel = D6ac

Titanium Alloy = Ti 6Al-4V

Nickel-Base Alloy = Inconel 718

Large Forgings

High Strength Steel = D6ac (Tooling Trials Only)

Titanium Alloy = Ti 6Al-4V

In addition to conformance with the majority of survey opinions relative to maximum utility, the selections represented materials familiar to all of the forging subcontractors, listed subsequently. Thus the program was not required to support materials oriented forging process development efforts on the parts of one or more of the subcontractors to provide equivalent state-of-the-art and to insure that the desired forging equipment comparisons would not be compromised by lack of experience with the materials.

C. Forging Equipment and Subcontractors

Selection of specific equipment to perform the forging comparisons was not straightforward. As will be discussed subsequently, force-times-distance machine (presses) and impact energy machine (hammers and HERF machines) ratings cannot be directly compared in terms of their relative abilities to produce approximately equivalent forgings. Yet, the program required matching their capabilities as closely as possible to provide valid comparisons upon completion. The survey, therefore, paid particular attention to relative ratings in terms of capabilities in providing equivalent degrees of useful work during forging of rib-and-web shapes of high temperature materials.

In addition, it was apparent that the equipment could not be separated from the knowledge of engineers, operators, and metallurgists with particular experience in material procurement, die design, process engineering, etc., for aerospace structural forgings if quality forgings were to be compared. For this reason the equipment which could be selected was limited to specific items employed by commercial forgers who: 1) were experienced in the production of aerospace structural forgings, and 2) indicated a willingness to participate in the experimental activities of the program. This alone limited program selection of a mechanical press to 4000 tons rated capacity which, in conjunction with the unit loading data previously discussed, dictated the plan area of the Figure 1 component and limited the available rating ranges from which the other intermediate size machines could be selected.

Based on all of the above considerations, the following equipment items and subcontractors were selected to produce forgings for comparison:

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Intermediate Size Forgings

1. Steam drop hammer of nominal rating of 12,000 pounds, Ladish Co.
2. Hydraulic press of a nominal rating of 6000 tons, Cameron Iron Works, Inc.
3. Mechanical press of a nominal rating of 4000 tons, Ladish Co.
4. HERF machine of a nominal rating of 400,000 foot pounds, Precision Metal Products (CEFF machine).

Large Forgings

1. Counterblow hammer of a nominal rating of 125,000 MKG, Ladish Co.
2. Hydraulic press of a nominal rating of 50,000 tons, Aluminum Company of America (Alcoa).

D. Forging and Evaluation Techniques

Completion of the survey also resulted in several problem areas relative to TRW selection of specific forging designs and forging techniques for the subcontractors to employ. The first involved definition of the degree of "precision" which was to be attempted in enveloping the intermediate size and large components by the forging designs. Although forgings corresponding most closely to the Figure 3 "close-tolerance" classification were considered desirable as a general goal, neither the Figure 3 classification system (envelope) nor Forging Industry Association tolerances(6) (accuracy and reproducibility) could be employed in quantitatively defining dimensional goals. Neither system defines dimensions or tolerances in relation to the actual components machined from the forgings, yet these relationships influence the quality and cost of the components. Further, neither system differentiates between equipment types in terms of potential advantages in providing greater component detail in specific areas of the forgings; e.g., impact energy machine advantages in minimizing web thickness, press and HERF machine advantages in providing ribs with minimum draft, etc. Second, it was obvious that the best comparisons of equipment capabilities would be achieved if the subcontractors themselves had latitude in performing their own design efforts and selected their own forging techniques. Third, some means had to be devised to insure that the subcontractor efforts technically paralleled each other toward the common objectives of a single comparative study.

After review of the above problems, program efforts were formulated based on the following premises: 1) that specific program dimensional and quality goals should relate to aerospace industry requirements for finished components rather than to the forgings themselves; 2) that forging subcontractors should be responsible for recommendation of specific forging designs and processing conditions to demonstrate the maximum capabilities of their respective equipment items in approaching the dimensional and quality goals of the program; and 3) that all subcontracts should be negotiated on the basis of common, mutually acceptable work statements which detailed program goals, process limitations, and subcontract delivery and report requirements individually for efforts involving the intermediate size and the large forgings. In terms of the goals and evaluation techniques, the following were established:

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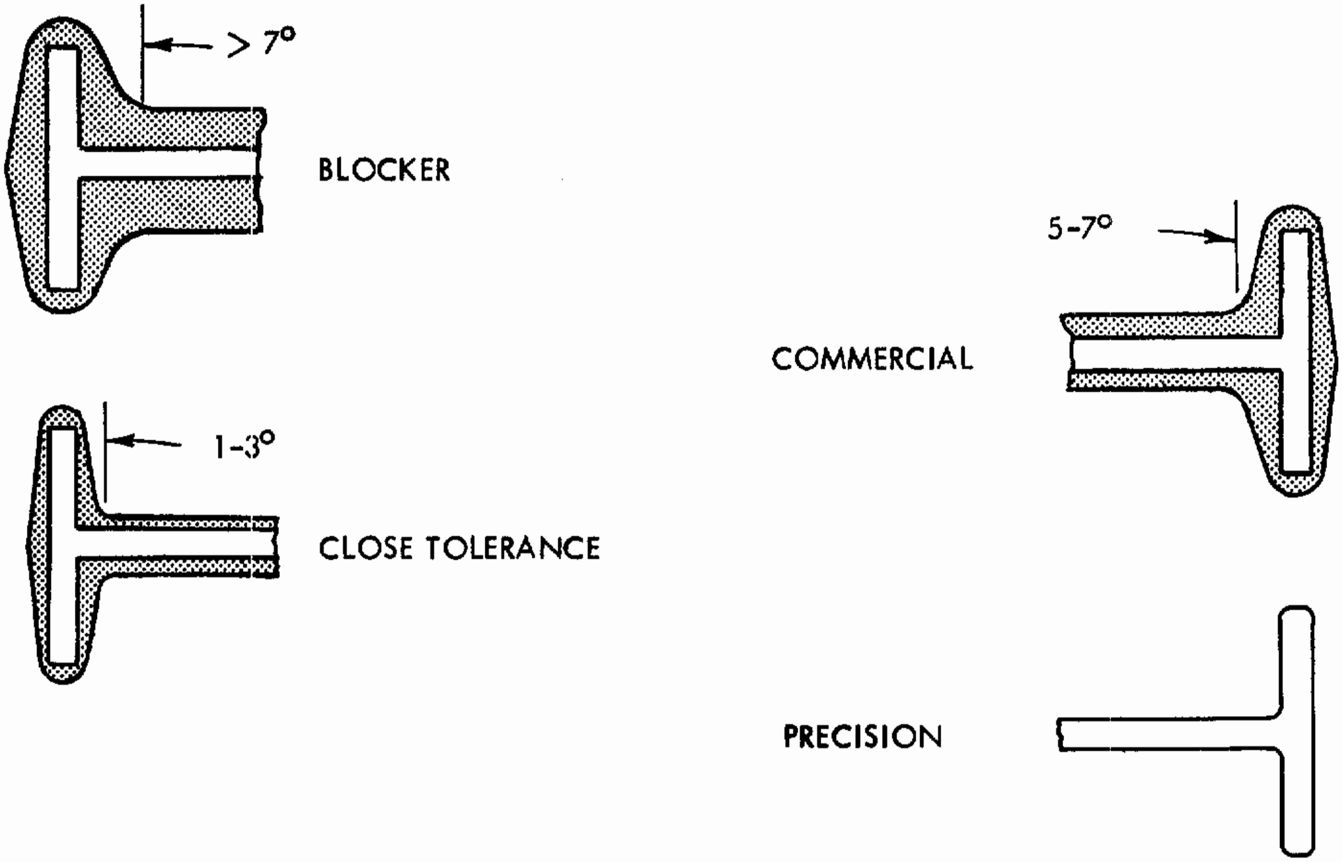

Figure 3. Forging Precision Classifications Based on the Characteristics of the Forging Design in Enveloping the Component Design. Reproduced from Reference 9.

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1. Dimensional comparisons of the forgings were to be based on their relative ability to be machined in a practical minimum number of passes to the component designs as determined by accurate profile inspection equipment and realistically defined maximum depths of cut; i.e., the ultimate goals were forgings from which a single finish machining pass (intermediate size) and two machining passes (large) could remove* a specified thickness of depleted or contaminated surface material and, at the same time, remove all excess material required by forging dimensional and tolerance considerations involving length, width, thickness, mismatch, radii, and draft angles (illustrated in Figures 4 and 5).

2. Quality comparisons of the forgings were to be based on their relative freedom from defects and their relative superiority of grain flow, microstructural characteristics, and mechanical properties of material heat treated to the highest tensile yield strength applicable to airframe structural use.

Separate work statements for efforts involving the intermediate size and the large forgings were negotiated among TRW and the previously listed forging subcontractors. Although similar, these work statements differed in the following general respects in addition to the obvious specific differences in equipment types and sizes and in number of materials to be forged:

1. Dimensional and quality goals for intermediate size forgings were equivalent for the three materials to be forged. In the efforts involving large forgings, however, the high strength steel forging comparisons were de-emphasized because the forgings were produced during tooling try-outs prior to subsequent production of the titanium alloy forgings. This was to provide maximum results while minimizing the high costs associated with manufacture, development, and operation of die systems to produce detailed forgings with the two large machines.

2. Dimensional goals were quite high for intermediate size forging efforts to promote demonstration of the relative capabilities of the four types of machines in producing highly detailed forgings. Since tolerance "stack-ups" related to machine guiding clearances, die accuracy, die wear, etc., currently prohibit practical consideration of such high degrees of detail in large forgings(6-8); the dimensional goals for the large counterblow hammer and the large press comparison were correspondingly less severe. The differences in goals are best realized by comparison of the single pass profile in Figure 4 with the total envelope in Figure 5.

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* It was not recommended that the forgings actually be machined. Note also, that comparison of forging tolerances involving straightness was not recommended, since straightness is primarily a function of cooling and post-forging heat treatment practices for the materials of program interest.

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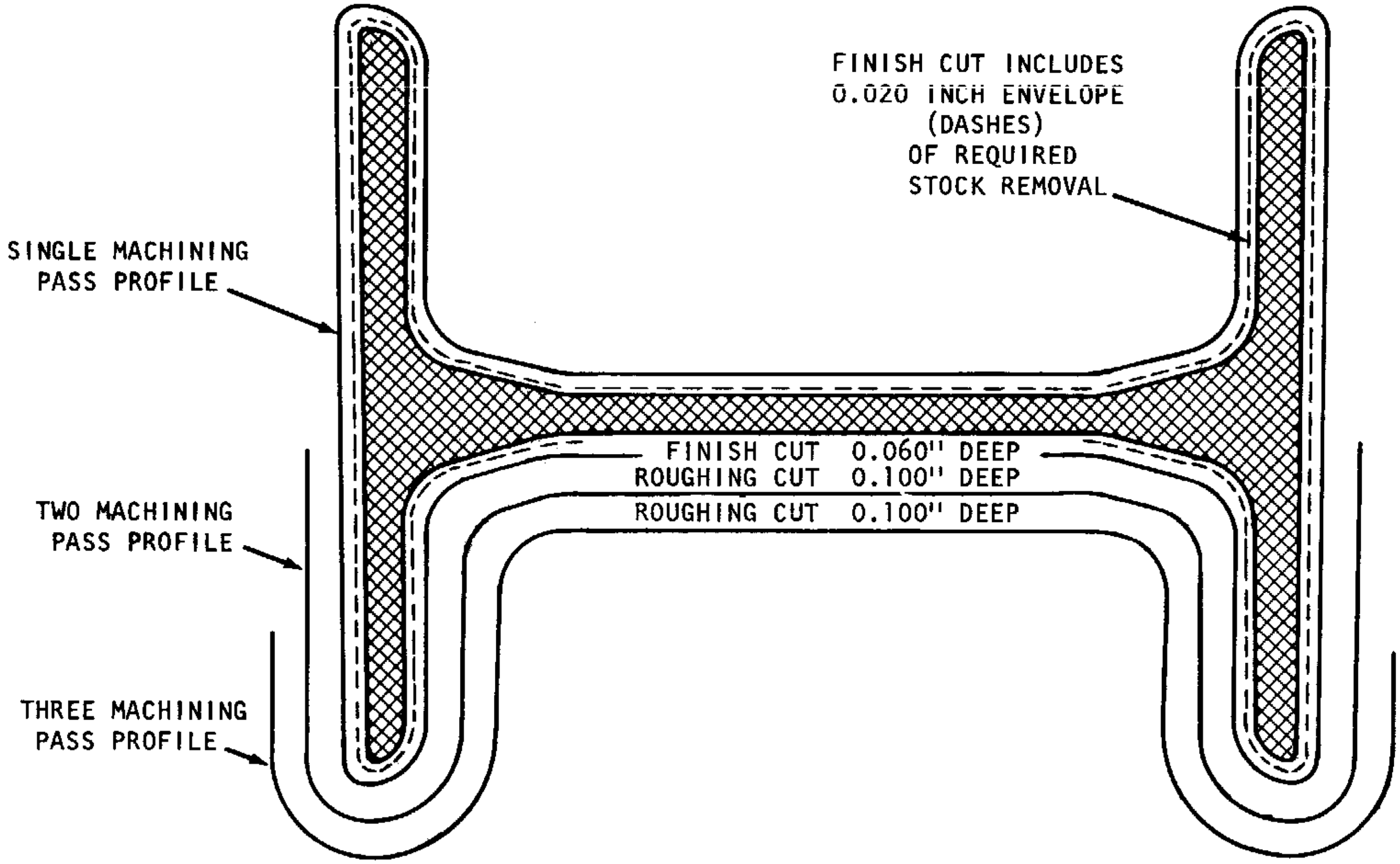

Figure 4. "Machining Pass" Concept for Rating Dimensional Characteristics of Intermediate Size Ti 6Al-4V Forgings. Envelopes of Excess Material Shown Superimposed Over the Fin Rib Component Cross Section (Cross Hatched) at Approximately Mid-Length. Comparable Envelope Thickness for Required Stock Removal, Finish Cut, and Roughing Cut, Respectively, were 0.040 Inch, 0.080 Inch, and 0.125 Inch for the D6ac Forgings; and 0.020 Inch, 0.050 Inch, and 0.080 Inch for the Inconel 718 Forgings.

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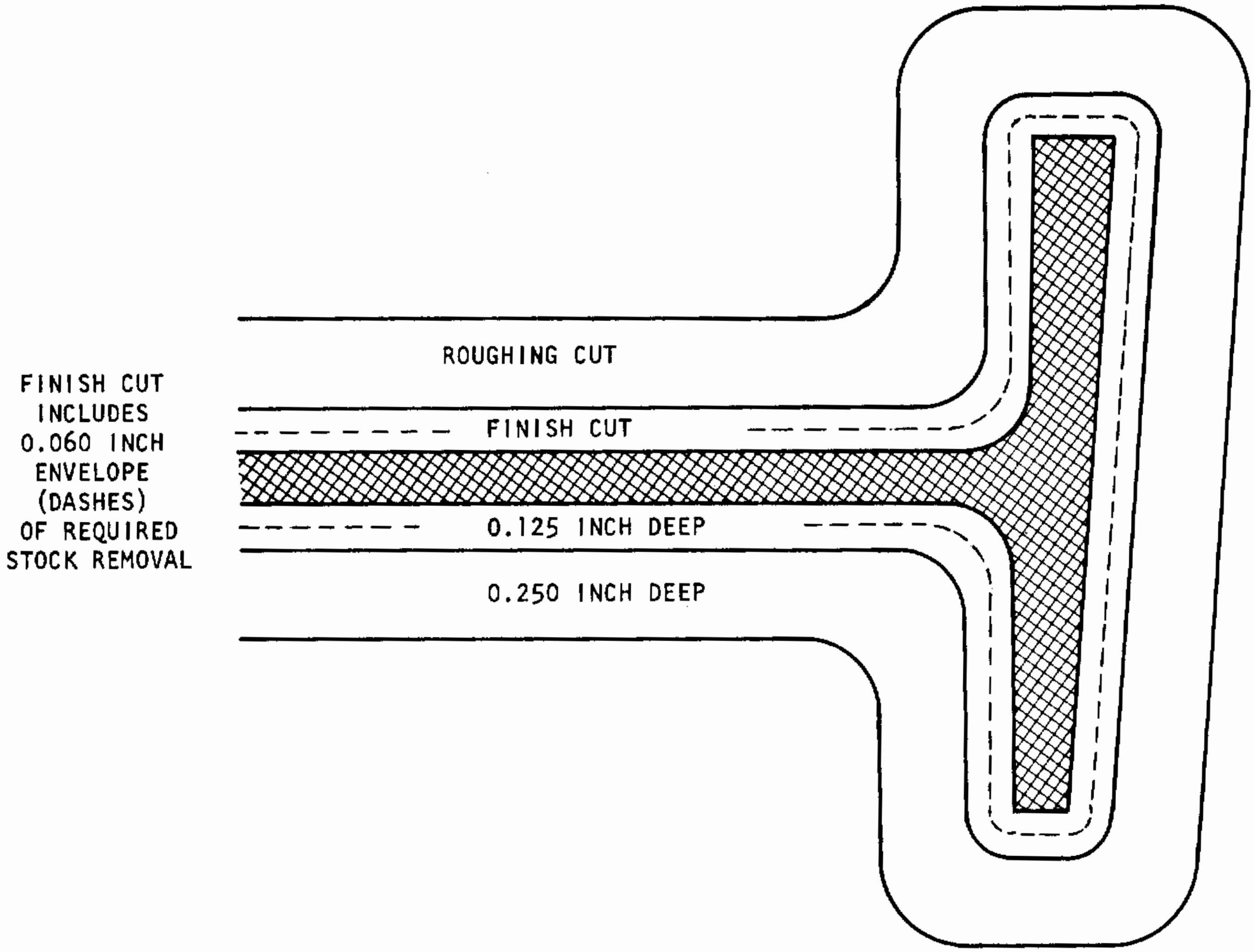

Figure 5. "Machining Pass" Concept for Rating Dimensional Characteristics of Large Ti 6Al-4V Forgings. Envelopes of Excess Material Shown Superimposed Over the Bulkhead Component Cross Section (Cross Hatched) at One End.

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IV PRODUCTION OF INTERMEDIATE SIZE FORGINGS

This report section describes the subcontracted design, tooling, and manufacturing efforts which were necessary to produce the 120 fin rib forgings (ten of each of the three materials from each of the four types of equipment) required for evaluation and comparison. Results of the subcontract efforts involving these intermediate size forgings are presented and discussed individually by equipment type in sub-sections A through D which follow. Results of the comparative evaluations performed by TRW are then presented in Section V of the report.

A. Steam Drop Hammer - Ladish Company

1. Forging Equipment

Forging hammers, as the name implies, perform work through rapid, repeated release of impact energy to the workpiece. The kinetic energy relationship $KE = 1/2\ MV^2$ applies to all hammers, thus the total energy transferred per blow, neglecting losses, can be calculated as a function of the moving weight and the closure rate of the dies at the moment of impact.

An illustration of a typical steam drop hammer design is shown in Figure 6. Basically, such a hammer is similar to a gravity drop hammer in operation except that steam pressure in the double acting upper cylinder provides both greater acceleration for the ram and upper die during the working stroke (variable per blow as a function of treadle control of the steam flow rate) and a means of rapidly returning the ram and upper die for the next stroke. During the blow the workpiece is supported by the lower die, the lower die holder, and the anvil; which together act as an inertia block to resist the blow and thus to assist in forcing the energy into the workpiece.

It is apparent that tooling changes during forging of different components with a steam drop hammer can moderately change the maximum energy capable of being delivered to the workpiece as functions of:

a) the thickness of both die blocks as this affects the stroke and thereby the distance through which the moving weight can be accelerated to maximum velocity,

b) the weight of the upper die block as this affects the total moving weight, and

c) the relationship between the total stationary or inertia block weight and the total moving weight as this ratio affects the relative portion of the energy transmitted into the foundation as "anvil losses".

It is further apparent, therefore, that although equipment producers can design to specific values for steam pressure and to approximate values for foundation support given the anvil and friction losses due to packings and guides, they cannot rate their hammers to other than nominal values for weights and stroke under conditions of maximum treadle. Once procured, the

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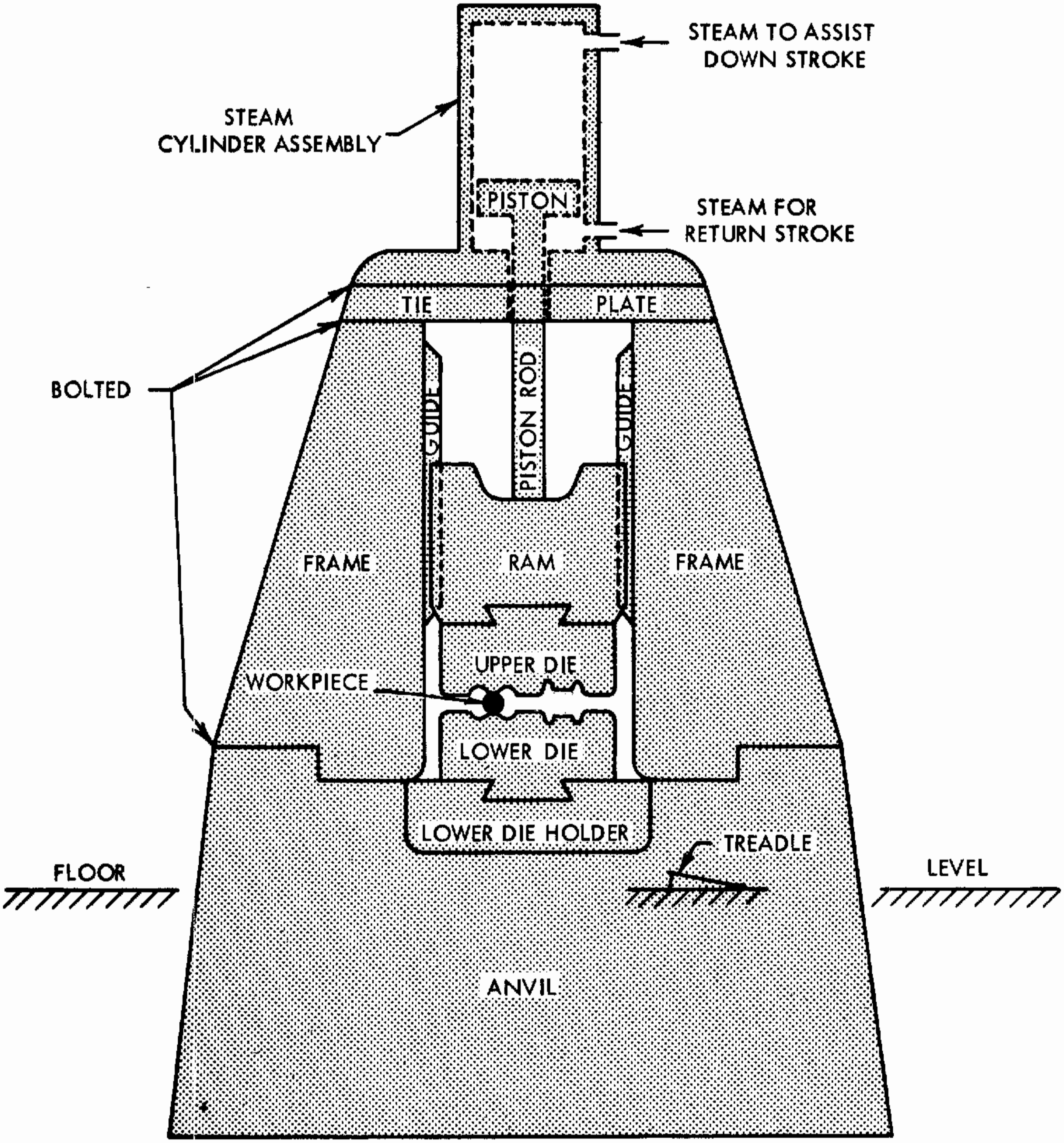

TIMBERS AND FOUNDATION BENEATH ANVIL

Figure 6. Simplified Illustration of Steam Drop Hammer Construction Showing Major Components. Steam Generation Facilities and Valving for Throttling (Treadle Controlled), Return, and Exhaust Not Shown. Multiple Impression Dies, as Illustrated, Were Not Used to Produce the Fin Rib Forgings.

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performance of a steam drop hammer relative to energy applied to the workpiece per blow depends significantly upon the characteristics of the foundation and upon the tooling supplied by the forger.

The 12,000 pound Erie Foundry Company steam drop hammer employed by the Ladish Company to produce the thirty required fin rib forgings is shown in Figure 7. This hammer is rated for a 43 inch stroke and a maximum impact (at contact) velocity of 25 feet per second under full treadle. Using the rated falling ram weight alone (12,000 pounds) the theoretical (discounting losses) kinetic energy per blow under conditions of maximum velocity impact can be calculated to be approximately 116,000 foot pounds. A theoretical maximum kinetic energy value approaching 140,000 foot-pounds per blow was reported by Ladish to be more correct, and can be calculated by assuming that the hammer was designed to achieve the rated maximum contact velocity with a moving assembly weight at least 20 percent in excess of the falling weight rating; i.e., ram weight = 12,000 pounds, approximate piston and rod weight = 1200 pounds, approximate average upper die weight = 1200 pounds. Ladish also indicated that an "all-out" blow is seldom used in actual practice, and that 85% of the maximum energy is a reasonable approximation of the average energy per "hard" blow. This results in an energy value of less than 120,000 foot-pounds per blow, and is the reason why Ladish listed the contact velocity as 22.8 feet per second (274 inches per second).

This hammer was, of course, used in multiple-blow operation to produce the fin rib forgings, and it should be noted that energy comparisons with other types of forging equipment should not be attempted without considering: 1) the accumulative energy release characteristics of multiple hammer blows, and 2) the variable treadle setting, discussed subsequently, which hammer operators frequently employ from the first to the last blow.

2. Tooling Concept and Finish Forging Design

The die parting line location and section details of the finish forging design employed by Ladish during production of fin rib forgings with the steam drop hammer are shown schematically in Figures 8 and 9. It can be noted that the finish die impression:

a) employed a horizontal parting line located at one (lower) edge of the rib detail rather than the "central parting line" (web plane) die concept more conventionally employed for "H" section rib and web forgings;

b) included the natural draft of the component (0° 40' along all outer surfaces of the side ribs) within a three degree typical external draft allowance in the upper die;

c) included a five degree typical internal draft allowance; and

d) was designed to produce typical fillet radii of 0.313 inch and typical corner radii of 0.125 inch on the forgings.

These features are all in accord with advanced tooling design and forging practices(1-3) for machines (hammers) which are not generally considered practical to equip with ejector mechanisms.

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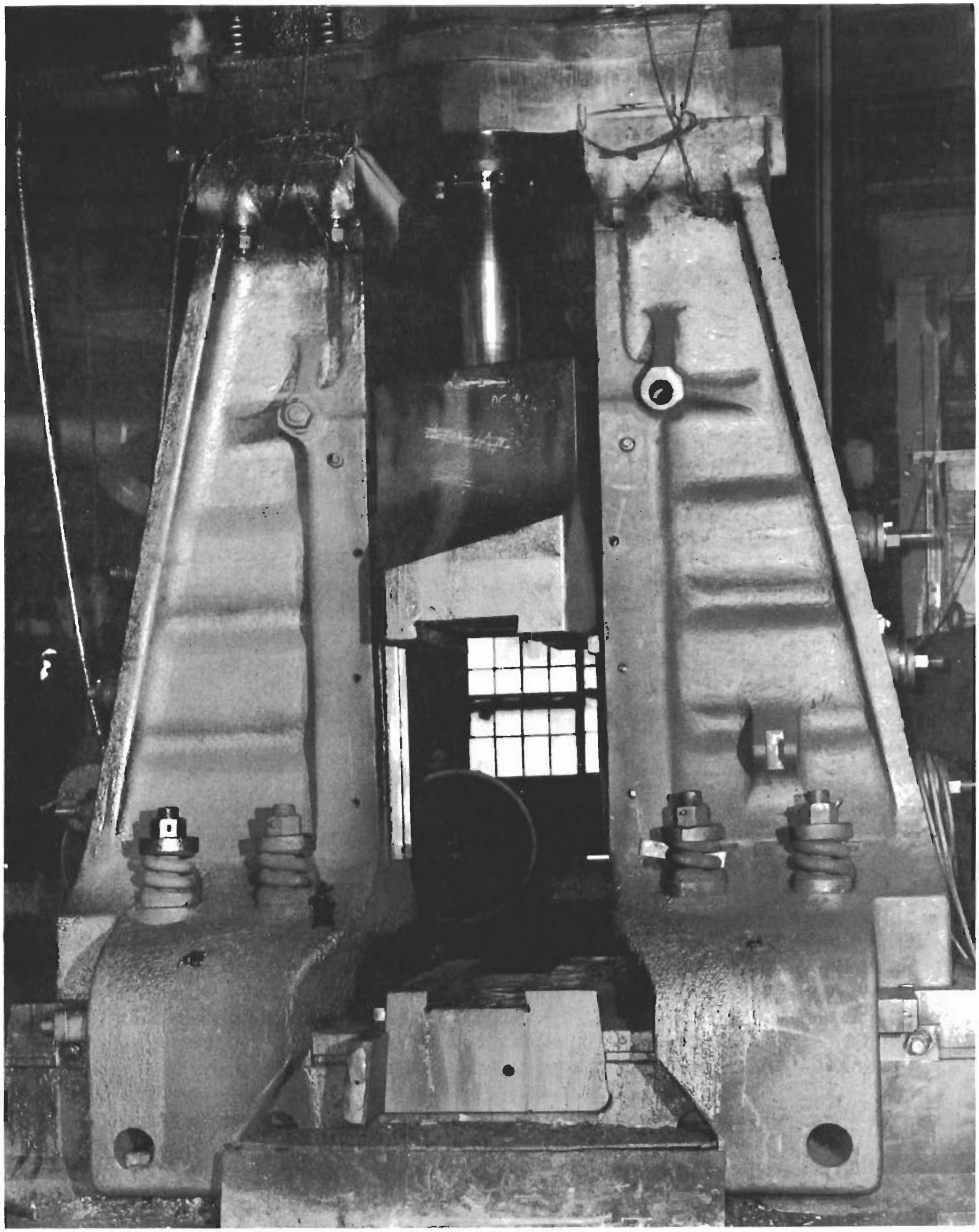

Figure 7. Steam Drop Hammer Rated at 12,000 Pounds Ram Weight and Employed by the Ladish Co. to Produce Fin Rib Forgings. Shown From Rear with Dies Removed. Operator's Position is on other Side. Note Exit End of Gas-Fired, Pusher Type Furnace at Right of Hammer Which was used to Heat all Workpieces for Forging.

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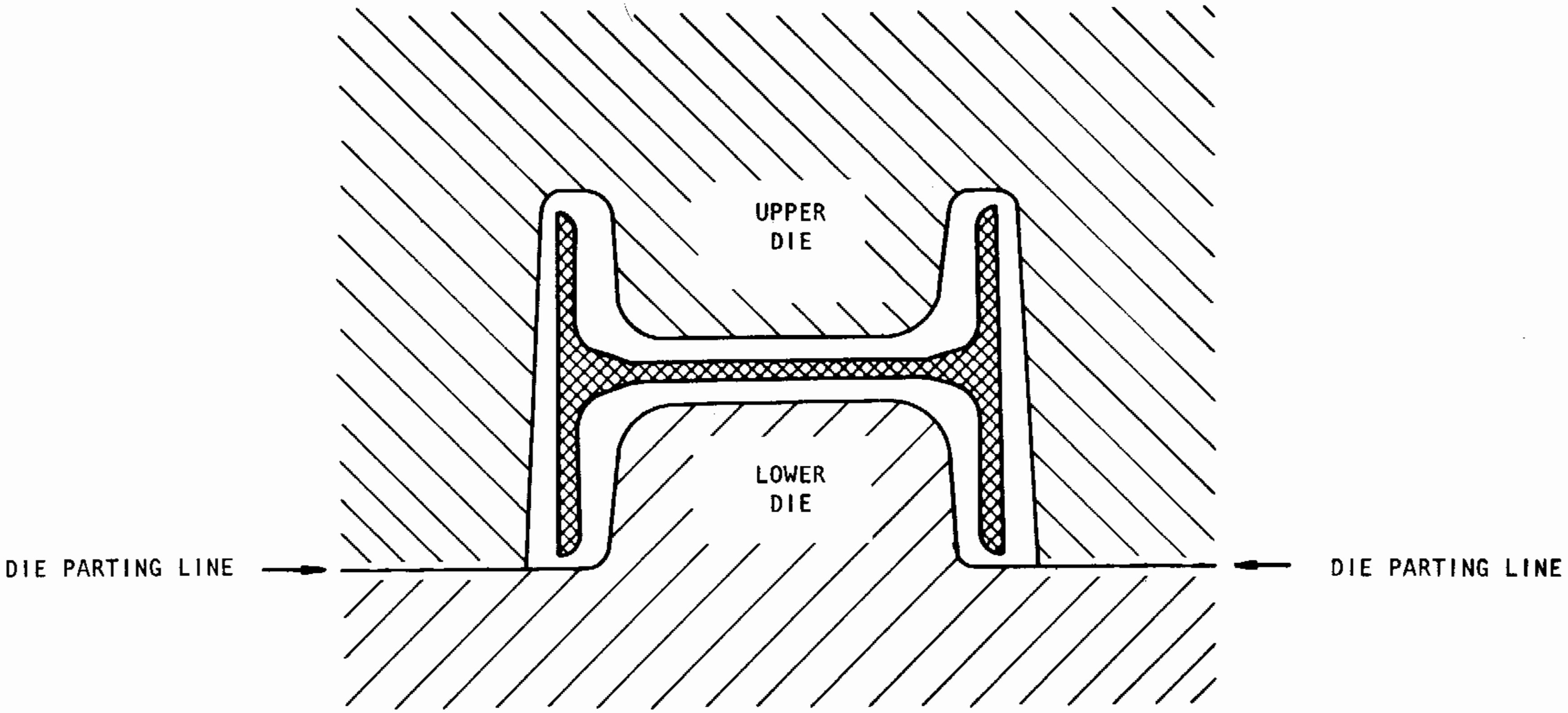

Figure 8. Schematic Illustration of Fin Rib Cross Section (at approximately mid-length) with Finish Forging Die Impression for 12,000 Pound Steam Drop Hammer Superimposed to Target Closure. Approximately Full Scale. Similar, Less Detailed Blocker Die Impressions for Prior Operations were Employed Inverted in Comparison to the Above Orientation. Also, Initial Forging Trials Employed the Finish Impression Inverted Relative to the Above - See Text.

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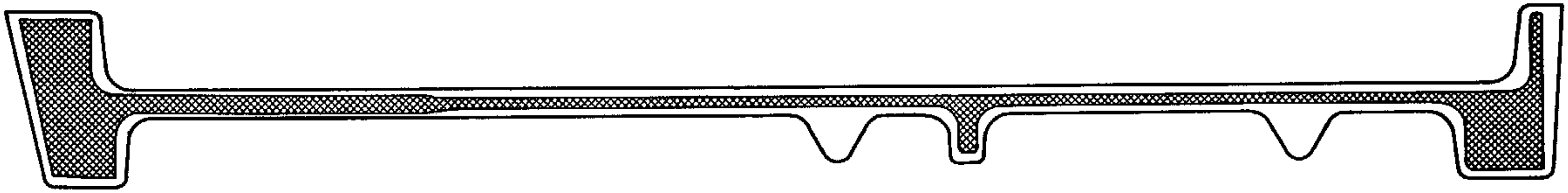

Figure 9. Illustration of Fin Rib Longitudinal Section (at mid-width) with Target Finish Forged Shape for 12,000 Pound Steam Drop Hammer Superimposed. Slightly Less than One-Half Scale. Shown in Correct Perspective for Initial Forging Trials, but Inverted Relative to Orientation in Finish Die Impression During Final Production of Intermediate Size Forgings. See Text.

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The two 60 degree included angle "pimples" which can be observed along the lower surface in Figure 9 represent the common locators applied by TRW to all of the intermediate size forging designs to serve for dimensional reference during inspection and evaluation of the forgings.

3. Staging Sequence and Starting Stock

The fin rib forging sequence of shapes, or stages, initially designed for the hammer forging effort is shown in Figure 10. During early die "try-outs" with carbon steel workpieces, this resulted in a moderate lack of fill condition at the three corners on the side away from the parting line. This can be observed in Figure 11. Additional trials conducted with larger starting billets of carbon steel and of Inconel 718, selected to span the range of resistance to metal flow, confirmed the inadequacy of the initial die sequence in preventing excessive amounts of metal from being lost from the corners as flash during the first and second blocker operations.

The modifications chosen by Ladish are partially illustrated in Figure 12. First, starting volume was increased in changing from 2-3/4 inch round-corner-square by 11-3/4 inch long stock, to a machined tapered cylinder 18-5/8 inch long with end diameters of 2-13/16 inch and 1-7/8 inch. Second, the tapered cylinder was flattened and then further tapered at the "nose" end during an open frame hammer forging operation to the preform shape in Figure 12. This degree of "preshaping" prior to the impression die operations is in marked contrast to the simple tapered rectangular preform shown in Figure 10. Third, the blocker shapes were altered to retain greater volume at the corners. This can be observed as increased corner thicknesses in Figure 12. Fourth, the dies for the finish shape were inverted in the hammer such that the parting line was at the bottom and the "hard-to-fill" corner detail was produced by the top die. This was in recognition that the lower-die side of a workpiece is chilled to a greater degree during multiple-blow hammer forging.

Modifications in the hammer forging dies which were also made to improve corner fill are discussed subsequently, and results of a third series of trials, this time with eight carbon steel and four Inconel 718 workpieces, confirmed that the sequence and tooling changes were effective in providing complete fill. During these trials, one Inconel 718 workpiece was withdrawn after each impression die forging operation to establish a permanent record of what each die produced. These forgings are shown in Figure 13.

Upon completion of the trials which resulted in the Figure 13 forgings; D6ac, Ti 6Al-4V, and Inconel 718 stock of 3 inch diameter was sectioned and machine tapered to twelve starting billets of each material to be forged. These resulted in the ten forgings of each which were delivered to TRW for evaluation. The data supplied by Ladish relative to starting stock composition and quality are listed in Table 1.

4. Forging Tooling

Separate sets of upper and lower dies were employed for each of the four impression-die hammer forging operations shown in Figure 12. Each set was identical except for the impressions, and each upper and lower block had

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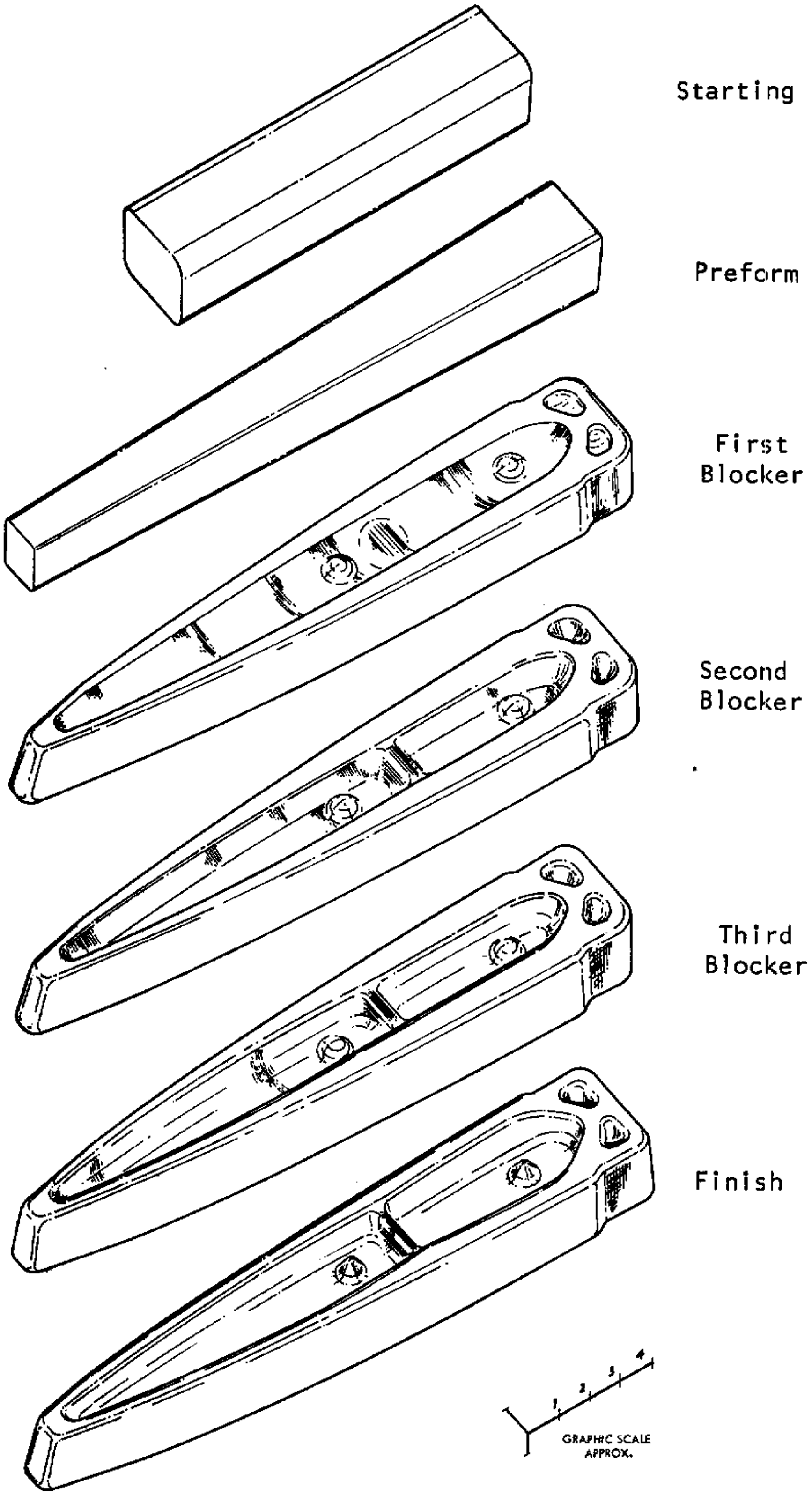

Figure 10. Illustration of Fin Rib Forging Staging Sequence Initially Designed for Forging Efforts with 12,000 Pound Steam Drop Hammer (Blockers and Finish). Blocker and Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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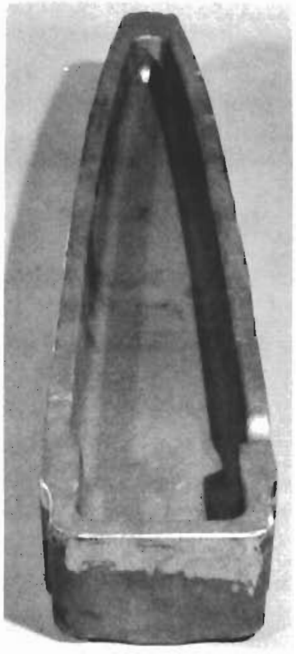
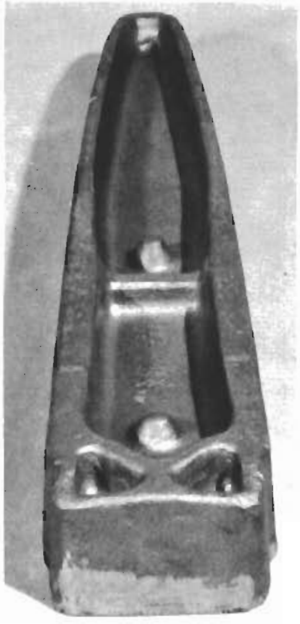


Upper Die Side



Lower Die Side

Figure 11. Carbon Steel Forging Produced During Initial Die Try-Outs with 12,000 Pound Steam Drop Hammer. Shown "As-Forged" Except for Sandblasting and Flash Trimming Operations. Approximately 0.35X.

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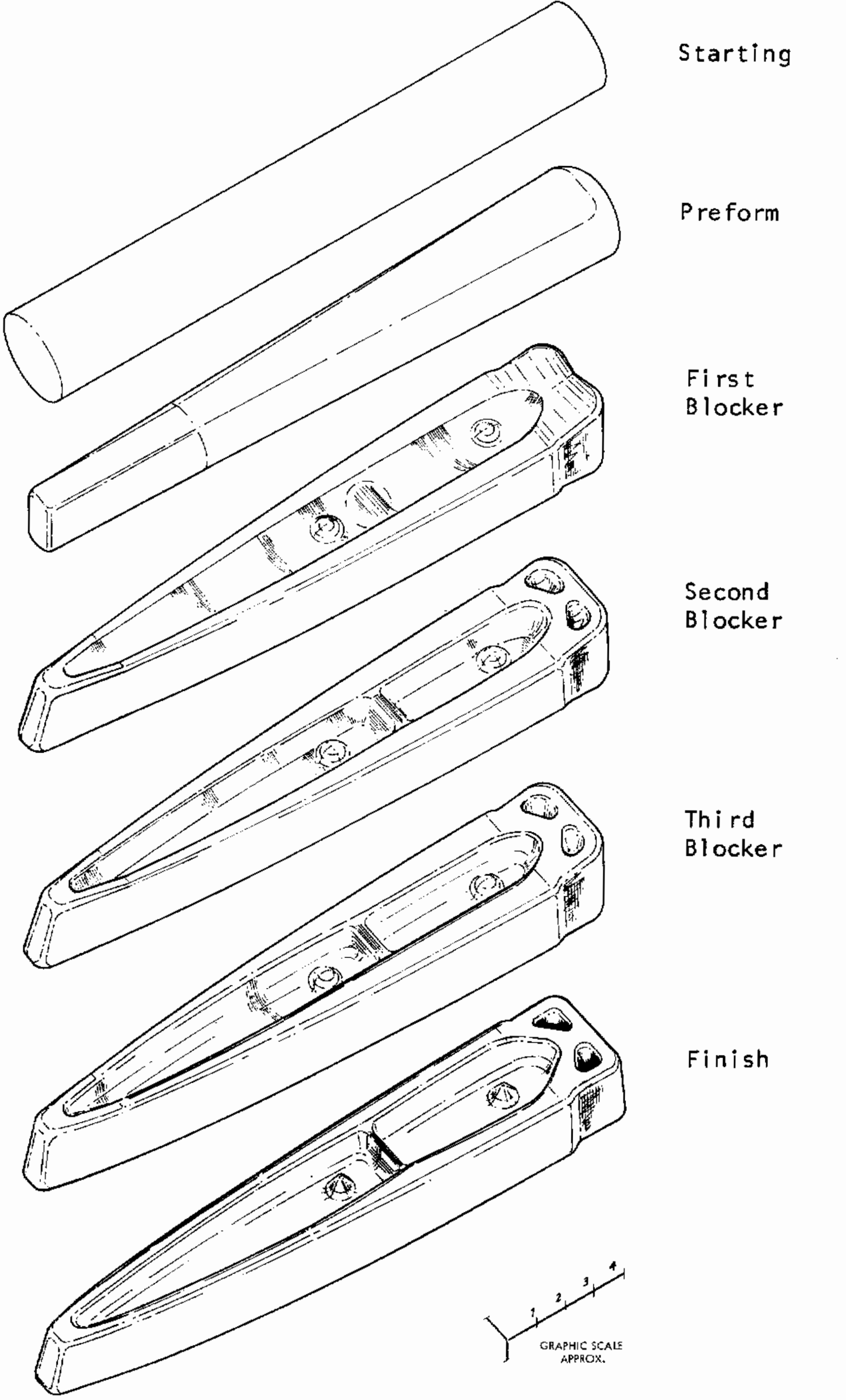

Figure 12. Illustration of Modified Fin Rib Forging Staging Sequence Employed for Final Production of Intermediate Size Forgings with 12,000 Pound Steam Drop Hammer (Blockers and Finish). Blocker Shapes are Shown Inverted to Reflect Lower Die Impression Detail. Note that Starting Stock was Machine Tapered Prior to Preforming - See Text.

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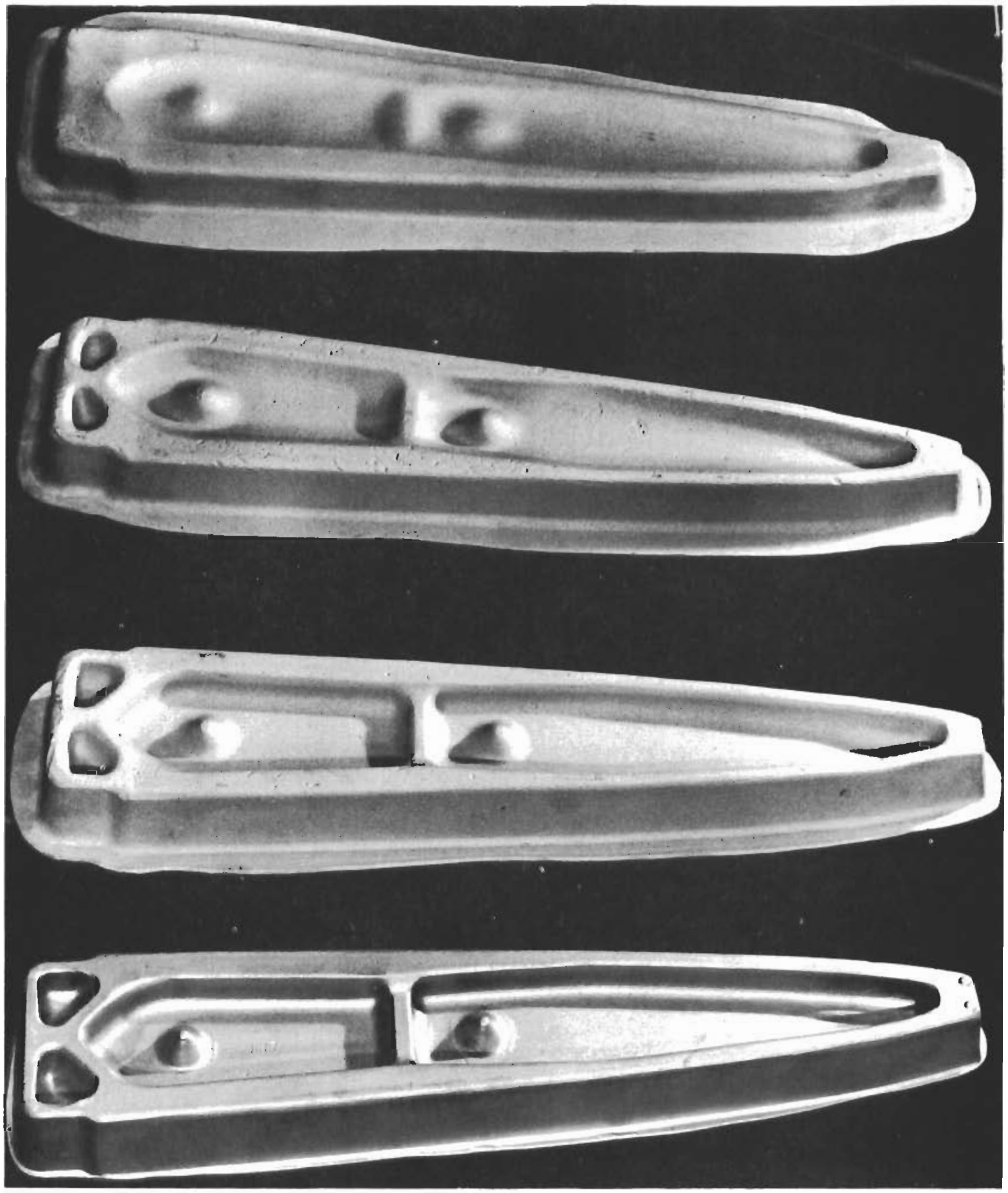

Figure 13. Intermediate and Finish Fin Rib Forgings of Inconel 718 Alloy Produced During the Third Series of Forging Trials with 12,000 Pound Steam Drop Hammer Prior to Final Production of Forgings for TRW Evaluation. Approximately 1/3X.

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TABLE I

Material Data for Intermediate Size Fin Rib Forgings Produced with a 12,000-Pound Steam Drop Hammer

Chemical Analysis	C	N	O	Al	V	H	Fe	Ti	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	B	Cb+Ta	Others
D6ac	0.46				0.10		Bal.		0.79	0.004	0.007	0.23	0.56	1.10	0.98	0.15				
Ti 6Al-4V	0.015	0.011	0.14	6.70	4.11	0.0034	0.21	Bal.												<0.05
IN 718	0.04			0.62			17.43	0.98	0.15	0.009	0.006	0.15	53.30	18.56	3.09	0.05	0.06	0.0038	5.50	

	D6ac	Ti 6Al-4V	IN 718
Material Source	Republic Steel Corp.	Titanium Metals Corp.	Carpenter Technology Corp.
Heat Number	Airmelt No. 8023794-3 VAR No. 3962210	K-2938	87807
Starting Stock Form	13 inch RCS billet drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.	17-1/2 inch round billet drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.	20 inch round ingot drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.
Starting Stock Weight	37.4 pounds before machining to taper, see text.	21.1 pounds before machining to taper, see text.	39.1 pounds before machining to taper, see text.
Procurement Specifications	AMS-6431	AMS-4967A	AMS-5664A
Other Inspection Procedures	Ultrasonically Inspected	Ultrasonically Inspected	Ultrasonically Inspected

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basic overall dimensions of approximately 30 inch length by 22 inch width by 10-1/2 inch height (not including the "dovetail" shank projection which held the dies). The dies were all prepared by conventional machining of wrought, prehardened blocks of Ladish D6 steel (nominal analysis 0.46C, 0.75Mn, 1.05Cr, 1.00Mo, 0.55Ni, 0.11V, bal. Fe). Hardness was within the range Rc 37 to 40.

Design concepts for each set of upper and lower dies are illustrated (as a side view relative to installation in the hammer) in Figure 14. Square guide posts and receptacles were machined into four corners of the blocks as shown to minimize mismatch at closure. These had generous radii and ramp angles (not shown) for engagement, and were characterized by very close vertical wall-to-wall clearances between the mating surfaces.

Figure 14 also illustrates that the impression dies for the hammer were designed for conventional use of flash to assist in forcing workpiece metal into the cavities. As initially employed during the first two series of trials, the first blocker dies were designed to close totally on the flash itself and the remaining dies in the sequence had 5/8 inch wide flash lands surrounded by gutters. These last three sets of dies were designed to control forging thickness by "kissing" on the large flat surfaces surrounding the gutters to produce approximately 1/8 inch thick flash at the land. After the second trials indicated continued difficulty in obtaining complete corner fill, however, several modifications in die design details were made in addition to the previously discussed changes in the staging sequence. First, the dies for the first blocker operation were modified to include flash gutters and 3/4 inch wide flash lands around the upper and lower impressions. Also, a 1/8 inch radius flash retainer groove was machined midway across the land at each end of both impressions. These details can be seen in Figures 15 and 16, which show the actual dies after completion of all program forging efforts. Second, the flash land details of the second blocker dies were modified to also be 3/4 inch wide with the retainer grooves at the ends of the impressions. Third, the upper finish die was modified to include 3/16 inch diameter vent holes from the hardest-to-fill impression recesses to allow possible trapped gases to escape through the sides of the block. Figures 17 and 18 show the finish dies after forging, and the vent holes can be observed at the base of the locator pimple impressions in Figure 18. The six vent holes locations are more easily seen in Figure 19, which shows typical hammer forgings produced of the D6ac, Ti 6Al-4V, and Inconel 718 materials prior to trimming of flash and of the protuberances produced by the vent holes.

The semicylindrical section at the upper right of the finish die impression in Figure 17 corresponds to the semicylindrical hole on the reverse side rib edge of the machined fin rib component which can be seen in Figure 1. This was considered a machining detail by TRW and it was deleted as a forging requirement from the Cameron Iron Works and the Precision Metal Products designs prior to manufacture of dies. This deletion, however, was inadvertently not transmitted to Ladish until after the hammer and mechanical press dies were completed. For this reason only the Ladish dies and the Ladish produced forgings contain this detail.

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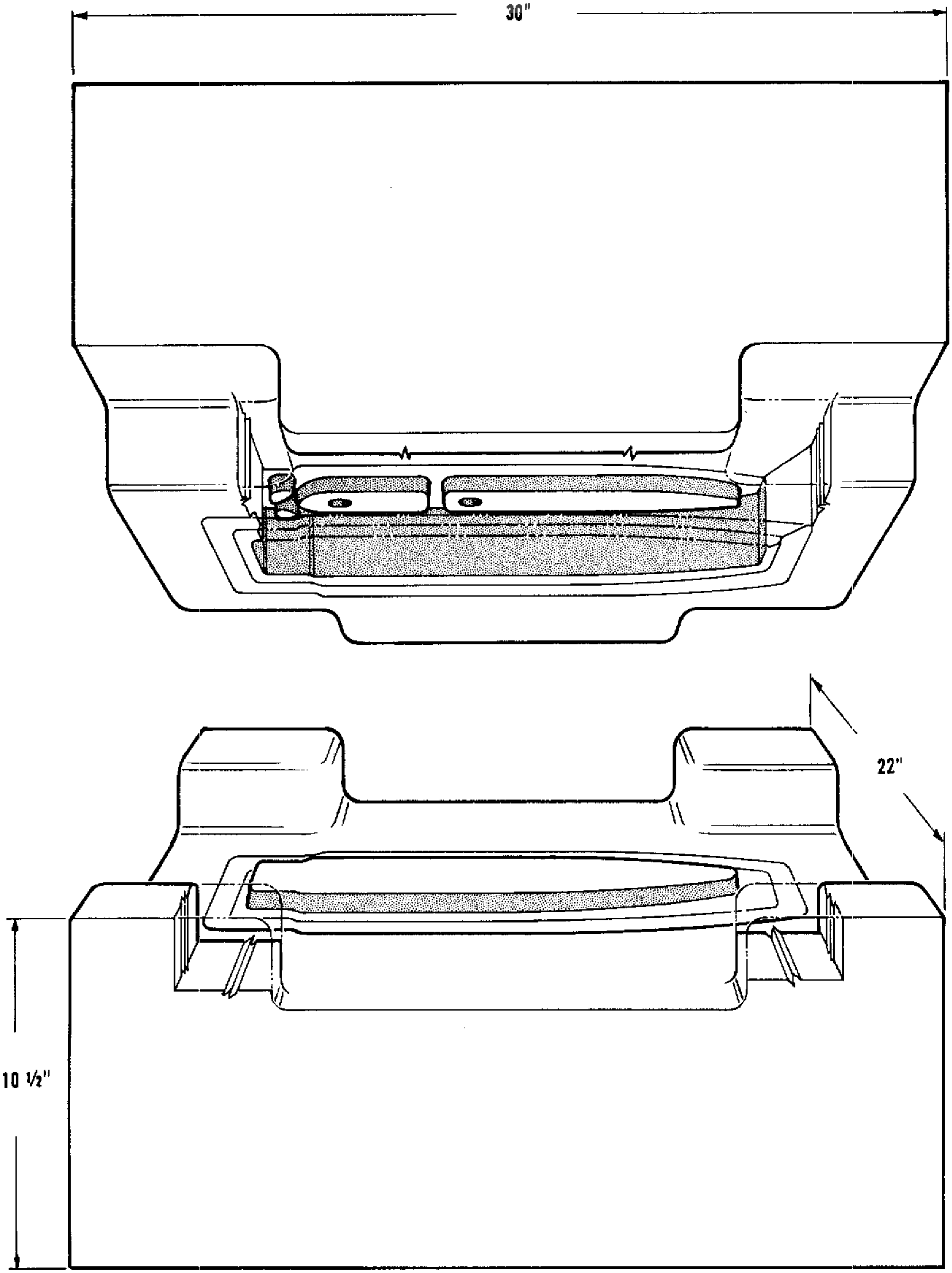

Figure 14. Schematic Illustration of Impression Dies for Finish Fin Rib Forging Operation with 12,000 Pound Steam Drop Hammer. Similar Dies for Prior Blocker Operations were Employed Inverted in Comparison to the Above Orientation.

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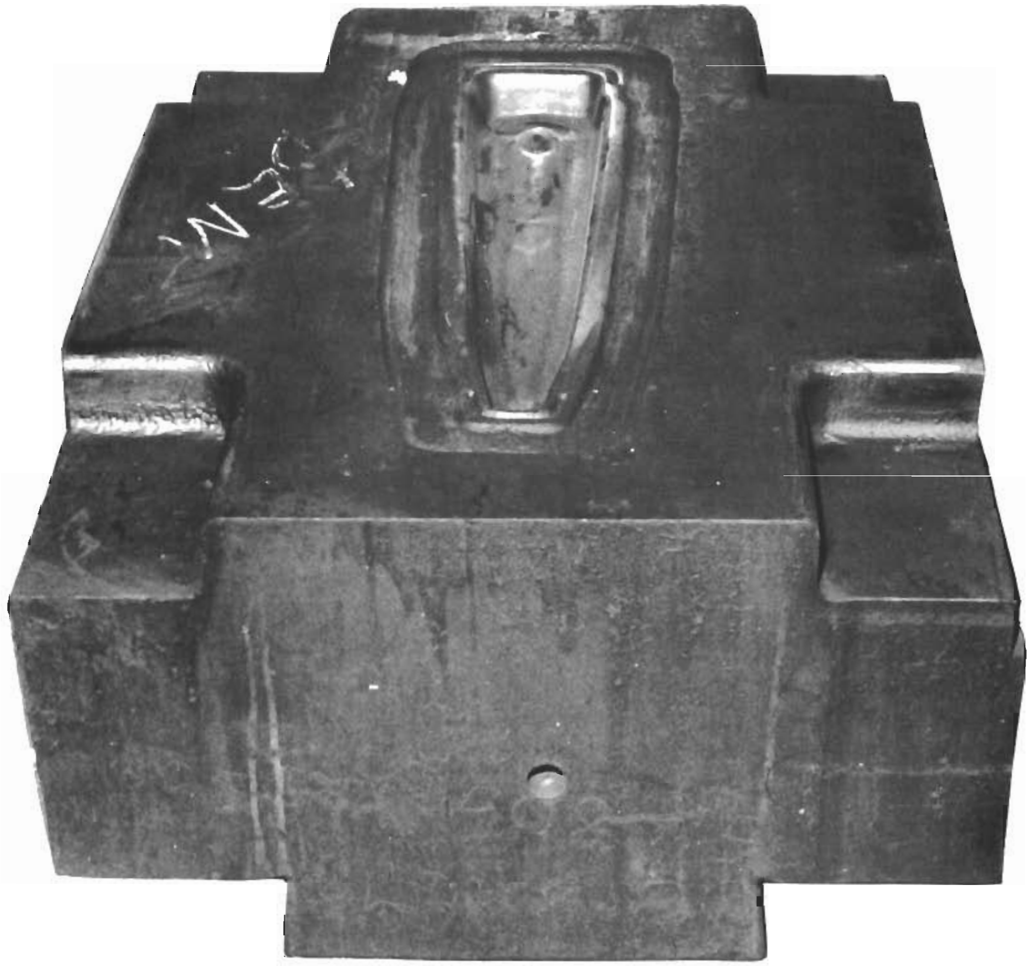

Figure 15. Lower Die for the First Blocker Forging Operation with the 12,000 Pound Steam Drop Hammer. Note Flash Retainer Grooves in Flash Lands at Ends of Impression. Photograph Taken after Completion of All Program Forging Efforts with the Hammer.

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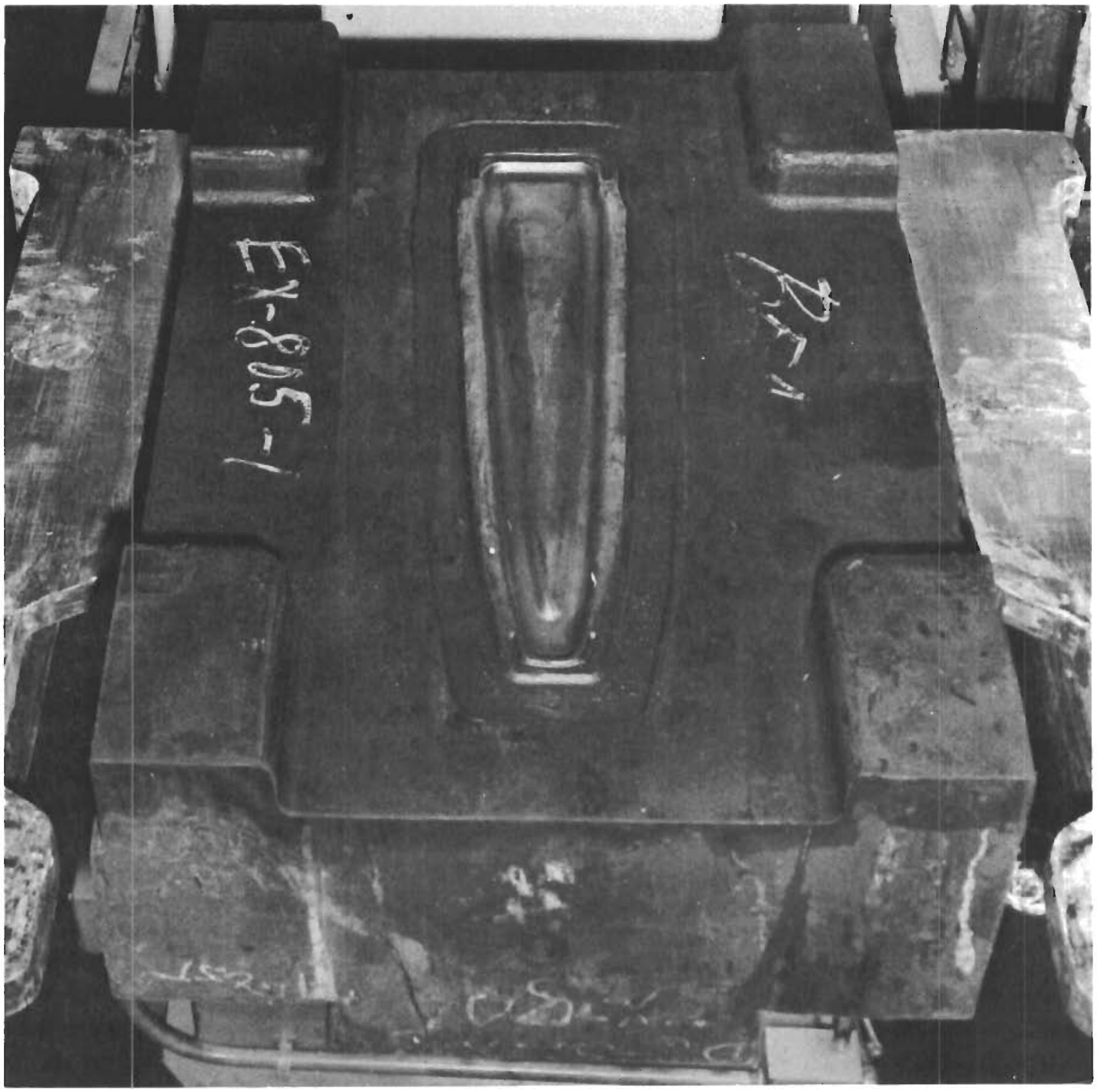

Figure 16. Upper Die for the First Blocker Forging Operation with the 12,000 Pound Steam Drop Hammer. Note Flash Retainer Grooves in Flash Lands at Ends of Impression. Photograph Taken after Completion of All Program Forging Efforts with the Hammer.

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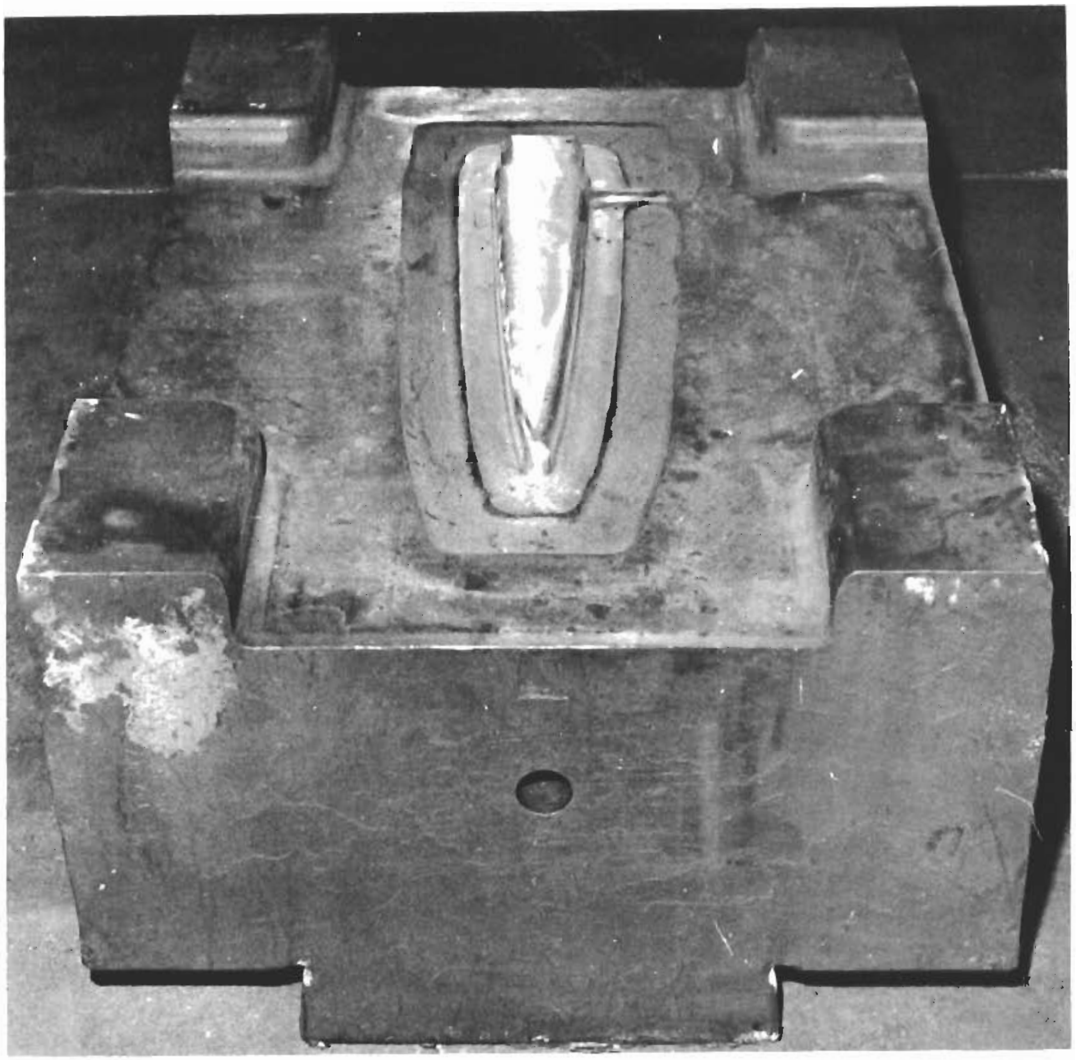

Figure 17. Lower Die for the Finish Forging Operation with the 12,000 Pound Steam Drop Hammer. Impression Polished and Photograph Taken after Completion of All Program Forging Efforts with the Hammer.

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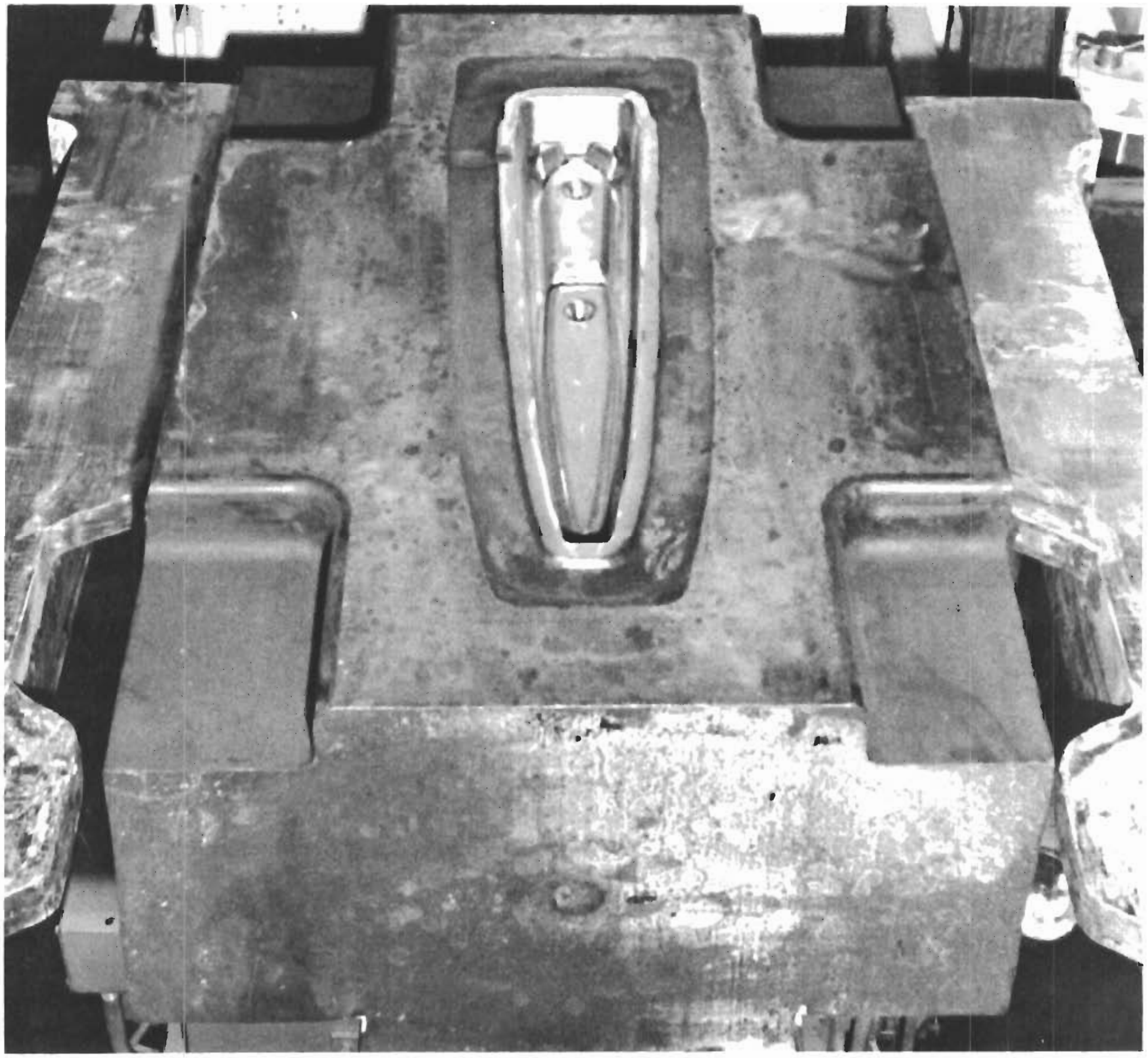

Figure 18. Upper Die for the Finish Forging Operation with the 12,000 Pound Steam Drop Hammer. Note Vent Holes at Base of Locator Pimple Impressions. Four Other Vent Holes at the Four Extremities of the Impression Cannot be Seen. Impression Polished and Photograph Taken after Completion of All Program Forging Efforts with the Hammer.

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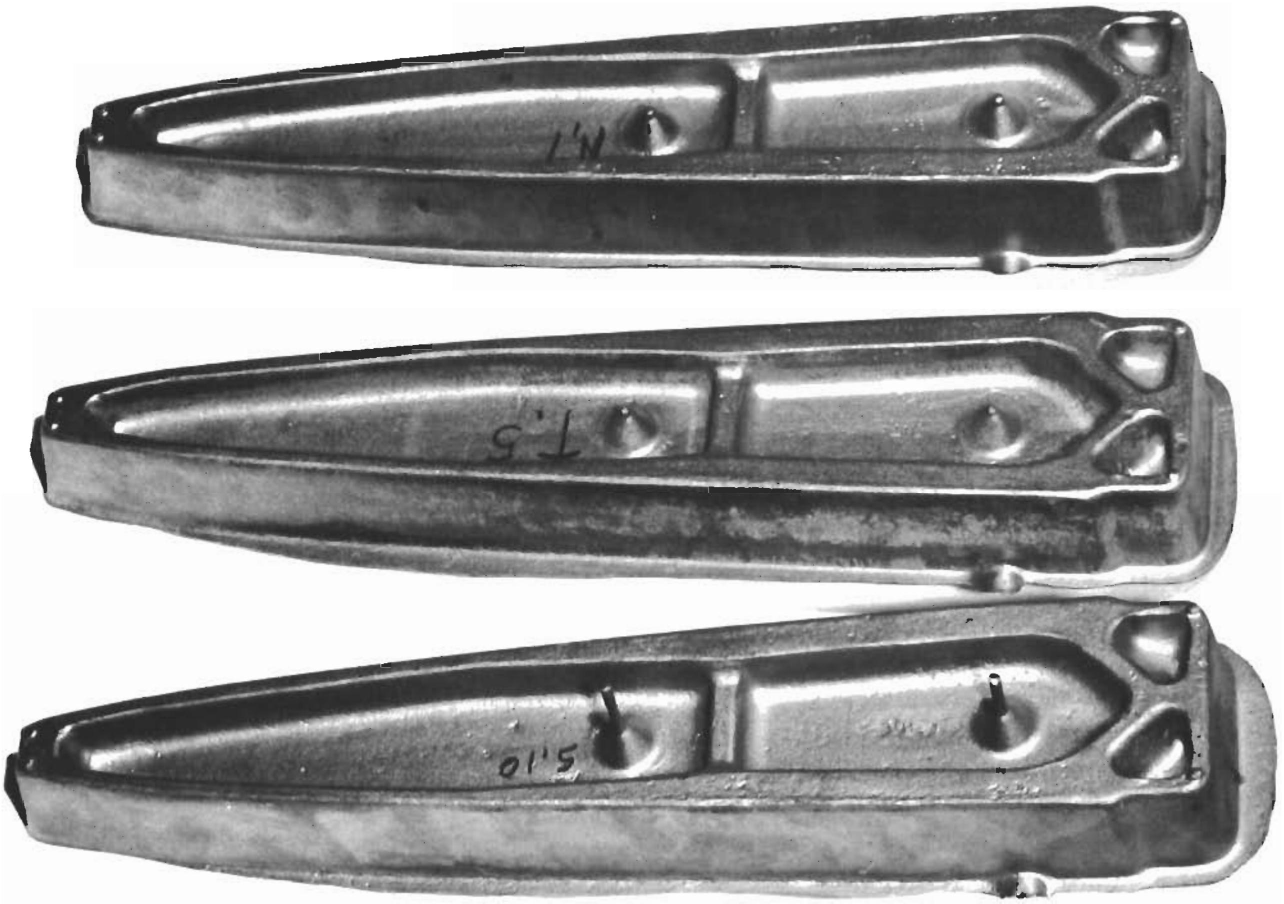

Figure 19. Representative Fin Rib Forgings of D6ac (bottom), Ti 6Al-4V (center), and Inconel 718 (top). Produced with 12,000 Pound Steam Drop Hammer During Final Production of Forgings for TRW Evaluation. Photographed Prior to Removal of Flash or Protuberances Left by Vent Holes in Upper Finish Die. Approximately 1/3X.

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In compliance with requirements of the common work statement for all subcontract efforts involving intermediate size forgings, workpiece dimensional shrinkage factors employed for the design of the impressions were predicated upon forging of the Ti 6Al-4V alloy below the beta transus. This feature also applied to all tooling for the other forging equipment types.

5. Forging Results

Forging of the twelve workpieces of each material with the 12,000 pound hammer proceeded without incident. For each set of impression dies the Ti 6Al-4V pieces were forged first, the Inconel 718 pieces were forged second, and the D6ac pieces were forged last, i.e., as a function of increasing heating temperature desired for forging. This allowed the most effective utilization of furnace and hammer time. As the last piece of one material was removed from the gas-fired pusher-type furnace, the furnace temperature controller was reset to the higher temperature for the next material. Removal of workpieces from the furnace and transfer to the hammer was accomplished with the assistance of a manipulator resembling a fork-lift truck with a gripping and manipulating mechanism in place of the forks.

The processing data recorded during these forging efforts are listed in Table 2. It can be noted that a protective coating, proprietary to Ladish, was painted onto the titanium alloy workpieces prior to heating for each forging operation. The steel and nickel-base alloy workpieces were heated and forged without a coating, but it should also be noted that the steel workpieces were heated in individual muffles to limit formation of scale. Each muffle was merely a piece of steel pipe with one end closed and the other end fitted with a cap. Scaling was reduced by retarding the supply of oxygen once the initial amount of oxygen within the muffle had combined with the steel. The cap and workpiece were removed from the muffle immediately prior to forging.

Intermediate operations included abrasive blasting, flash trimming by torch cutting and grinding, and conditioning as necessary by grinding. These procedures were conducted after each of the three blocker forging operations in the sequence. The finish forgings were abrasive blasted at Ladish and trimmed at TRW by band sawing and grinding.

Of the twelve D6ac hammer forgings produced, the ten delivered are shown in Figures 20 and 21. The mottled surface appearance of the Figure 20 forgings is the result of nonuniform abrasive blasting at TRW after trimming and before photography (this effect is even more pronounced in subsequent figures showing the titanium alloy and nickel-base alloy forgings). The surfaces were observed to exhibit slight scale pitting effects, particularly those surfaces formed by the lower die impression. Upon visual examination, several of the forgings also exhibited indications of minor laps in the fillet radii from mid-length to the "nose" end of the cavity formed by the lower die. The most severe such condition is shown in Figure 22 after localized application of red dye penetrant and developer (the latter is a white powder which "blots" the penetrant back out from open surface defects) to improve photographic resolution. Although the indication was noted to be virtually free of penetrant, as can be observed

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TABLE 2

Processing Data for Intermediate Size Fin Rib Forgings Produced with a 12,000-Pound Steam Drop Hammer(a)

	Material		
	D6ac	Ti 6Al-4V	IN 718
Furnace Type	Gas Fired	Gas Fired	Gas Fired
Furnace Atmosphere	Muffles Used - See Text	Neutral to Slightly Oxidizing-Products of Combustion	Neutral to Slightly Oxidizing-Products of Combustion
Furnace Temperature	2200°F ±25° All Stages	1750°F ±25° All Stages	2000°F ±25° - Preform 1900°F ±25° - First Blocker 1850°F ±25° - All Others
Protective Workpiece Coating	None	Proprietary	None
Heating Times	1 Hour Maximum	1 Hour Maximum	1 Hour Maximum
Transfer Times	30 Seconds Maximum	30 Seconds Maximum	30 Seconds Maximum
Die Lubricant	Proprietary-Swab	Proprietary-Swab	Proprietary-Swab
Die Temperatures	300°F Minimum 800°F Maximum	300°F Minimum 800°F Maximum	300°F Minimum 800°F Maximum
Number of Blows per Stage	7 to 9 Average	5 to 7 Average	6 to 10 Average
Number of Reheats	None	One Piece Reheated During First Blocker Forging Operation	Four Pieces Reheated During Finish Forging Operation
Cooling Methods	Air	Air	Air
Post Forging Thermal Treatment	None	None	None
Contact Velocity (in./sec.)(b)	100 to 274	100 to 274	100 to 274

(a) - Preform operation conducted with open frame hammer - see text.

(b) - Not reported by Ladish since hammers are extremely difficult to instrument for treadle setting versus energy and contact velocity in multiple blow operation. Values listed are gross approximations by TRW for "order-of-magnitude" comparisons with data in Tables 4, 6, and 8 only. Ranges indicate values through multiple blow operation with varying treadle settings.

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Figure 20. Ten High Strength Steel (D6ac) Fin Rib Forgings Produced with 12,000 Pound Steam Drop Hammer for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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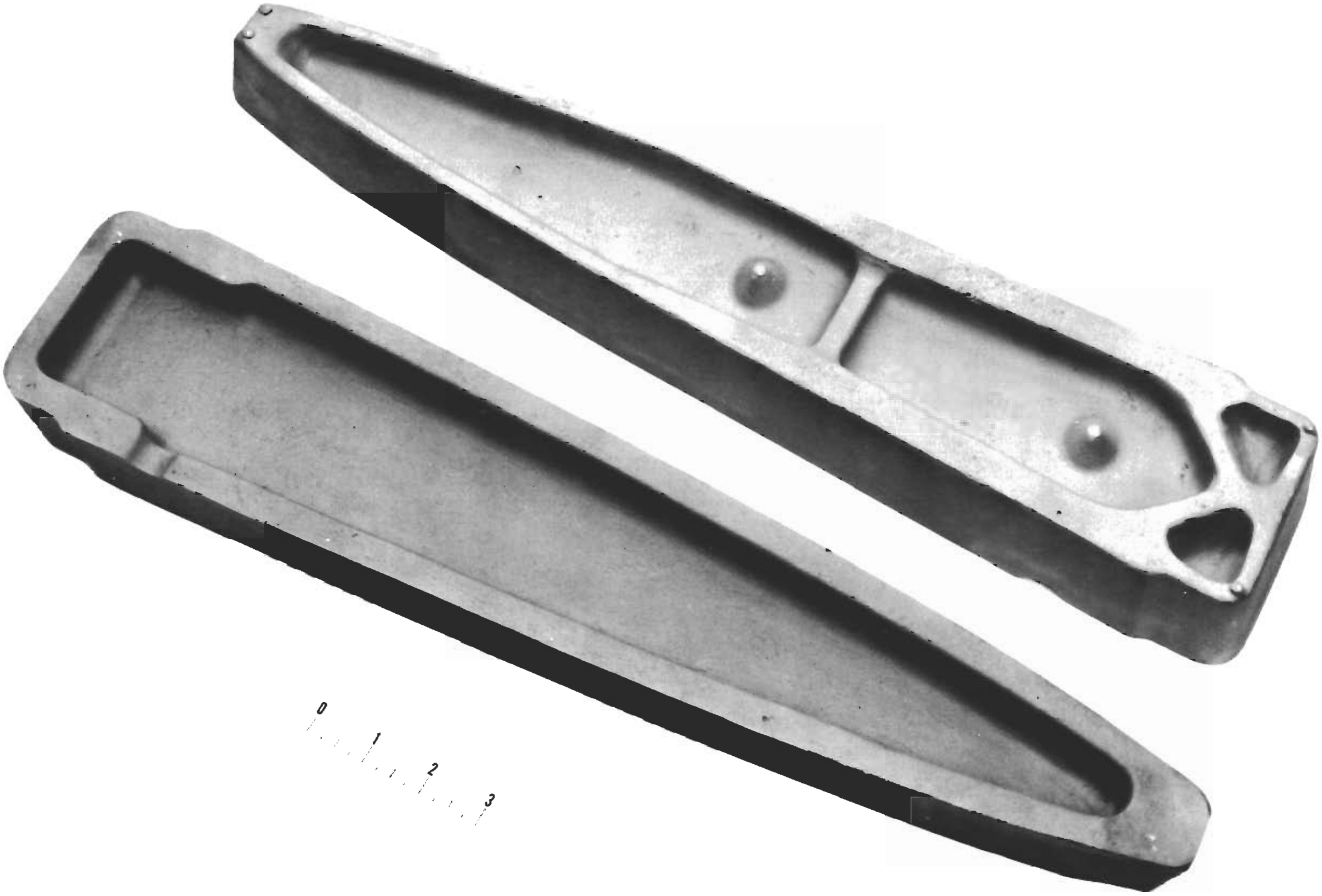

Figure 21. Close-Up of Two of the D6ac Forgings Produced with the 12,000 Pound Hammer and Delivered to TRW.

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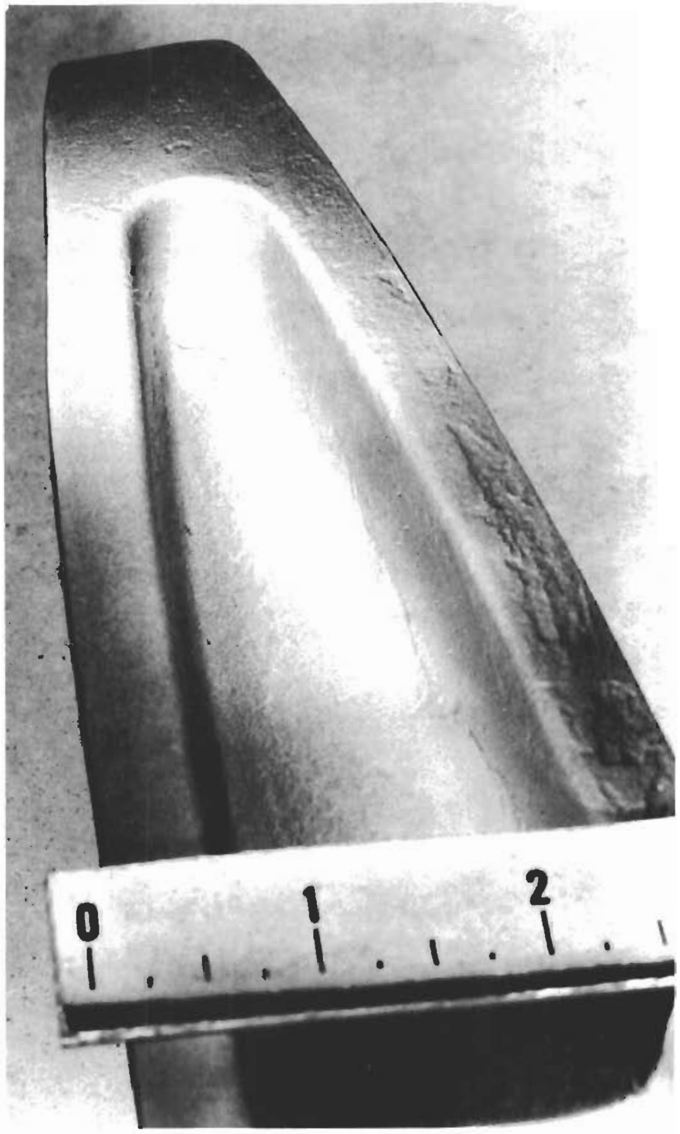

Figure 22. Indication of Lap Along Fillet Radius of the Twelfth D6ac Fin Rib Forging Produced (of Twelve Forgings Total, the Tenth of the Ten Delivered to TRW) During Final Forging Efforts with the 12,000 Pound Steam Drop Hammer. Shown after Application of Red Dye Penetrant and Developer to Improve Photographic Resolution.

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in the photograph; it nevertheless was the subject of subsequent study during fluorescent penetrant inspection and metallographic evaluation, as will be described later.

The ten Ti 6Al-4V forgings delivered are shown in Figures 23 and 24. The upper forging in Figure 24 exhibits a very slight lack-of-fill condition at the corners. This forging, serialized number one, was forged first of the entire series and, with the fourth forging produced (see fourth forging from left in Figure 23), represented the only hammer forgings delivered without vent hole detail at the corners. The surfaces of the titanium alloy forgings were observed to be quite good except for a slight waviness of web surface metal, particularly that formed by the lower die. The eighth and ninth forgings delivered also contained indications of a defect at the "nose" end of the inner rib surface formed by the upper die. This is shown in Figure 25. The unusual web surface condition and the rib sidewall defects were also subjects of metallographic studies, the results of which are covered in the discussion of the TRW evaluation of forging quality which follows.

The Inconel 718 forgings delivered to TRW are shown in Figures 26 and 27. In addition to being completely filled and exhibiting no visible defects, the surfaces of these ten forgings were all particularly smooth as is apparent in the photographs.

B. Hydraulic Press - Cameron Iron Works, Inc.

1. Forging Equipment

Among the four types of forging equipment, hydraulic presses are the most straightforward to design and operate. They are rated on the basis of tons of force with which one die can press the other. Relative movement among major mechanical components is slow and is cushioned by the hydraulic medium, thus strengths of these components can be designed on the basis of cycling static forces with little consideration for impact loadings. Deflections and tooling heights do not severely influence the design since the available force is much more independent of ram position than with other forging equipment. The stroke length and the rate of ram travel throughout the stroke are essentially functions only of cylinder-piston assembly lengths and volume of fluid pumped. Further, the rate of die closure may be programmed by adjusting a throttling valve in the fluid supply line.

To accomplish useful work, the hydraulic press must supply force through a distance. A 6000 ton press, for example, is theoretically capable of accomplishing 12,000,000 foot-pounds of work in operating at full pressure through a 12 inch stroke. Unlike impact energy machines, however, which must release a given amount of energy, hydraulic presses do not exert force (build up pressure) except in proportion to the resistance offered, thus they only accomplish work as a function of this resistance times the distance traveled. In impression die forging of structural components, a press is rarely required to exert full force from the time the dies first contact the workpiece until the impression is filled. Comparisons of theoretical work capabilities between hammers and presses are therefore only valid if based on integrated force-times-distance data for the specific forging in the case of the press. It is apparent, however, that

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Figure 23. Ten Titanium Alloy (Ti 6Al-4V) Fin Rib Forgings Produced with 12,000 Pound Steam Drop Hammer for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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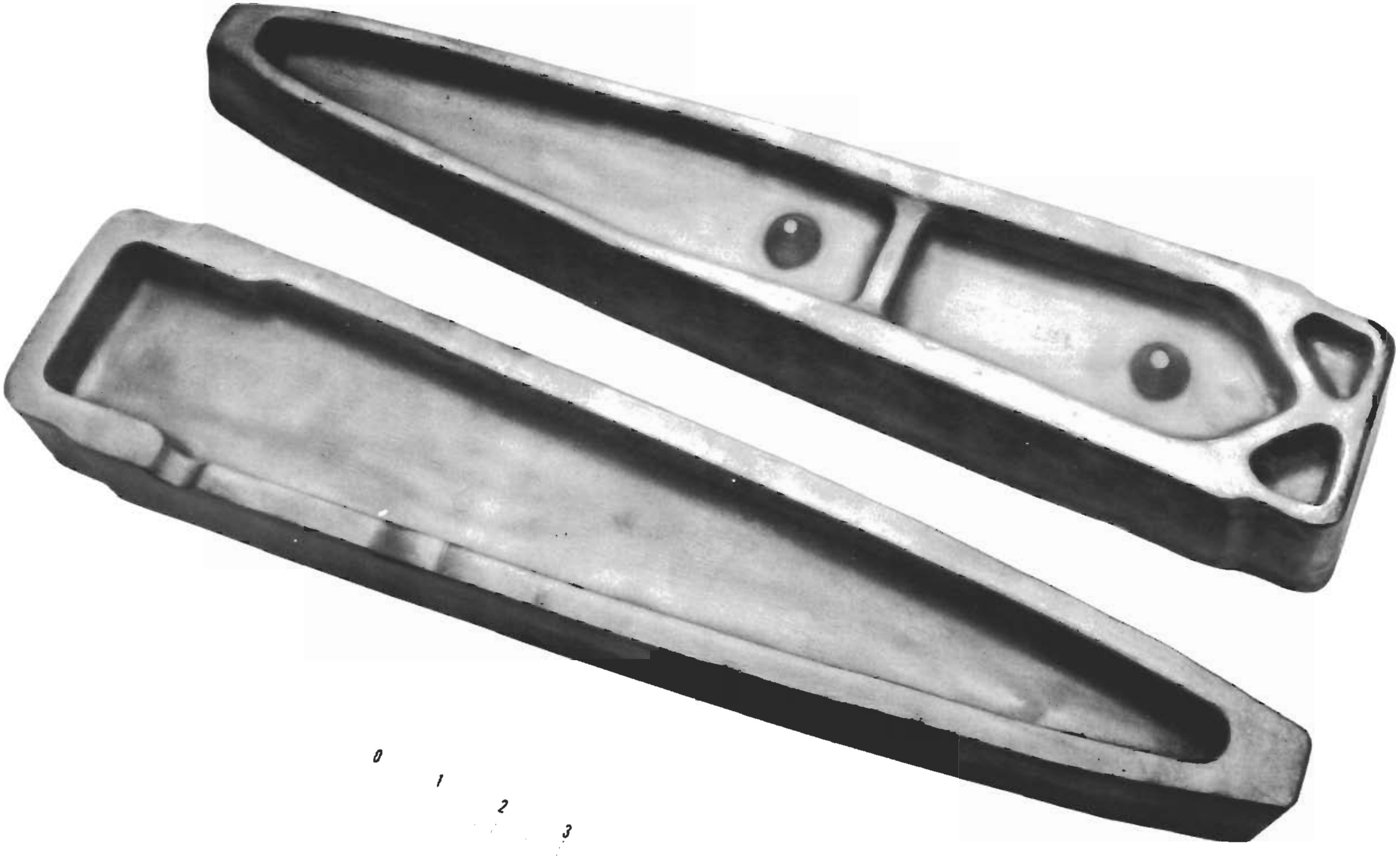

Figure 24. Close-Up of Two of the Ti 6Al-4V Forgings Produced with the 12,000 Pound Hammer and Delivered to TRW.

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Figure 25. Defect on Inner Rib Surface of the Eleventh Ti 6Al-4V Fin Rib Forging Produced (of Twelve Forgings Total, the Ninth of the Ten Delivered to TRW) During Final Forging Efforts with the 12,000 Pound Steam Drop Hammer. Shown after Application of Red Dye Penetrant and Developer to Improve Photographic Resolution.

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Figure 26. Ten Nickel-Base Alloy (Inconel 718) Fin Rib Forgings Produced with 12,000 Pound Steam Drop Hammer for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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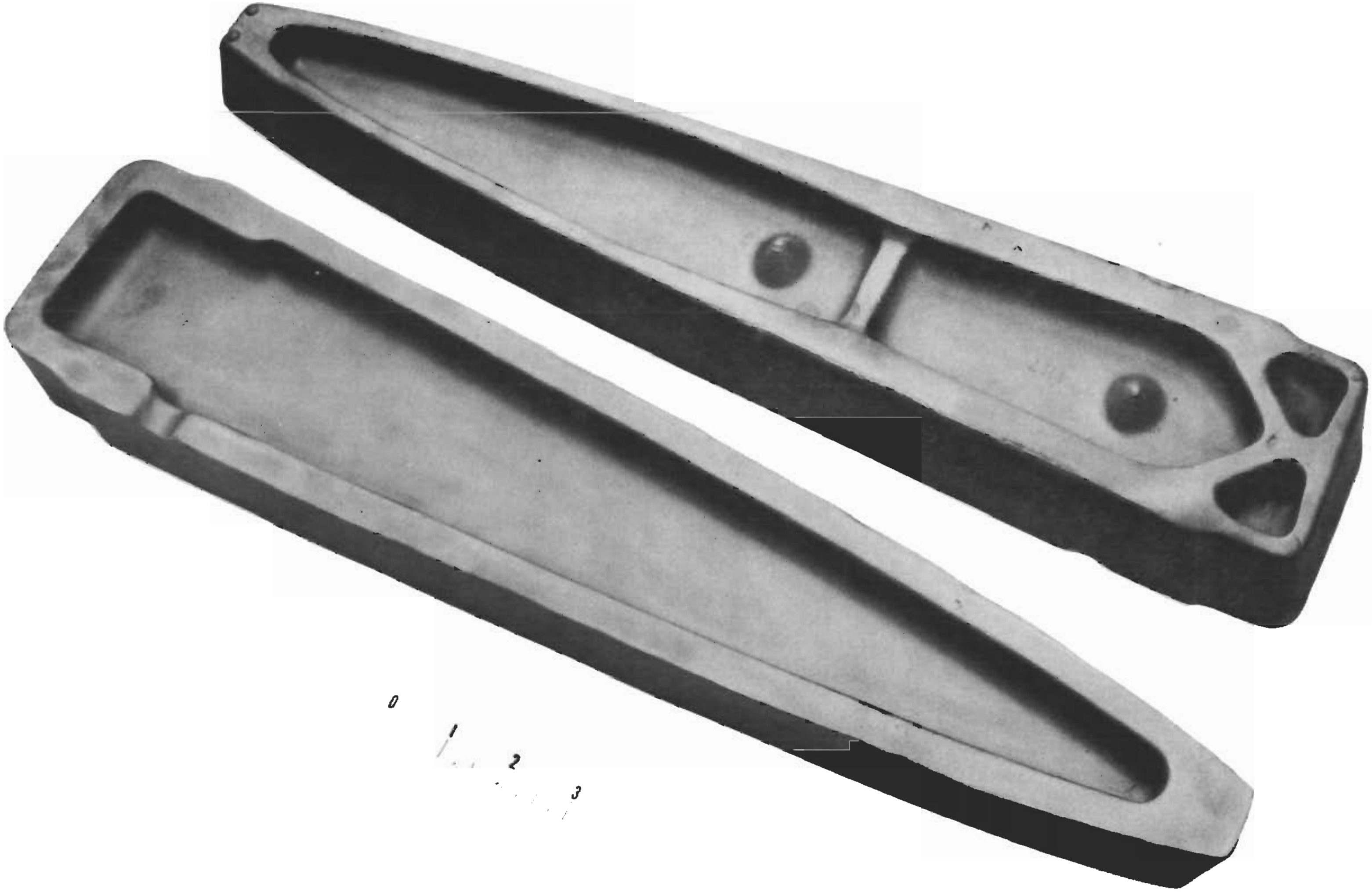

Figure 27. Close-Up of Two of the Inconel 718 Forgings Produced with the 12,000 Pound Hammer and Delivered to TRW.

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that hydraulic presses are favored for exceptionally "high profile" components which require long piercing or extrusion type forging operations.

The frame of a hydraulic press must resist the full force which the ram cylinders are capable of exerting. Cylinder placement, however, is flexible, and the low impact loads involved allow reliable designs of major structural components based upon yield strength or fatigue data for the materials employed. This has resulted in a range of different frame designs depending on designer or customer preference. The two most commonly employed in the United States, "push-down" and "pull-down", are illustrated in Figure 28. The "pull-down" sketch also illustrates a pertinent feature in engineering with hydraulics: additional cylinders may be provided to energize accessory rams for greater flexibility in die design.

Figure 29 shows the "push-down" type 6000 ton Lake Erie Engineering Corp. hydraulic press used by Cameron Iron Works to produce the fin rib forgings. The rated maximum ram speed for the press under load was reported to be 1 inch per second. Cameron also reported that the pumping system is of the air-water accumulator type. A separate low pressure hydraulic system as is frequently employed to accomplish "rapid ram advance" prior to the working portion of the stroke was not available with the 6000 ton press. Instead, it is equipped with a "gravity drop" system to advance the ram at a faster rate. During the program, the upper die was observed to contact the workpiece at a reported rate of 3 to 4 inches per second, to dwell for a fraction of a second as the press operator sequentially pulled a lever shutting the ram cylinder from a gravity sump and pushed another lever opening the cylinder to high pressure water, and to forge the workpiece at the slower rate.

2. Tooling Concept and Finish Forging Design

Cameron Iron Works approach to production of the fin rib forgings was considerably different from that discussed previously for the hammer. The overall tooling concept reflected an opinion that a hydraulic press could best produce the fin rib forgings in tooling without a horizontal parting line, with virtually no draft allowances, and without flash lands and gutters in the accepted senses of the terms(1-3).

The general features of such tooling are illustrated for the finish forging operation in Figure 30. The die "parting line" was merely a vertical extension of the rib along its upper edge. This was, in essence, duplicated with a vertical extension of the rib along its lower edge. The lower die insert also served as a full web profile ejector after the forging stroke was accomplished, thus avoiding distortion and impressions on web surfaces as can occur through use of pin-type ejectors. The use of techniques which employ "locking up" on flash to complete filling of the cavity were also avoided because the "difficult-to-fill" cavity recesses associated with more conventional designs were supplementary exhaust passages for excess metal in the Figure 30 concept.

Use of these techniques has several general effects. First, all other factors being equal, the maximum force necessary to forge the finish shape is reduced. In consideration that: 1) hydraulic presses in this

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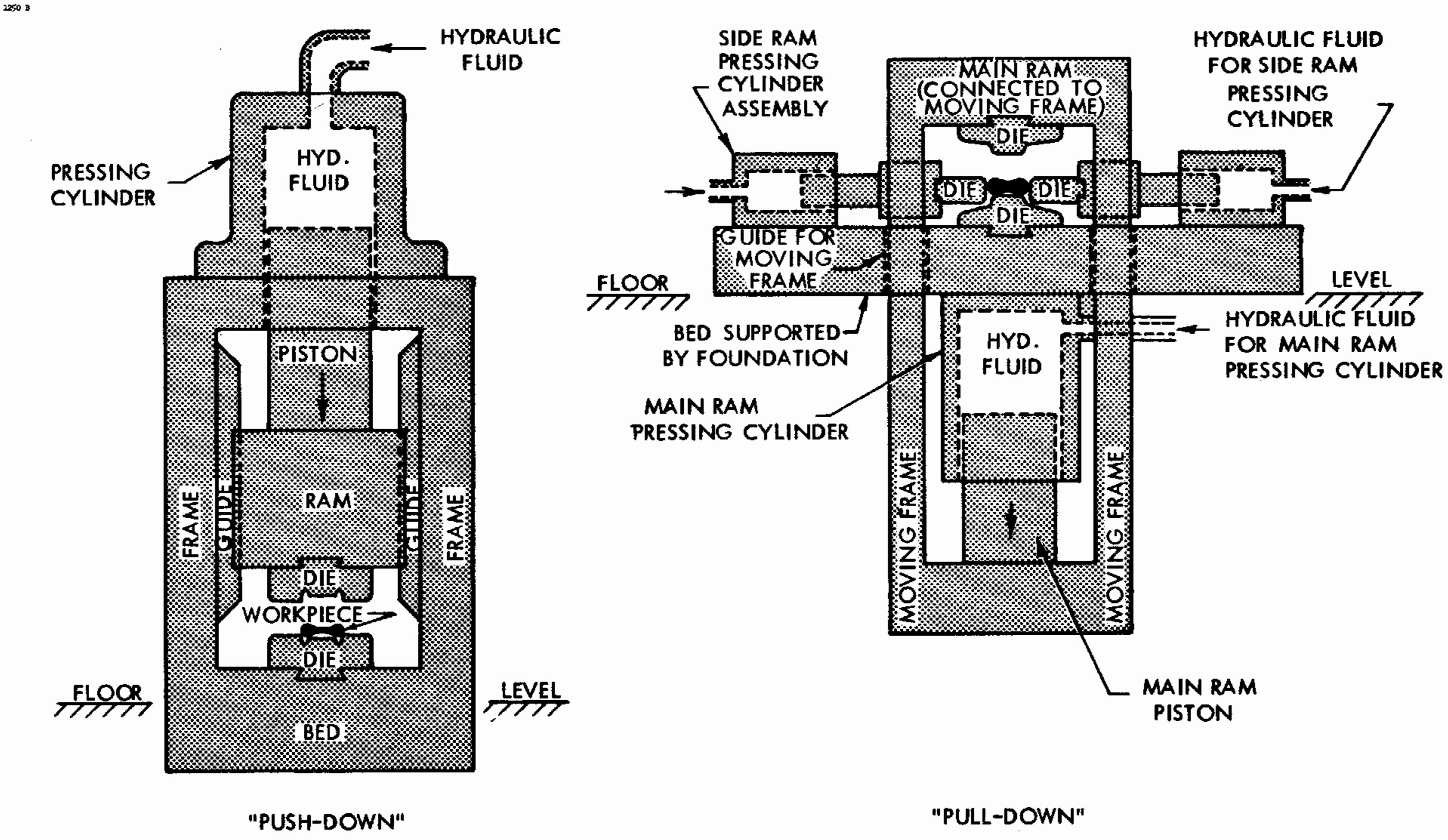

"PUSH-DOWN"

"PULL-DOWN"

Figure 28. Highly Simplified Illustrations of "Push-Down" and "Pull-Down" Hydraulic Forging Presses Showing Major Components. The "Pull-Down" Sketch Additionally Illustrates Employment of Auxiliary Side Rams (Equally Compatible with "Push-Down" Presses) for Complex Die Systems. Hydraulic Pumping and Valving Systems Not Shown.

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Figure 29. Hydraulic Forging Press Rated at 6000 Tons of Force and Employed by Cameron Iron Works, Inc., to Produce Fin Rib Forgings. Shown with Dies Removed. Note Gas-Fired Furnace Behind the Press at Right which was Used to Heat All Workpieces for Forging, and Large Manipulator on Rails Between Furnace and Press.

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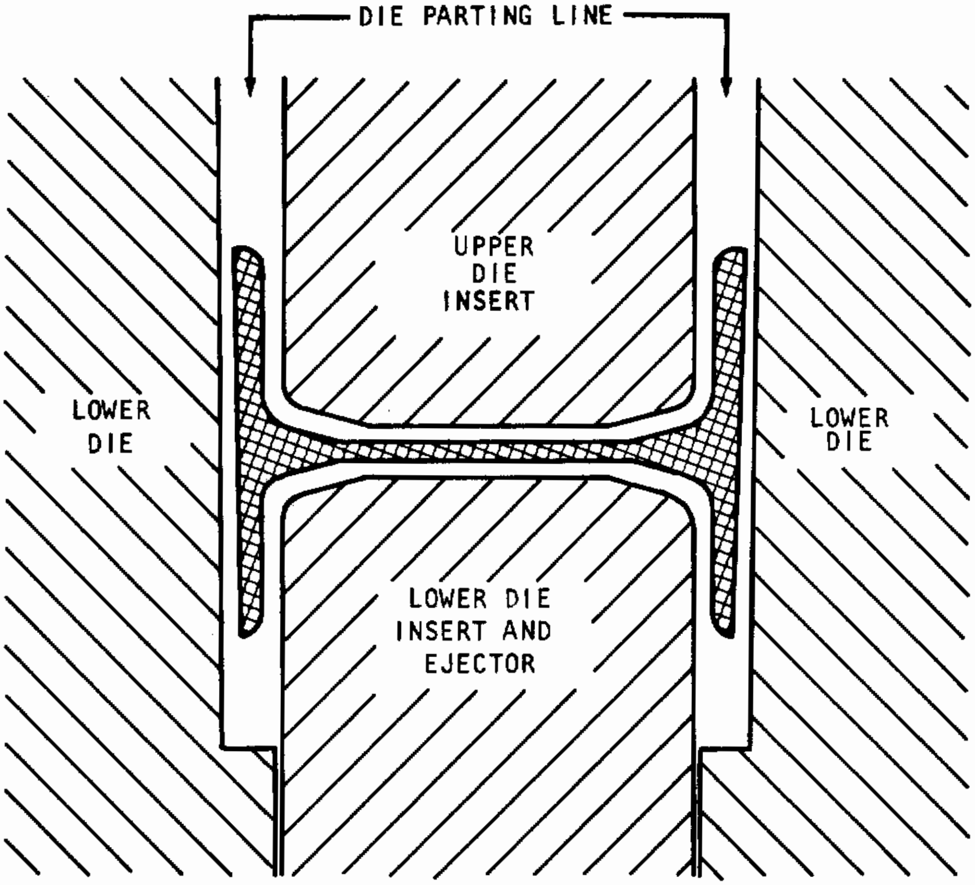

Figure 30. Schematic Illustration of Fin Rib Cross-Section (at approximately mid-length) with Finish Forging Die Impression for 6000 Ton Hydraulic Press Superimposed to Target Closure. Approximately Full Scale.

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size range have typically slower closure rates (thus promoting greater "die chilling") than the other machine types, and 2) the common work statement limited subcontractors to use of conventional die steels (and thereby conventional die temperatures); reductions of total force and of unit forces on tooling impressions surfaces are critical requirements for hydraulic presses during forging of thin sections of high temperature materials. Second, the fact that side and end rib metal is extruded without restriction reduces the possibility of defects in the rib-web radii and should promote uniform grain flow if staging sequence designs are correct. Third, successful use of the technique places heavy responsibility on the designer of the staging sequence if variable rib thicknesses are involved because of the tendency for excessive amounts of metal to exhaust through the thickest "ports" (the fin rib component includes such variable rib thickness, as can be observed in Figure 1). Fourth, forging trim line length is doubled because the "flash" (actually excess rib height) must be removed from both the lower and the upper rib edges.

The finish fin rib forging design initially targeted for the forging efforts with the 6000 ton hydraulic press is illustrated in longitudinal cross section in Figure 31. The essentially zero draft characteristics of the design are apparent. The sharp corner radii at the ends merely reflect that "flash" is most effectively "trimmed" in this instance by milling the rib edges all around at both the top and bottom.

3. Staging Sequence and Starting Stock

Early die try-outs, during which carbon steel stock was forged through the initially designed sequential shapes, Figure 32, resulted in five locations where lack of fill was observed. These can be seen in the forging shown in Figure 33. Three pertained to the same three corner areas that were discussed for the initial hammer forging trials, but were unfilled to a considerably more severe degree. The other two occurred to a lesser degree along the top edges of the upper side ribs, and were attributed to the thicker lower side ribs opposing these areas which promoted flow of excessive metal downward before the upper rib cavities could be completely filled.

As will be noted later (in the caption for Figure 47), a partial dam was provided on the lower die insert for the finish forging operation to restrict the further downward flow of side rib metal after formation of the thicker lower rib areas. In addition, modifications in starting stock volume and in the staging sequence were effected, resulting in the modified sequence in Figure 34. Specific changes from the early efforts included: 1) substitution of 2 inch diameter (2-1/8 inch diameter in Inconel 718) by 26 inch long starting stock for the previous 1-11/16 inch diameter by 25 inch long stock; 2) changing from one to two upsetting operations in modified conical closed die cavities in a 1400 ton hydraulic press to form the preform shape; and 3) changes in the blocker shape to improve relative metal distribution for the finish operation.

Subsequent forging trials with D6ac workpieces confirmed the effectiveness of the tooling, reworked to the modified sequence, in providing complete fill. Results from one Ti 6Al-4V forging which was also forged during this trial, however, indicated that very high forging pressures -

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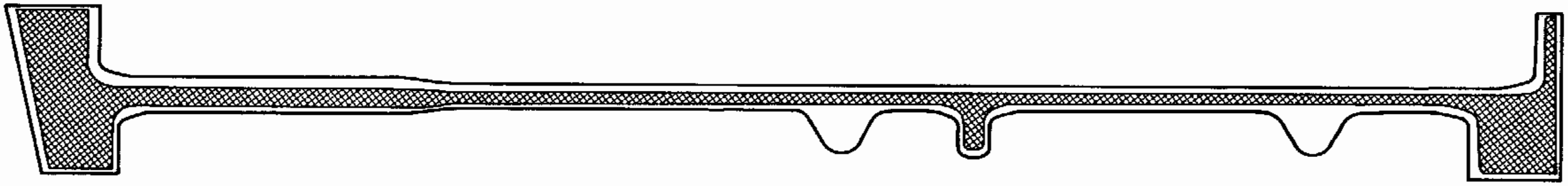

Figure 31. Illustration of Fin Rib Longitudinal Section (at mid-width) with Target Finish Forged Shape for 6000 Ton Hydraulic Press Superimposed. Slightly Less than One-Half Scale.

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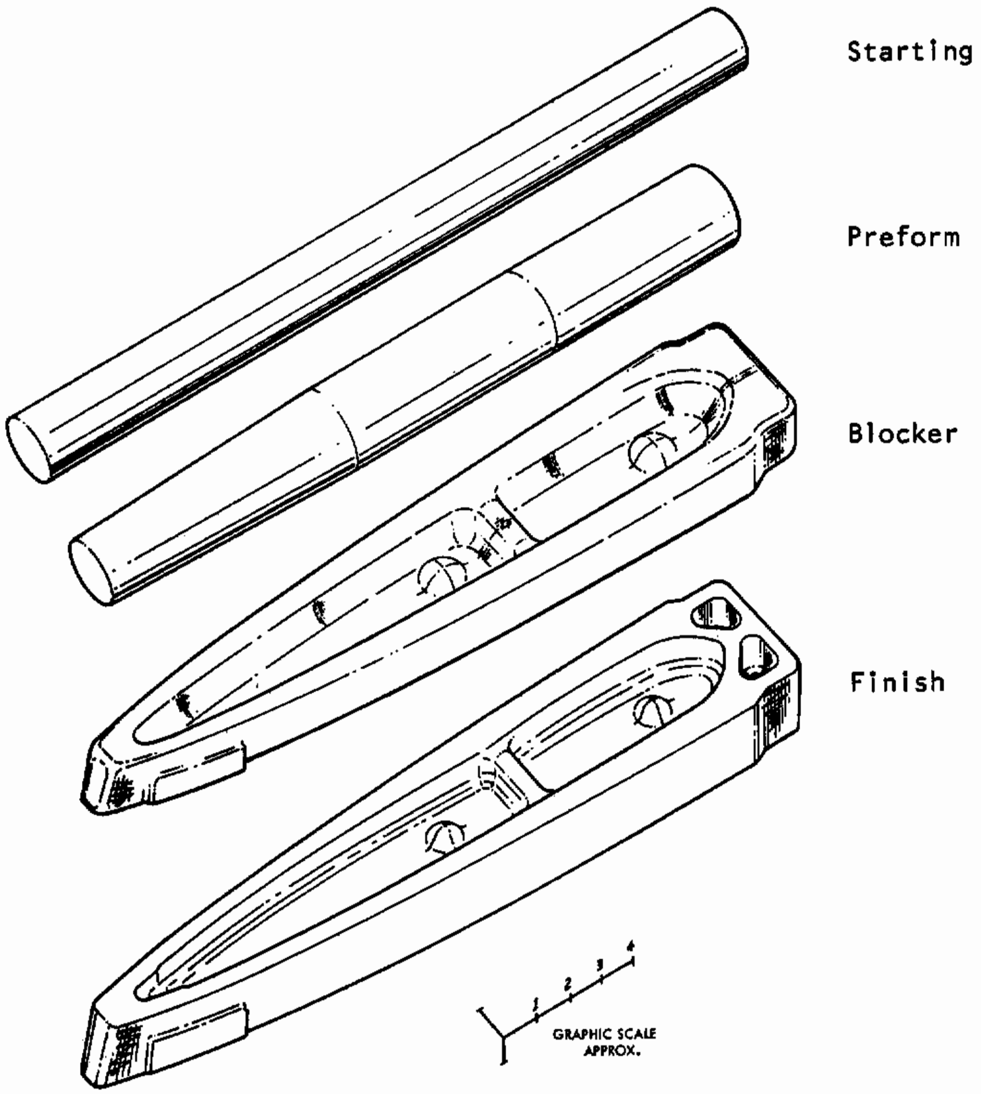

Figure 32. Illustration of Fin Rib Forging Staging Sequence Initially Designed for Forging Efforts with 6000 Ton Hydraulic Press (Blocker and Finish). Blocker and Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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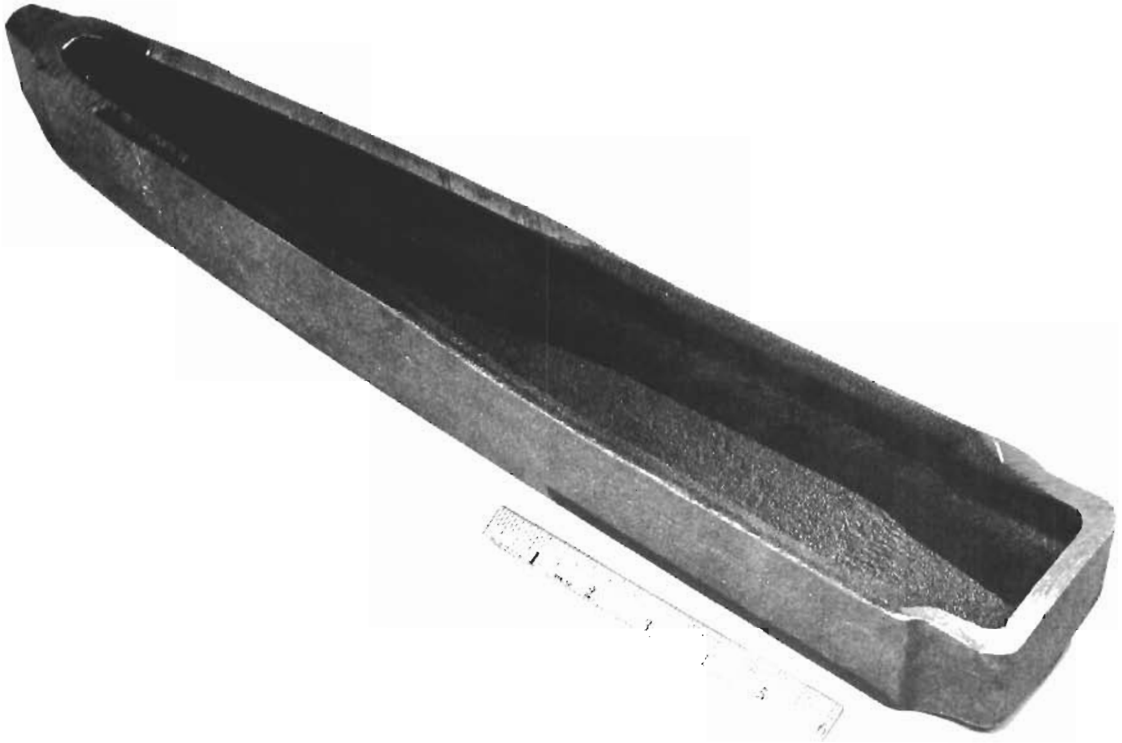
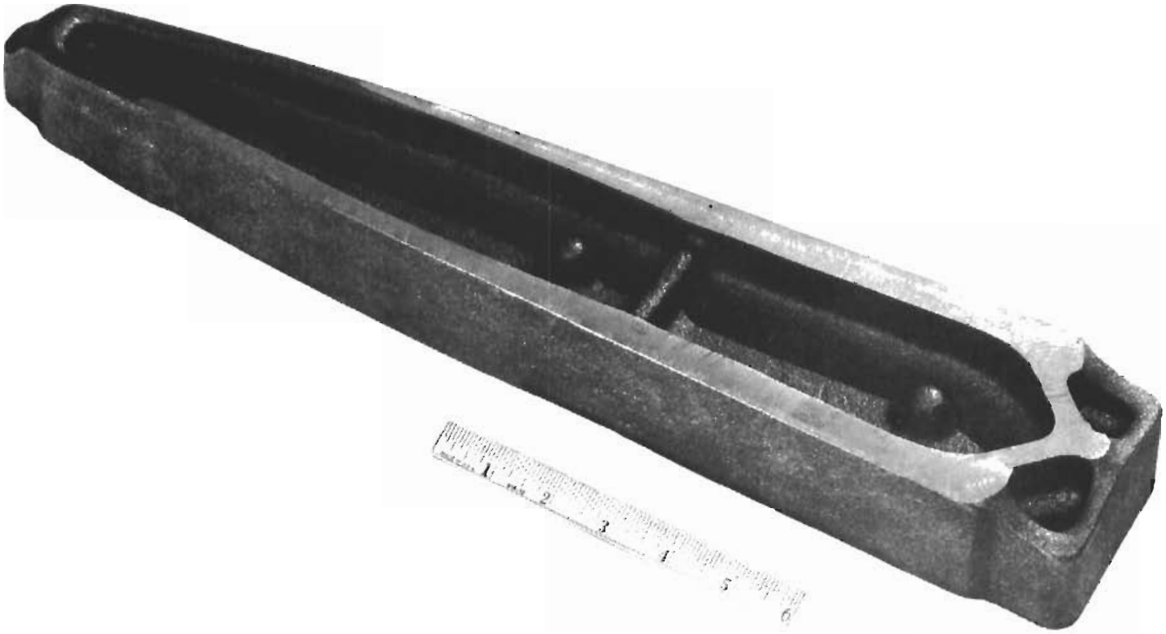


Upper Die Side



Lower Die Side

Figure 33. Carbon Steel Forging Produced During Initial Die Try-Outs with 6000 Ton Hydraulic Press. Shown "As-Forged" Except for Grit-Blasting and "Flash Trimming" (see text) Operations.

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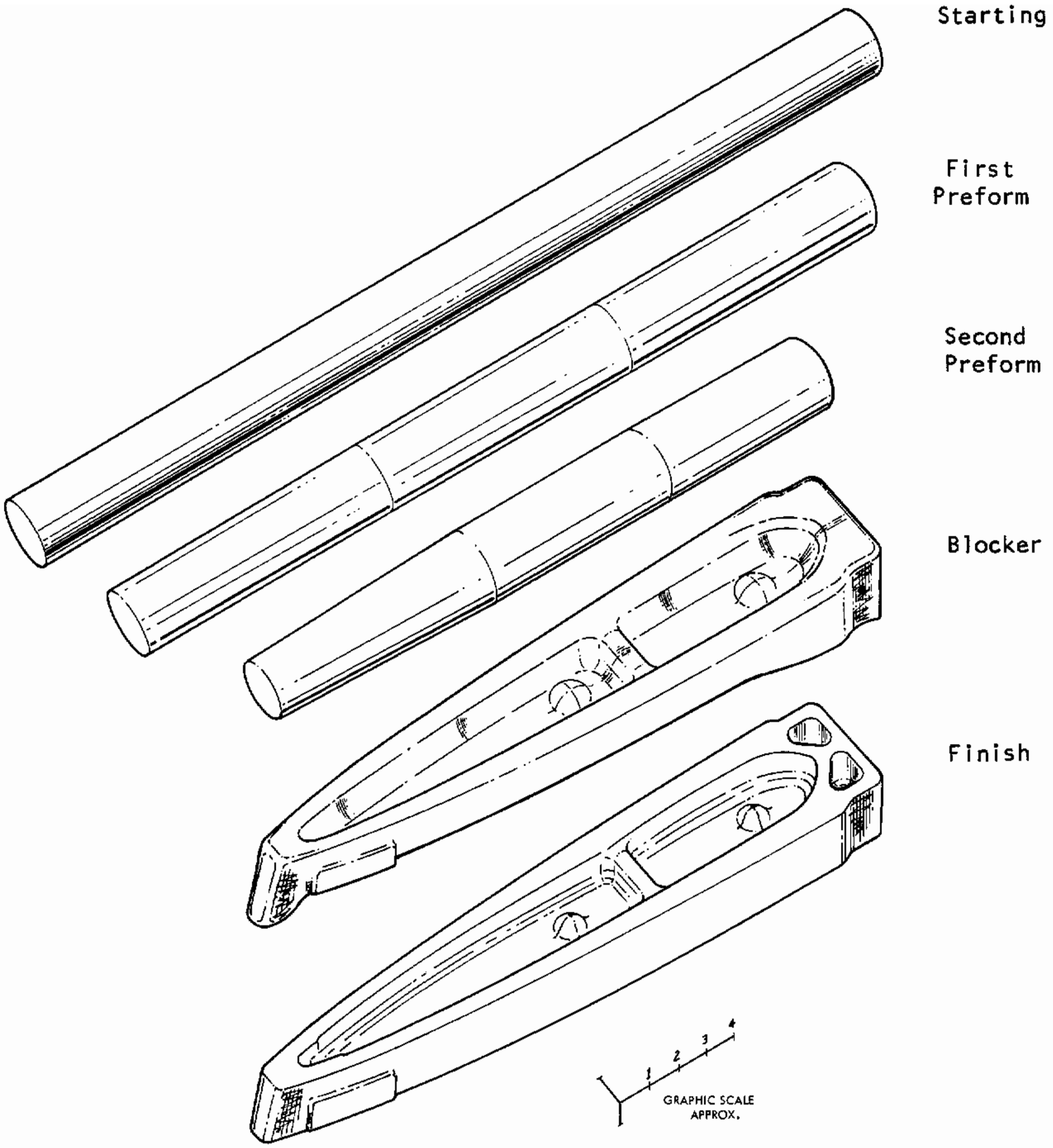

Figure 34. Illustration of Modified Fin Rib Forging Staging Sequence Employed for Final Production of Intermediate Size Forgings with 6000 Ton Hydraulic Press (Blocker and Finish). Blocker and Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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of the order of 60 to 70 tons per square inch - would be required to attain the targeted 0.300 inch web thickness for the titanium alloy. This was attributed to the significant increase in flow stress which occurs with a modest decrease in temperature for the titanium alloy in comparison to the steel. Actual blocker and finish shapes produced with the modified tooling in the 6000 ton hydraulic press are shown in Figures 35 and 36.

Data for the 2 inch diameter D6ac and Ti 6Al-4V, and for the 2-1/8 inch diameter Inconel 718 starting stock employed by Cameron to produce the forgings are listed in Table 3. As with the stock previously described for hammer forging by Ladish, it can be noted that all starting stock procured by Cameron for hydraulic press forging efforts was ultrasonically inspected for internal defects.

4. Forging Tooling

The multiple impression forging tooling designed and manufactured for the 6000 ton hydraulic press is shown in Figure 37. Two 33 inch square by 14 inch high wrought blocks of Cameron Iron Works "Z-2" die steel (analysis range: 0.28 to 0.33C, 0.60 to 0.80Mn, 0.20 to 0.35Si, 0.80 to 1.00Cr, 0.40 to 0.80Mo, 2.20 to 2.50Ni, 0.10 to 0.15V, bal. Fe) were heat treated to a hardness within the range Rc 40 to 44. These served as master blocks for preparation of the upper and the lower impressions for the blocker and finish operations in the Figure 34 staging sequence. Conventional machining was employed for tooling details such as guidepost and lift-ring holes, and also to prepare a "fullering"(2) impression which can be seen at the edge. The blocker impression and the sidewalls for the finish impression in the lower die were prepared by EDM techniques; as were the die steel inserts subsequently installed in the lower die finish impression (which also acted as the ejector), and in the upper die blocker and finish impressions. The inserts were of the same steel and hardness as the master blocks.

The above tooling is also shown schematically in Figure 38, and it can be noted that the fullering edge is not included. It was initially considered that preforming might be accomplished by fullering of large diameter stock. However, separate tooling was prepared to accomplish the preforming operation by closed die upsetting of smaller diameter stock in the 1400 ton press when it was established that the repetition rate characteristics of the 6000 ton press were inadequate to prevent excessive chilling during the multiple-stroke operation required by the fullering edge.

Control of match tolerances (mismatch) was afforded by the cylindrical guide posts and control of minimum forging thickness was designed to be provided by "kissing" the large flat surfaces of the master blocks in the Figure 38 design.

5. Forging Results

Preforming and blocking of the hydraulic press forgings was successfully performed as scheduled. Processing data are listed in Table 4, and it can be noted that the D6ac pieces were heated in a muffle to retard scale formation. A "wash heating" procedure (immediately placing back in the furnace for reheating) was employed between the two preforming operations

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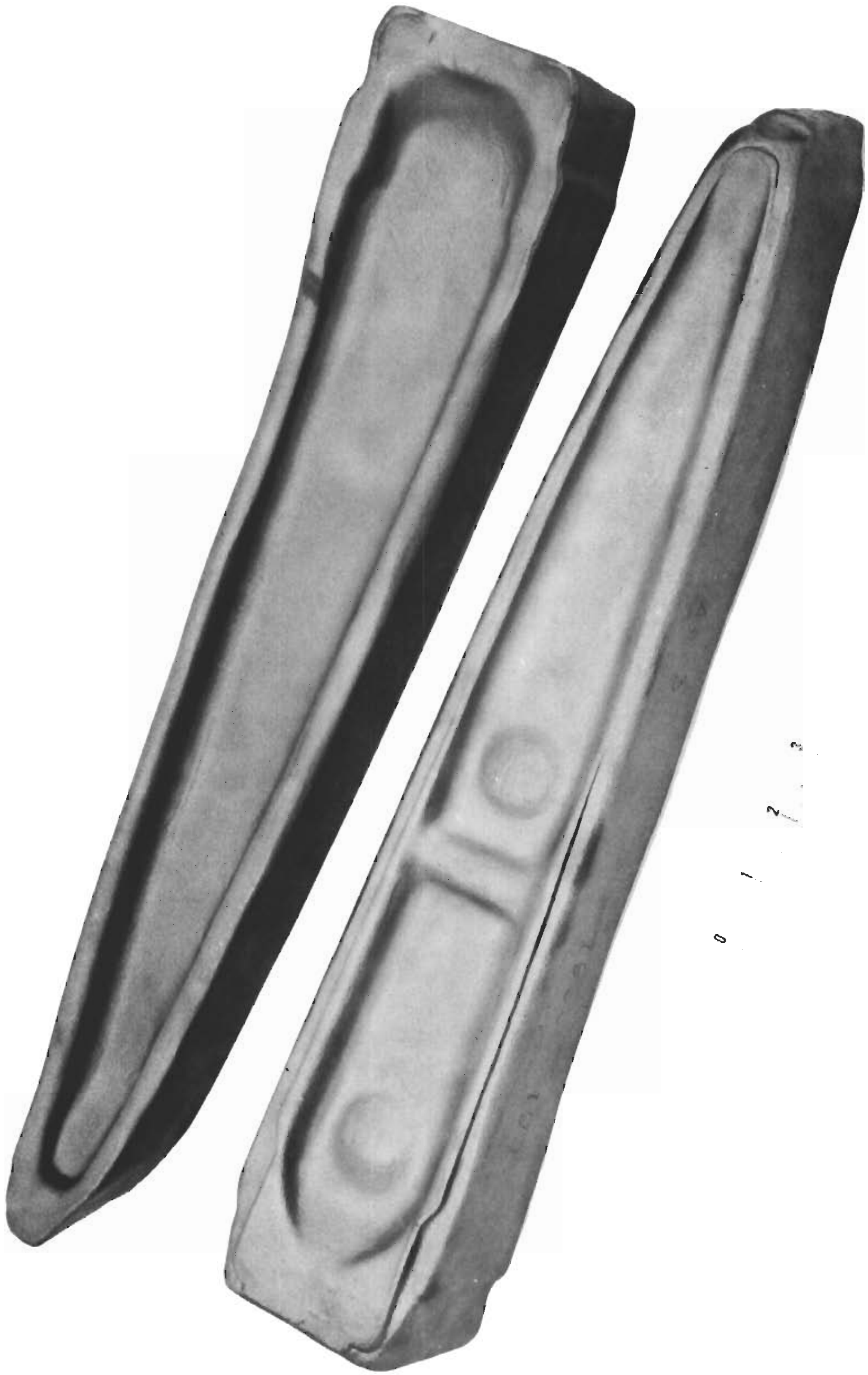

Figure 35. Both Sides of Inconel 718 Intermediate Stage Forging Produced with 6000 Ton Hydraulic Press in Modified Blocker Die Impression. Used in Production of Workpieces Subsequently Finish Forged with 6000 Ton Press and Delivered to TRW.

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Figure 36. Upper (left) and Lower (right) Die Views of D6ac Forging Produced with 6000 Ton Hydraulic Press. As-Forged and Abrasive Blasted Prior to "Trimming" of Excess Rib Height.

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TABLE 3

Material Data for Intermediate Size Fin Rib Forgings Produced with a 6000-Ton Hydraulic Press

Chemical Analysis	C	N	O	Al	V	H	Fe	Ti	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	B	Cb + Ta
D6ac	0.47				0.12		Bal.		0.74	0.006	0.005	0.27	0.50	1.01	1.01				
Ti 6Al-4V	0.022	0.013	0.12	6.4	4.3	0.006	0.21	Bal.											
IN 718	0.044			0.52			Bal.	0.91	0.09	0.002	0.006	0.11	52.73	18.97	2.97	0.03	0.14	0.004	5.21/0.02

	D6ac	Ti 6Al-4V	IN 718
Material Source	Crucible	Titanium Metals Corp.	Allvac
Heat Number	S-18532-85-2	K-2002	7376
Starting Stock Form	2 inch dia. by 26 inches long	2 inch dia. by 26 inches long	2-1/8 inch dia. by 26 inches long
Starting Stock Weight	23.2 pounds	13.1 pounds	27.4 pounds
Procurement Specifications	AMS-6431	AMS-4967A	AMS-5664A
Other Inspection Procedures	Ultrasonically Inspected	Ultrasonically Inspected	Ultrasonically Inspected

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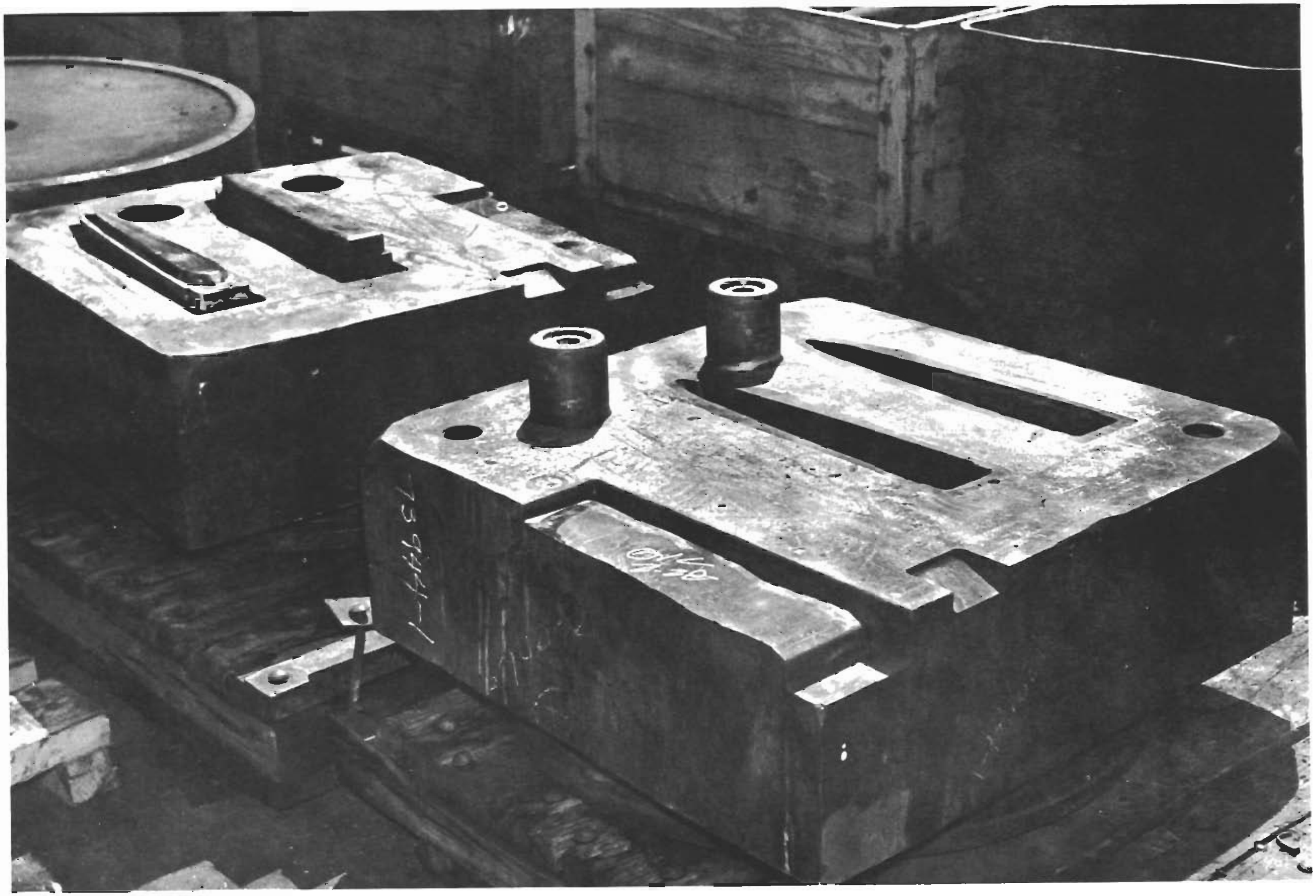

Figure 37. Multiple Impression Dies for Blocker and Finish Fin Rib Forging Operations with 6000 Ton Hydraulic Press.

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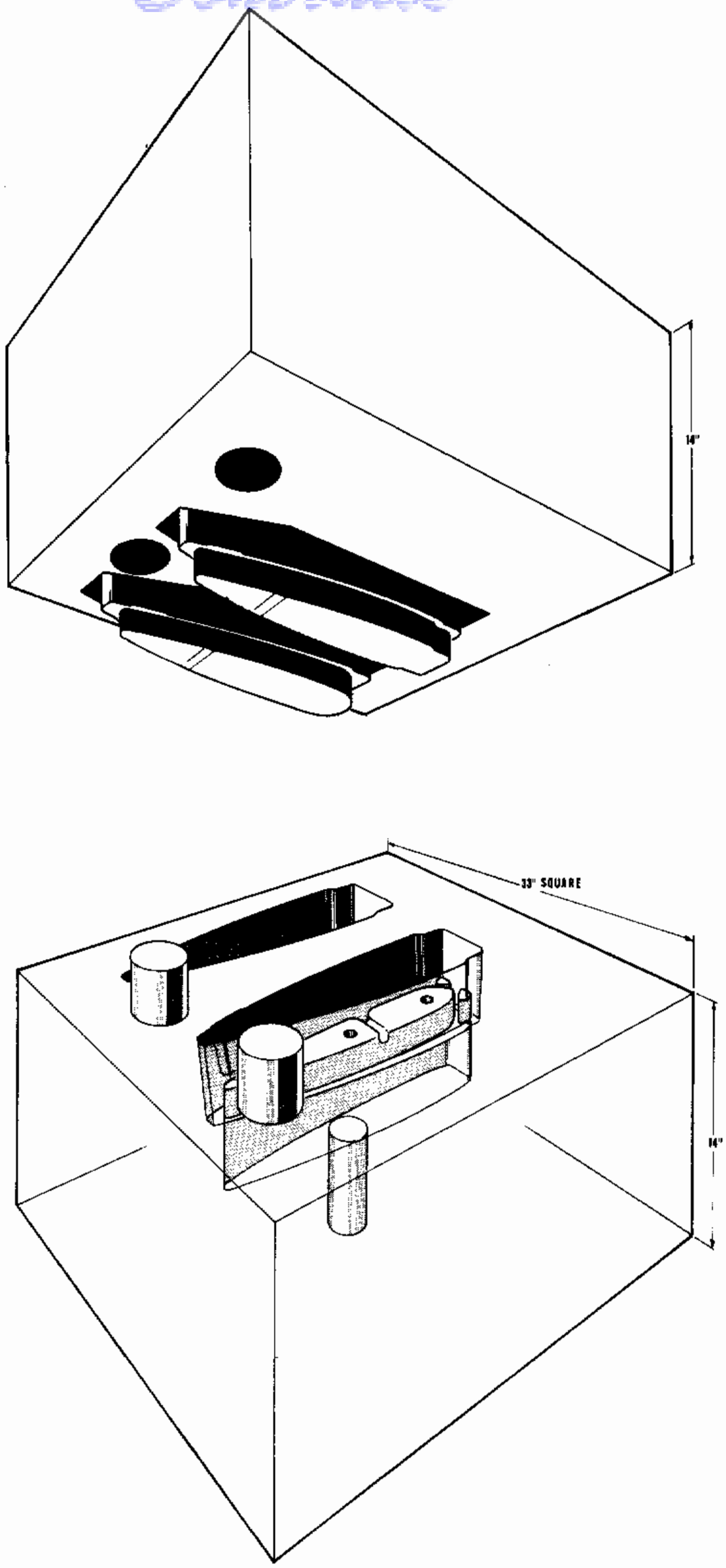

Figure 38. Schematic Illustration of Multiple Impression Dies for Blocker and Finish Fin Rib Forging Operations with 6000 Ton Hydraulic Press.

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TABLE 4

Processing Data for Intermediate Size Fin Rib Forgings Produced with a 6000-Ton Hydraulic Press[a]

	Material		
	D6ac	Ti 6Al-4V	IN 718
Furnace Type	Gas Fired	Gas Fired	Gas Fired
Furnace Atmosphere	Muffle Used - All Stages	Muffle Used for Finish, Other Stages - Air	Muffle Used for Finish, Other Stages - Air
Furnace Temperature	2150°F ±25° All Stages	1750°F ±25° All Stages	2075°F ±25°F - Preforms 2050°F ±25°F - Others
Protective Workpiece Coating	None	Proprietary	None
Heating Times	3/4 Hour - Preforms and Blocker 1/2 Hour - Finish	3/4 Hour - Preforms and Blocker 1/2 Hour - Finish	3/4 Hour - Preforms and Blocker 1/2 Hour - Finish
Transfer Times	30 to 45 Seconds	30 to 45 Seconds	30 to 45 Seconds
Die Lubricant	Graphite in Oil-Swab	Graphite in Oil-Swab	Graphite in Oil-Swab
Die Temperature	Heated-Die Temperature Proprietary	Heated-Die Temperature Proprietary	Heated-Die Temperature Proprietary
Number of Strokes per Stage	One	One	One
Number of Reheats	None	None	None
Cooling Methods	Air	Air	Air
Post Forging Thermal Treatment	None	None	None
Contact Velocity (in./sec.)	3 to 4	3 to 4	3 to 4
Pressing Velocity (in./sec.)	1	1	1

(a) - Preform operations conducted with 1400 Ton Hydraulic Press - see text.

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and reheating was accomplished as the tooling was changed. Thus the titanium alloy workpieces were not recoated and none of the workpieces received any intermediate conditioning until all upsetting was completed. "Second preform" and "blocker" forgings did, however, experience these intermediate operations.

Transfers of the heated workpieces to the press dies were conducted manually for the first three operations. The equivalent transfer time listed in Table 4 for the finish operation must, however, be interpreted with recognition that a different transfer procedure was employed. To minimize heat losses during travel from the relatively distant furnace (see Figure 29) during this operation, heating of all three materials was accomplished by placing the workpiece in the muffle which had been placed in the furnace. The muffle itself was larger than the ones previously described for the hammer effort, but also consisted of a section of steel pipe with one end closed and a cap for the other end. After removal of the cap, the transfer was conveniently accomplished with a minimum of heat loss by transporting the muffle to the press with the manipulator, also shown in Figure 29, and presenting the open end to the crew member assigned to load the press.

The finish forging operation was completed only after considerable difficulty related to chilling of workpieces, and subsequent die failure due to overloading in attempting to obtain complete fill. The first three pieces forged were Ti 6Al-4V alloy. Three thousand tons (representing an average of approximately 54 tons per square inch over the 56 square inch forging) applied to the first piece produced good fill except at the three corners in the lower die; i.e., the "nose" end and the two corners behind the "lugs" in the lower die which produced the triangular impressions near the blunt end of the Figure 1 view side of the forgings. The second piece was forged with 3500 tons (62.5 tons per square inch average), but was reported by Cameron to have reached only the same degree of die closure as the first. After forging it was noted that the "lugs" in the lower die insert were bent toward the corners of the master block cavity at an estimated 20 degree angle, and cracks were visible at the base of each "lug". The lower die insert was then replaced with a new one and a third Ti 6Al-4V forging was produced, again at 3500 tons of total force. This forging was observed to be more completely filled than the previous two, and is shown after "trimming" in Figure 39.

In view of the high tonnage requirements for finish forging of the Ti 6Al-4V, the decision was made to finish forge the D6ac blocker forgings prior to continuing with the titanium alloy or commencing with Inconel 718. However, 3000 tons of force were required to achieve die closure; and the "lugs" were observed to have bent, separated from the lower die insert, and lodged in the forging. At this point the forging run was discontinued in favor of redesign of the lower die insert to a simple, spherical radius "lug" design in place of the virtually no-draft, trangular "lugs" which formed the pockets in the Figure 39 forging.

The finish forging operation was completed using lower die inserts of the modified design. In addition, the total press force was limited to 2500 tons of the 6000 tons available during production of the forgings required for the TRW evaluation. This was in recognition that, in the Cameron finish die design where the rib metal is not "locked-up" by the cavity or by flash lands, the projected area of the web-forming insert surfaces were required to resist virtually the entire forging force. Since the area of the

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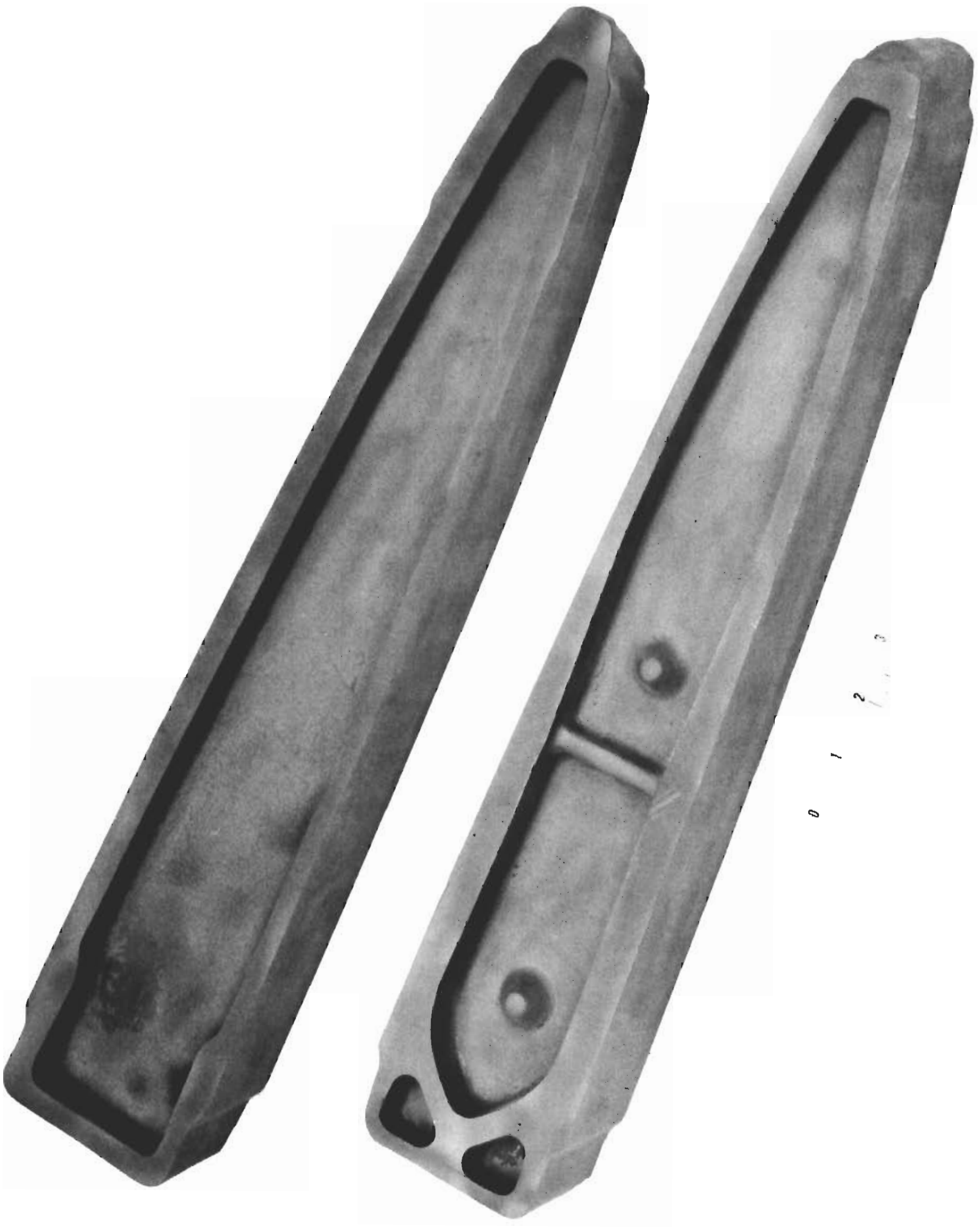

Figure 39. Both Sides of Ti 6Al-4V Finish Forging Produced with 6000 Ton Hydraulic Press. Shown after "Trimming" by Milling Excess Rib Heights. Note Detailed Triangular Impressions at Blunt End of Lower Die Side. Tooling Failed in This Area after Very Few Forgings were Produced - See Text.

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lower insert was only of the order of 30 square inches versus 56 square inches for the overall cavity, the average unit force on the insert was almost twice that of the average unit force calculated on the basis of the overall area. Thus, 3500 tons and 2500 tons of total force were actually equal to average unit forces in excess of 116 and 83 tons per square inch, respectively, when considered a function only of lower insert surface area. Also, unit loads in localized areas of impression die surfaces exceed unit loads calculated as an average.

Cameron reported that the 83 tons per square inch figure approached the yield strength of the "Z-2" die material and would be considered too high for an extended production run. Production, at 2500 tons total force, of the ten D6ac forgings, however, caused no visible deterioration of the upper and lower inserts. The forgings can be seen in Figures 40 and 41, and the change in the lower insert "lug" design is well illustrated by comparing the lower forging in Figure 41 with that in Figure 39. The steel forgings can be observed to be completely filled except for a moderate lack-of-fill condition at the "nose" end formed by the lower die.

The nine Ti 6Al-4V finish forgings produced with the same tooling inserts and the same 2500 ton total force limitation are shown in Figures 42 and 43. The piece on the left of Figure 42 is the Figure 39 forging produced previously with 3500 tons of force. The lower die views of the nine forgings on the right in Figure 42 and the close-up view in Figure 43 illustrate the moderate lack-of-fill condition at the "lug" corners and the more severe lack-of-fill at the "nose" which occurred. In addition, seven of the ten titanium alloy forgings delivered contained defects along inner and/or outer rib surfaces which were visually discernible to varying degrees of severity. The most severe of these are shown in Figure 44, and they were reported by Cameron to be due to tearing of surface metal which had been chilled excessively by the dies prior to build-up of hydraulic pressure to the degree necessary for deformation to occur. The degree of variation in the severity of these defects observed among the forgings is attributed to a marginal surface temperature condition quite sensitive to minor variations in processing practices related to transfer time, die temperature, dwell time prior to pressure build-up, etc.

The Inconel 718 forgings delivered to TRW are shown in Figures 45 and 46. Forging commenced using the same lower die insert used for production of all of the steel and titanium alloy forgings. The progressive flattening of the "lugs" on the insert which occurred required changing of the insert after only three pieces were forged. The new insert then also provided only three finish forgings before flattening of the "lugs" made the insert useless. These two examples of rapid, progressive, local die failure are mirrored in the two groups of three forgings each at the left of the lower photograph in Figure 45, i.e., the first and fourth forging from the left show good lug detail, the second and fifth exhibit some evidence of insert "lug" failure, etc. It is interesting to note the degree of the corresponding increase in web thickness at the blunt end of the forging which accompanied the progressive "lug" failures under the 2500 tons total press force applied. This can be observed in the upper photograph in Figure 45 which shows the same forgings from the upper die side. The forging run was terminated at this point and the four forgings at the right of Figure 45 progressed only through the blocker impression.

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Figure 40. Ten High Strength Steel (D6ac) Fin Rib Forgings Produced with 6000 Ton Hydraulic Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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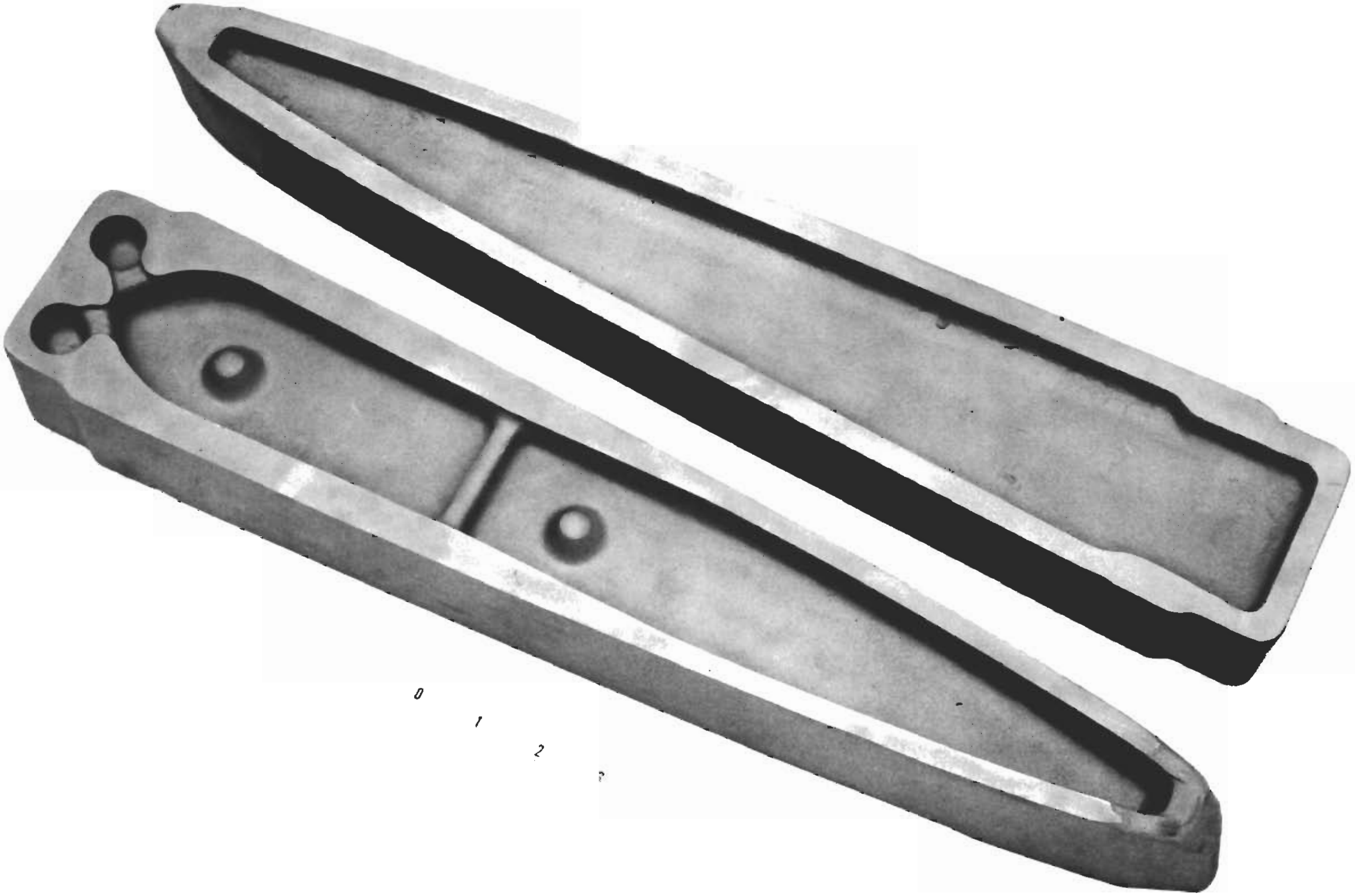

Figure 41. Close-Up of Two of the D6ac Forgings Produced with the 6000 Ton Hydraulic Press and Delivered to TRW.

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Figure 42. Ten Titanium Alloy (Ti 6Al-4V) Fin Rib Forgings Produced with 6000 Ton Hydraulic Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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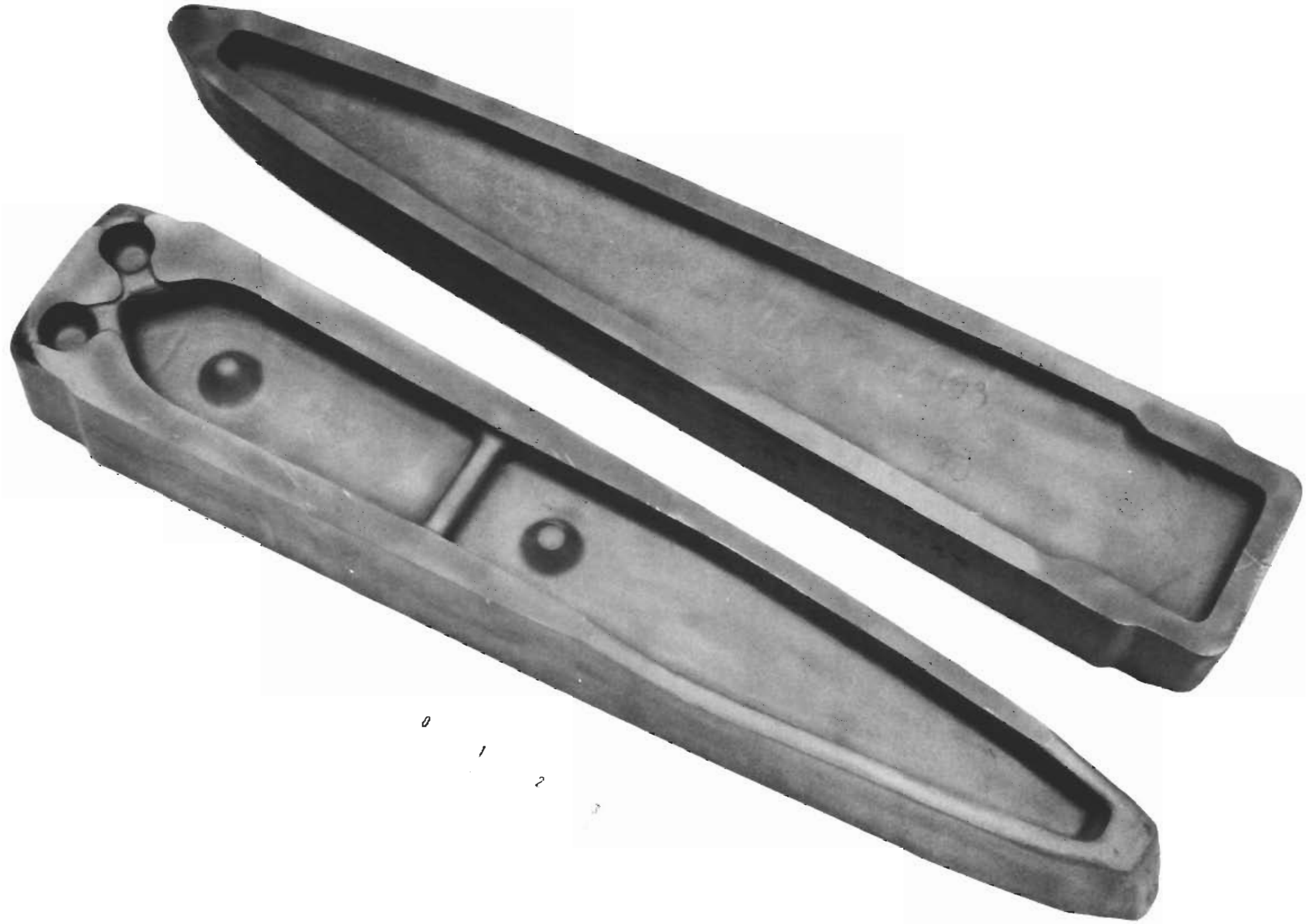

Figure 43. Close-Up of Two of the Ti 6Al-4V Forgings Produced with the 6000 Ton Hydraulic Press and Delivered to TRW.

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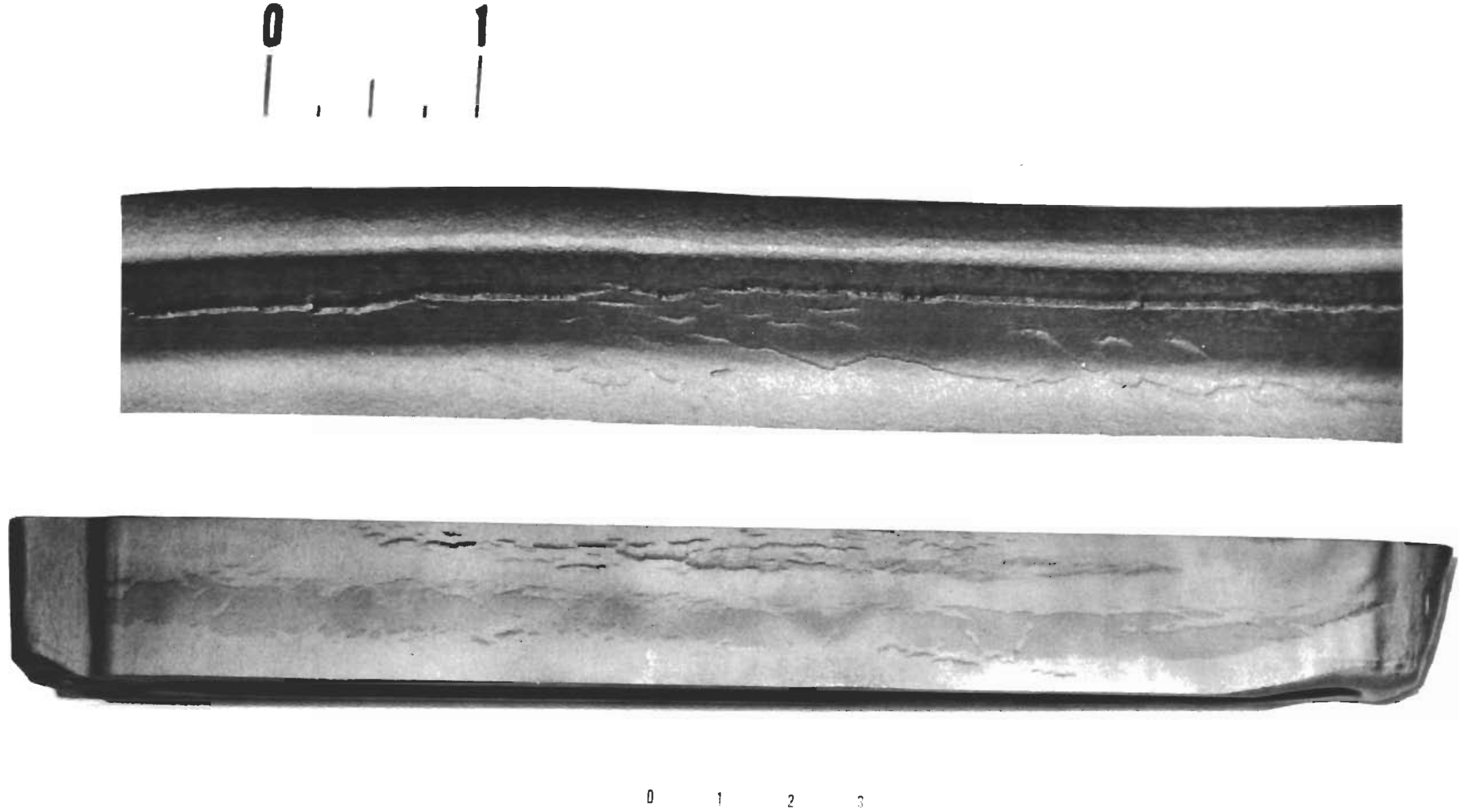

Figure 44. Defects on Inner (Top) and Outer (Bottom) Rib Surfaces of Fifth and Tenth, Respectively, Ti 6Al-4V Forgings Produced (of Ten Forgings Total) During Final Forging Efforts with the 6000 Ton Hydraulic Press.

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Figure 45. Ten Nickel-Base Alloy (Inconel 718) Fin Rib Forgings Produced with 6000 Ton Hydraulic Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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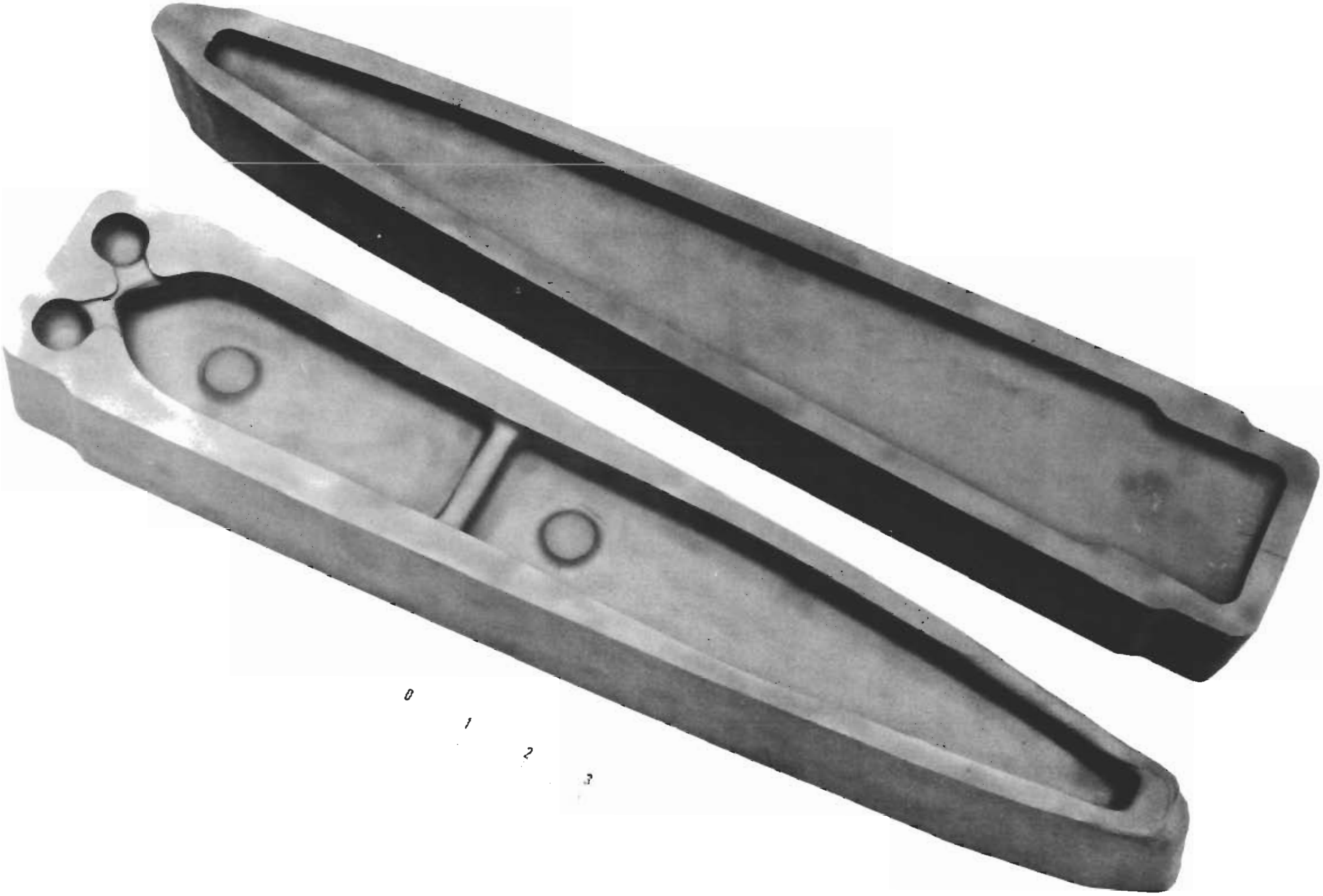

Figure 46. Close-Up of Two of the Inconel 718 Forgings Produced with the 6000 Ton Hydraulic Press and Delivered to TRW.

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Initial study of the six Inconel 718 finish forgings delivered revealed a lack-of-fill condition inversely related, as would be expected, to the web thickness; i.e., the third and sixth forgings exhibit considerably poorer fill than the first and fourth. This was chiefly apparent at the "nose" end. Also, the first, second, and fifth forgings produced experienced very slight surface tearing in web areas surrounding the mid-length locator pimple. This can be seen in Figure 45.

Figure 47 shows the lower die inserts after forging of the Inconel 718 alloy. The flattening of the hemispherical "lugs" is primarily attributed to localized overloading under marginally safe conditions of average unit load over the projected surface area. Thermal softening of these projections may have occurred to some degree during the dwell between the "gravity drop" and the pressing portion of the press ram cycle. However, if this factor were predominantly responsible for the failure, the "lugs" of the left insert in Figure 40 should exhibit a much greater degree of deformation than those of the right insert. This is because the left insert briefly rested on, and then forged, ten hotter pieces of D6ac (compared to Inconel 718 - see Table 4) and nine cooler pieces of Ti 6Al-4V prior to forging of the three Inconel 718 pieces referenced in the sub-caption; whereas the right insert only experienced the thermal environment imposed by momentarily resting on and then forging the three pieces of Inconel 718.

Discussion near the end of this report is concerned with the relative merits of the four machine types. However, it is obvious and certainly can be concluded at this point that the action through the total down stroke of the particular hydraulic press employed in this instance was too slow to prevent workpiece chilling and to allow effective forging of close tolerance structural shapes within the materials, shape, and die steel limitations imposed by the program work statement for intermediate size forgings.

C. Mechanical Press - Ladish Company

1. Forging Equipment

Sketches illustrating the operating principles of a typical crankshaft-type mechanical forging press are shown in Figure 48. The sketches do not refer to any particular manufacturer's equipment. Of the five mechanical press producers interviewed during the initial program survey, three types of frame construction and three concepts for connecting the ram to the crankshaft were represented. The solid frame and pitman-arm-and-pin construction suggested in the sketch is shown for simplicity and actually, when combined as shown, represents no commercially available equipment.

Ratings of mechanical presses can be confusing to those accustomed to inertial energy released by hammers or tons of force generated by hydraulic presses. In operation, a typical mechanical press extracts inertial energy from a continuously rotating flywheel by means of air-operated clutch and brake assemblies, Figure 48(a), which connect the flywheel to the crankshaft through one crankshaft revolution; i.e., 360 degrees of arc, Figure 48(b). This is translated to one cycle of vertical reciprocating motion of the ram by the pitman assembly (or, in one design, a "scotch-yoke" mechanism) with assistance of the ram guides. The maximum downward force of the ram is generally expressed in tons.

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Figure 47. Lower Die Inserts of Tooling Used for Finish Fin Rib Forging Operation with 6000 Ton Hydraulic Press Limited to 2500 Tons Total Force. Note Distortion of Hemispherical "Lugs" at Blunt End of Inserts. Note also the "Partial Dams" Provided on Insert Sidewalls to Prevent Excessive Downward Flow of Rib Metal after Thicker Section Ribs have Formed - See Text.

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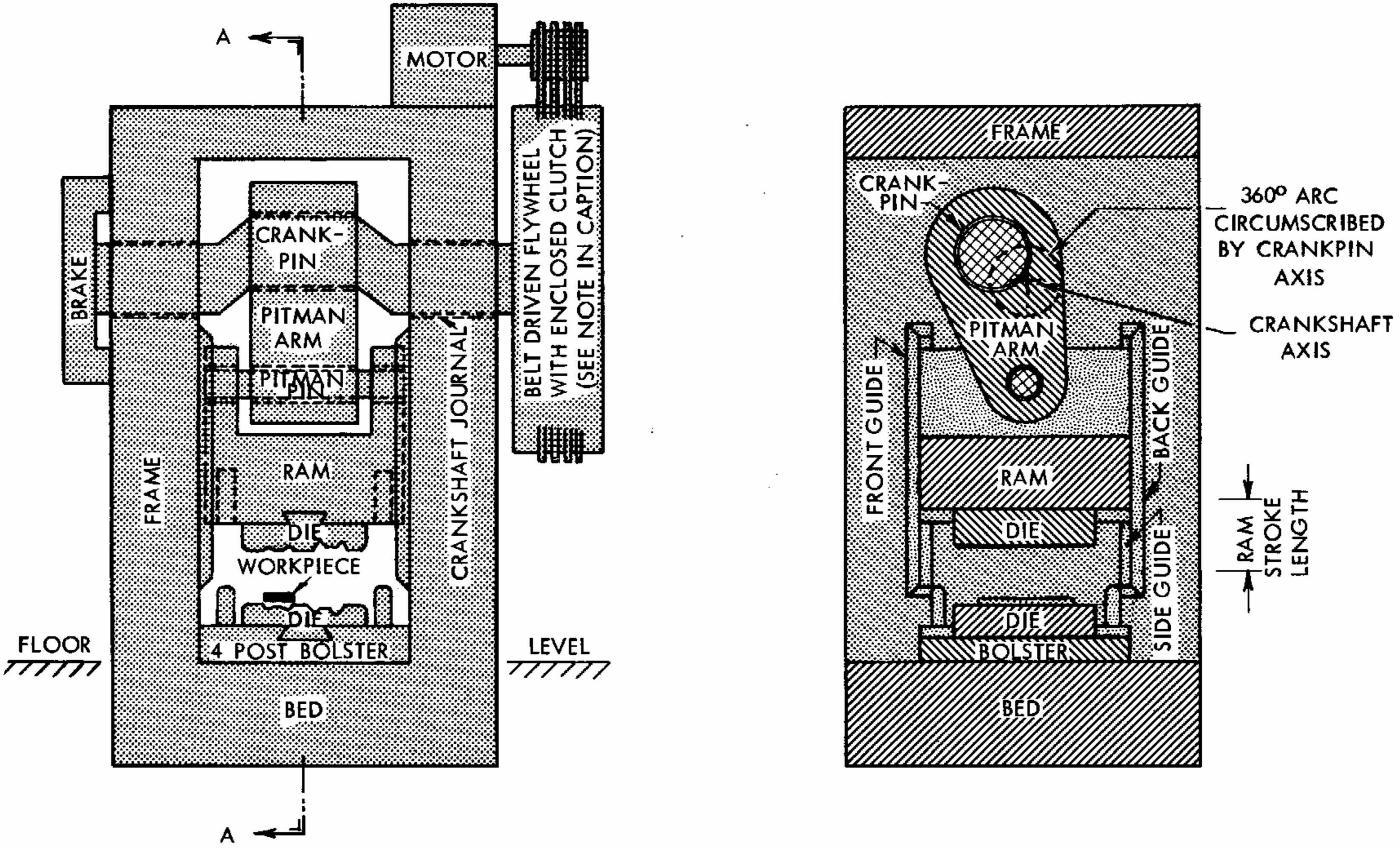

(a) FRONT VIEW

(b) CENTER SECTION SIDE VIEW

Figure 48. Highly Simplified Illustrations of Crankshaft-Type Mechanical Forging Press Showing Major Components. Note that, for Simplicity, Motor and Flywheel Placement are Shown Incorrectly. Multiple Impression Dies, as Illustrated, Were Not Used to Produce the Fin Rib Forgings.

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Several features of this ram cycle are apparent. First, the stroke is fixed as the diameter of the arc circumscribed by the eccentric (crankpin axis) of the crankshaft. Second, the ram velocity is a function of the ram position; changing from zero at "top dead center" of the crankpin, to maximum linear velocity near 90° of crankshaft arc (at 90° with the scotch-yoke design), and again to zero at 180° of arc (at maximum die closure) when the crankpin is in "bottom dead center" position. This varying ram velocity from 90 to 180° degrees of arc is illustrated in Figure 49(a). Third, the force available is also a function of the ram position and theoretically, by mechanical advantage, is in inverse proportion to the ram velocity. Thus, at the "bottom dead center" position, an infinite force would be generated if it were not for tensile deflections of the frame, bending deflections of the crankshaft, etc. Further, it can be appreciated that the force available higher in the stroke is significantly less than when dies are virtually closed. Fourth, since the stroke is fixed, the force developed is a function of the resistance which the frame, crankshaft, and all other members in the "force circuit" afford to deflection. This is illustrated for the frame in Figure 49(b), and it can be appreciated that such elasticity as indicated would not allow the press to generate significant force in traveling through its stroke. Due to this fixed stroke, rigidity of major structural components is of greater significance in the design of mechanical presses than it is in design of hammers and hydraulic presses.

The above is theoretical and doesn't take into account the flywheel slowdown which occurs slightly at top dead center as the clutch is engaged and subsequently due to any force generated against resistance through a distance by the ram during the working portion of the stroke. It does, however, illustrate why mechanical presses must be chosen for specific forging operations on the basis of kinetic energy stored in the flywheel, horsepower, and slip characteristics of the drive motor which must re-accelerate the flywheel, and torque which the clutch is capable of transmitting. A press capable of structurally resisting repeated 4000 ton loads, for example, would require exceptionally generous flywheel energy and clutch torque ratings in order to deliver 4000 tons of force at a point high in the downward stroke as might be immediately required to "break-through" in a forward extrusion operation. Yet an otherwise identical press would perform satisfactorily with much lower flywheel and clutch ratings for such "low profile" work as structural impression die forging where maximum force is required when the dies are virtually closed.

The 4000 ton press employed for the program's mechanical press forging effort is shown in Figure 50. This is a Ladish modified, crankshaft-pitman-type press originally manufactured by the Clearing Division of U.S. Industries, Inc. The frame is of welded steel plate construction held vertically in compression throughout the stroke by four prestressed tie rods at the corners. Mainshaft diameter at the journals (30 inches) and the stroke afforded by the eccentric (18 inches) are moderately large in comparison to those frequently specified for 4000 ton mechanical presses designed for forging. Geometric factors and clutch torque characteristics are such that the ram force rating of 4000 tons occurs 5/8 inch above "bottom dead center" (full closure). Again, this height where the rated force is available is moderately large in comparison to values frequently specified for 4000 ton mechanical forging presses. These features indicate that the force rating for the Figure 50 press is probably somewhat conservative. The "cycle rate" rating of the press is 36 strokes per minute; i.e., if the clutch were

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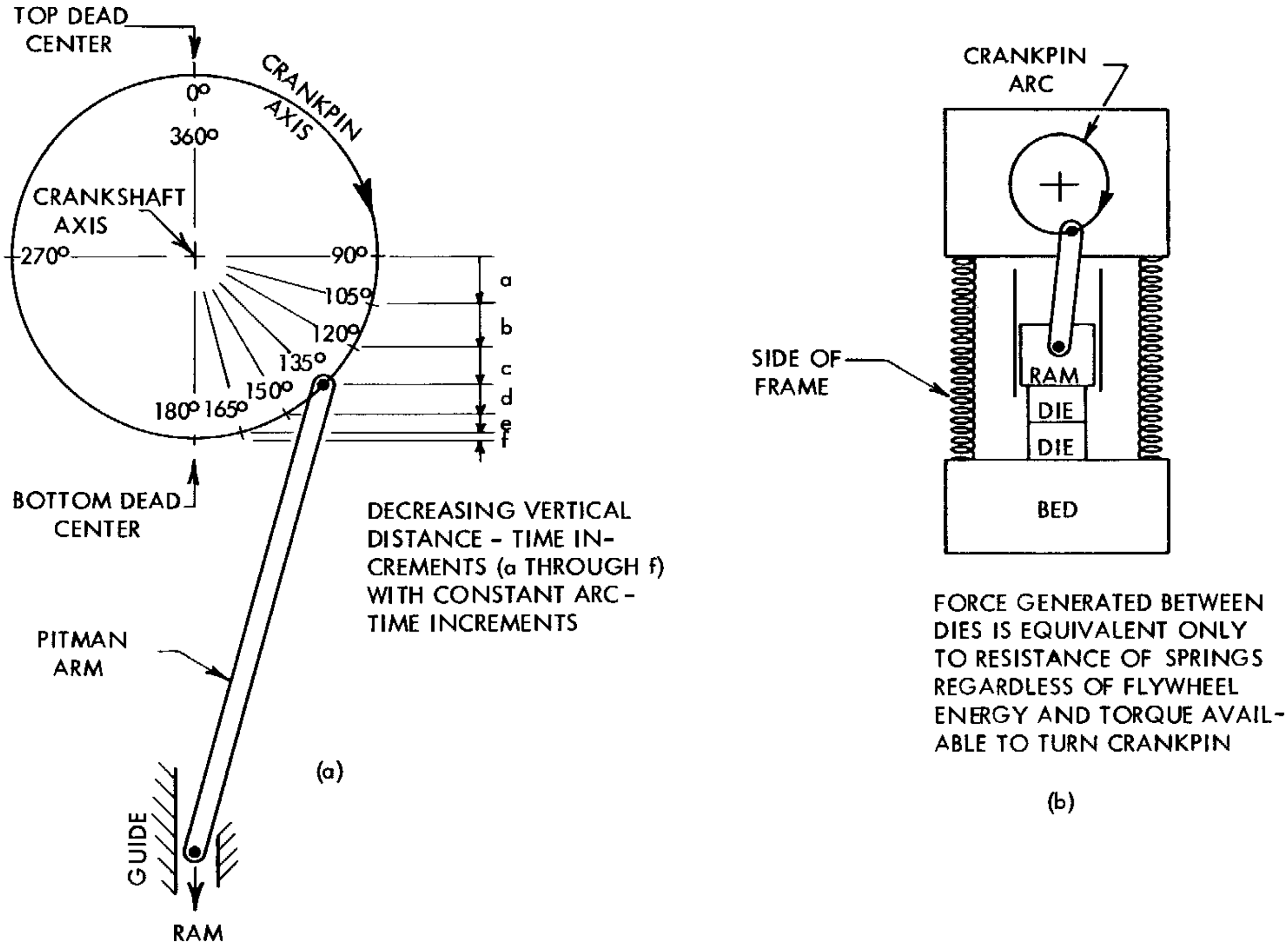

Figure 49. Schematic Illustrations of: (a) Ram Velocity Characteristics of Crankshaft-Type Mechanical Forging Presses, and (b) the Necessity for Exceptionally Rigid Frame Members between the Crankshaft Journals and the Press Bed. The Ram Velocity Increments are Actually Slightly Different from the "a through f" Increments Above, Due to the Tilting and Straightening Action of the Pitman Arm through the Cycle of a Crankshaft-Pitman-Type Press.

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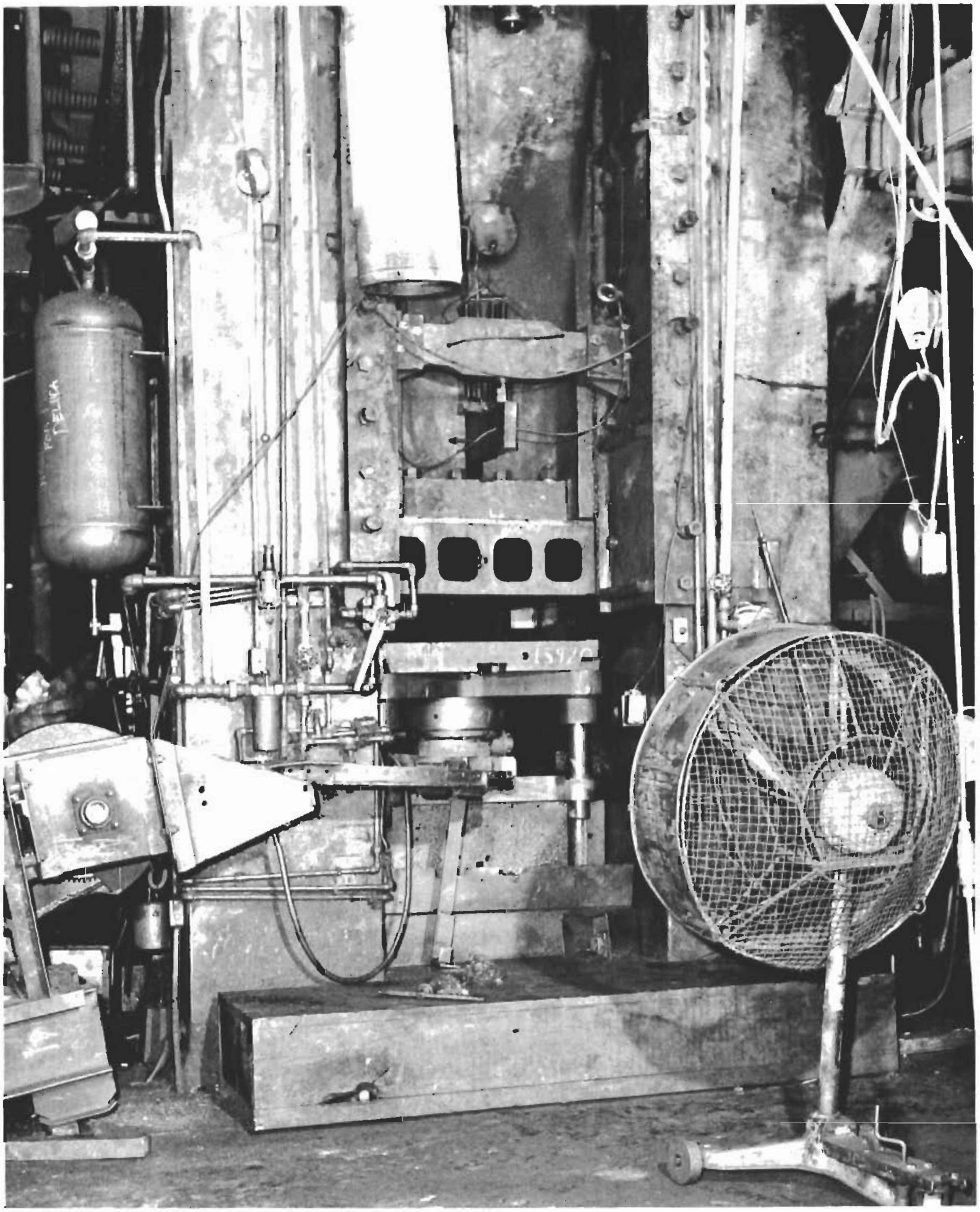

Figure 50. Mechanical Forging Press Rated at 4000 Tons of Force and Employed by Ladish Co. to Produce Fin Rib Forgings. Dies Shown Partially Installed are Not Pertinent to Program. Conveyor at Left of Press Brings Heated Workpieces to Press Operator from Exit End of Gas-Fired, Pusher Type Furnace (Not Shown).

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continuously engaged and the brake were disengaged, the ram would go through 36 complete cycles per minute against no load. This rating is useful in establishing approximate ram speed curves for mechanical presses and, although related, should not be considered as an indication of potential production rates.

2. Tooling Concept and Finish Forging Design

The die parting line location and section detail illustration of the finish forging configuration for the mechanical press are shown in Figures 51 and 52. It can be noted that these Ladish designs are identical to those previously discussed for the steam drop hammer; i.e., parting line location at one edge of the rib, three degree external draft, five degree internal draft, and typical fillet and corner radii of 0.313 and 0.125 inch, respectively.

3. Staging Sequence and Starting Stock

The fin rib forging staging sequence initially designed for the mechanical press, Figure 53, was also identical to that illustrated for the hammer, Figure 10. Round-corner-square stock was first preformed to the shape shown with open dies in an open frame hammer. This was then forged through the three blocker shapes and the finish shape with four separate sets of impression dies in the mechanical press. As with the initial tooling try-outs with the hammer, excessive flash losses from corner areas were experienced during the first and second blocker operations with carbon steel workpieces initially forged through the mechanical press die sequence. This resulted in the lack-of-fill condition at the corners which is evident in Figure 54. As can be noted by comparison with Figure 11, however, the lack-of-fill condition was considerably more severe after mechanical press forging.

A second series of forging trials, this time with greater starting stock volume and with starting billets of both carbon steel and Inconel 718 materials to span the range of resistance to metal flow, was then conducted with the mechanical press dies designed to the initial sequence. Results of these trials confirmed the earlier indication that the sequence required modification of the Figure 53 progressive shapes in addition to use of larger starting billets. Also, the results confirmed the dissimilar flash loss comparison observed earlier between the steam drop hammer and the mechanical press after review of results of the initial die try-outs with each machine. As before, the losses were particularly excessive during mechanical press forging. Since workpiece materials, heating and lubrication conditions, and forged shapes were essentially alike for these two Ladish efforts, the difference in forging response had to be attributed to differences in the tooling and/or in the operating characteristics of the machines themselves. The lesser restraint afforded by the narrower flash lands and the unrestricted gutters of the initially designed mechanical press dies (described later) was considered to be partially responsible. Also, the closure rates of the two machines are widely variant and the forging mode is different; i.e., single stroke versus multiple blow operation. This latter factor was also considered partially responsible for the differences in forging response for the reasons suggested in the following two paragraphs.

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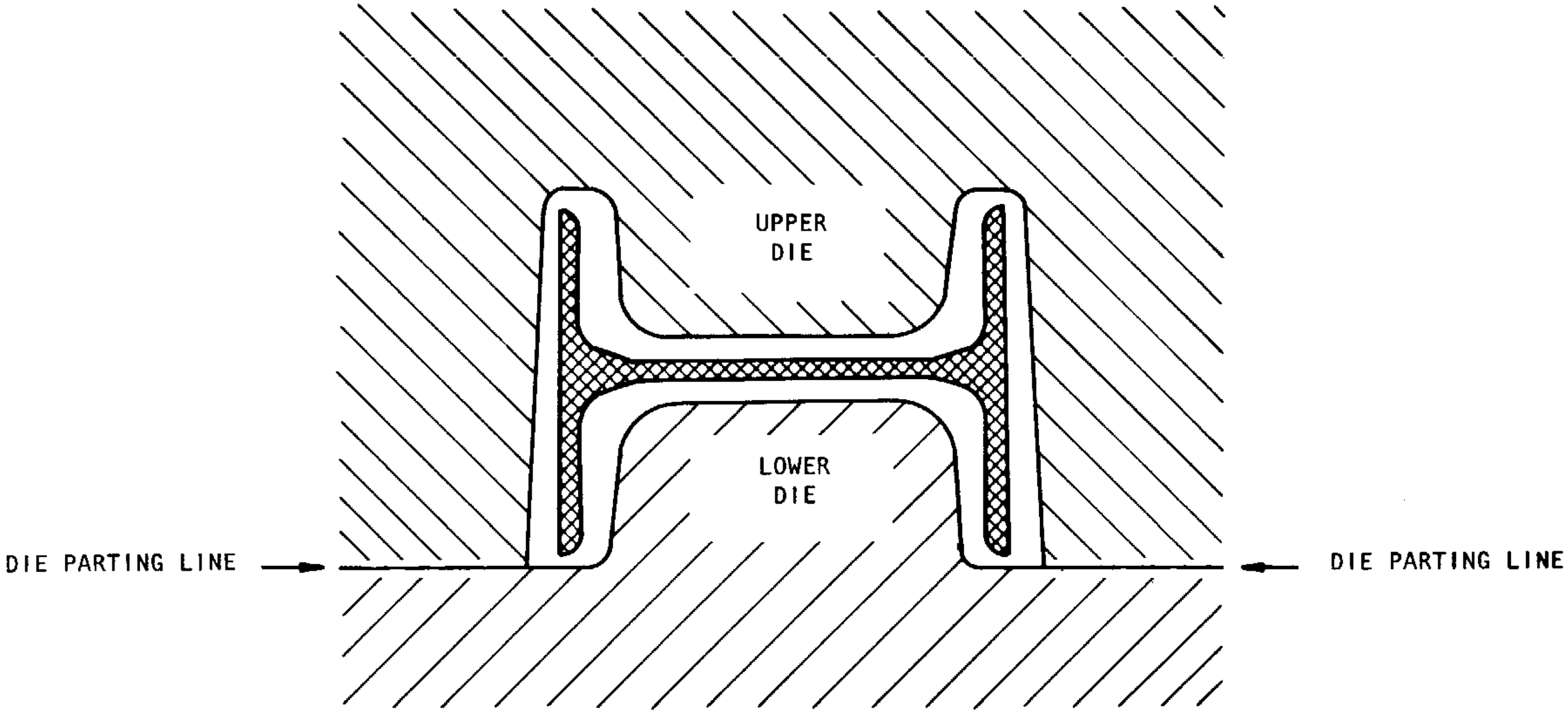

Figure 51. Schematic Illustration of Fin Rib Cross Section (at approximately mid-length) with Finish Forging Die Impression for 4000 Ton Mechanical Press Superimposed to Target Closure. Approximately Full Scale. Similar, Less Detailed Blocker Die Impressions for Prior Operations were Employed Inverted in Comparison to the Above Orientation. Also, Initial Forging Trials Employed the Finish Impression Inverted Relative to the Above - See Text.

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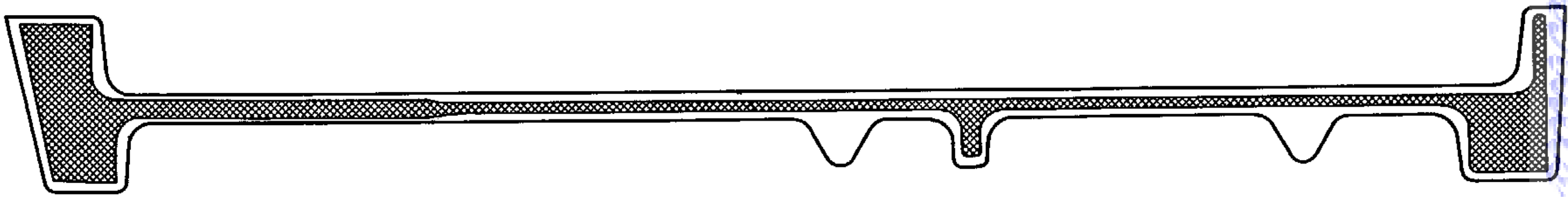

Figure 52. Illustration of Fin Rib Longitudinal Section (at mid-width) with Target Finish Forged Shape for 4000 Ton Mechanical Press Superimposed. Slightly Less than One-Half Scale. Shown in Correct Perspective for Initial Forging Trials, but Inverted Relative to Orientation in Finish Die Impression During Final Production of Intermediate Size Forgings - See Text.

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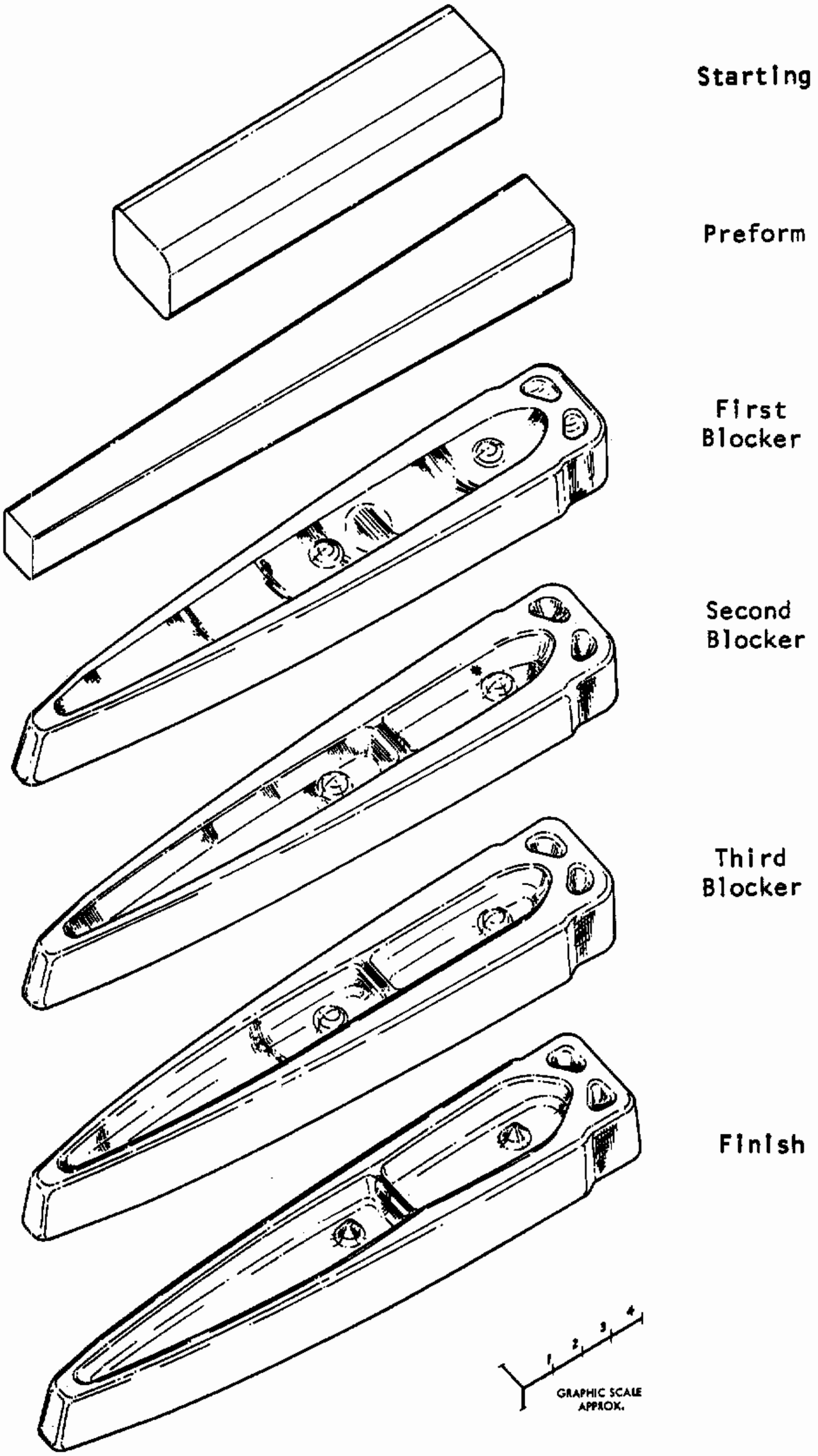

Figure 53. Illustration of Fin Rib Forging Staging Sequence Initially Designed for Forging Efforts with 4000 Ton Mechanical Press (Blocker and Finish). Blocker and Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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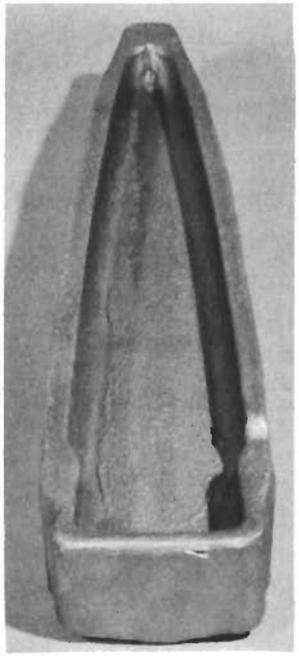
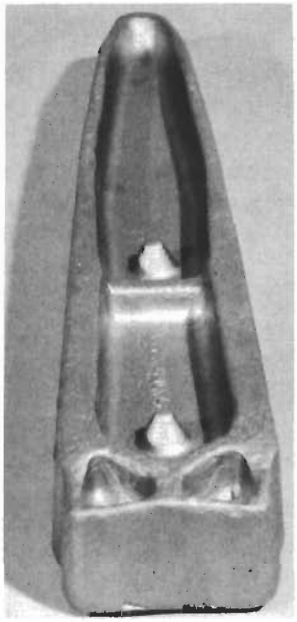


Upper Die Side



Lower Die Side

Figure 54. Carbon Steel Forging Produced During Initial Die Try-Outs with 4000 Ton Mechanical Press. Shown "As-Forged" Except for Sandblasting and Flash Trimming Operations. Approximately 0.35X.

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Of the four machine types compared, the mechanical press is the most reproducible, but the least flexible in operation. From the time the operator trips the control which disengages the brake and engages the clutch, the specific design characteristics of the dies installed and the particular set of single-fixed-stroke closure characteristics originally designed into the press are highly responsible for the forging results. Operator control of the process, assuming the proper die setup has been achieved, is essentially limited to "on die" temperature and lubricant factors. In this instance, inability to accurately predict metal flow during staging sequence and die design for a complex structural can easily result in a succession of forging trials and die rework efforts until satisfactory forgings are produced. This is because mill shapes available as starting stock tend to be symmetrical whereas structural rib-and-web forgings such as the fin rib forgings are not. Thus, the primary purpose of preforming and early blocking operations in such sequences is gross redistribution of metal volume within the die impressions to change from a generally symmetrical to a specific unsymmetrical shape which can be detailed during later operations. With dies designed for use of flash in a single-fixed-stroke machine, the redistribution requirements can be so severe at a point in the stroke where flash lands are still far apart that the only alternatives are to design for excessive flash losses in certain areas, to change parting line concepts, or to insert additional intermediate tooling stages and forging operations early in the sequence.

Also, of the four machine types, forging hammers are the most flexible in operation. In hammer forging of a complex shape, a skilled operator typically "nudges" the workpiece into the impression with low energy blows until the first hint of a flash protuberance is apparent at the last area around the parting line. During this procedure, flash is formed and chilled first at areas representing the least resistance to lateral flow. The formation and chilling of flash in these areas, in turn, tends to change the direction of preferential metal flow to new areas within the cavity until flash is formed and chilled there also. Once the ability to "lock-up" on flash at all areas has been achieved without experiencing particularly excessive flash losses at any area, the operator depresses the hammer treadle further and completes the forging operation with high energy blows. In other words, the operator of a machine designed for variable energy, multiple-blow operation is somewhat more capable of compensating for the inadequacies of tooling in reducing flash losses due to severe flow requirements or unanticipated flow patterns. It should be noted that the operator of a high powered, rapid-repeating hydraulic press also has some measure of this flexibility by operating his machine in a progressive, multiple-stroke mode.

The common subcontract work statement for intermediate size forgings limited the number of impression dies for the fin rib forgings to four sets. It also included provision that only the last two forging operations were required to be performed with the machine under study. Since the results of repetitive forging trials with each machine had already demonstrated the differences between hammer and mechanical press forging of the first and second blocker shapes, Ladish elected to hammer forge through the second blocker operation in the Figure 55 sequence rather than perform the extensive development which was indicated to be necessary to successfully press forge these early shapes. Thus, those changes in starting stock size, preforming techniques and preform shape, and first and second blocker shapes which have

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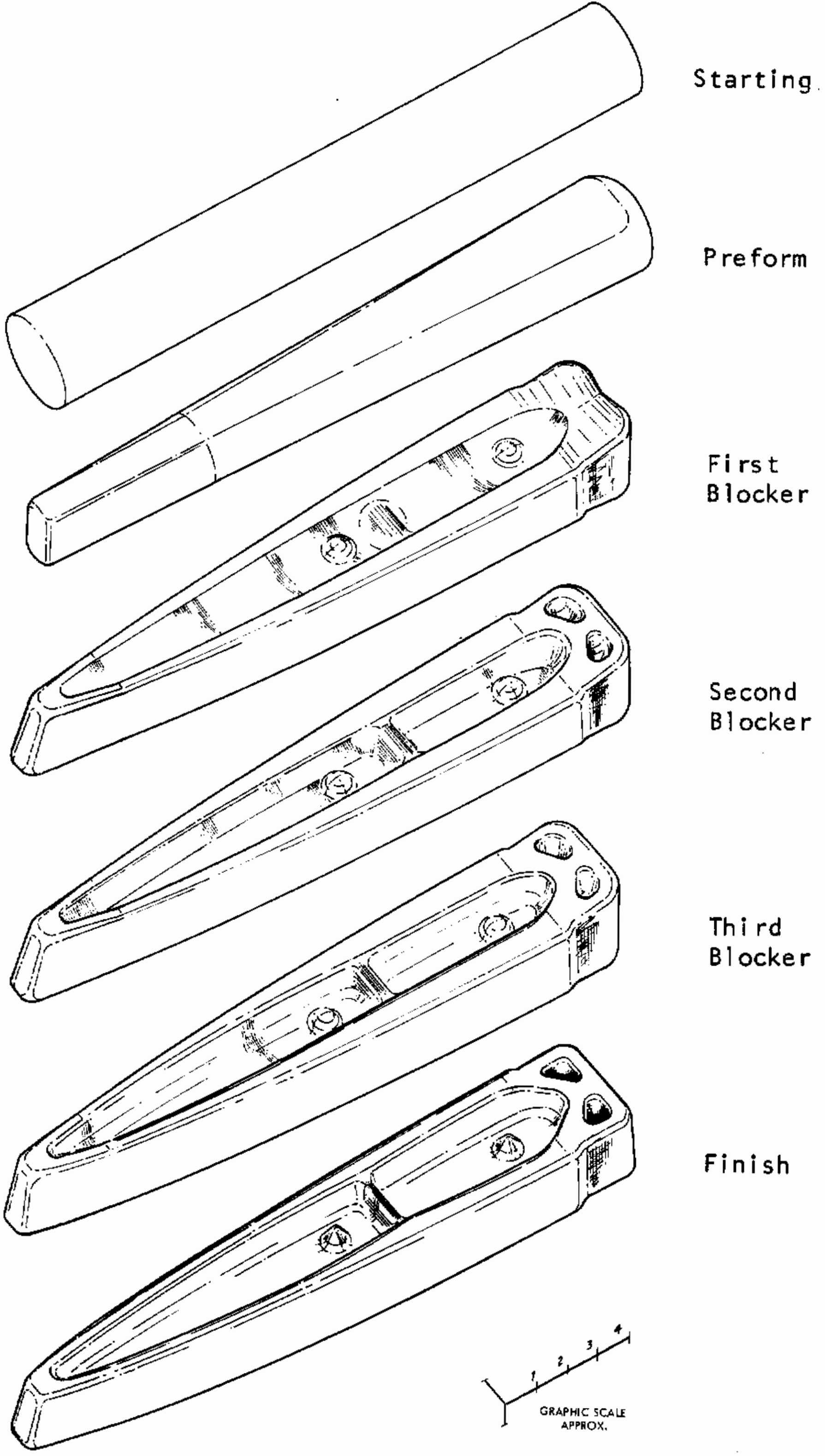

Figure 55. Illustration of Modified Fin Rib Forging Staging Sequence Employed for Final Production of Intermediate Size Forgings with 4000 Ton Mechanical Press (Third Blocker and Finish Only - See Text). Blocker Shapes are Shown Inverted to Reflect Lower Die Impression Detail. Note that Starting Stock was Machine Tapered Prior to Preforming.

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already been described for the steam drop hammer effort apply equally to Figure 55; and only the second blocker and finish operations were conducted with the mechanical press during the later efforts which resulted in delivery of forgings to TRW for evaluation. Other changes from the initial (Figure 53) mechanical press staging sequence included alteration of the third blocker shape to retain greater volume at the corners, as can be seen in Figure 55, and inverting the finish shape such that the parting line was at the bottom - again coinciding with the changes employed during final production of fin rib forgings with the hammer.

The same 3 inch diameter D6ac, Ti 6Al-4V, and Inconel 718 starting stock used during production of the hammer forgings was also used for the mechanical press forgings. Composition and quality data are listed in Table 5.

4. Forging Tooling

Although the impressions were the same for the hammer and the mechanical press, the dies were considerably different. Again, separate upper and lower dies were employed for the mechanical press forging operations shown in Figures 53 and 55, but the blocks were relatively small, had no integral guide posts to assist in control of mismatch, had no "kissing" surfaces to assist in control of thickness, had no "dovetail" projections to hold them in the machine, and were of a different material.

The essential design features of the mechanical press dies can be seen in Figure 56. The basic block sizes were 28 inch length by 12 inch width by 7 inch height (lower) and 6 inch height (upper). Such dies are frequently termed "inserts" because they are contained and held by large die holders (bolsters or "shoes") which, in turn, are fitted to the press bed and ram face. Control of mismatch was afforded by cylindrical bolster guide posts, and thickness dimensions were governed by the fixed stroke characteristics of the crankshaft-type mechanical press itself.

Flashline details can be seen in Figures 57 through 59, which show actual dies after completion of all program forging efforts with the mechanical press. Approximately 1/2 inch wide flash lands surrounded the impressions, and the flash gutters then extended without restriction to the edges of the blocks. Die closure was adjusted during tooling setup in the press such that flash thickness at the land was approximately 1/8 inch. The dies for the first and second blocker operations in the mechanical press during early trials were similar except that the first blocker die was initially designed to close totally on the flash itself. After the previously discussed decisions to employ hammer forging techniques through the second blocker shape, the only modifications of the remaining press dies were: 1) the alteration of the third blocker lower die to retain greater volume at the corners; 2) the inversion of the finish dies to place the parting line at the bottom as in Figure 51; and 3) the addition of six vent holes to the upper finish die. Although not discernible in Figure 59, the vents were identical in size and location to those previously described for the upper finish die for the hammer.

The dies for the mechanical press were prepared by conventional machining of wrought, prehardened blocks of Ladish D9 steel (nominal analysis 0.46C, 0.75Mn, 1.05Cr, 1.00Mo, 0.55Ni, 0.50V, bal. Fe). The similarity to

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TABLE 5

Material Data for Intermediate Size Fin Rib Forgings Produced with a 4000-Ton Mechanical Press

Chemical Analysis	C	N	O	Al	V	H	Fe	Ti	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	B	Cb+Ta	Others
D6ac	0.46				0.10		Bal.		0.79	0.004	0.007	0.23	0.56	1.10	0.98	0.15				
Ti 6Al-4V	0.015	0.011	0.14	6.70	4.11	0.0034	0.21	Bal.												<0.05
IN 718	0.04			0.62			17.43	0.98	0.15	0.009	0.006	0.15	53.30	18.56	3.09	0.05	0.06	0.0038	5.50	

	D6ac	Ti 6Al-4V	IN 718
Material Source	Republic Steel Corp.	Titanium Metals Corp.	Carpenter Technology Corp.
Heat Number	Airmelt No. 8023794-3 VAR No. 3962210	K-2938	87807
Starting Stock Form	13 inch RCS billet drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.	17-1/2 inch round billet drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.	20 inch round ingot drawn down by Ladish to 3 inch dia. by 18-5/8 inches long.
Starting Stock Weight	37.4 pounds before machining to taper, see text.	21.1 pounds before machining to taper, see text.	39.1 pounds before machining to taper, see text.
Procurement Specifications	AMS-6431	AMS-4967A	AMS-5664A
Other Inspection Procedures	Ultrasonically Inspected	Ultrasonically Inspected	Ultrasonically Inspected

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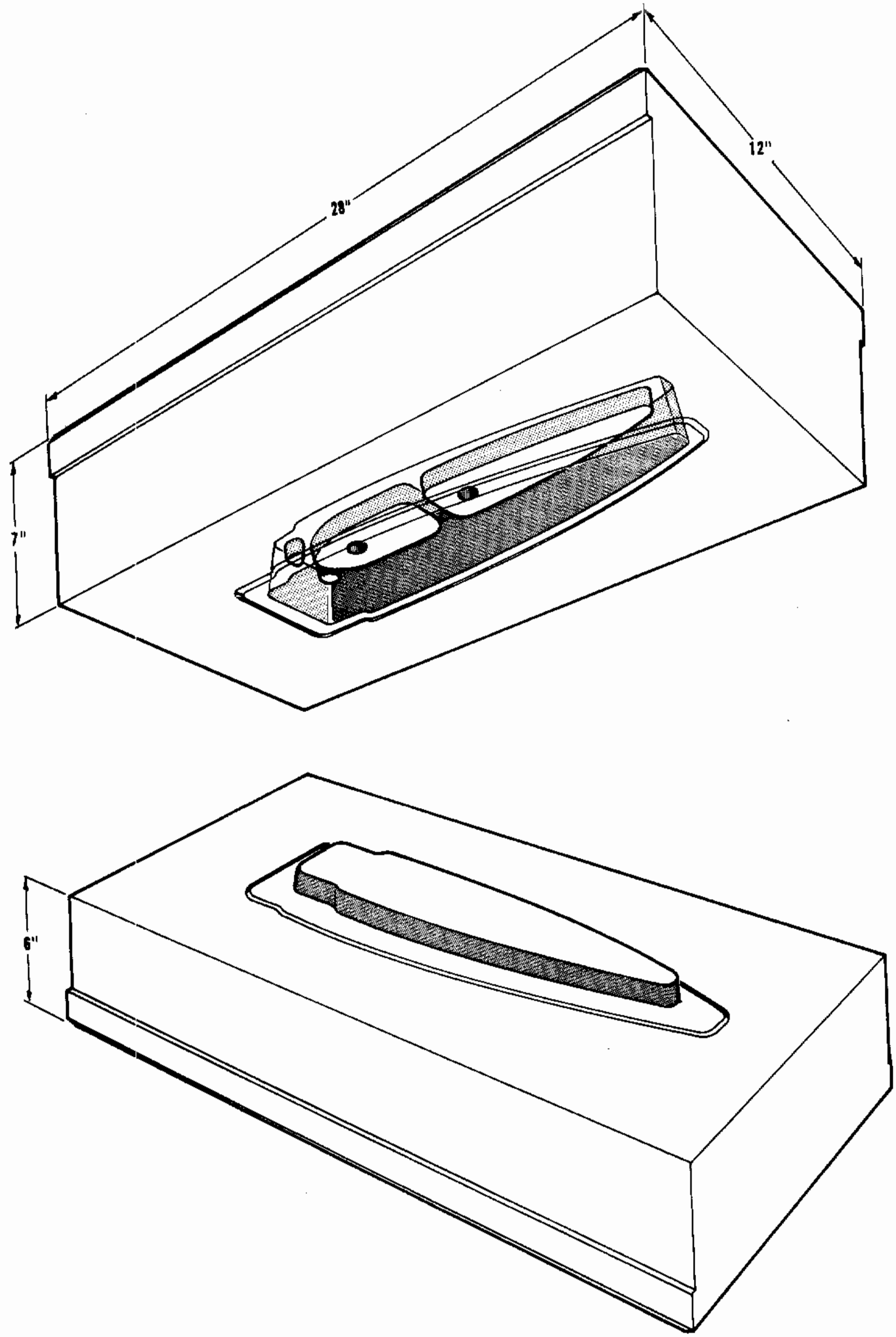

Figure 56. Schematic Illustration of Impression Dies for Finish Fin Rib Forging Operation with 4000 Ton Mechanical Press. Similar Dies for the Prior Blocker Operation were Employed Inverted in Comparison to the Above Orientation.

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Figure 57. Upper (Top) and Lower (Bottom) Dies for the Third Blocker Operation with the 4000 Ton Mechanical Press. Photograph Taken after Completion of All Program Forging Efforts with the Mechanical Press.

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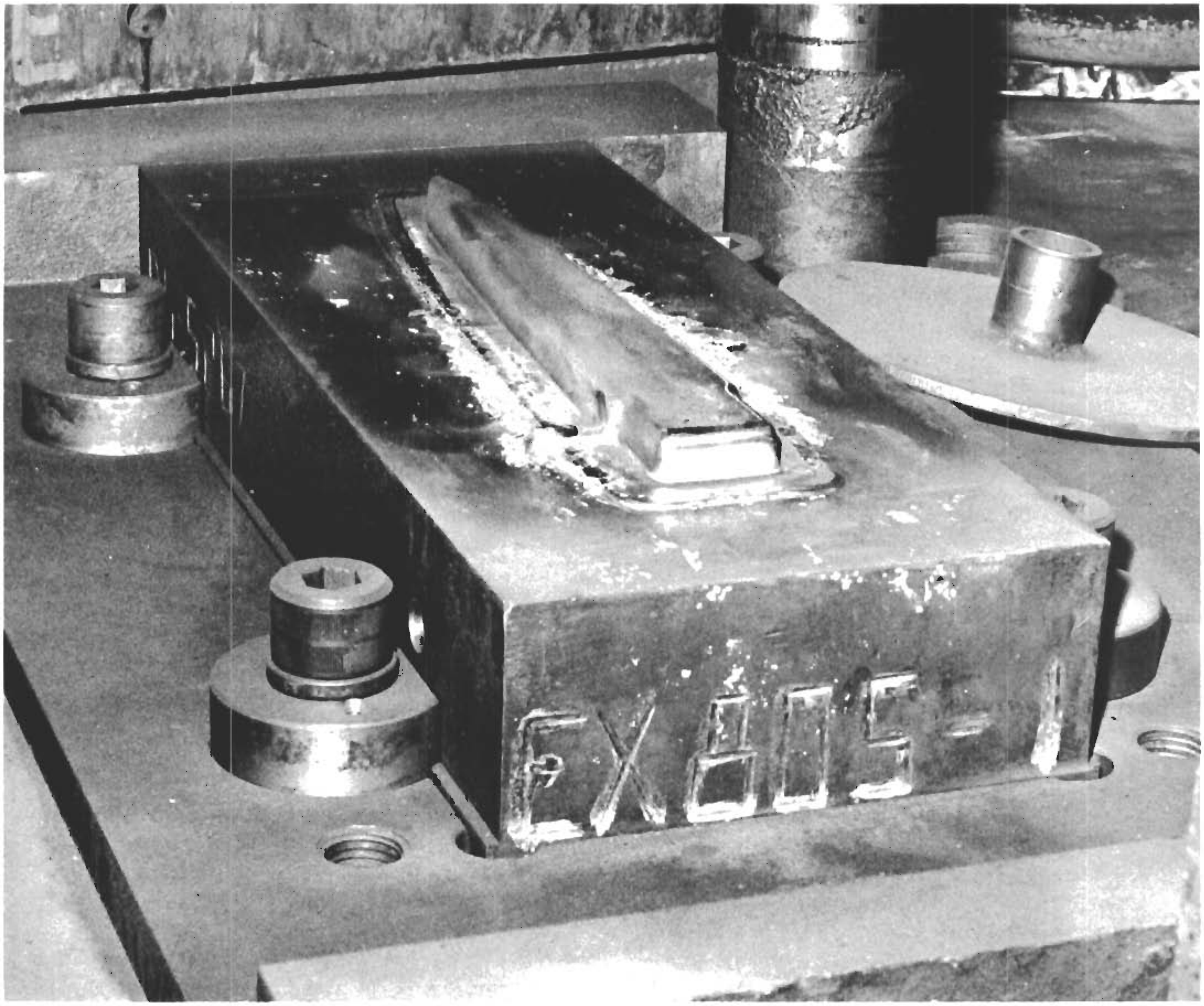

Figure 58. Lower Die for the Finish Forging Operation with the 4000 Ton Mechanical Press. Shown in Lower Half of Four-Post Bolster after Completion of Program Forging Efforts and Removal of Bolster from the Press.

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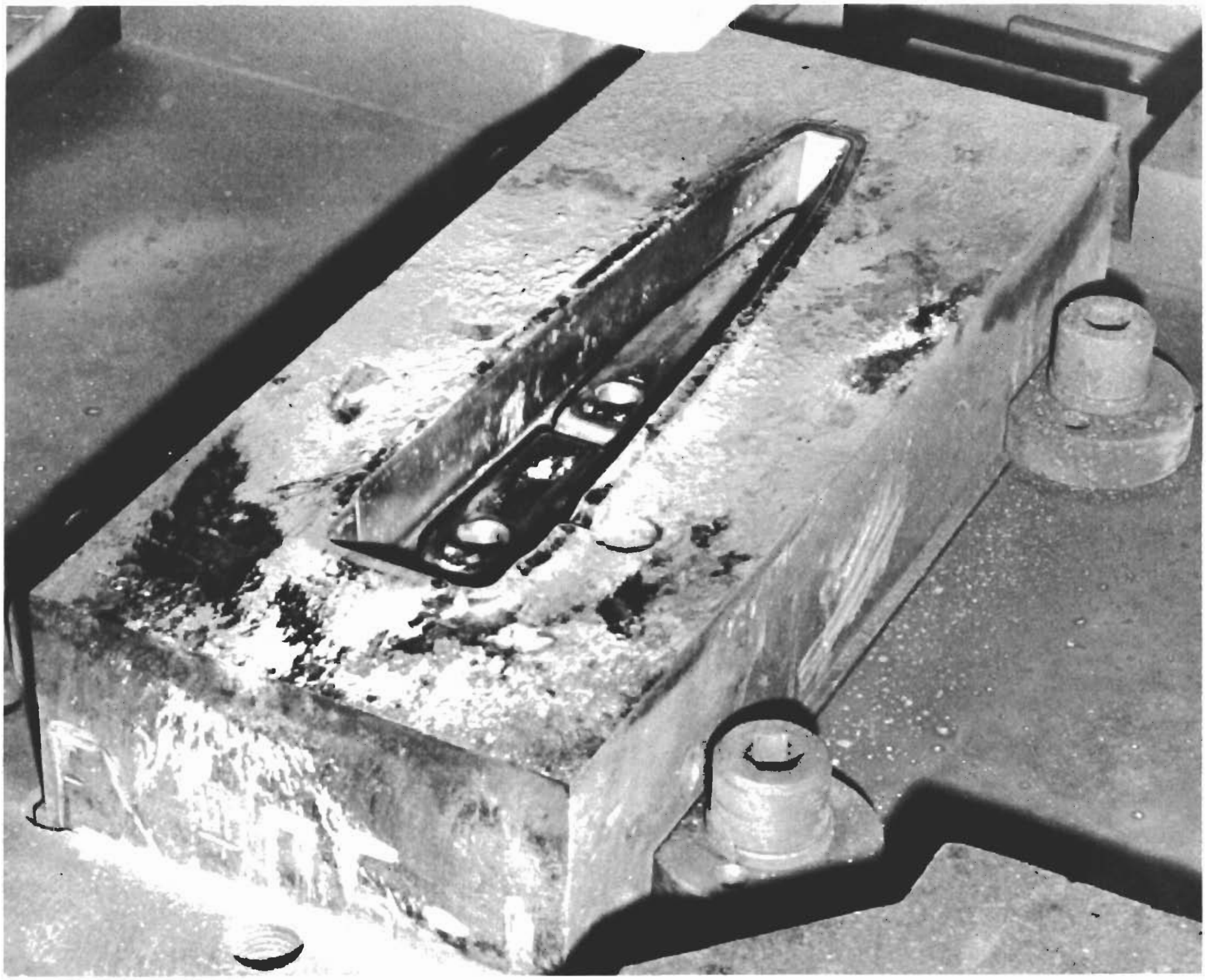

Figure 59. Upper Die for the Finish Forging Operation with the 4000 Ton Mechanical Press. Shown in Upper Half of Bolster after Completion of Program Forging Efforts and Removal of Bolster from the Press.

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the Ladish D6 composition previously listed for the hammer dies is evident. However, the increased vanadium content improves elevated temperature strength and resistance to tempering(10). These characteristics are desirable for mechanical press forging because the longer total pressure-contact time with the hot workpieces (in comparison to hammer forging) exposes impression surfaces to a moderately more severe thermal environment. Hardness of the mechanical press dies was within the range Rc 40 to 44.

5. Forging Results

Twelve workpieces of each of the three materials were forged through the third blocker and the finish operation with the mechanical press in accordance with the processing conditions listed in Table 6. Heating techniques paralleled those employed during previous hammer forging; i.e., the same type of muffles were utilized to retard scale formation with the D6ac and a large gas fired, pusher-type furnace was employed. Intermediate operations at Ladish again included abrasive blasting, flash trimming by torch cutting and grinding, and conditioning as necessary by grinding; and the ten finish forgings of each material which were delivered to TRW were abrasive blasted at Ladish and trimmed at TRW by band sawing and grinding. After trimming, the finish forgings were measured and were noted to be approximately 59 square inches in plan area, as were the hammer forgings.

Prior to trimming it was noted that the D6ac finish forgings produced with the mechanical press contained less noticeable vent hole protuberances than did the comparable hammer forgings, Figure 19. Nevertheless, the ten D6ac forgings delivered were generally well filled as can be observed in Figures 60 and 61. No surface defects were visually apparent.

The ten Ti 6Al-4V mechanical press forgings delivered are shown in Figures 62 and 63. These forgings were also generally well filled, although half of them (numbers 1, 2, 5, 9, and 10 from left to right in Figure 62) did not contain the same degree of upper die corner detail as did the D6ac forgings (Figure 60). There were no serious visible defects on the titanium alloy forging surfaces. However, several of the forgings exhibited indications of initiation of a surface tearing condition at localized areas of rib sidewalls. These indications were so slight that photographs were not taken. This condition was the subject of subsequent fluorescent penetrant and metallographic study, to be discussed later.

All of the ten Inconel 718 mechanical press forgings delivered exhibited slight lack of fill in the corners representing the extremities of the upper die cavity. This can be observed in Figures 64 and 65. The cracks which these forgings exhibited in web areas, particularly on the upper die side, are also apparent in the two figures. Several of these were very severe, as can be seen in Figure 66. Ladish reported that this type of defect was not observed during hammer forging through the second blocker operation, but that such cracking had also occurred during the third blocker (mechanical press) operation and had necessitated extensive conditioning. "Grind out" impressions from this intermediate conditioning operation which did not fill during finish forging can also be seen in Figures 64 and 65.

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TABLE 6

Processing Data for Intermediate Size Fin Rib Forgings Produced with a 4000-Ton Mechanical Press(a)

	Material		
	D6ac	Ti 6Al-4V	IN 718
Furnace Type	Gas Fired	Gas Fired	Gas Fired
Furnace Atmosphere	Muffles Used - See Text	Neutral to Slightly Oxidizing-Products of Combustion	Neutral to Slightly Oxidizing-Products of Combustion
Furnace Temperature	2200°F ±25°F-Third Blocker and Finish	1750°F ±25°F-Third Blocker and Finish	1850°F ±25°F-Third Blocker and Finish
Protective Workpiece Coating	None	Proprietary	None
Heating Times	1 Hour Maximum	1 Hour Maximum	1 Hour Maximum
Transfer Times	30 Seconds Maximum	30 Seconds Maximum	30 Seconds Maximum
Die Lubricant	Proprietary - Swab	Proprietary - Swab	Proprietary - Swab
Die Temperature	300°F Minimum 800°F Maximum	300°F Minimum 800°F Maximum	300°F Minimum 800°F Maximum
Number of Strokes per Stage	One	One	One
Number of Reheats	None	None	None
Cooling Methods	Air	Air	Air
Post Forging Thermal Treatment	None	None	None
Contact Velocity (in./sec.)(b)	7-Third Blocker 4-Finish	7-Third Blocker 4-Finish	7-Third Blocker 4-Finish
Deformation Time (sec.)(b)	0.06-Third Blocker 0.03-Finish	0.06-Third Blocker 0.03-Finish	0.06-Third Blocker 0.03-Finish

(a) - Preforming conducted with open frame hammer and first and second blocker operations performed with 12,000 pound steam drop hammer. See Table 2 for processing data.

(b) - Not reported by Ladish. Approximated by TRW on the basis of progressive thickness reductions of mid-length web material using data for presses operated by TRW which have similar, but not identical stroke, cycle rate, and pitman arm characteristics. Values listed should be used for "order-of-magnitude" comparisons only.

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Figure 60. Ten High Strength Steel (D6ac) Fin Rib Forgings Produced with 4000 Ton Mechanical Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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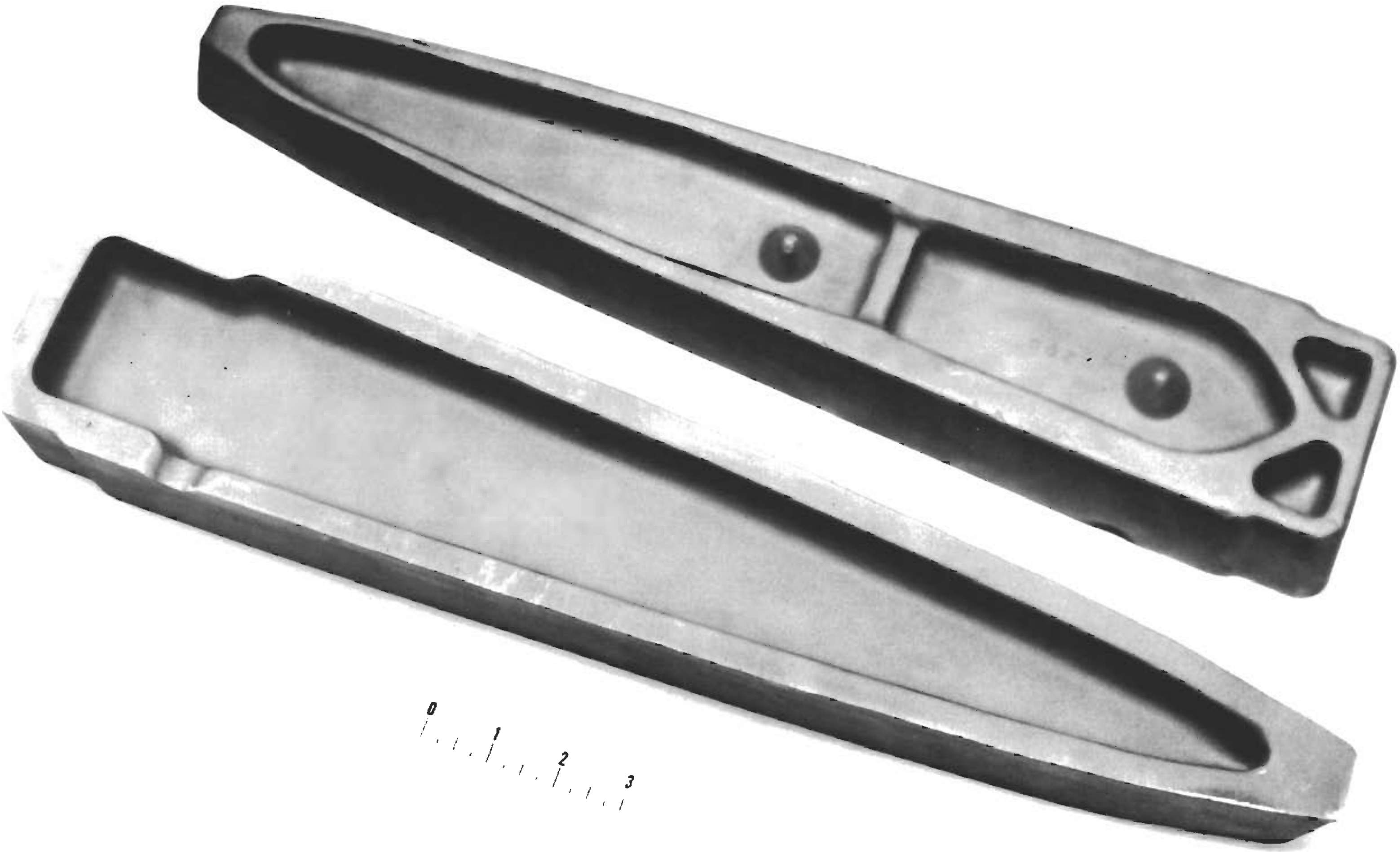

Figure 61. Close-Up of Two of the D6ac Forgings Produced with the 4000 Ton Mechanical Press and Delivered to TRW.

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Figure 62. Ten Titanium Alloy (Ti 6Al-4V) Fin Rib Forgings Produced with 4000 Ton Mechanical Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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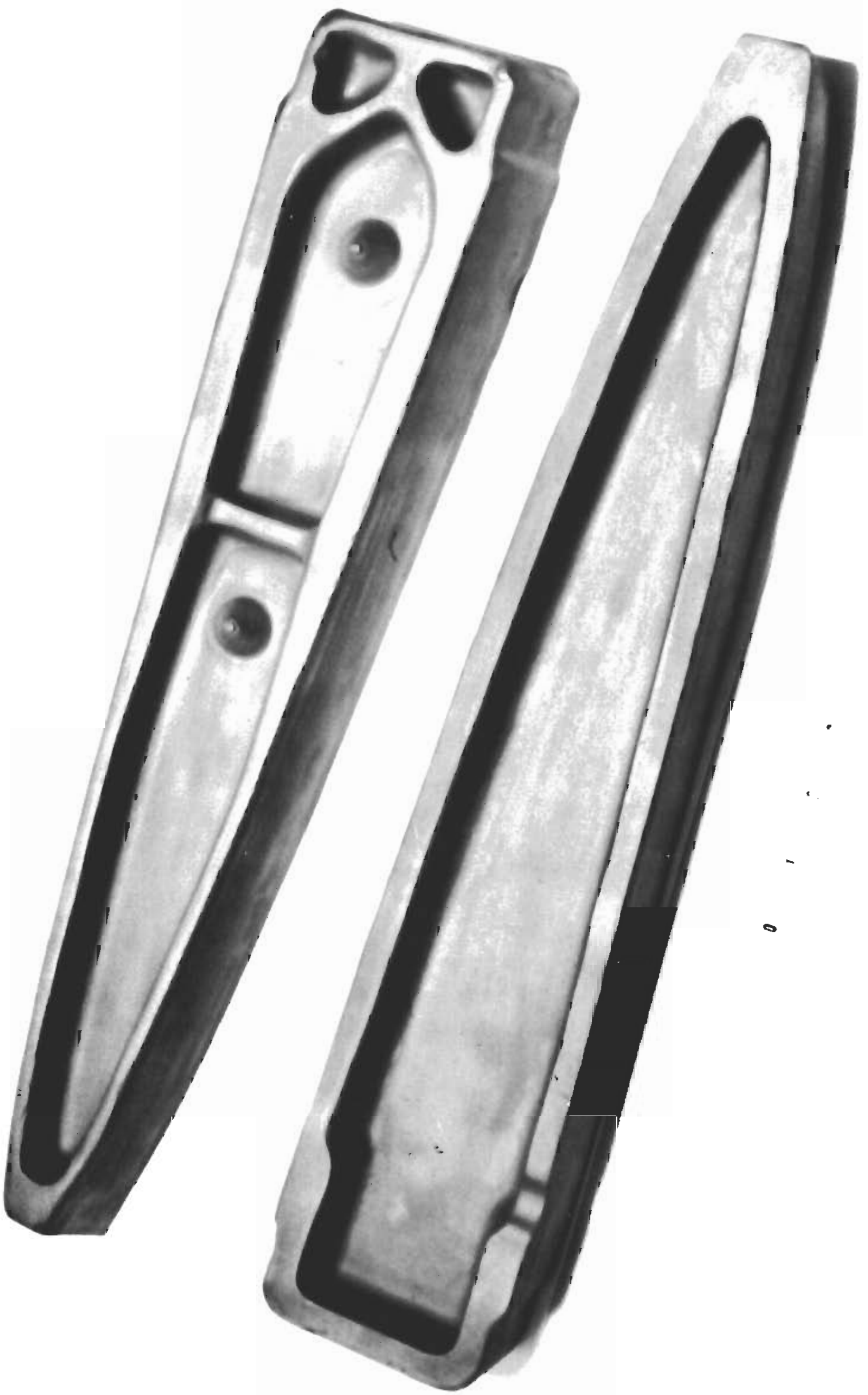

Figure 63. Close-Up of Two of the Ti 6Al-4V Forgings Produced with the 4000 Ton Mechanical Press and Delivered to TRW.

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Figure 64. Ten Nickel-Base Alloy (Inconel 718) Fin Rib Forgings Produced with 4000 Ton Mechanical Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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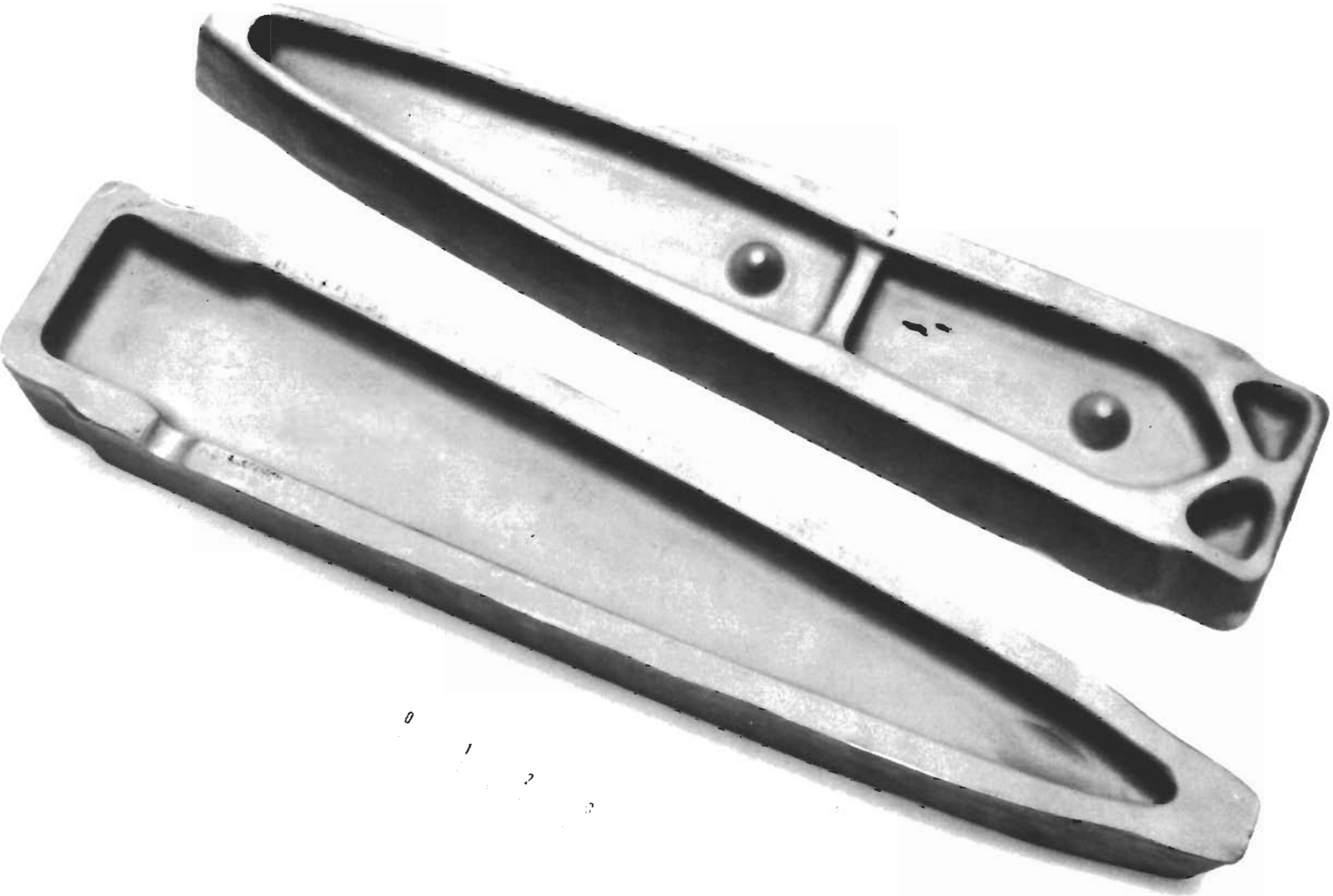

Figure 65. Close-Up of Two of the Inconel 718 Forgings Produced with the 4000 Ton Mechanical Press and Delivered to TRW.

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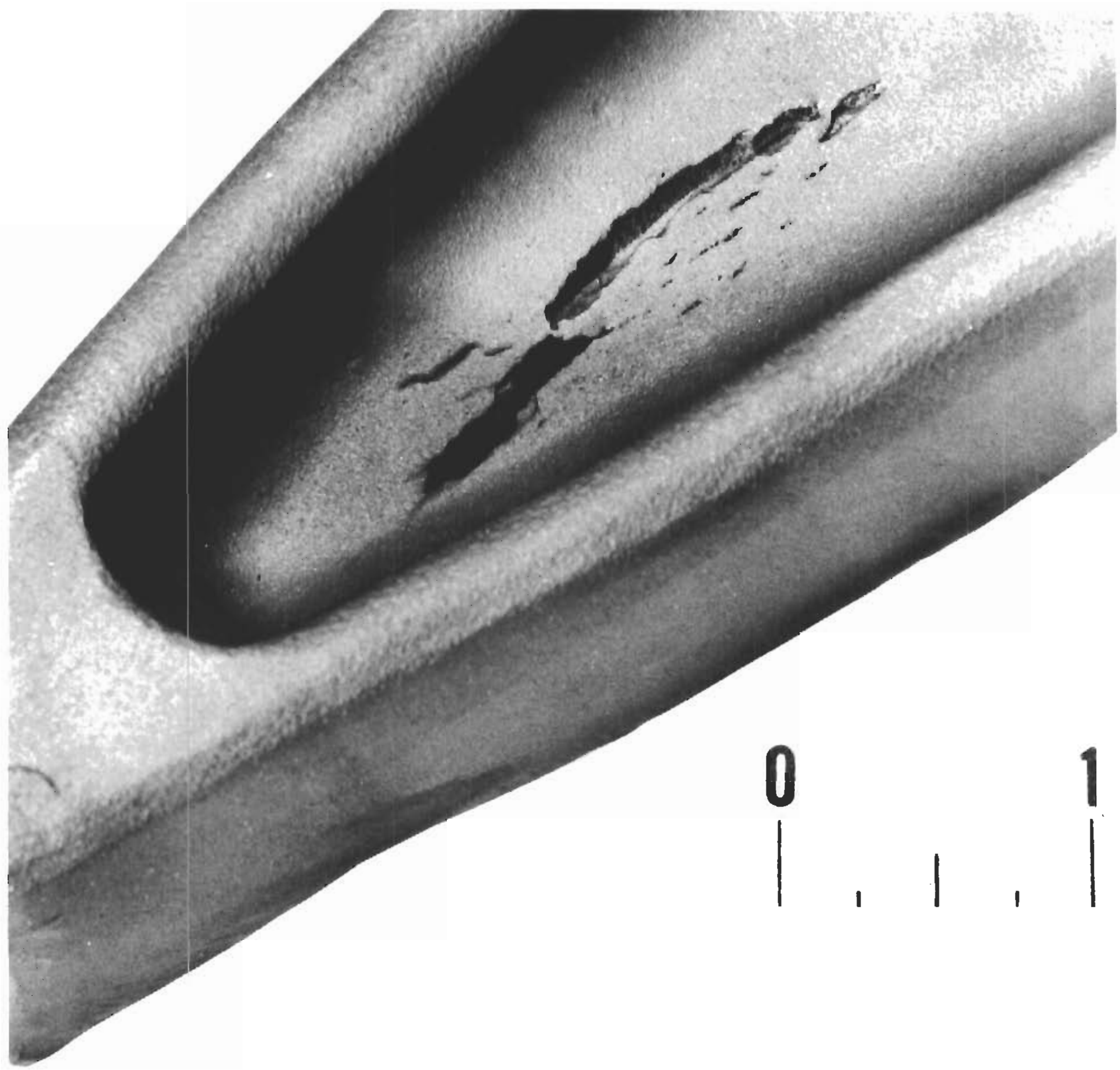

Figure 66. Severe Cracking in Web Surface of the Fifth Inconel 718 Fin Rib Forging Produced (of Twelve Forgings Total, the Third of the Ten Delivered to TRW) During Final Forging Efforts with the 4000 Ton Mechanical Press.

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Cracking defects which occur during forging of sound nickel-base alloy stock can be usually attributed to: 1) deformation of incorrectly heated metal (furnace temperature set too low, slow transfer, etc.) or of chilled surface metal (die closure rate too slow) to a degree exceeding its ductility; or 2) incipient melting at grain boundaries of these characteristically "hot short" materials due to initial (furnace temperature set too high) or adiabatic (die closure rate too rapid) overheating. As will be described later, metallographic examination of material sectioned through the crack in the sixth from the left forging at the top of Figure 64 indicated "cold tearing" as the failure mode. This, plus the fact that the cracks were quite deep (i.e., not shallow tears as might possibly be expected due to die chilling), suggests that the Inconel 718 workpieces may have been mechanical press forged at too low a temperature or that additional intermediate tooling stages may have been necessary.

As with the hammer forging effort, die failures were not experienced during mechanical press forging of the fin rib shapes. In contrast, however, the flash loss and cracking difficulties experienced during development and production of the mechanical press forgings strongly suggest that satisfactory staging sequence designs and processing conditions for forging with a steam drop hammer can be considerably less than ideal when attempting to arrive at the same finish shape with a mechanical press.

D. CEFF-Type HERF Machine - Precision Metal Products Div., Macrodyne-Chatillon Corp.

1. Forging Equipment

Since public demonstration of the first "Dynapak" in 1958, pneumo-mechanical HERF machines have been modified and refined to the point where reliable machines representing several different design concepts have been employed for impression die forging. These HERF machine types, although significantly different in engineering features, have several basic principles which are common. All are essentially very high velocity, single-blow hammers which, since velocity is squared in the kinetic energy equation, require much less moving weight than do conventional hammers to achieve the same impact energy per blow. All are rated at a maximum die closure velocity, under conditions of maximum energy, of approximately 65 feet per second at impact. All employ controlled high pressure inert gas "triggered" by a quick-release mechanism to "fire" (rapidly accelerate) the ram. All currently are characterized by relatively slow cycle rates due to hydraulic ram retraction devices. And all were designed in some manner to employ counterblow principles to minimize foundation requirements and energy losses.

Pneumo-mechanical high energy rate forging of the fin rib shape was conducted with a Model HE-55 CEFF (Controlled Energy Flow Forming) machine as illustrated in the simplified diagram in Figure 67 and as shown in Figure 68. CEFF machines are available in different sizes and are marketed by the Weingarten-CEFF Corp. of San Diego, California. The Model HE-55 is rated for a maximum of 400,000 foot-pounds of impact energy per blow. This closely approximates 55 meter tons (metric tons, thus equivalent to 55,000 meter kilograms, or MKG), and it is interesting to note that the "55" in the model designation represents the maximum impact energy design rating

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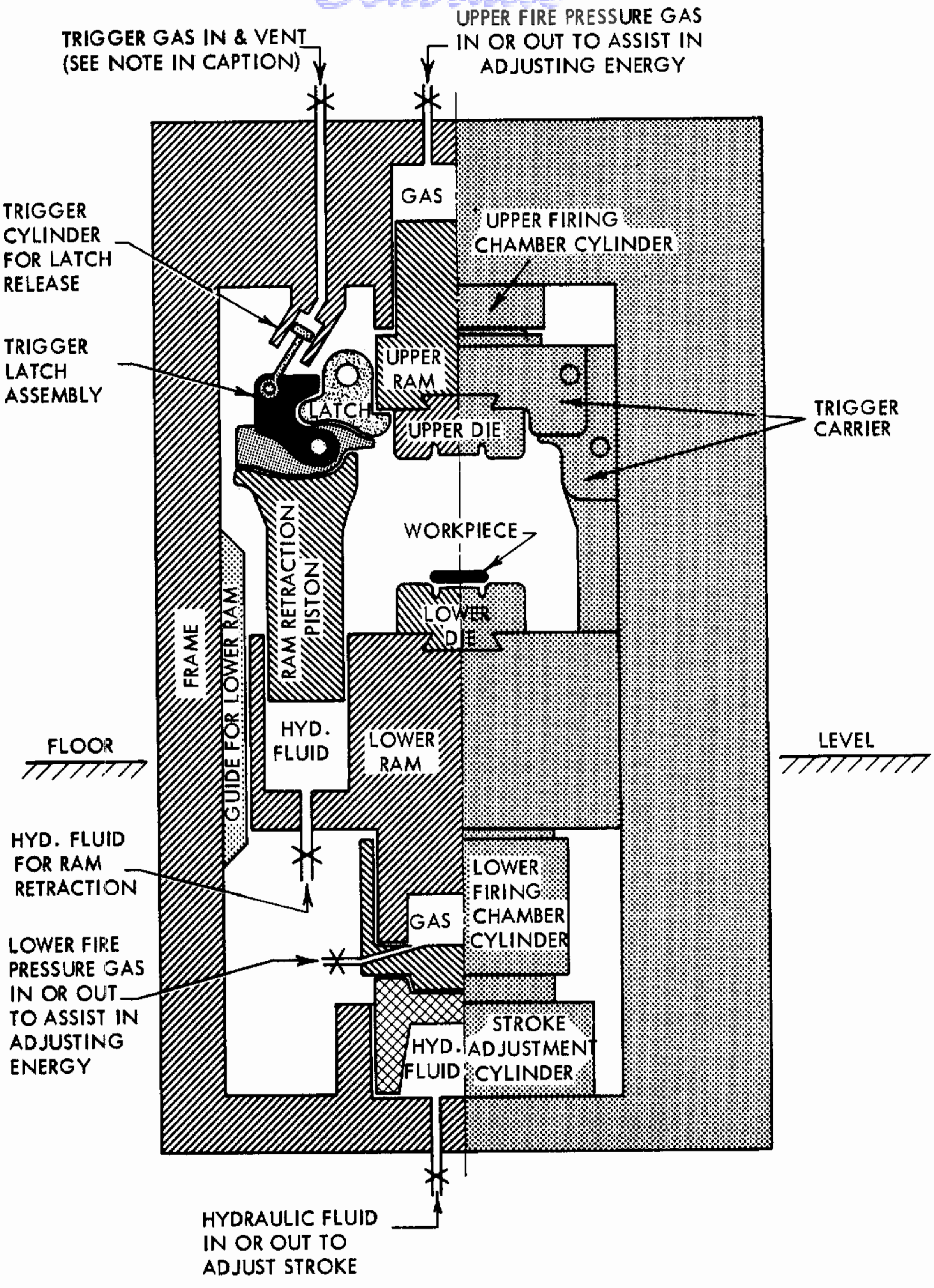

Figure 67. Simplified Illustration of Model HE-55, CEFF-Type HERF Machine Showing Major Components. Note that, for Simplicity, Upper Ram Guiding within the Trigger Carrier is not Shown, and Trigger Cylinder is Shown Incorrectly. Trigger Gas is Actually not Vented, but is Recompressed Hydraulically between Strokes.

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Figure 68. Model HE-55, CEFF-Type HERF Machine Rated at 400,000 Foot Pounds per Blow. Similar to Machine Employed at Precision Metal Products Div., Macrodyne-Chatillon Corp. to Produce Fin Rib Forgings. Dies Shown Installed are not Pertinent to Program.

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in meter tons. Maximum die closure velocity at contact for the HE-55 is actually rated slightly in excess of 65 feet per second, and the minimum cycle time between full energy blows is 8 seconds. Since the masses of the moving rams and die systems are fixed during forging of any specific shape, energy values less than maximum are achieved by lowering the contact velocity. This is afforded by lowering the gas pressures in the separate firing chamber cylinders which drive the upper and lower rams and/or by shortening the stroke with the hydraulic stroke adjustment cylinder beneath the lower ram.

The heating furnaces employed with the CEFF machines at Precision Metal Products are of the electric resistance, rotary hearth type; and an endothermic atmosphere is provided as an option to air to minimize scaling on steel workpiece surfaces during heating for precision forging operations. Although not visible in Figure 68, the furnace door is only twelve to fifteen feet from the machine to facilitate rapid manual transfer.

2. Tooling Concept and Finish Forging Design

Precision Metal Products' approaches to employment of the CEFF machine in meeting program goals for the intermediate size fin rib forgings are illustrated in Figures 69 and 70. It may be noted that die impression concepts for the finish operation were quite similar to those discussed for the hammer and the mechanical press, but that the finish forging outline was not inverted and more closely enveloped the component outline. Specific features included: 1) a horizontal parting line located along the upper edge of the rib; 2) employment of the zero degree, forty minute natural external draft and of ejector pins to release the forgings from the lower die cavity; 3) five degree internal draft; and 4) typical as-forged fillet and corner radii of 0.160 inch and 0.130 inch, respectively. The design essentially represented a 0.050 inch envelope over all fin rib component surfaces, with additional stock in specific areas to accommodate radii and internal draft.

3. Staging Sequence and Starting Stock

Initial Precision Metal Products forging trials were conducted with minimal size starting stock, a staging sequence in which the intermediate shapes did not represent overfilled corners, Figure 71, and tooling which provided virtually no relief for flash. One of the carbon steel forgings produced under these conditions is shown in Figure 72. The "nose" and the corners next to the "blunt end pockets", representing the extremities of the lower die cavity, can be observed to be incompletely formed. These characteristics are, of course, similar to those previously discussed for the results of initial efforts with the other machines. In addition, the CEFF machine carbon steel forgings exhibited a moderate lack-of-fill condition along the upper rib edge near the "blunt" end. This can also be seen in Figure 72. Increased total metal volume was indicated as a corrective step, with greater emphasis during intermediate shaping to provide proportionately greater volume increases at the corners prior to the finish blow.

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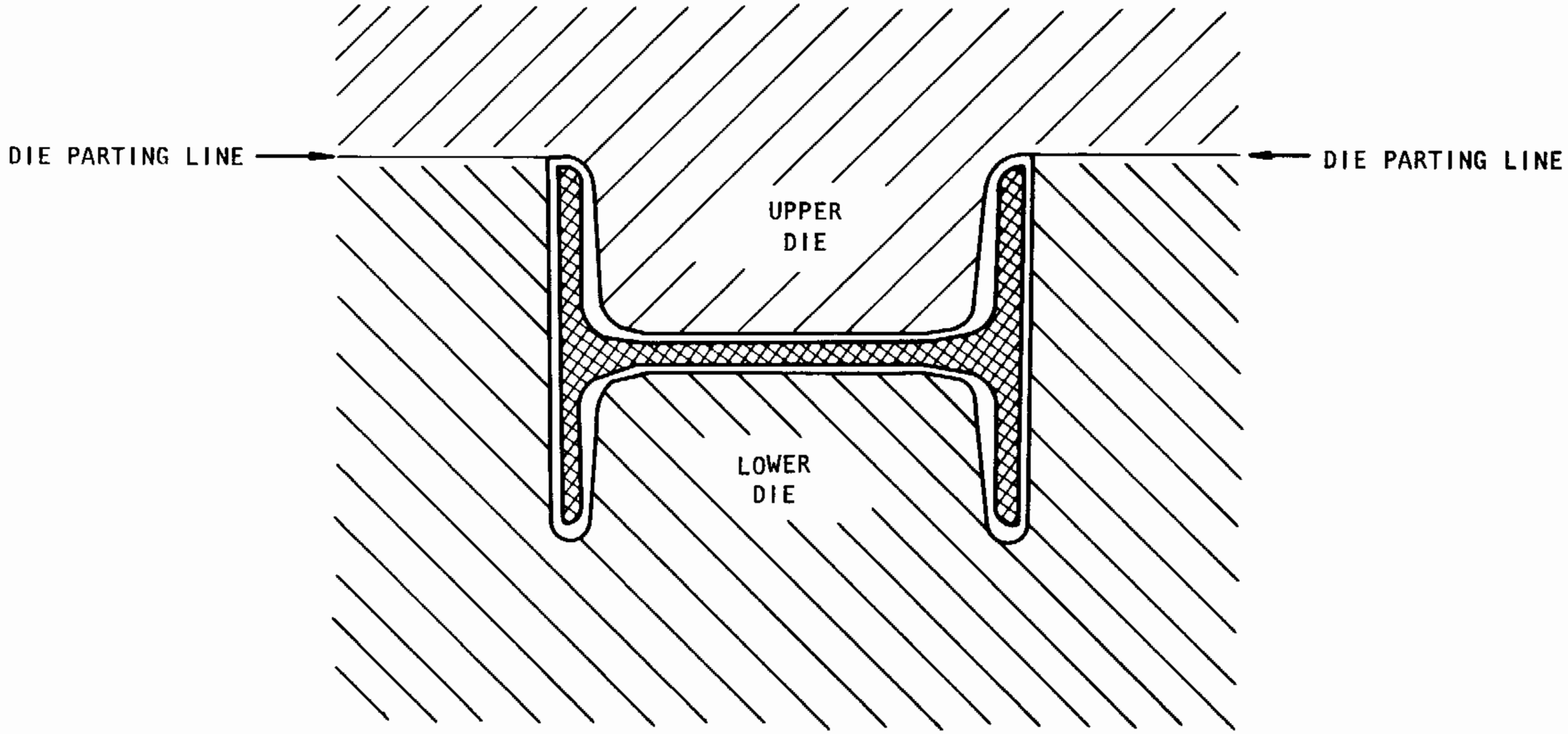

Figure 69. Schematic Illustration of Fin Rib Cross Section (at approximately mid-length) with Finish Forging Die Impression for 400,000 Foot-Pound CEFF-Type HERF Machine Superimposed to Target Closure. Approximately Full Scale.

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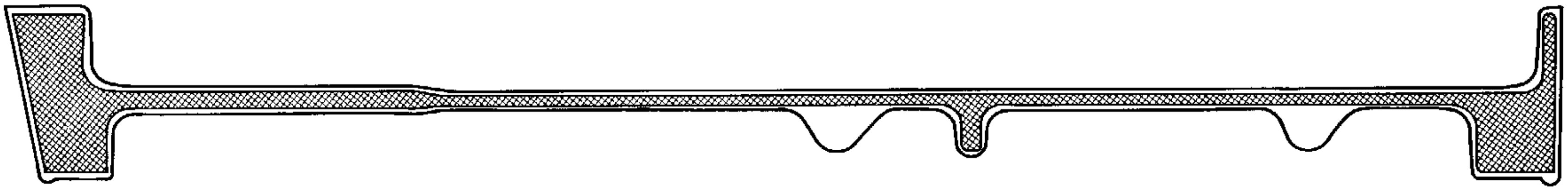

Figure 70. Illustration of Fin Rib Longitudinal Section (at mid-width) with Target Finish Forged Shape for 400,000 Foot-Pound CEFF-Type HERF Machine. Slightly Less than One-Half Scale.

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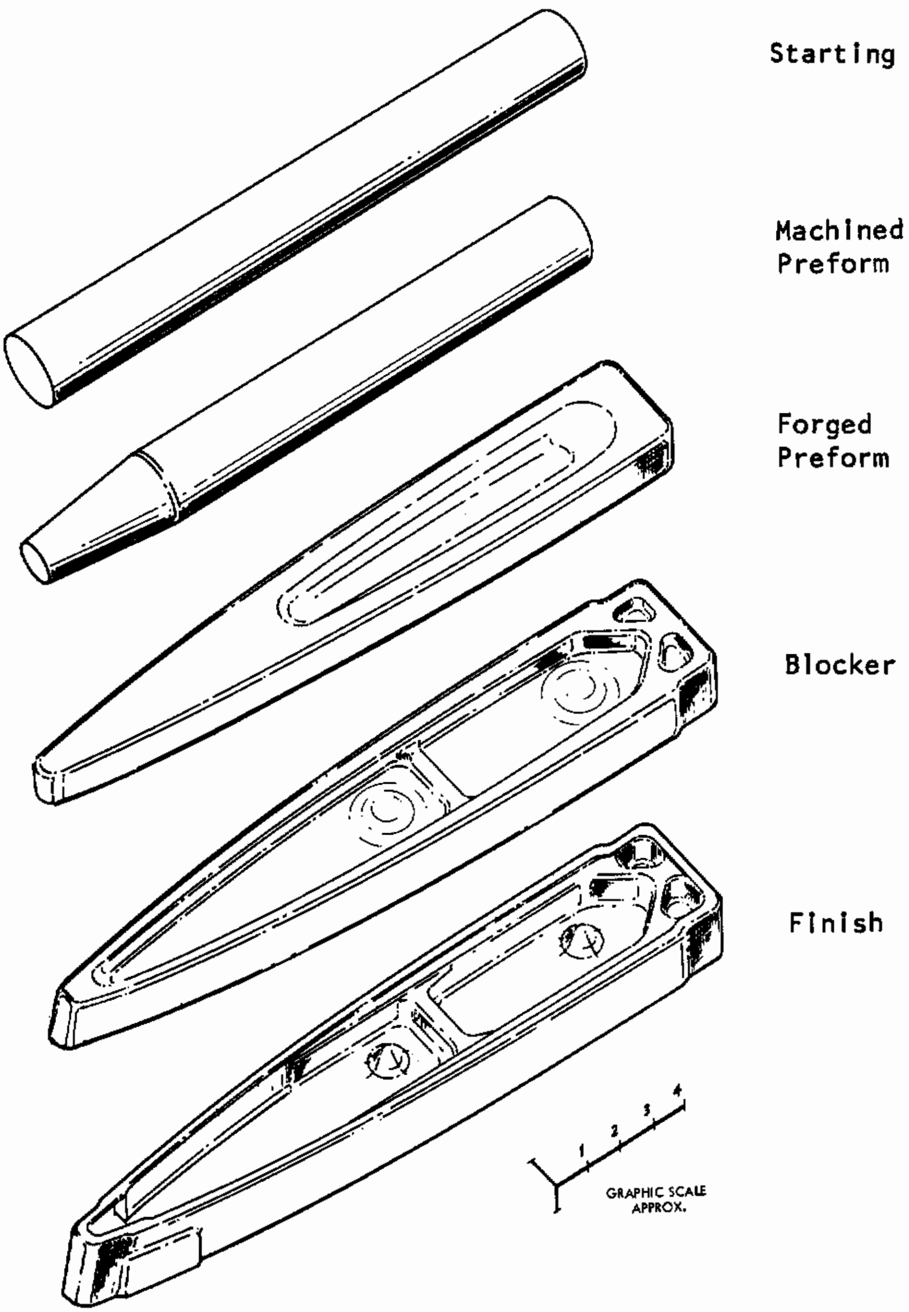

Figure 71. Illustration of Fin Rib Forging Staging Sequence Initially Designed for Forging Efforts with 400,000 Foot-Pound CEFF-Type HERF Machine (Forged Preform Through Finish). Forged Preform Through Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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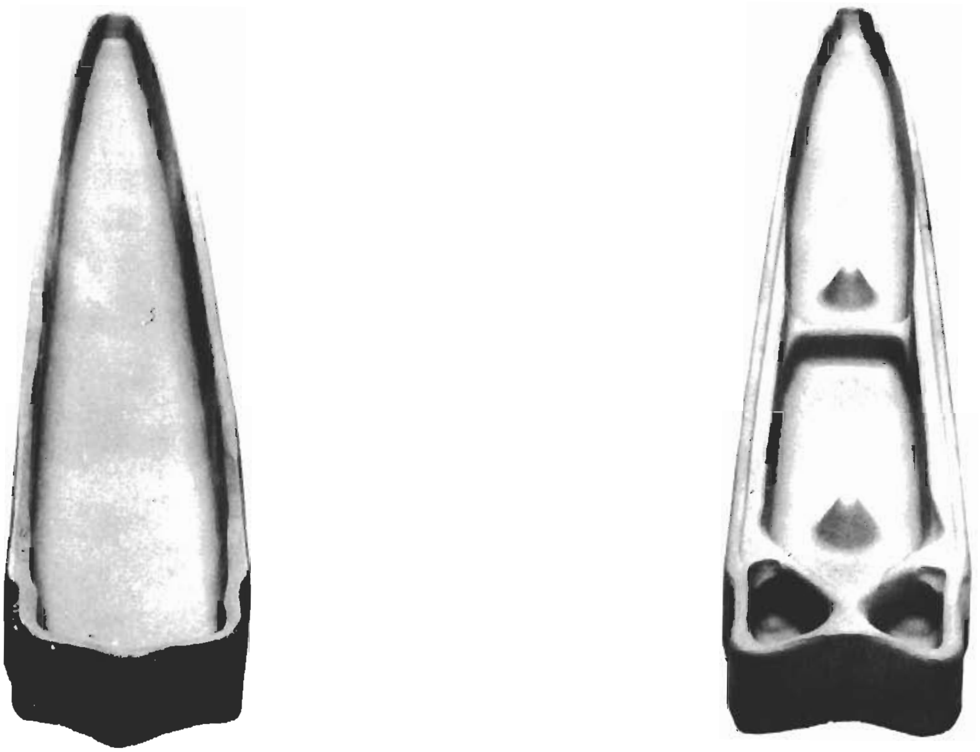

Upper Die Side

Lower Die Side

Figure 72. Carbon Steel Forging Produced During Initial Die Try-Outs with 400,000 Foot-Pound CEFF-Type HERF Machine. Shown "As-Forged" Except for Sandblasting and Flash Trimming Operations. Approximately 0.40X.

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The stock size and intermediate shape corrections employed by Precision Metal Products prior to production of the forgings required for program evaluation are illustrated in the Figure 73 modified staging sequence for the CEFF machine. First, length of the 2-inch diameter starting billet was increased from 16 to 18-1/2 inches. Second, the machined preform was changed from a tapered to a vertical wedge configuration, as shown, which was prepared by a milling operation. Third, the forged preform shape was significantly altered from a constant thickness shape to a variable thickness configuration which can be seen in Figure 73 to be the thickest at the ends. Fourth, the blocker shape was altered to include slightly greater volume at the "nose" end. This can be observed as increased thickness in this area on the lower die side of the blocker shape.

Precision Metal Products forged eighteen pieces of stock of each of the three materials during the final forging efforts with the CEFF machine. Of these, the first two or three of each material were used to establish the correct machine energy settings for each operation, and ten of each material were shipped to TRW for evaluation. Pertinent data for the starting stock procured are listed in Table 7.

4. Forging Tooling

Die design and die materials selection were considered to be particularly critical for the efforts with the CEFF machine. This was for two basic reasons. First, being an opposed ram counterblow machine, considerations of foundation and/or frame resilience cannot act in reducing the high forces which must be resisted by the dies during "hard" (short metalworking stroke) blows. This requires use of relatively large die blocks which must be of a particularly tough die steel. Second, the adiabatic heating of the workpiece which frequently results from high metal flow rates, and the subsequent delay prior to release of the forging by hydraulic ejector mechanisms currently common to all HERF machines can subject impression surfaces to a severe thermal environment. This requires that die steels also be carefully selected for elevated temperature strength and resistance to tempering.

The tooling designed by Precision Metal Products to accommodate this environment during production of the fin rib forgings is shown in Figure 74 for the finish operation. The basic lower die block size was 32 inch length by 16 inch width by 16 inch height, and similar sets of dies were prepared for the preform and the blocker operations. All tooling was prepared from wrought AISI Type H-13 die steel (nominal analysis: 0.40C, 0.30Mn, 1.00Si, 5.00Cr, 1.35Mo, 1.00V, bal. Fe), except for the lower die blocks for the first two operations which were of Finkl "FX" wrought die steel (nominal analysis: 0.55C, 0.75Mn, 0.30Si, 0.95Cr, 0.35Mo, 0.95Ni, bal. Fe). The Finkl blocks were procured prehardened to the "Finkl No. 2" temper (Rc 37 to 40), and all H-13 tooling was specified to be hardened and triple tempered to a hardness within the range Rc 44 to 46. EDM techniques were employed to prepare the impressions for the three sets of dies.

The large H-13 lower die block for the finish forging operation was an object of difficulty during its manufacture. After final tempering it was noted that this die had not responded adequately to heat treatment

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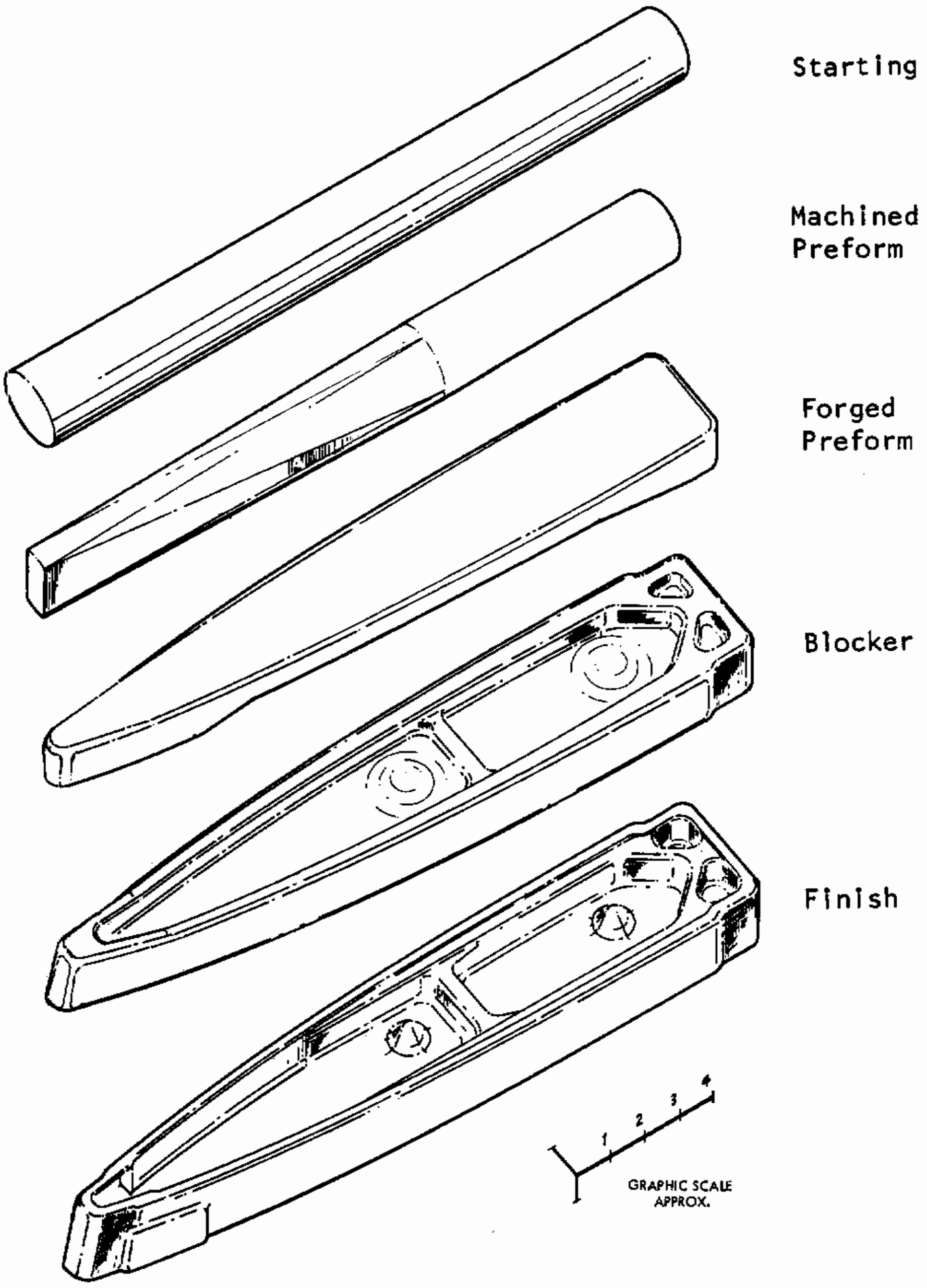

Figure 73. Illustration of Modified Fin Rib Forging Staging Sequence Employed for Final Production of Intermediate Size Forgings with 400,000 Foot-Pound CEFF-Type HERF Machine (Forged Preform Through Finish). Forged Preform Through Finish Shapes are Shown Inverted to Reflect Lower Die Impression Detail.

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TABLE 7

Material Data for Intermediate Size Fin Rib Forgings Produced with a 400,000 Foot-Pound CEFF-Type HERF Machine

Chemical Analaysis	C	N	O	Al	V	H	Fe	Ti	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	B	Cb+Ta
D6ac	0.47				0.12		Bal.		0.74	0.006	0.005	0.27	0.50	1.01	1.01				
Ti 6Al-4V	0.018	0.006	0.18	6.35	4.16	0.0080	0.19	Bal.											
IN 718	0.050			0.49			Bal.	1.05	0.08	0.003	0.007	0.15	53.43	17.95	3.05	0.05	0.14	0.0052	5.23

	D6ac	Ti 6Al-4V	IN 718
Material Source	Crucible	Harvey Aluminum	Universal Cyclops
Heat Number	S-18532-85-2	X-73	K-68181-K2
Starting Stock Form	16.5 pounds before machining to preform, see Figure 73.	9.3 pounds before machining to preform, see Figure 73.	17.3 pounds before machining to preform, see Figure 73.
Procurement Specifications	AMS-6431	AMS-4967A	AMS-5664A
Other Inspection Procedures	Ultrasonically Inspected	Ultrasonically Inspected	

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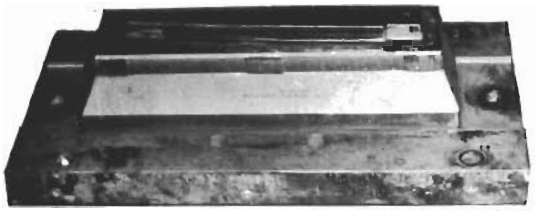
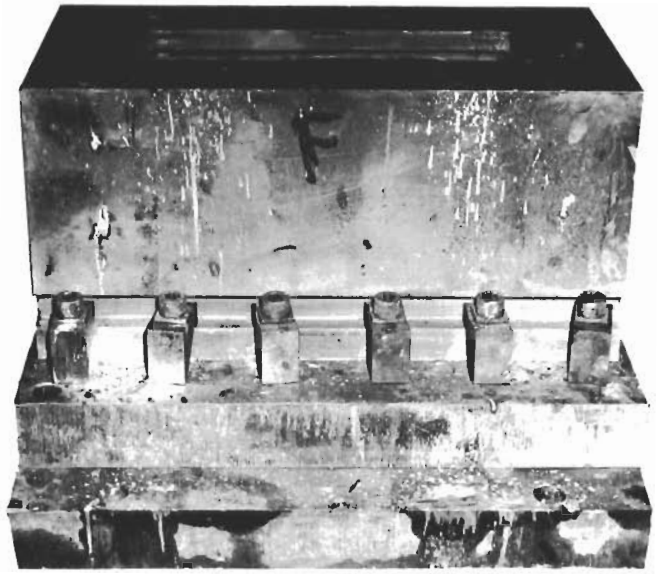


Upper Die and Die Holder
(shown inverted)

Ejector



Lower Die, Die Holder
and Spacer Block

Figure 74. Impression Dies Used for Finish Fin Rib Forging Operation with 400,000 Foot-Pound CEFF-Type HERF Machine.

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and measured within the range Rc 38 to 40. After the initial die try-outs with carbon steel workpieces, the die was annealed and rehardened in an attempt to reach the desired Rc 44 to 46 range, but again the hardness was within the range Rc 38 to 40. In addition, the heat treatment was noted to have caused a slight distortion of the impression which resulted in a cavity width increase of 0.035" at the most severely distorted area. The die was employed in this condition for final production of all D6ac and Ti 6Al-4V forgings, but was ground out and resurfaced with harder filler material during finish forging of the Inconel 718 as will be noted in subsequent discussion.

The sketch in Figure 75 serves to illustrate the manner in which the control of tolerances was assisted by the CEFF machine dies. The rectangular platform in the upper die was engaged and surrounded by the corresponding rectangular hole in the lower die when the dies were approximately 1 inch from full closure. This vertical wall, extremely tight clearance, "integral rectangular guide post" assisted machine guiding in governing match tolerances. Minimum thickness was initially fixed by "kissing" surfaces within the hole which surrounded the flash gutter as illustrated, assuming that no flash would be forced beyond the gutter. The lower die flash land was only 1/8 inch wide and was surrounded by a very small (5/32 inch radius) gutter, and there were no flash details in the upper die. The design initially included provision for approximately 1/32 inch thick flash at the land when the "kissing" surfaces met.

In addition to necessary changes to accommodate the modified staging sequence, the CEFF machine tooling was altered after the initial trials to provide greater flashline relief for excess metal. For the finish tooling, the lower die flash land height was reduced to provide approximately 0.015 inch thicker flash at the land, and the previous "kissing" surface surrounding the upper die impression was removed by grinding at an angle to provide relief for flash forced beyond the lower die gutter. Thus, control of thickness tolerances during final production of the forgings for TRW evaluation was more a function of machine energy settings and the reproducibility with which the energy could be repeatedly delivered at one setting.

Overall, the finish tooling prepared for the CEFF machine featured particularly tight "lock up" on flash with very little relief for excess metal, even after modification. This required that preform and blocker operations provide very accurate redistribution of metal volume prior to the finish blow, and also that machine energy be capable of extremely accurate control. It must be appreciated that tightly "locking up" on a filled cavity under conditions where significant blow energy yet remains to be expended will result in an extremely high, virtually instantaneous force acting to distort the impression and expand the sidewalls of the cavity.

5. Forging Results

CEFF machine forging of the eighteen D6ac and the eighteen Ti 6Al-4V starting billets through the preform and blocker operations in the Figure 73 sequence was accomplished without difficulty. Processing data are listed in Table 8. The steel pieces were heated in an endothermic atmosphere

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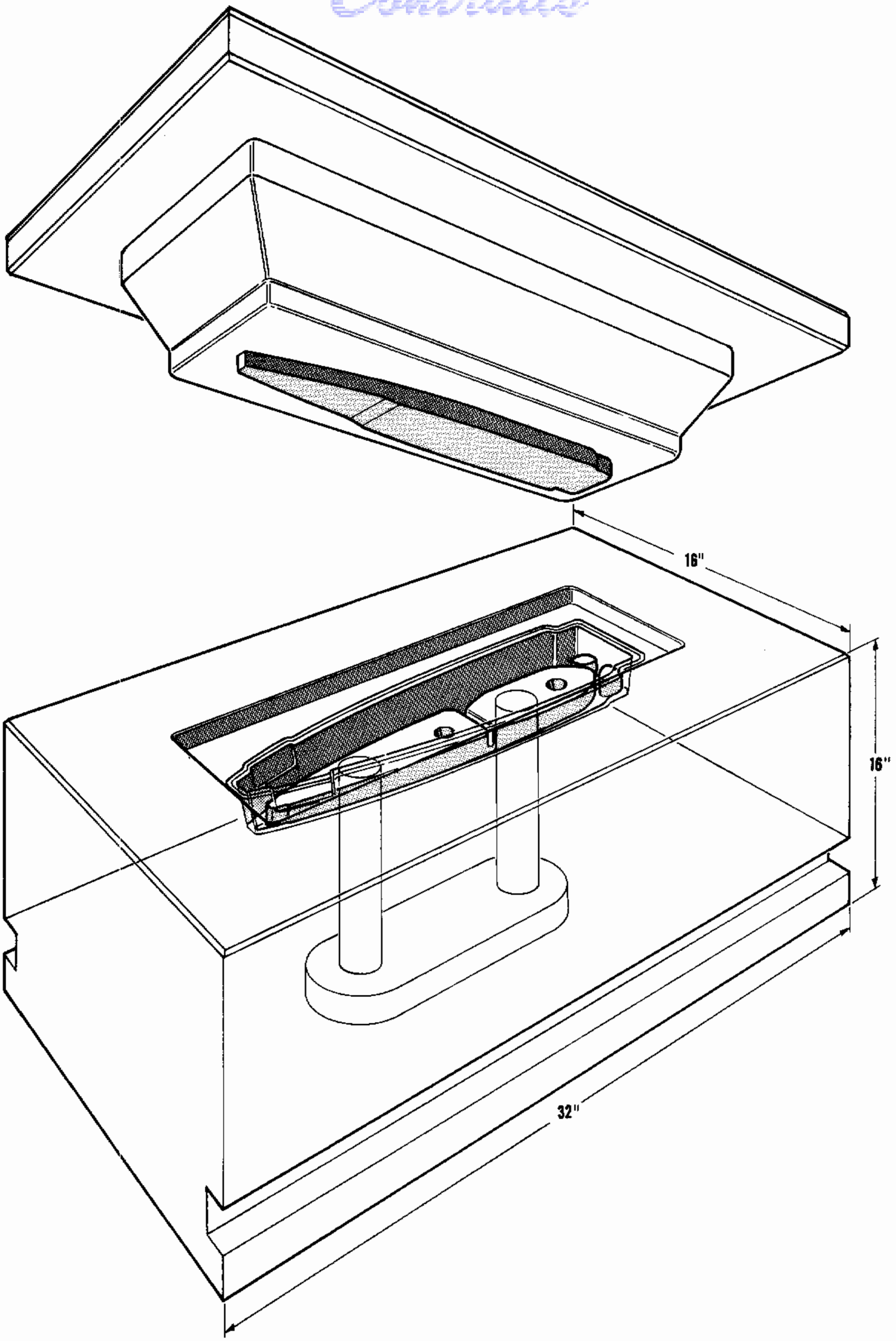

Figure 75. Schematic Illustration of Impression Dies for Finish Fin Rib Forging Operation with the 400,000 Foot-Pound CEFF-Type HERF Machine.

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TABLE 8

Processing Data for Intermediate Size Fin Rib Forgings Produced with a 400,000 Foot-Pound CEFF-Type HERF Machine

	Material		
	D6ac	Ti 6Al-4V	IN 718
Furnace Type	Electric Resistance	Electric Resistance	Electric Resistance
Furnace Atmosphere	Endothermic	Air	Air
Furnace Temperature	2250°F ±25°F All Stages	1750°F ±25°F All Stages	2050°F ±25°F-Preform and Blocker 2000°F ±25°F-Finish
Protective Workpiece Coating	None	Ceramic-Dipped	None
Heating Times	2 Hours-Preform 1-1/4 Hours-Blocker 1 Hour -Finish	2 Hours-Preform 1-1/4 Hours-Blocker 1 Hour -Finish	2-1/2 Hours-Preform 1-1/2 Hours-Blocker 1-1/4 Hours-Finish
Transfer Times	5 to 8 Seconds	5 to 8 Seconds	5 to 8 Seconds
Die Lubricant	Colloidal Graphite in Water-Spray	Colloidal Graphite in Water-Spray	Colloidal Graphite in Water-Spray
Die Temperature	375 to 600°F-AISI H-13 Dies 300 to 500°F-Finkl FX Dies	375 to 600°F-AISI H-13 Dies 300 to 500°F-Finkl FX Dies	375 to 600°F-AISI H-13 Dies 300 to 500°F-Finkl FX Dies
Number of Blows per Stage	One	One	Preform-Two Blocker-Three Finish -Six
Number of Reheats per Stage	None	None	Preform-Two Blocker-Three Finish -Three
Cooling Method	Air	Air	Air
Post Forging Thermal Treatment	1200°F for 1 Hour after Each Stage	1500°F for 1 Hour after Final Stage	1950°F for 1 Hour after Each Stage
Machine Energy (ft./lbs.)(a)	Preform-175,000 Blocker-250,000 Finish -255,000	Preform-178,000 Blocker-255,000 Finish -285,000	Preform-77,000(2) Blocker-77,000(1) & 81,000(2) Finish -81,000(4) & 125,000(2)
Contact Velocity (in./sec.)(a)	Preform-492 Blocker-600 Finish -606	Preform-494 Blocker-606 Finish -642	Preform-324(2) Blocker-324(1) & 336(2) Finish -336(4) & 420(2)

(a) - Machine energies and contact velocities used after initial forging trials of up to three pieces. Machine energies and contact velocities recorded for IN 718 indicate the number of blows at the preset machine energy.

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whereas those of the titanium alloy were precoated to minimize the effects of oxygen by dipping in a ceramic slurry and drying prior to heating. The manual transfers to the CEFF machine were accomplished very quickly, and it may be noted that Precision Metal Products conducted post forging thermal treatments to minimize residual stresses prior to intermediate trimming and conditioning. It was considered surprising that the machine energies required to produce the preform and the blocker shapes from D6ac heated to 2250°F and Ti 6Al-4V heated to 1750°F were virtually the same.

Inconel 718 did not exhibit good forging response during single blow preforming with the CEFF machine. Seven preforms prepared in this manner contained severe cracks, were scrapped, and were replaced with seven additional starting billets to maintain a run of eighteen forgings. Subsequent partial preforming at minimum machine energy (77,000 foot pounds) produced less severe cracks. A maximum allowable thickness reduction of 30 percent per blow was then established, and the preforms were prepared by a two-blow, limited deformation procedure in which a 0.400 inch thick shim was placed between the dies for one blow after which preforms were reheated and restruck without the shim. Although this "multiple-blow" procedure resulted in eighteen acceptable Inconel 718 preforms, it was not as successful during the blocker operation. Here, a progression of two shims and three blows to again limit web thickness reduction to 30 percent maximum resulted in eight sound blocker forgings, two forgings with repairable cracks, and eight forgings which were scrapped due to severe cracks in upper rib areas near the "nose" end.

Processing data for CEFF machine forging of the three materials through the finish operation are also listed in Table 8. For the D6ac forgings the correct energy level was established at 255,000 foot pounds with the second piece, and the remaining sixteen workpieces were single-blow forged through the finish dies in a manner identical to forging of the second. The ten forgings of this group which were delivered to TRW are shown in Figure 76, and Figure 77 shows two of the ten in closer perspective. The D6ac forgings were delivered after trimming and abrasive blasting by Precision Metal Products. Also, excess metal at ejector pin locations on the web surfaces formed by the lower die had obviously been removed by manual grinding. No defects were visually discernible on the forgings delivered, and the forgings appeared to be generally well filled.

Difficulties were experienced with the lower finish die during CEFF machine forging of the D6ac fin ribs. As with the hydraulic press tooling, the difficulties involved bending of the "lugs" which formed the triangular pockets near the blunt end of the lower die side of the forging. This bending became so severe during forging of the sixth and seventh D6ac workpieces that cracks appeared at the base radii of the "lugs" and the two forgings were scrapped due to insufficient rib thickness near the blunt end corners. At this point the triangular "lugs" were removed from the die and were each replaced with a simple cylindrical "lug" having a hemispherical end. The difference in the forgings can be observed in Figure 76 by comparing the five forgings on the left with those on the right.

Figures 78 and 79 illustrate the Ti 6Al-4V CEFF machine forgings delivered to TRW. A slightly variable fill condition existed at the corners, particularly at the "nose" end representing the lower die cavity. This can

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Figure 76. Ten High Strength Steel (D6ac) Fin Rib Forgings Produced with 400,000 Foot-Pound CEFF-Type HERF Machine for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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Figure 77. Close-Up of Two of the D6ac Forgings Produced with the 400,000 Foot-Pound CEFF-Type HERF Machine and Delivered to TRW.

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Figure 78. Ten Titanium Alloy (Ti 6Al-4V) Fin Rib Forgings Produced with 400,000 Foot-Pound CEFF-Type HERF Machine for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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Figure 79. Close-Up of Two of the Ti 6Al-4V Forgings Produced with the 400,000 Foot-Pound CEFF-Type HERF Machine and Delivered to TRW.

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be seen in the lower photograph in Figure 78. A second area of slightly variable fill existed along the upper rib at the blunt end of the forgings, and this can be observed in the upper photograph in Figure 78.

As with the steel forgings, the titanium alloy forgings had been subjected to a post forging thermal treatment and had been trimmed, abrasive blasted, and manually reworked by grinding to remove excess metal at ejector pin locations prior to delivery. It was also noted that several of the Ti 6Al-4V forgings had been ground along rib-web fillets and that cracking defects existed in the fillets and along inner rib sidewalls bordering the fillets. The cracks were not open, and are shown representatively in Figure 80 after application of red dye penetrant and developer to improve photographic resolution.

Precision Metal Products reported noting the cracks on seventeen of the forgings during penetrant inspection of the eighteen Ti 6Al-4V forgings produced. After a "repair grinding pass" in the fillet areas of several forgings the cracks were observed upon reinspection to still exist but to a lesser degree. Two of the forgings were then sectioned at two locations and the cracks were reported to range from 0.030 to 0.060 inch deep. Since this represented excess material enveloping the fin rib component and also because the program work statement prohibited repair operations on finish forgings for delivery, nine of the ten Ti 6Al-4V forgings delivered were reported by Precision Metal Products to contain the fillet cracks. The cracks were, of course, subsequently studied during the TRW evaluation of the forgings, and will be further discussed in the next section of this report.

The D6ac and the Ti 6Al-4V CEFF machine forgings were produced with the lower finish die at a hardness level within the range Rc 38 to 40, as previously discussed. Since the flow stresses of nickel-base alloys within their correct working temperature ranges are considerably higher than are those of alloy steels and titanium alloys, it was believed that finish forging of the Inconel 718 blocker shapes with the die in this condition would result in permanent distortion of the impression and sticking of the ejector mechanism. Trial forging with Inconel 718 workpieces confirmed this, as the large lower die projection which formed the web deformed and partially choked the side rib cavities. Following these trials the finish lower die impression was extensively relieved by grinding and a 1/4 inch thick layer of "Eureka 72" filler rod was deposited. This weld filler material is similar to the base H-13 die steel in composition. The air hardened weld layer was then tempered with a hand torch to a hardness of approximately Rc 44, and the impression was reformed with two EDM roughing operations and one EDM finish operation. In addition, the ejector pins were noted to have upset during the trials, and the ejector assembly was replaced with one having shorter pins to reduce the length-to-diameter ratio.

In view of the cracking difficulties experienced in preforming and blocking of the Inconel 718 pieces, a somewhat complicated forging schedule was also established to produce the finish shape. Three separate heating operations were employed and the workpieces received two low energy blows for each heating; i.e., six blows were struck, four at 81,000 foot pounds of energy each and the final two at 125,000 foot pounds of energy each,

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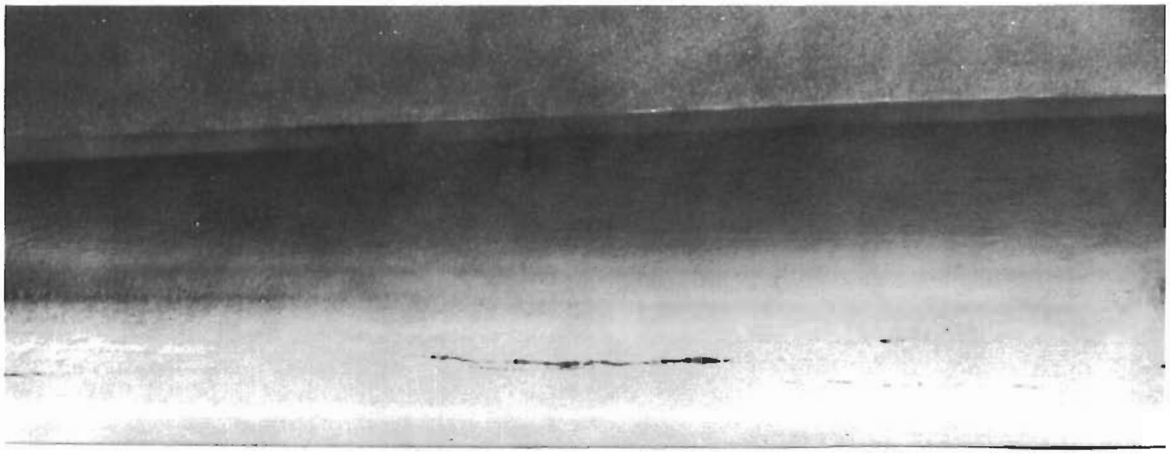
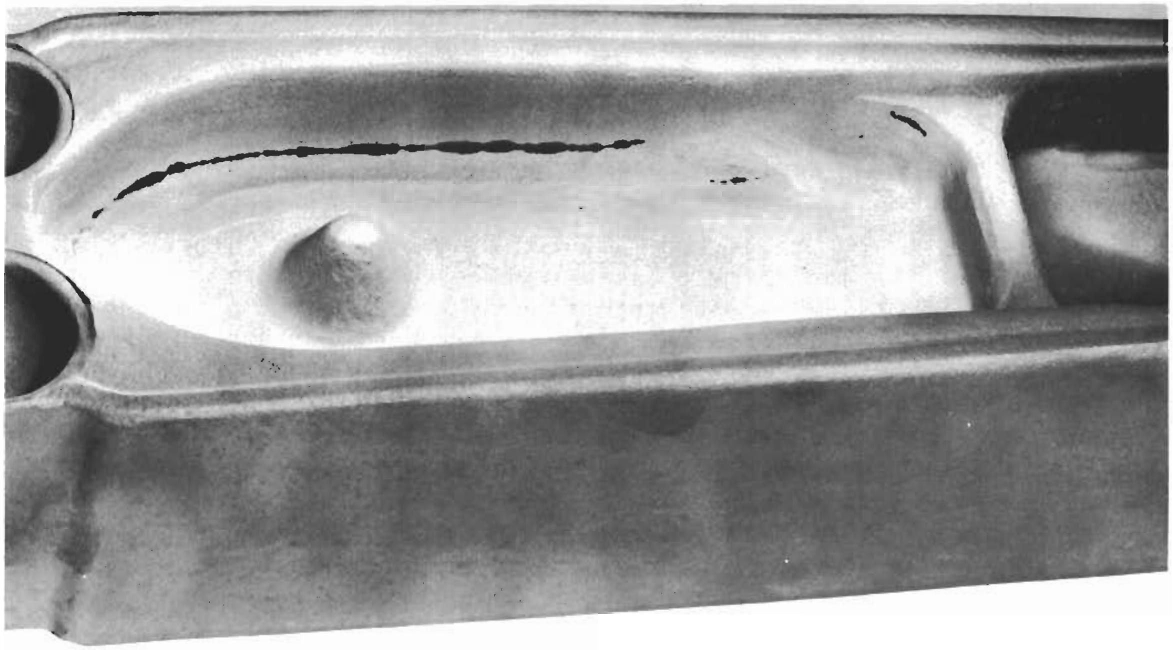


Upper Die Side



Lower Die Side

Figure 80. Defects on Inner Rib Surfaces of Thirteenth (Top) and Sixth (Bottom) Ti 6Al-4V Forgings Produced (of Eighteen Forgings Total; the Fifth and the Second, Respectively, of the Ten Delivered to TRW) During Final Forging Efforts with the 400,000 Foot-Pound CEFF-Type HERF Machine. Shown after Application of Red Dye Penetrant and Developer for Improved Photographic Resolution.

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to finish forge the Inconel 718 workpieces with the CEFF machine. The transfer from the furnace was reported to have been accomplished in 5 to 8 seconds, Table 8, and the total time for transfer and both blows was approximately 20 seconds.

Prior to the third heating operation (i.e., after four blows at 81,000 foot pounds each), the partially finished Inconel 718 forgings were observed to be completely filled in upper rib areas toward the "nose" end. This condition, illustrated in Figure 81, was considered to represent a block to further metal movement in this large area and it was believed that the remaining low energy blows scheduled would not be sufficient to flash out the excess metal in this area to a degree sufficient to allow complete rib fill in other areas. For this reason all of the partially finished Inconel 718 forgings were conditioned by milling all rib surfaces to a uniform total height of 1.65 inches except for the blunt end corners of the lower die side which were left unfilled at this rib height, and the "nose" which was left overfilled on both sides. The "nose" end overfill was particularly accentuated on the upper die side as can be observed for the five forgings at the upper left in Figure 82, and it can also be noted that the lower die side of these same forgings were conditioned to blend corners and remove excess metal which resulted from excessive deflection of the ejector pins.

Finish forging of the first four Inconel 718 workpieces through the final two blows of 125,000 foot pounds each was accomplished without difficulty. Upon striking the second blow to the fifth piece, however, the upper die failed in shear near the blunt end. The five finish forgings produced are shown at the right of Figure 82 and two are shown in the close-up in Figure 83. It can be observed that these did not fill completely, particularly near the hemispherical pockets at the blunt end, and Figure 84 illustrates the type of cracking defects which the finish forgings contained. Efforts to produce satisfactory nickel-base alloy fin rib forgings with the CEFF machine were terminated at this point for two reasons. First, it was apparent that a major tooling redesign would be required to achieve any significant measure of improved success. Second, there appeared to be little point in further development of a multiple-low-energy-blow process for a high-energy, relatively slow recycling machine when the energy levels established fell within the capabilities of the previously described steam drop hammer which was designed for rapid recycling multiple-blow operation.

The lack of frame and foundation resiliency as an influence in reducing die forces during forging with a counterblow impact energy machine has been mentioned. Use of opposed rams allows greater force to be imparted to the workpiece - which frequently is desirable. It also requires that the same greater force must be resisted by the die impressions - which can be equally undesirable. Calculation of instantaneous peak die forces with an impact energy machine or of local die forces at "pressure points" within the impression with any type of forging machine is, at best, extremely difficult. It is interesting, however, to note the theoretical average unit force through deformation of Inconel 718 forgings during the final two 125,000 foot-pound blows, assuming the complete absence of an elastic or plastic response by the tooling and rams. Dimensional data recorded by Precision Metal Products indicates that the majority of the web area decreased 0.12 inch or 0.01 foot as a result of the total 250,000 foot-pounds of energy imparted. Since the

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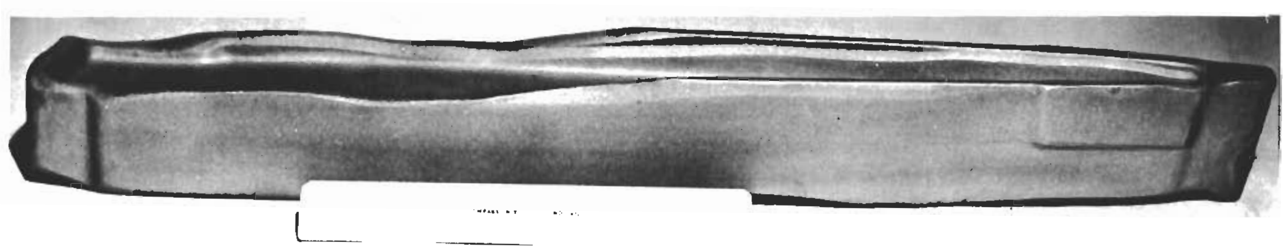
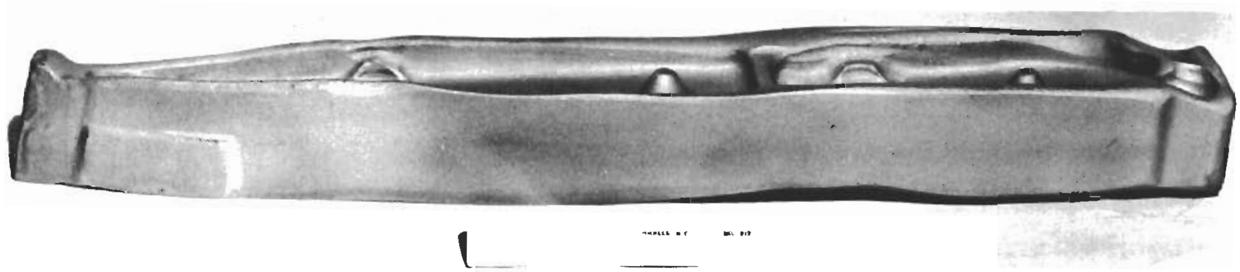


Upper Die Side Up



Lower Die Side Up

Figure 81. Inconel 718 Partial Fin Rib Forgings after Four Low Energy Blows (81,000 Foot-Pounds Each) in the Finish Dies Employed with the 400,000 Foot-Pound CEFF-Type HERF Machine. Note that Forward Half of Ribs are Completely Formed on Upper Die Side in Contrast to Variable Rib Height in All Other Areas.

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Figure 82. Five Partial (Left) and Five Finish (Right) Nickel-Base Alloy (Inconel 718) Fin Rib Forgings Produced with 400,000 Foot-Pound CEFF-Type HERF Machine for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for Both of the Forging Operations. Blocker Forgings Shown after Milling Ribs (See Text), Conditioning, and Abrasive Blasting. Finish Forgings Shown after Trimming and Abrasive Blasting.

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Figure 83. Close-Up of Two of the Inconel 718 Forgings Produced with the 400,000 Foot-Pound CEFF-Type HERF Machine and Delivered to TRW.

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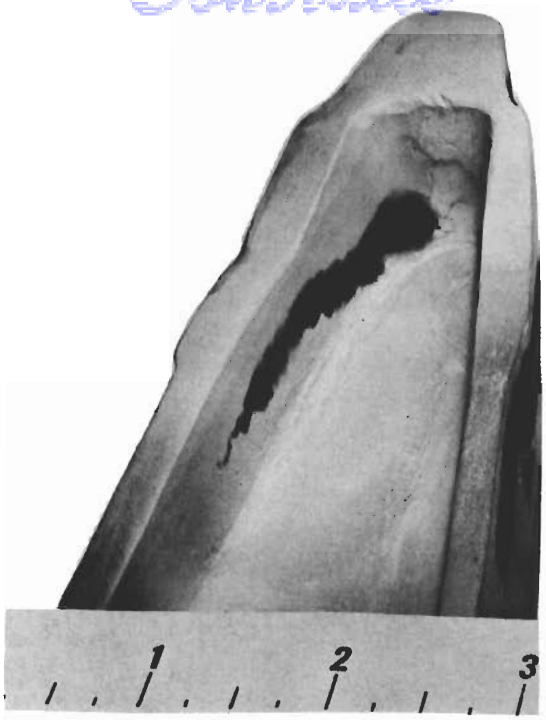
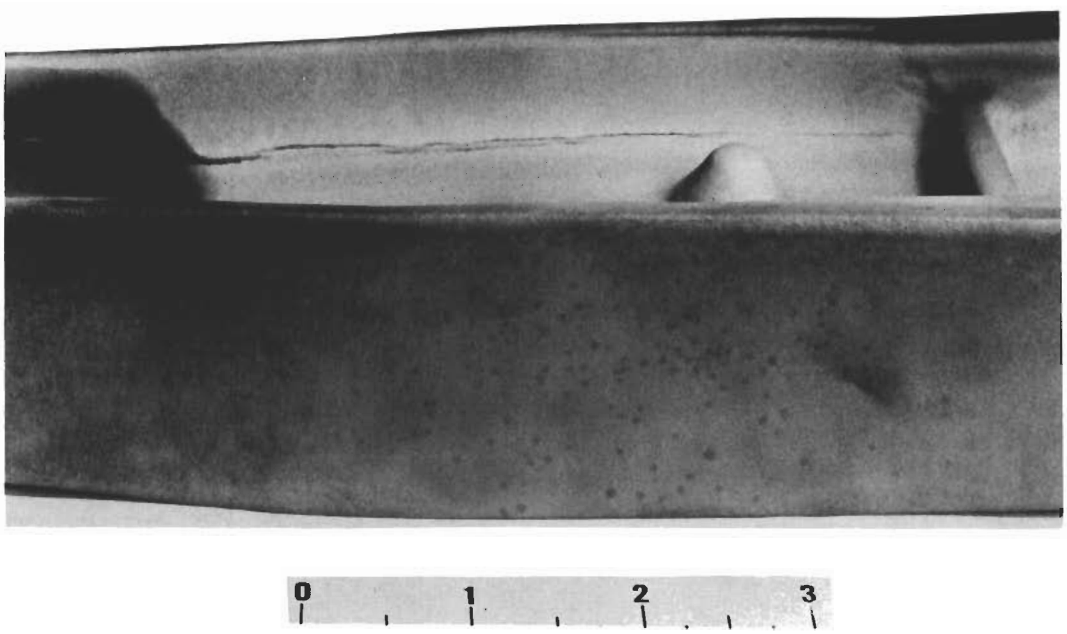


Upper Die Side



Lower Die Side

Figure 84. Defects on Rib Surfaces and at Radii of First (Top) and Third (Bottom) Inconel 718 Forgings Produced (of Five Forgings Total which were Processed Through the Final Blow in the Finish Dies) During Final Forging Efforts with the 400,000 Foot-Pound CEFF-Type HERF Machine. Shown after Application of Red Dye Penetrant and Developer for Improved Photographic Resolution.

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average total force throughout the distance represents the total energy divided by the total distance, an average force of 25,000,000 pounds would result. This figure, divided by the 54 square inch plan area of the CEFF machine finish forgings, would then represent an average unit force of 463,000 psi. As would be expected, the figure checks when calculated from the F = Ma relationship, where "a" represents the value for uniform deceleration from the 35 foot per second contact velocity to zero velocity through one half of the thickness reduction achieved by the two blows - again assuming a completely rigid machine and tooling. The utility of an average die force value calculated only as a function of deformation distance permanently experienced by the workpiece is discussed during subsequent description of results achieved in forging with the large counterblow hammer.

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V EVALUATION AND COMPARISON OF INTERMEDIATE SIZE FORGINGS

Upon delivery to TRW, all intermediate size forgings were serialized with a prefix indicating the forging source, machine, and material; and with a number from 1 to 10 corresponding to the order in which the forgings received had been produced. Thus, forging number PC-S9 referes to the Precision Metal Products, CEFF machine, D6ac Steel forging which was produced ninth of the ten delivered to TRW; LH refers to Ladish Hammer; CH stands for Cameron Hydraulic; LM indicates Ladish Mechanical; and T and N relate to the titanium alloy and the nickel-base alloy respectively. As a second example, forging number LM-T4 refers to the fourth Ti 6Al-4V forging produced (of the ten delivered) by Ladish with the mechanical press. The four Inconel 718 blocker forgings from the hydraulic press effort and the five Inconel 718 blocker forgings from the CEFF machine effort, which were shipped to complete the respective orders in spite of finish die failures, were not evaluated. This reduced the total number of fin rib forgings evaluated from 120 to 111.

After all forgings had been identified by marking with metal stamps in accordance with the above system, they were trimmed (Ladish forgings only), sandblasted, visually inspected for lack-of-fill areas and indications of surface defects, and photographed. Results of these preliminary TRW efforts have already been described in the previous section of this report. Subjects of TRW evaluation procedures which were then scheduled for the forgings included weight, dimensions, freedom from defects, as-received macro- and microstructure, response to heat treatment (hardness and microstructure), and certain mechanical properties. The specific procedures employed and the results obtained are presented and discussed in this section as separate functions of precision, quality, and properties comparisons; sub-sections A, B, and C, respectively, which follow.

A. Precision

As indicated in report Section III-D, precision in forging of rib and web shapes is difficult to define. This is because the term relates to three different characteristics of the overall forging process. The first of these involves the dimensional reproducibility which can be achieved during repetitive production of forgings. Such reproducibility requires a machine stroke and a guiding system which affords dimensionally consistent repetitive die closures. Also, consistency in: 1) starting material composition and in starting and intermediate shapes; 2) workpiece heating, transfer, and location practices; 3) die heating and lubrication practices; and 4) post forging transfer and cooling practices is required. In addition, there is the effect of die wear on tolerances.

As a second definition, precision is a function of the dimensional accuracy which can be achieved in producing a single forging within the desired series. This involves competence in understanding metal flow, shrinkage factors, and tooling deflections so that the dies can be correctly designed; accuracy in machining dies and in aligning them (setting-up) in the machine; and the processing practices employed to manipulate and cool the resulting forgings. Accuracy and reproducibility relate only to the forging designs (not to the component) and are expressed in terms of tolerances for

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length, width, thickness, mismatch, and straightness. In terms of commercial forging practices, such tolerances have been well defined in the literature by the Forging Industry Association(6), and by the Ladish Company(7,8) as functions of forging size, shape, and material.

For airframe structurals, for which forgings are almost always produced oversize, the third aspect of precision involves the closeness within which the forging design, without tolerances, envelops the component design. Along with length, width, and thickness dimensions, forging draft angles and radii are of importance since the components are generally designed with no draft and minimum radii. Precision in this context can be loosely defined by the "blocker-commercial-close tolerance-precision" design terminology illustrated in Figure 3. Although such a classification system can be very generally related to difficulty in forging, it must be appreciated that close tolerance forging of a structural with shallow ribs and a 1 inch thick web might well prove to be easier than producing a "commercial" forging enveloping a component with particularly high ribs and a 0.050 inch thick web; i.e., the design detail of the component must be known if the classification system is to have specific meaning to the forging designer.

The degrees of precision targeted as envelopes of excess metal have already been illustrated for the steam drop hammer, the hydraulic press, the mechanical press, and the CEFF machine in Figures 8 and 9, 30 and 31, 51 and 52, and 69 and 70, respectively. Levels of reproducibility and accuracy, and the envelope characteristics actually achieved with the individual machines are given below.

1. Weights

Specific forging weights and weight tolerances were not targeted as program goals. Comparison of tolerance levels, however, is useful as a means of comparing the degrees of reproducibility achieved with each machine.

a) Procedures

All finish forgings were individually weighed in the trimmed and sandblasted condition. A Homs Model 300HH beam balance was employed which is graduated in pounds and decimal parts, and is accurate to 0.01 pounds.

b) Results

Weight comparisons for the fin rib forgings received by TRW are presented by machine and materials categories in Table 9. The data in the first column represent the arithmetic average (mean) weight per forging for each total group of ten received if they were produced in a single forging run without changing the die setup. This average value for each group was calculated by dividing the total weight for the ten forgings by ten. The second column lists the total variation (range) in weight exhibited within the group. This value for each group was obtained by subtracting the weight of the lightest forging in the group from that of the heaviest. The data in the third column are standard deviation values and are statistically derived from the formula

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TABLE 9

Weight Characteristics of Fin Rib Forgings[a]

Machine	Material	Total Group of Ten[b]			Selected Group[c]		
		Average Weight (pounds)	Total Variation (pounds)	Standard Deviation (pounds)	Average Weight (pounds)	Total Variation (pounds)	Standard Deviation (pounds)
Steam Drop Hammer	D6ac	18.62	0.53	0.16	18.70	0.30	0.11
	Ti 6Al-4V	10.78	0.31	0.11	10.80	0.20	0.09
	IN 718	21.44	0.57	0.17	21.49	0.40	0.15
Hydraulic Press	D6ac	18.37	0.53	0.15	18.42	0.36	0.12
	Ti 6Al-4V	-	-	-	10.42	0.15	0.05
	IN 718	-	-	-	21.60	1.56	0.83
Mechanical Press	D6ac	18.51	0.85	0.34	18.71	0.23	0.09
	Ti 6Al-4V	10.67	0.18	0.06	10.65	0.13	0.05
	IN 718	21.77	0.52	0.18	21.83	0.52	0.18
CEFF Machine	D6ac	-	-	-	12.08	0.40	0.15
	Ti 6Al-4V	7.35	0.25	0.08	7.32	0.11	0.04
	IN 718	-	-	-	12.79	1.65	0.63

(a) - Finish forgings only after trimming and blasting.

(b) - For those groups only in which all ten forgings delivered to TRW were finish forged in a single die set-up.

(c) - The last seven of the ten delivered for each group from the hammer and the mechanical press. For the hydraulic press: D6ac, the last seven of the ten delivered; Ti 6Al-4V, the nine delivered which contained hemispherical "pockets" (see Figure 42); Inconel 718, the six finish forgings produced (see Figure 45). For the CEFF machine; D6ac, the five delivered which contained hemispherical "pockets" (see Figure 76); Ti 6Al-4V, all but the first and the sixth of those delivered; Inconel 718, the five finish forgings produced (see Figure 82).

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$$s = \sqrt{\frac{\Sigma x_i - n \left(\frac{\Sigma x_i}{n}\right)^2}{n - 1}}$$

where:

s = the value for standard deviation,

Σx_i = the sum of the individual values measured, in this case weight in pounds,

n = number of values represented, in this case the number of forgings within each group.

The standard deviation value represents one half of the total tolerance statistically anticipated at a one sigma confidence level and based on a normal frequency distribution curve. A small value is therefore statistically indicative of a process with less scatter, or greater reproducibility.

The fourth, fifth, and sixth columns in Table 9 were prepared in recognition that two factors prohibit effective use of the "groups of ten" concept in evaluating machine reproducibility, and that more selective subgroups must be chosen from within the groups of ten to achieve this purpose. The first of these factors involves changes in tooling setup during the forging run as occurred in several instances; for example, when the triangular lugs were replaced with hemispherical ones prior to forging of the sixth through tenth D6ac forging with the CEFF machine. These two groups of five D6ac forgings varied in weight and in thickness dimensions; thus averages, ranges, and standard deviation values for the total group of ten should not be considered as representative of the reproducibility which can be achieved with the CEFF machine.

The second reason for selecting smaller subgroups for evaluation and comparison, even when all ten forgings were produced in a single setup, involves recognition that early forgings in a repetitive series can vary moderately due to other influences involving furnace temperature stabilization, tooling setup refinement, initial lack of familiarity of the crew with the specifics of the operation, etc. In all instances except one where all ten forgings within the machine-material categories were repetitively produced without incident, therefore, only the last seven of the ten are included in the "selected group" data listed in Table 9. The exception involved the titanium alloy forgings produced with the CEFF machine. In this case, the first and the sixth forgings delivered (actually the fifth and fourteenth of the eighteen produced in this case) were unaccountably heavier and thicker, and the other eight were employed for the selected group since they all appeared to be close to each other in weight and in thickness dimensions. It should be noted that, in order to minimize confusion during handling of data, the forgings eliminated from the selected groups within the six categories representing the steam drop hammer and the mechanical press were not chosen on the basis of whether they were the first, second, or third; the second, fourth, or fifth; etc., of the groups of twelve actually produced by Ladish. In these cases, then, at least the first three and no more than the first five of the forgings produced were eliminated in forming the selected groups for evaluation.

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Review of the results in Table 9 suggests several comparisons relative to the weight characteristics of the fin rib forgings. First, as would be anticipated, the selected groups proved to be considerably more reproducible than the total groups in relation to weight tolerances. Removal of but two of the ten titanium alloy forgings produced by the CEFF machine, for example, reduced the average weight only 0.03 pounds, but also reduced the range to less than half and the standard deviation to half. This effect is even more noticeable by removal of the first three mechanical press-D6ac forgings (which, in this case, actually represent the second, third, and fourth of the series of twelve produced). Second, the average weights of CEFF machine forgings can be noted to be approximately 2/3 of those of the others; and the weights of the hammer, hydraulic press, and mechanical press forgings within any materials category were particularly close to each other. Third, the difficulties experienced in hydraulic press forging and in CEFF machine forging of the Inconel 718 material can be seen to have strongly influenced the weight tolerances in these two instances.

In order to provide improved perspective for comparison of tolerance levels achieved with materials of different densities; the individual weights of forgings within the selected groups were converted to volumes and the average, total variation, and standard deviation values were recalculated. These results are listed in Table 10. Also, in recognition that tolerances are frequently associated with the nominal value upon which they are placed, the table also lists the tolerance values expressed as percentages of the average forging volumes. Relative to ability in having achieved more reproducible control of forging volume, the results favor the mechanical press forgings of the D6ac material and the hammer forgings of Inconel 718. For the Ti 6Al-4V forgings the results can be observed to favor the CEFF machine, the mechanical press, and the hydraulic press; depending on the column in which the values are being compared.

2. Dimensions

The dimensional characteristics of the fin rib forgings were scheduled for very comprehensive evaluation. This was because one of the major goals of the program was initially that of establishing the minimum number of machining passes necessary to remove the envelope of excess metal, as previously discussed in report Section III-D and illustrated in Figure 4. The dimensional accuracy and reproducibility with which the forgings met their design targets in enveloping the fin rib components were evaluated in two different manners. First, all forgings were measured at numerous locations using conventional micrometers and radius gages. Second, the forgings were then measured with an electronic "X-Y coordinate, probe-scan" machine and the resulting "raw" data was analyzed employing computer techniques to furnish direct readings of envelope thicknesses. Procedures and results of the conventional dimensional inspections performed are discussed next in this report section. Although the efforts with the computer cannot be considered successful due to the apparent need of additional computer programming development for dimensional inspection purposes, the techniques and results are nevertheless subsequently described for general interest.

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TABLE 10

Volume Characteristics[a] of Selected Groups[b] of Fin Rib Forgings

Machine	Material	Average Volume (inch^3)	Total Variation (inch^3)	Standard Deviation (inch^3)	Total Variation (% of Ave.)[c]	Standard Deviation (% of Ave.)[d]
Steam Drop Hammer	D6ac	65.85	1.06	0.39	1.60	0.59
	Ti 6Al-4V	67.51	1.25	0.55	1.85	0.81
	IN 718	73.31	1.35	0.52	1.86	0.72
Hydraulic Press	D6ac	65.49	1.27	0.42	1.96	0.65
	Ti 6Al-4V	65.63	0.94	0.30	1.44	0.47
	IN 718	72.97	6.79	2.79	9.31	3.83
Mechanical Press	D6ac	65.88	0.81	0.31	1.23	0.48
	Ti 6Al-4V	66.56	0.84	0.33	1.27	0.49
	IN 718	73.74	1.76	0.61	2.38	0.83
CEFF Machine	D6ac	42.53	1.43	0.53	3.35	1.23
	Ti 6Al-4V	45.72	0.69	0.25	1.50	0.54
	IN 718	43.21	5.59	2.14	12.94	4.96

(a) - Calculated from the individual forging weights using density values of 0.284, 0.160, and 0.296 pounds per cubic inch, respectively, for D6ac, Ti 6Al-4V, and Inconel 718.

(b) - The selected groups identified in Table 9.

(c) - Total variation in volume divided by average volume, converted to percent.

(d) - Standard deviation value for volume divided by average volume, converted to percent.

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a) Procedure - Conventional Techniques

Width, thickness, depth, and radius measurements were obtained at 146 locations on each of the 111 forgings. Sixty-six of these measurements on each forging were obtained to ±0.001 inch accuracy with micrometers of various sizes. The remaining 86 measurements involved radii and were obtained at fillet and corner radii to ±1/64th inch accuracy with conventional radius gages.

Although pocket depth, cross and end rib thicknesses, rib height at corners, etc., were obtained; the majority of the measurements were taken at the five inspection section planes, B-B through F-F, illustrated in Figure 85. This was because the finished component dimensions were identified on the fin rib blueprints at these five sections planes; thus, accurate calculations of forging envelope thicknesses were facilitated at these locations.

b) Results - Conventional Techniques

Analysis of the radius data revealed nothing of significance. The radii generally corresponded to the design radii within the accuracy of the gages. Analysis of the much more accurate micrometer data, however, revealed variations from design targets in several respects. Rib thicknesses from one side to the other of the CEFF machine forgings varied fairly consistently from 0.015 to 0.040 inch at different section planes regardless of material. This was attributed to the sidewall distortion which occurred during annealing and rehardening of the lower finish die, as previously discussed. Left to right rib thickness variations were also noted for certain of the hydraulic press forgings. In this case, however, the differences ranged from zero variation to as much as 0.100 inch for certain forgings, and the reasons for this variation could not be identified with any recorded differences in processing. It must be presumed that one side of the impression began to fill before the other during finish forging of only certain of the forgings, and that the resultant unbalanced force in these instances caused a lateral deflection of the die inserts. Rib thicknesses of the steam drop hammer and the mechanical press forgings were quite uniform.

Rib heights and web thicknesses are directly related to the die closure characteristics afforded by the machines. Comparison of the rib height data revealed moderate variations from design targets (accuracy) and from forging to forging within a machine-materials category (reproducibility). These variations were noted to be similar, but more pronounced, upon comparison of web thickness data. The web thickness comparisons are presented in Tables 11, 12, and 13 as functions respectively of the steel, the titanium alloy, and the nickel-base alloy forgings. Since one side of section plane D-D in Figure 85 lies along the height of the cross rib, as illustrated, the web thickness data in Tables 11 through 13 are given for only the other four section plane locations. Also, it should be noted that only the "selected groups" of forgings previously identified during discussion of weights have been considered in Tables 11 through 13. In each of the tables the first three columns list average thicknesses at the center of the web, total ranges of variation in thickness, and the calculated standard deviations. The range and standard deviation values can be considered as overall and as statistical expressions, respectively, of thickness reproducibility within the selected

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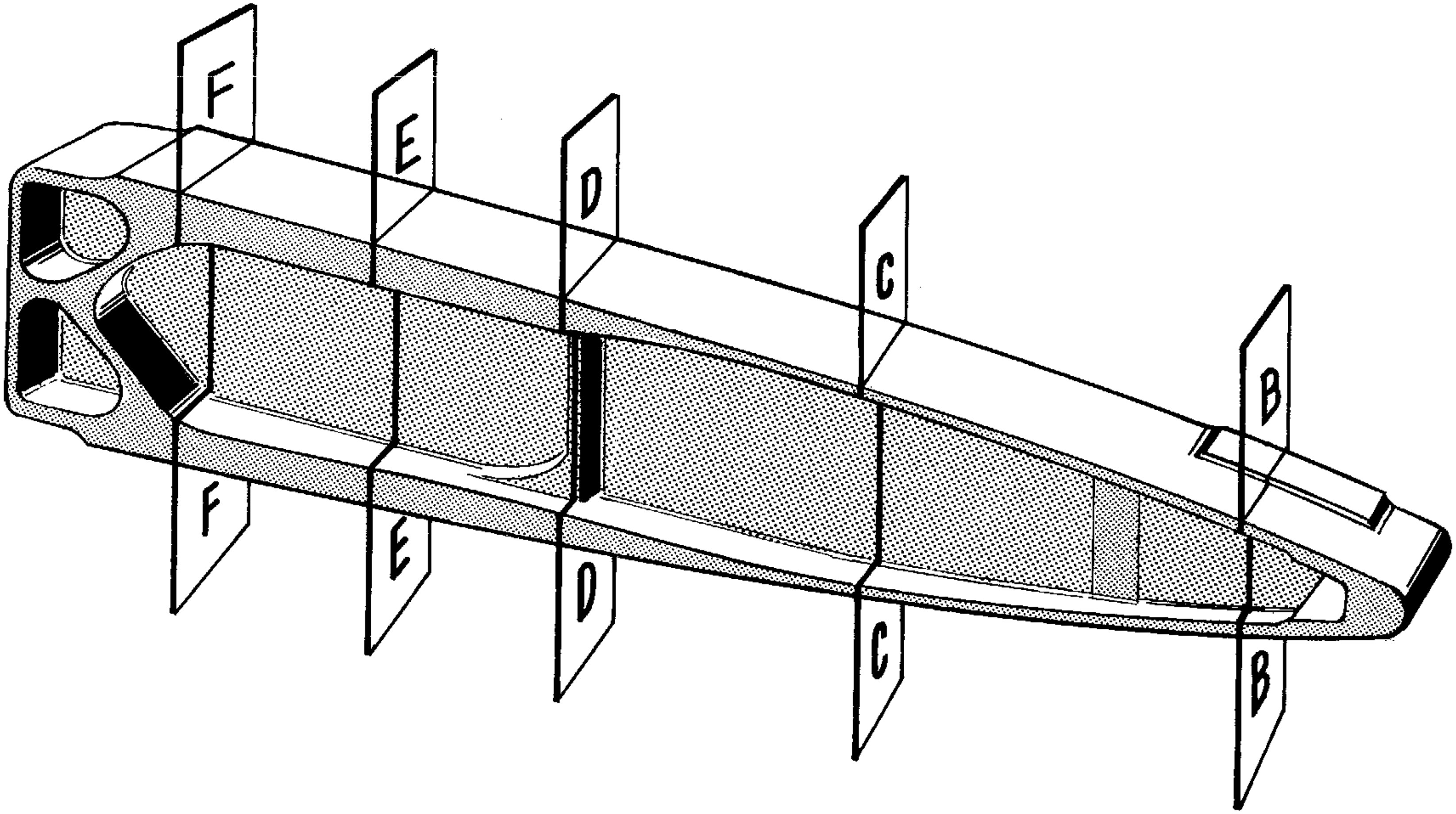

Figure 85. Locations of Inspection Section Planes Employed for Dimensional Evaluation of Fin Rib Forgings.

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TABLE 11

Web Thickness Characteristics of Selected Groups[a] of D6ac Fin Rib Forgings

Machine	Inspection Section Plane	Average Thickness (inches)	Total Variation (inches)	Standard Deviation (inches)	Target[b] Thickness (inches)	Average Off-Target (inches)	Average Envelope (inches)
Steam Drop Hammer	B-B	0.391	0.035	0.012	0.372	+0.019	0.082
	C-C	0.449	0.030	0.013	0.372	+0.079	0.175
	E-E	0.429	0.051	0.017	0.372	+0.057	0.165
	F-F	0.412	0.028	0.009	0.372	+0.040	0.156
	Ave.		0.036	0.013			
Hydraulic Press	B-B	0.480	0.055	0.018	0.428	+0.052	0.126
	C-C	0.515	0.020	0.008	0.300	+0.215	0.208
	E-E	0.663	0.062	0.023	0.300	+0.363	0.282
	F-F	0.663	0.046	0.019	0.300	+0.363	0.282
	Ave.		0.046	0.017			
Mechanical Press	B-B	0.402	0.015	0.006	0.372	+0.030	0.087
	C-C	0.466	0.038	0.013	0.372	+0.094	0.183
	E-E	0.463	0.021	0.008	0.372	+0.091	0.182
	F-F	0.437	0.049	0.016	0.372	+0.065	0.169
	Ave.		0.031	0.011			
CEFF Machine	B-B	0.256	0.027	0.011	0.328	-0.072	0.014
	C-C	0.206	0.030	0.012	0.200	+0.006	0.053
	E-E	0.209	0.005	0.004	0.200	+0.009	0.055
	F-F	0.194	0.036	0.014	0.200	-0.006	0.047
	Ave.		0.025	0.010			

(a) - The selected groups identified in Table 9.

(b) - Targeted as minimums by each forging source. Section C-C targets correspond to web thicknesses illustrated in Figures 8, 30, 51, and 69.

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TABLE 12

Web Thickness Characteristics of Selected Groups[a] of Ti 6Al-4V Fin Rib Forgings

Machine	Inspection Section Plane	Average Thickness (inches)	Total Variation (inches)	Standard Deviation (inches)	Target[b] Thickness (inches)	Average Off-Target (inches)	Average Envelope (inches)
Steam Drop Hammer	B-B	0.419	0.045	0.016	0.375	+0.044	0.096
	C-C	0.456	0.031	0.012	0.375	+0.081	0.178
	E-E	0.452	0.053	0.019	0.375	+0.077	0.176
	F-F	0.439	0.042	0.016	0.375	+0.064	0.170
	Ave.		0.043	0.016			
Hydraulic Press	B-B	0.512	0.042	0.013	0.428	+0.084	0.142
	C-C	0.523	0.029	0.010	0.300	+0.223	0.212
	E-E	0.632	0.050	0.015	0.300	+0.332	0.266
	F-F	0.631	0.034	0.011	0.300	+0.331	0.266
	Ave.		0.039	0.012			
Mechanical Press	B-B	0.393	0.052	0.016	0.375	+0.018	0.083
	C-C	0.455	0.026	0.010	0.375	+0.080	0.178
	E-E	0.456	0.025	0.010	0.375	+0.081	0.178
	F-F	0.399	0.057	0.021	0.375	+0.024	0.150
	Ave.		0.040	0.014			
CEFF Machine	B-B	0.267	0.036	0.012	0.328	-0.061	0.020
	C-C	0.251	0.018	0.007	0.200	+0.051	0.076
	E-E	0.252	0.022	0.008	0.200	+0.052	0.076
	F-F	0.217	0.025	0.009	0.200	+0.017	0.059
	Ave.		0.025	0.009			

(a) - The selected groups identified in Table 9.

(b) - Targeted as minimums by each forging source. Section C-C targets correspond to web thicknesses illustrated in Figures 8, 30, 51, and 69.

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TABLE 13

Web Thickness Characteristics of Selected Groups[(a)] of Inconel 718 Fin Rib Forgings

Machine	Inspection Section Plane	Average Thickness (inches)	Total Variation (inches)	Standard Deviation (inches)	Target[(b)] Thickness (inches)	Average Off-Target (inches)	Average Envelope (inches)
Steam Drop Hammer	B-B	0.466	0.075	0.026	0.372	+0.094	0.119
	C-C	0.547	0.033	0.014	0.372	+0.175	0.224
	E-E	0.528	0.040	0.016	0.372	+0.156	0.214
	F-F	0.503	0.036	0.013	0.372	+0.131	0.202
	Ave.		0.046	0.017			
Hydraulic Press	B-B	0.772	0.261	0.105	0.428	+0.344	0.272
	C-C	0.737	0.238	0.108	0.300	+0.437	0.319
	E-E	0.852	0.279	0.120	0.300	+0.552	0.376
	F-F	0.862	0.270	0.132	0.300	+0.562	0.381
	Ave.		0.262	0.116			
Mechanical Press	B-B	0.459	0.137	0.049	0.372	+0.087	0.116
	C-C	0.589	0.046	0.019	0.372	+0.217	0.245
	E-E	0.566	0.170	0.063	0.372	+0.194	0.233
	F-F	0.554	0.032	0.014	0.372	+0.182	0.227
	Ave.		0.096	0.036			
CEFF Machine	B-B	0.320	0.093	0.041	0.328	-0.008	0.046
	C-C	0.313	0.095	0.040	0.200	+0.113	0.107
	E-E	0.312	0.131	0.052	0.200	+0.112	0.106
	F-F	0.326	0.115	0.046	0.200	+0.126	0.113
	Ave.		0.109	0.045			

(a) - The selected groups identified in Table 9.

(b) - Targeted as minimums by each forging source. Section C-C targets correspond to web thicknesses illustrated in Figures 8, 30, 51, and 69.

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groups of forgings. The fourth and fifth columns list the forging design target thicknesses and the degree to which the target values were missed by the average thickness values. Each fifth column value, then, is a measure of the average inaccuracy in meeting the target forging thickness at a specific location. It should be emphasized that the target thicknesses employed by TRW for the evaluation were minimum design values for which plus tolerances for closure are normally applied before discussing "inaccuracy". In this case, however, the minimum values were employed without tolerances for purposes of comparison. The sixth column in the tables lists envelope data for the web centers at the four different section plane locations, and was derived by subtracting the component web thicknesses at these locations from the average forging web thicknesses and dividing the remainder by two. Not considering tolerances, the actual fin rib web thickness was 0.228 inch at Section B-B and was 0.100 inch at the other three section plane locations.

Careful scrutiny and comparison of the data in Tables 11 through 13 reveals a number of interesting observations. First, slight to moderate differences in reproducibility characteristics are indicated by the variation and the standard deviation values. For the D6ac material, Table 11, the average range and standard deviation data favor the CEFF machine, the mechanical press, the hammer, and the hydraulic press forgings in that order. For Ti 6Al-4V, Table 12, the data favor the CEFF machine, hydraulic press, mechanical press, and hammer. For Inconel 718, Table 13, the hammer forgings proved to be most consistent, followed by the mechanical press forgings, the CEFF machine forgings, and the hydraulic press forgings. As a second observation, considerably thinner, more difficult forgings were targeted as products of the CEFF machine. Yet, the forgings from this machine exhibited average web thicknesses as close, and in some instances closer, to the target values than the forgings produced by the other machines. Third, inaccuracy (i.e., consistent inability to meet dimensional targets) in the hydraulic press forgings appears to be associated with inability of the particular press guiding and the die system to prevent "cocking" of the dies and/or the inserts from front to rear under load. This resulted in "blunt end" web thicknesses which were consistently much greater than the target thickness in comparison to "nose" web thicknesses relative to the target in this area.

Unlike the results from the hydraulic press forgings, the major cause for inaccuracy relative to target web thicknesses for the steam drop hammer, the mechanical press, and the CEFF machine forgings appears to be associated with differences in deflection (elastic distortion under load) of the portions of the die impressions which formed the web. The different degrees to which this occurred can be approximated by comparing the "off target" values in Tables 11 through 13 from section plane to section plane. As an example, for titanium alloy forgings, Table 12, the maximum variation in "average off target" values from section to section was 0.037 inch for hammer forgings (between sections B-B and C-C), 0.063 inch for mechanical press forgings (between sections B-B and D-D), and 0.113 inch (B-B versus D-D) for CEFF machine forgings. For each machine, these variations are indicative of variable unit loads at different areas of impression surfaces as would be expected. However, the differences in degree to which this factor appears to be influenced by the type of machine also suggests that the mechanical press dies were subjected to considerably greater forces than were the hammer dies in arriving at the same forged shape, and that the CEFF machine dies experienced significantly higher forces yet in providing the more difficult shape.

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To summarize, results of the dimensional evaluation of Inconel 718 fin rib forgings favor those produced by the steam drop hammer. For the D6ac and Ti 6Al-4V forgings, however, reproducibility and accuracy factors appear to have generally offset each other. Within the limits of the selected groups represented, the forgings produced by the CEFF machine were most reproducible in terms of forging-to-forging consistency of web thickness values taken at the same section plane location. The hammer forgings rated third (D6ac) and fourth (Ti 6Al-4V) in these instances. However, this order is reversed when but one major accuracy factor, die deflection, is under consideration. Here, differences in deflection of impression surfaces from sections B-B to D-D alone were responsible for variation in web thickness of the Ti 6Al-4V forgings from the CEFF machine which were greater by 0.013 inch than the total excess web thickness targeted (0.100 inch) to accommodate all of the previously discussed factors which influence dimensional reproducibility and accuracy of forgings. This suggests that, although reproducibility of energy level from blow to blow is quite good, a truly close tolerance forging practice to produce such structurals as was only attempted with the CEFF machine is not within the capabilities of the machine unless the quantity of forgings desired is sufficiently large to economically justify the time and effort necessary to "develop" the dies; i.e., conduct a series of trials with intermediate dimensional inspection of forgings and modification of dies until the impressions under load correspond to the shape desired. Also, the influence of such high die forces as create large variations in section-to-section deflection characteristics must be considered as a contributing factor to poor die life.

c) Procedure - Computer Techniques

The same five section planes in Figure 85 were employed as dimensional references for those program efforts which resulted in attempts at computer calculation of envelope thicknesses of excess metal, and computer graphics superimposition of forging cross section profiles over those of the fin rib component itself. The forgings were located (from their web pimples) and were held vertically in a special fixture mounted on a machinist's turntable. This assembly was, in turn, mounted to the bed of a Sheffield Ferranti Type 52 Coordinate Inspection Machine as shown in Figure 86. The X and Y "readouts" can be seen at the top of the machine, and the auxiliary "print-out" which was actually employed to record the X and Y data for each section plane of each of the 111 forgings can be seen at the right of the photograph.

A sharply pointed steel probe, which can also be seen in Figure 86, was employed to contact the forging and record the data at as many as 120 points around the periphery of any one section plane. The probe is shown in the section C-C location at a position on the outer sidewall of a CEFF machine forging. Not apparent are the scribe lines placed on both outer sidewalls to begin and end the data taking and to provide matching reference for eventually putting together the data for the halves of each profile inspected; i.e., the procedure actually followed was to inspect one half of the periphery, to rotate the turntable exactly 180 degrees, and to inspect the profile of the other half of the periphery. Also not apparent is the fact that the probe point was at a lateral angle of 45 degrees from the main part of the probe and that the whole probe was "cammed" to rotate

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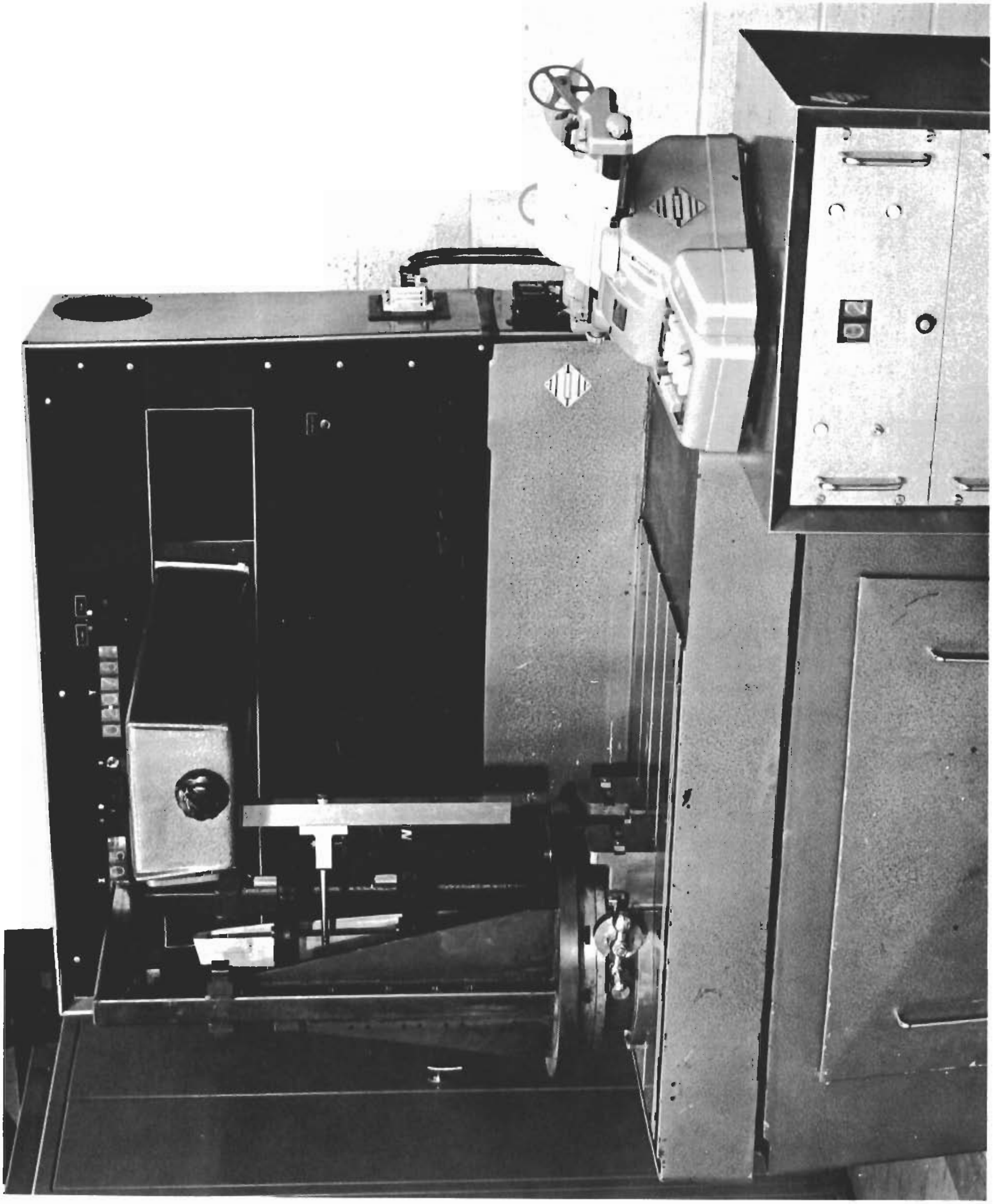

Figure 86. Sheffield-Ferranti Type 52 Coordinate Inspection Machine with Holding Fixture and Fin Rib Forging as Employed to Obtain "X-Y" Profile Data at Section Planes Illustrated in Figure 85. Note Accessory "Print Out" Unit also Employed to Record Data.

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180 degrees around a lateral centerline in such a manner that the reference of the point itself was not lost. In this manner the probe could contact all inner and outer sidewall surfaces of the half section being inspected.

Completion of probing of each section plane resulted in two sheets of print-out data with an X and a Y column on each. The data were "raw"; i.e., not referenced to anything but itself, since the computer program was to: 1) locate from the beginning and ending points corresponding to the scribe lines from which the data were taken for each half profile; 2) invert the data for the second half so that a complete profile resulted at each section; 3) establish correct X and Y reference lines corresponding to the center of the width and the center of the height of the forging at the appropriate section plane; and 4) superimpose the then referenced forging profile over that obtained for the same section of the finished component from the fin rib blueprint. Accuracy of the Sheffield Ferranti machine itself is ±0.001 inch. Accuracy of the data obtained however, is more of the order of ±0.002 or 0.003 inch, depending on the rigidity of the probe assembly and the skill of the operator in employing it.

The computer graphics facility initially employed for calculation, plotting, and superimposition of the fin rib forging-component cross section profiles is shown in Figure 87. The print-out data from the Sheffield Ferranti machine were first transposed to punch cards which were placed in the card "reader" in the center of Figure 87. The IBM-1130 computer was programmed to then perform a series of steps with the data, illustrated in simplified form in the schematic diagrams (a) through (f) in Figure 88 such that the attached Calcomp-763 unit could directly plot the forging profile with the appropriate component profile superimposed properly in terms of correct balance of the envelope. In addition to the cards with X-Y data, of course, other cards were placed in the "reader" which identified the necessary characteristics of the component profile from the finite radii and the straight line dimensional data provided on the blueprint.

d) Results - Computer Techniques

Several difficulties were experienced during initial attempts to compute and plot the profiles. CEFF machine forgings were initially inspected and evaluated, and as many as 120 data points had been taken to represent the section profiles from these forgings. Upon matching of starting and ending points to accomplish the necessary inverting of one half of the data, however, the computer was found to be completely intolerant of inspection tolerances. Both points could not be matched for this reason, so the "second half" data was actually computer rotated 180 degrees around one matched point as shown in Figure 88(b) after making the two circled points shown in Figure 88(a) coincident. Thus, as far as the computer was concerned, all inspection tolerances were "stacked up" at the other matching point - the uncircled one on the right sidewall of Figure 88(b). This would not have created difficulties if "straight line point-to-point" programming and plotting had been employed. However, a sophisticated curve fitting program was used to establish the most accurate forging profiles from the point data and to reduce the number of necessary data points. This program was mathematically derived, took several X-Y data points into consideration at all times, and was such that the

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Figure 87. Computer Graphics Facility Consisting of IBM-1130 Computer and Calcomp-763 Plotter. Employed for Necessary Calculations and Plotting to Superimpose Fin Rib Forging Cross Section Profiles over Those of the Component.

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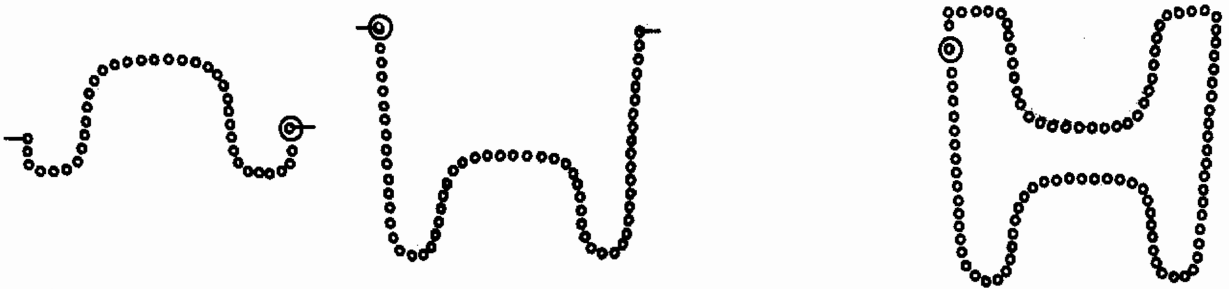
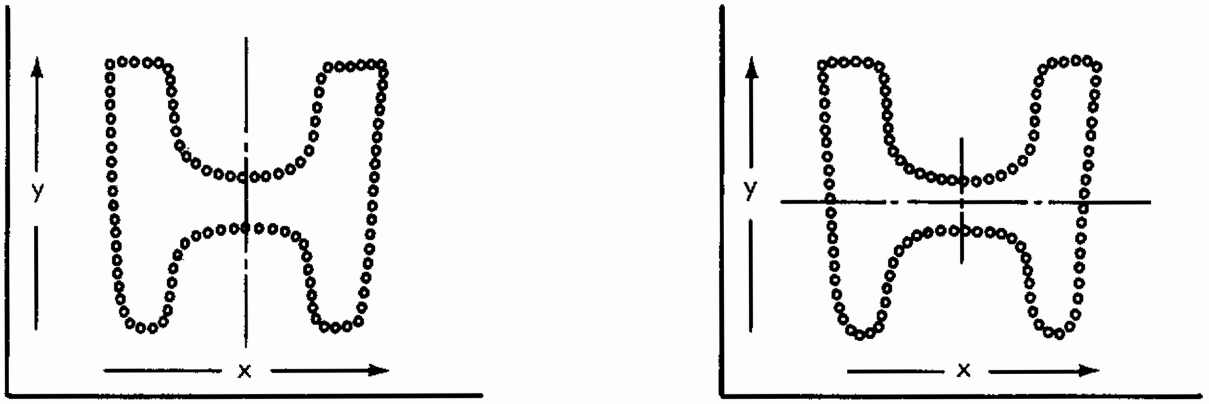


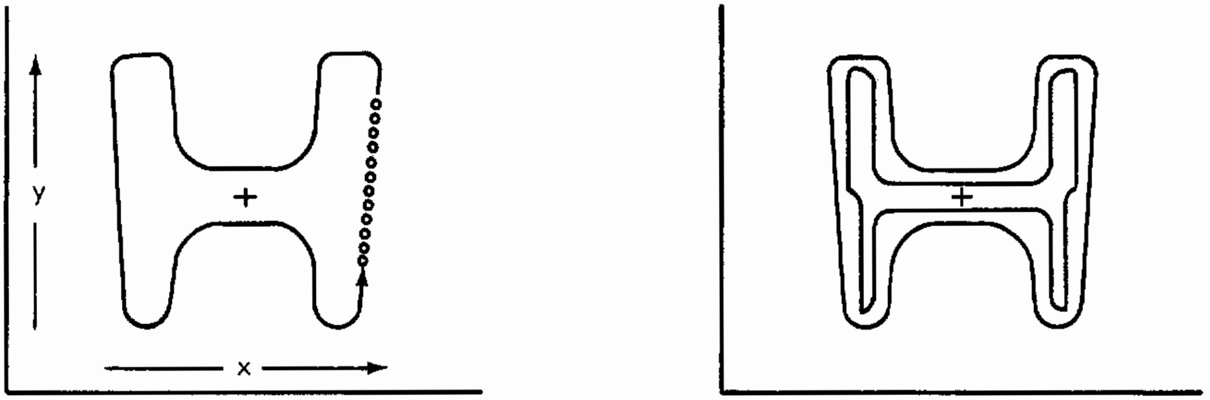
(a) Two halves of "raw x-y" data referenced to each other by starting and ending points.

(b) Matching of points marked ◎ and inversion of one half of data.



(c) Establishment of "x" centerline from average of all "x" values.

(d) Establishment of "y" centerline from average "y" value of two upper and two lower points closest to "x" centerline.



(e) Mathematically derived interconnection of data points using existing curve fitting program.

(f) Balancing of component (blueprint) profile within forging (measured) profile by superimposition of "x" and "y" centerlines.

Figure 88. Simplified Flow Chart of Computer Program Employed for Superimposition of Fin Rib Component Profiles within Those of Forging Profiles Prior to Calculation of Minimum and Maximum Envelope Thicknesses. Section B-B Illustrated.

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computer developed a new parabolic equation every 0.025 inch in guiding the plotter. This program proved to be intolerant of sharp corners. At the tolerance "stack-up" point on the right side, the plotter drew generous, confused curves in attempts to mathematically link the mismatched points. Similar behavior also occurred at the two sharp points which represented the parting lines where flash had been ground.

In both of the above instances, removal of the punch cards representing the mismatch or corner data allowed the computer to better adapt the curve fitting program to the data. Nevertheless, irregularities in the line for the upper right sidewall did sometimes occur, as can be observed in the section D-D outer profile for the CEFF machine forging in Figure 89. Also, the sharp points at the flash lines were plotted as curves, the radii of which varied because the inspection data were taken with random spacing. This characteristic can be observed for all 20 profiles in Figures 89 and 90 representing D6ac forgings from the four machine types.

After the CEFF machine forgings had been inspected and early trials with the Figure 88 program had resulted in the plots as shown at the left of Figure 89, the inspection procedures were changed in a manner which adversely affected the accuracy of the profiles to an unanticipated degree. The computer programmer indicated that less data points should be taken because time on the IBM-1130 computer was proving to be excessive. In retrospect, the computer program should have been changed, not necessarily the data taking method. Nevertheless the steam drop hammer, hydraulic press, and mechanical press forgings were dimensionally inspected by recording only 40 to 50 data points per profile instead of the previous 100 to 120. This resulted (eventually, as discovered after the forgings had been sectioned for various destructive evaluation procedures) in the irregularities, particularly around radii, which can be observed in the forging profiles in Figures 89 and 90 representing the hammer and the press forgings. Apparently the curve fitting routine was incapable of developing correct equations in working around corners with an insufficient number of actual data points to guide it.

Two other characteristics of the forging profiles plotted by computer graphics are apparent in comparing those in Figure 90 and the right side of Figure 89 with those on the left of Figure 89. First, rib heights of the hydraulic press forgings were trimmed by milling after referencing from the web surface containing the locater pimples. This procedure would have been adequate if target die closure had been achieved. However, computer balancing of the overly thick forging web sections over those of the components resulted in favoring of the lower ribs with excess metal as can be observed. Second, for some reason probably associated with insufficient data points representing flat web surfaces for correct establishment of the Y centerline (see Figure 88(d)), certain of the forging profiles tended to be skewed; i.e., the X centerline appeared to have been correctly established, but the Y centerline appeared to have been established at some angle other than 90 degrees to the X centerline. This characteristic can be noted to be particularly severe at section D-D for the hammer and the two presses, and a mathematical sub-routine inserted into the computer program to determine the angle and re-establish the Y axis failed to correct the problem.

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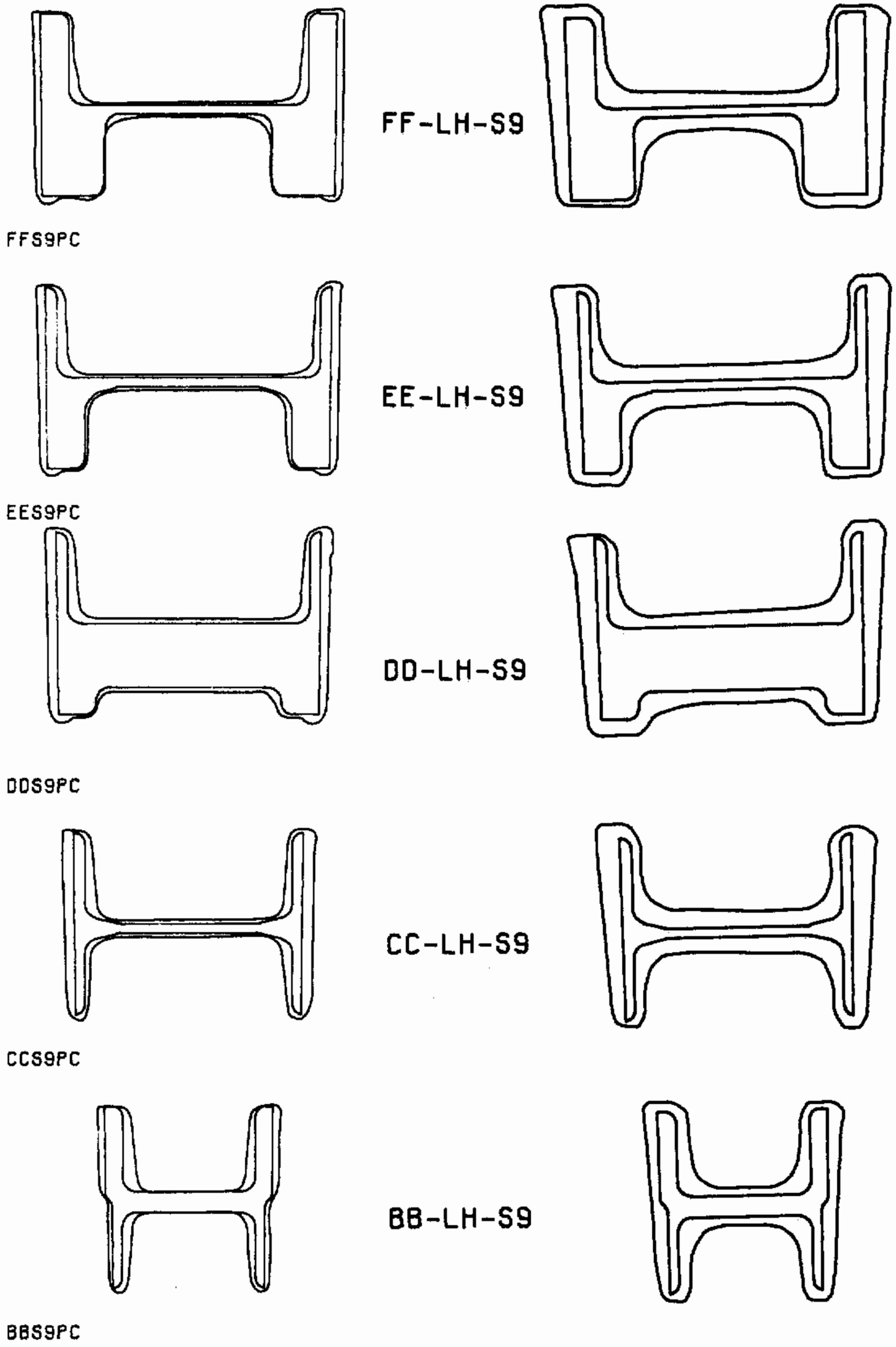

Figure 89. Computer Graphics Superimposition of Inspection Section Profiles of Fin Rib Component and D6ac Fin Rib Forgings Produced with the CEFF Machine (left) and the Steam Drop Hammer (right). Note that Forging Profiles are Incorrect - Particularly Those on the Right - See Text. Plotted 5/8 Scale - Further Reduced in Reproduction.

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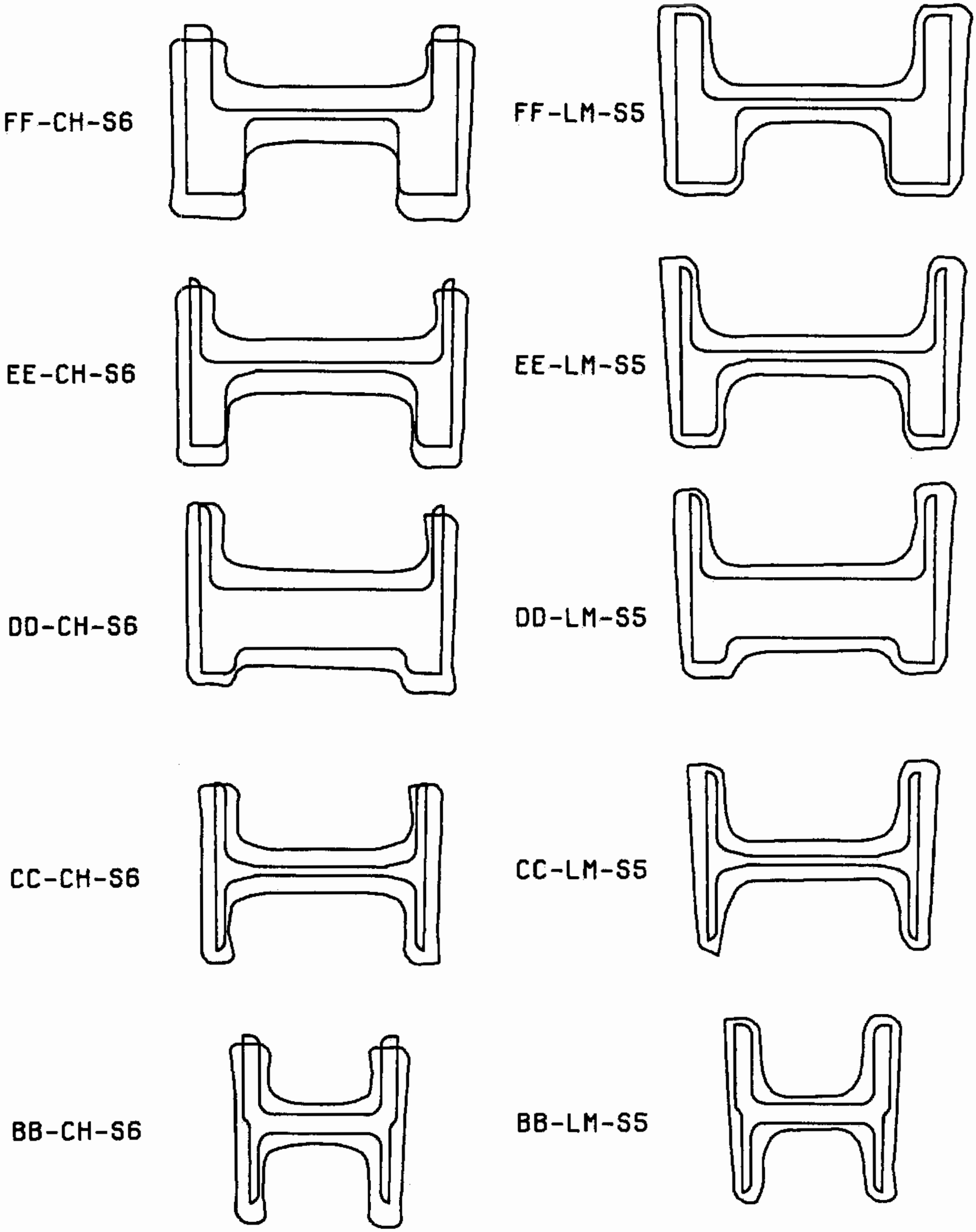

Figure 90. Computer Graphics Superimposition of Inspection Section Profiles of Fin Rib Component and D6ac Fin Rib Forgings Produced with the Hydraulic Press (left) and the Mechanical Press (right). Note that Forging Profiles were Plotted Incorrectly for Reasons Described in Text. Plotted 5/8 Scale - Further Reduced in Reproduction.

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Although inaccurate in detail for the reasons described, the Figures 89 and 90 profiles are nevertheless presented to generally illustrate the envelopes of excess metal for purposes of comparison with the targets in Figure 8, 30, 51, and 69. Actual minimum and maximum envelope thicknesses were calculated by a much more complicated program prepared for a much faster and larger (an IBM 360/50) computer. For this effort, the punch card dimensional data were recorded on magnetic tape to accommodate a faster "reader" for more effective use of the large computer. The program in this instance divided the profiles into 12 regions to maintain positive envelope thickness values, identified 42 points on each component profile, determined the length of the lines "fanning" from each of the 42 points to intermediate points every 0.025 inch along the forging profile from the two inspection data points closest to the boundaries of the region, and printed out the length values for the shortest line established from each of the 42 component profile locations. The computer then printed out the smallest and the largest of these values as the minimum and maximum envelope thicknesses and, as an extra, calculated and printed the left and right rib heights, the web thickness at the X centerline, and radii values at ten locations around the forging profile.

The potential value of the above computer program and data is readily apparent when one considers TRW's intent to apply the Figure 4 machining pass classification system to five sections of each of the 111 forgings inspected. Unfortunately, the data proved to be suspect to a degree which prevented its use in evaluating and comparing the forgings. Heights and thicknesses only infrequently corresponded, within reasonable limits which could be explained by inspection tolerances, to those measured with the micrometers. Radii values proved to be inconsistent due, again, to the random spacing of too few data points in these areas. And, although derived from the same punch card inspection data and Figure 88 superimposition program, the envelope values printed out by the large computer did not correspond to those observed on the plots guided by the smaller computer. For example, the print-out would frequently list very small values, such as 0.005 inch as the minimum envelope thickness for a section; yet the minimum envelope on the 5/8 scale plot for the same section would as frequently measure 1/16 of an inch.

The envelope thickness data from the large computer and the Figures 89 and 90 plots for the hammer and the press forgings were obtained for evaluation at the same time. Further efforts at evaluation and comparison of the data were discontinued when it was recognized that the insufficient number of data points and the resulting improper establishment of the Y centerline and incorrect superimposition of Y axis profile data were responsible for inaccuracies virtually impossible to correct by mathematical modifications of the computer programs. The reason for the different indications of envelope thickness provided by the two computers from the same data was never established.

In terms of actual program results, the lack of finite envelope thickness data (except at central web areas, see Tables 11, 12, and 13) cannot be considered critical. This is because other factors proved to be sufficiently discriminating to allow direct comparison of equipment capabilities and to minimize the importance of envelope thickness comparisons. Because overall press action was too slow to prevent excessive chilling of workpieces, the hydraulic press could not achieve target closures without damaging the dies. Due to previous lack of experience in producing such structural shapes of such

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materials with HERF techniques, the CEFF machine effort employed a finish shape which could not be produced within the limitation of reasonable die life and which, for the titanium alloy and the nickel base alloy forgings, caused variations in deflection in die surfaces greater than tolerance variations anticipated from all causes.

If a much faster action had been available to allow the hydraulic press to reach target closure and if the CEFF machine dies were to be redesigned to provide reasonable die life and an envelope accommodating all reproducibility and accuracy tolerance factors, it must be suggested that the envelope characteristic of the forgings from all four machine types would probably have been quite similar and would normally have varied more as a function of the material being forged. It is also considered significant that; within the limitations of conventional, reasonably economical die systems and forging practices as imposed by the program work statement; none of the four machine types demonstrated superior ability to control combined reproducibility and accuracy tolerances to a degree which would suggest a capability in providing high strength steel, titanium alloy, or nickel-base alloy structural forgings designed to extremely close tolerance envelopes.

B. Quality

The term "quality", as applied to a forging, can be considered to relate to three basic characteristics. First, it infers that the forging is free of defects such as cracks, laps, inclusions, etc. Second, the term relates to internal macro- and microstructural features which, in conjunction with chemistry and post forging heat treatment, govern the mechanical property levels of the forging. Third, in selected circumstances "quality" can involve surface conditions such as surface finish and surface chemistry change effects such as "alpha case" on titanium alloys, decarburization of carbon and alloy steels, etc.

Surface finish was not a subject of the TRW evaluation of intermediate size forgings from the four machine types because the forgings were designed with allowances for excess metal surrounding all areas of the fin rib component. All of the 111 forgings were, however, subjected to fluorescent penetrant inspection for surface defects; and selected forgings from each of the 12 equipment-materials categories were sectioned to evaluate macro- and microstructural characteristics and to attempt to establish causes for the surface defects observed.

1. Freedom from Defects

a) Procedures

The fin rib forgings were all inspected for surface defects using post emulsification fluorescent penetrant (P.E. Zyglo) techniques in accordance with specification MIL-1-6866B, Type I, Method B. Small sections were subsequently taken from defective areas of selected forgings; and the sections were mounted, polished, etched, and studied with a conventional light microscope. Etchants employed were: D6ac, 2 percent Nital; Ti 6Al-4V, 2 percent hydrofluoric acid plus 2 percent nitric acid in water; Inconel 718, electrolytic with 3 percent chromic acid in water. Photomicrographs were prepared at magnifications of 75X and 250X as required for reporting purposes.

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b) Results

Results of fluorescent penetrant inspection generally served to confirm visual indications of defects shown representatively in Figures 22, 25, 44, 46, 66, 80, and 84. Several exceptions were, however, noted. The slightly wavy web surfaces previously noted on the hammer forged Ti 6Al-4V fin ribs did not retain penetrant, but fillet radii for 8 of the 10 forgings of this series were observed to contain indications of minor defects. Longitudinally oriented linear defects which had not been observed visually were also detected on the web surfaces of two of the Ti 6Al-4V forgings produced with the hydraulic press. In addition, the previously discussed but not photographed indication of a slight surface tearing condition on outer rib sidewalls of several Ti 6Al-4V forgings produced with the mechanical press was confirmed as a defective condition. All of the defective conditions found are illustrated and discussed by material class in the paragraphs which follow.

The metallographic study of defect areas sectioned from representative D6ac steel forgings involved only those produced by the hammer and the hydraulic press. Fluorescent penetrant inspection indicated that six of the 10 D6ac forgings produced with the steam drop hammer contained defects along fillet radii as shown in Figure 22. A photomicrograph of a cross section through this condition is shown in Figure 91. It can be observed that the radius actually contained a slight projection which itself contained what appears to be a slight lap. The entire projection appears to be decarburized and it is possible that it was formed as a result of scale formation in this area prior to the final blows. Although the origin of this condition cannot be confirmed, it represents such a small indication that it is considered technically more correct to classify it as a surface irregularity rather than as a defect.

Although fluorescent penetrant inspection revealed no indications of defects in D6ac forgings produced with the hydraulic press, the mechanical press, and the CEFF machine; the severe internal crack shown in Figure 92 was found at Section C-C of the sixth D6ac forging produced with the hydraulic press after sectioning for grain flow studies (discussed later). The crack extended the total distance from web metal with lateral grain flow to rib edge metal with vertical grain flow, but it did not propagate through to the surface. This crack is presumed to be the result of a residual stress in this area, and the crack itself probably formed during sectioning. It is possible to envision vertical tensile forces during forging with this die concept within the triangle which bounds the transition area from lateral to vertical flow.

Visual and fluorescent penetrant inspection revealed defective or potentially defective areas on Ti 6Al-4V forgings produced by all four types of machines. Fluorescent penetrant inspection revealed indications of minor defects in fillet radii of eight of the ten alloy forgings produced with the steam drop hammer. Also, the eighth and ninth forgings of the ten hammer forgings delivered were observed to have more severe defect indications on an inner rib wall in the "nose" end as previously shown in Figure 25. Photomicrographs of cross sections representative of both of these types of indications are shown in Figure 93. The higher magnification (250X) photomicrograph on the left revealed that the fillet radius condition is minor and

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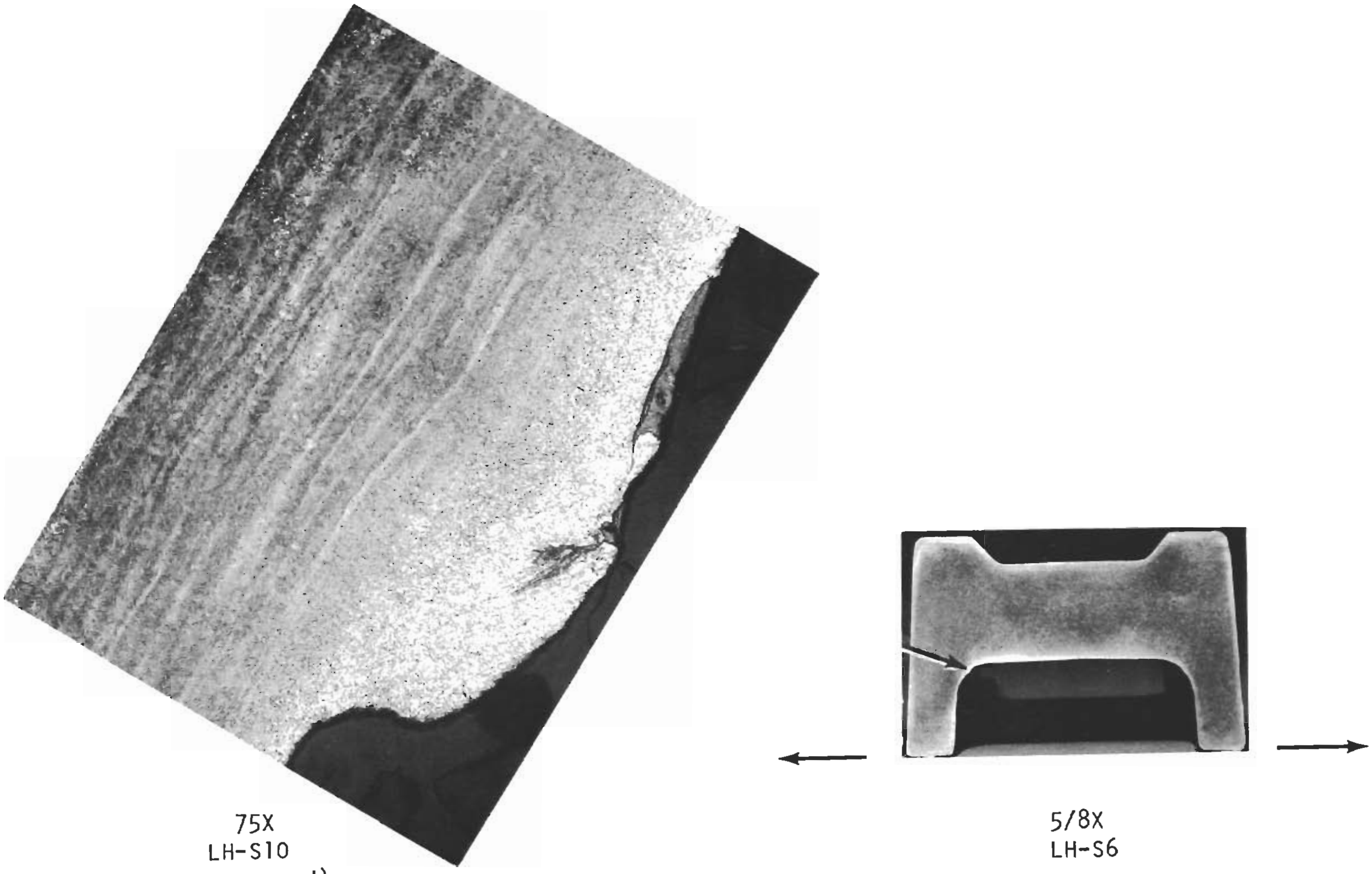
75X
LH-S10
(As-Forged)

5/8X
LH-S6

Figure 91. Surface Irregularity with Small Lap in Fillet Radius of D6ac Fin Rib Forging Produced with the Steam Drop Hammer. Arrow in Small Section Illustrates Typical Location Only. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. Also See Figure 22.

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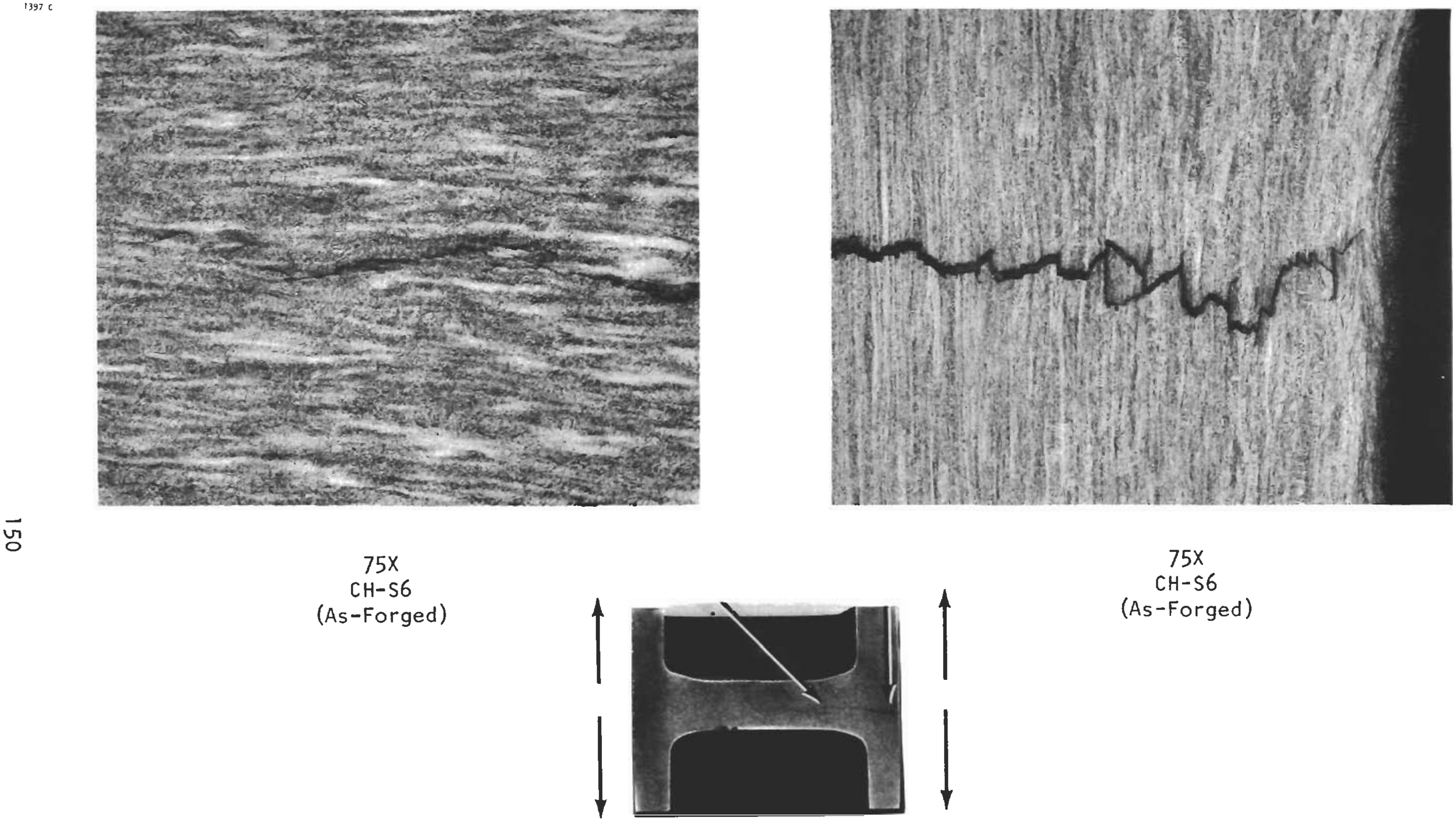

75X
CH-S6
(As-Forged)

5/8X
CH-S6

75X
CH-S6
(As-Forged)

Figure 92. Severe Crack Found after Sectioning D6ac Fin Rib Forging Produced with the Hydraulic Press. Note that the Crack Does Not Extend to the Surface. Arrows in Small Section Indicate Actual Locations of Photomicrographs. External Arrows Indicate Directions of Metal Flow at Die Parting Lines During Finish Forging Operation.

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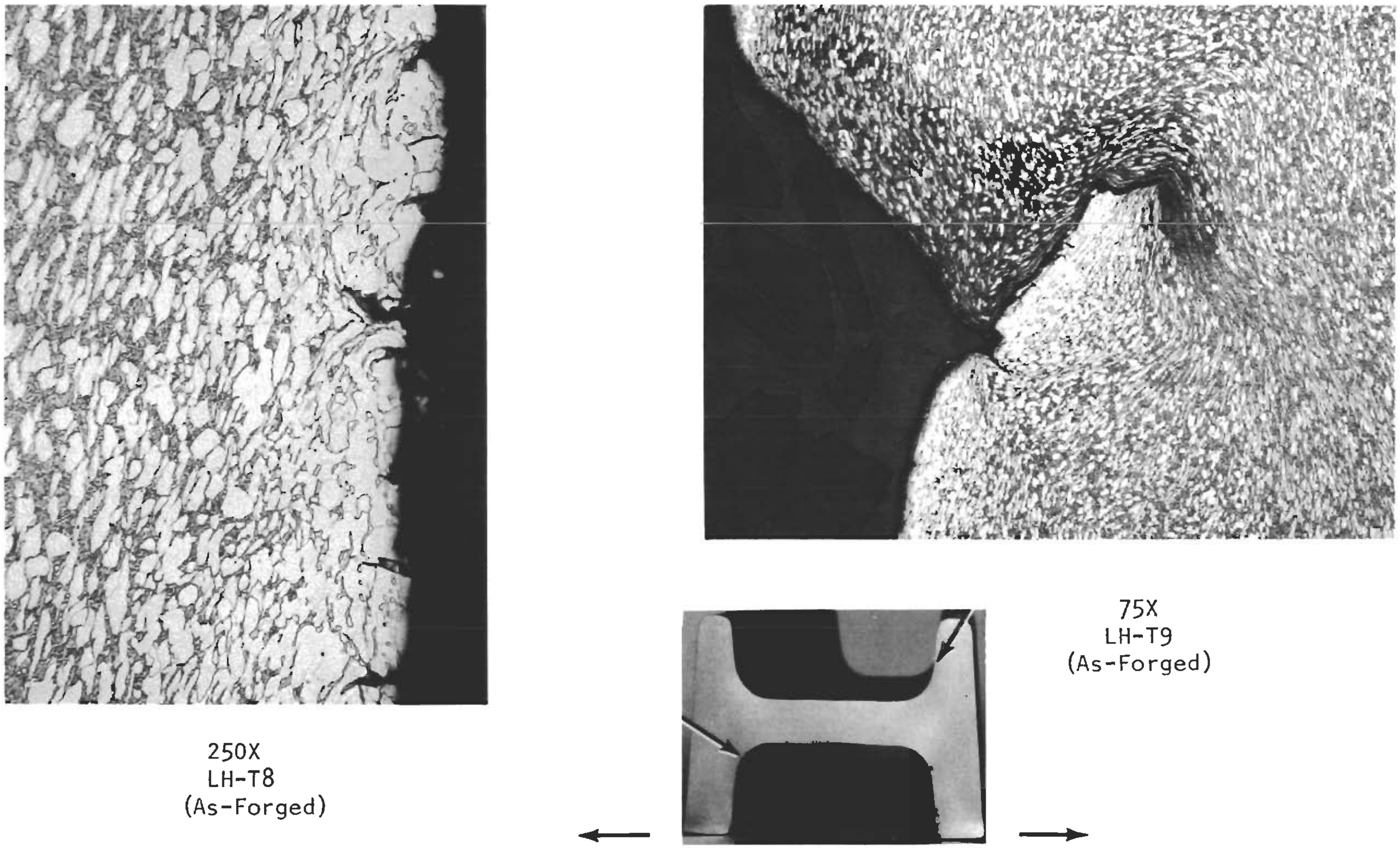

250X
LH-T8
(As-Forged)

5/8X
LH-T6

75X
LH-T9
(As-Forged)

Figure 93. Surface Condition in Fillet Radius (left) and Defect in Inner Rib Wall (right) of Certain (See Text) Ti 6Al-4V Fin Rib Forgings Produced with the Steam Drop Hammer. Arrows in Small Section Illustrate Typical Locations Only. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. For Rib Wall Defect also see Figure 25.

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would probably be removed by a chemical conditioning (acid etch) operation prior to machining of the components. The tiny cracks are presumed to be the result of surface tensile stresses during deformation of the "alpha case" (a hardened and embrittled surface layer caused by interstitial diffusion of oxygen, an alpha phase stabilizer) which is represented in the photomicrograph by a larger concentration of the white phase at the surface. Normal-to-surface tensile stresses tend to be greatest at fillet radii of rib and web forgings as the corresponding corner radii of the dies becomes smaller in progressing through a standard die sequence.

No positive explanation can currently be advanced for the unusual shape for the more severe defect at the right of Figure 93, or for the reason that it occurred in only one localized area of only two forgings in the series of ten. It can be observed, however, that one side of the defect appears to contain "alpha case" whereas the other does not. Also, the rib sidewall surface below the defect appears to contain considerable more "alpha case" than does the comparable surface immediately above the defect. These observations suggest that surface metal with "alpha case" formed during heating for forging was "lapped" (i.e., folded over) by interior metal at this location during the finish forging operation.

Fluorescent penetrant inspection revealed that seven of the ten Ti 6Al-4V forgings produced by the hydraulic press contained what appeared to be surface tears on inner and outer rib sidewalls. The more severe of these had been noted visually, and the most severe have been shown in Figure 44. Photomicrographs of cross sections through these defects are shown in Figure 94, and they are apparently the result of nonuniform flow of surface and near surface metal. This can also be observed in the small cross section included in the figure. As previously indicated, the Cameron report suggested that the defects occurred because of excessive chilling of surface metal by the dies prior to build-up of sufficient hydraulic pressure for deformation to occur.

Fluorescent penetrant inspection also revealed indications of fine cracks on web surfaces on two of the Ti 6Al-4V fin rib forgings produced by the hydraulic press. These had not been observed visually, and a photomicrograph of material sectioned through one of them (at 250X) is shown in Figure 95. In both instances the indications were on the surface formed by the lower impression; i.e., the surface which is presumed to have been chilling at a faster rate as the ram and upper die were descending. It can be noted in the photomicrograph that the crack formed along one edge of what appears to be a narrow band representing an oriented, more severely deformed microstructure. Such "shear bands"(11) angling to the surface are indicative of transition zones between metal which is sliding at the surface and metal which is not. These zones, therefore, actually represent locations where, on one side, the force required to overcome interfacial friction at the surface is less than that required to overcome the flow stress of the material itself ("slip", surface sliding) whereas, on the other side, the reverse is true ("stick", internal flow). Assuming that lubrication practices are properly controlled, the surface transition zones and accompanying angular internal "shear bands" can be considered to be principally the result of: 1) variable flow stress within the cross section due to a variable thermal profile caused by nonuniform chilling or nonuniform adiabatic heating; and 2) variable forces normal to the surface at different locations within

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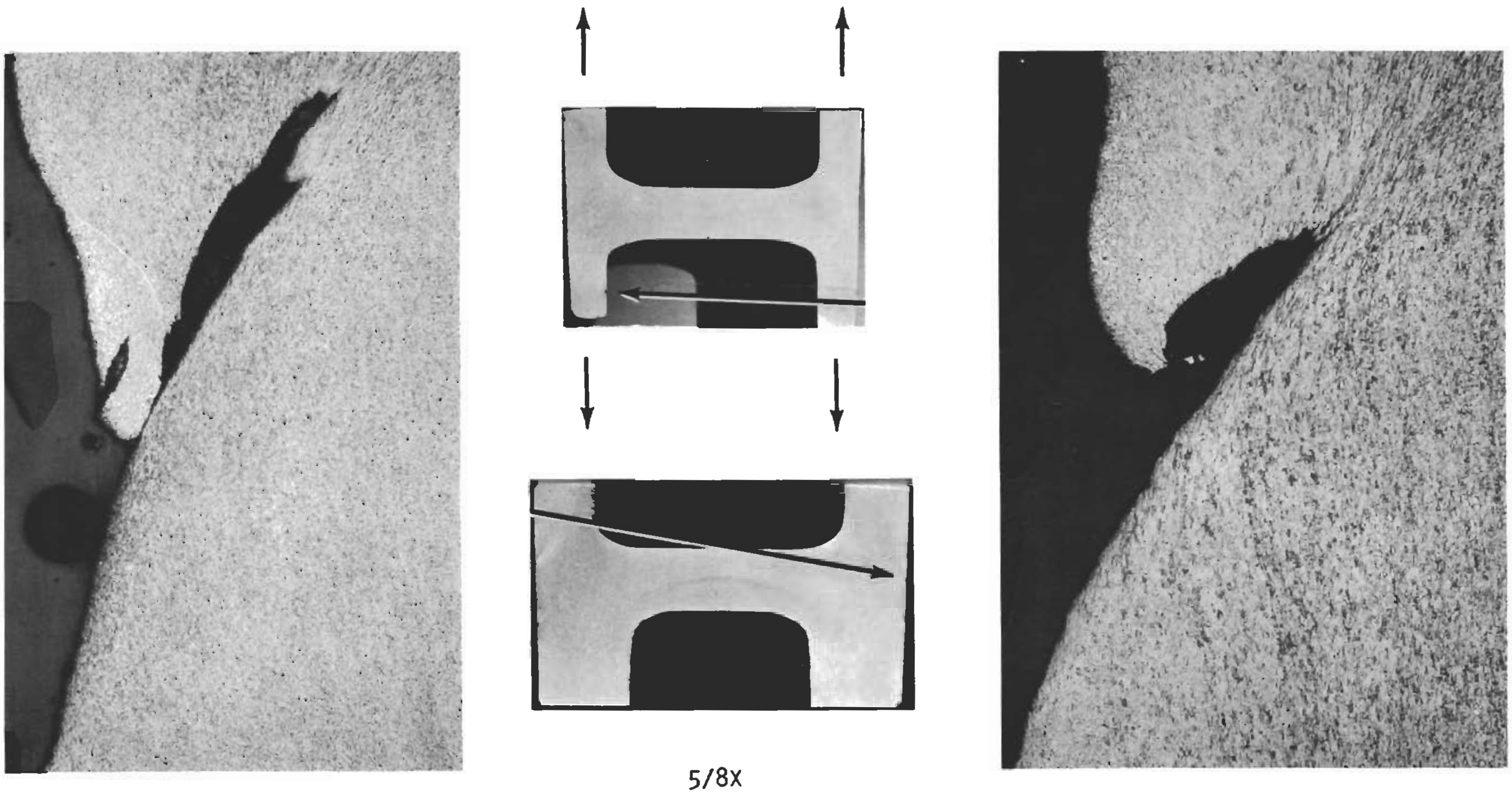

75X
CH-T10
(As-Forged)

5/8X
CH-T6

75X
CH-T5
(As-Forged)

Figure 94. Defects in Outer Rib Wall (left) and Inner Rib Wall (right) of Certain (See Text) Ti 6Al-4V Fin Rib Forgings Produced with the Hydraulic Press. Arrows in Small Sections Illustrate Typical Locations Only. External Arrows Indicate Directions of Metal Flow at Die Parting Lines During Finish Forging Operation. Also see Figure 44.

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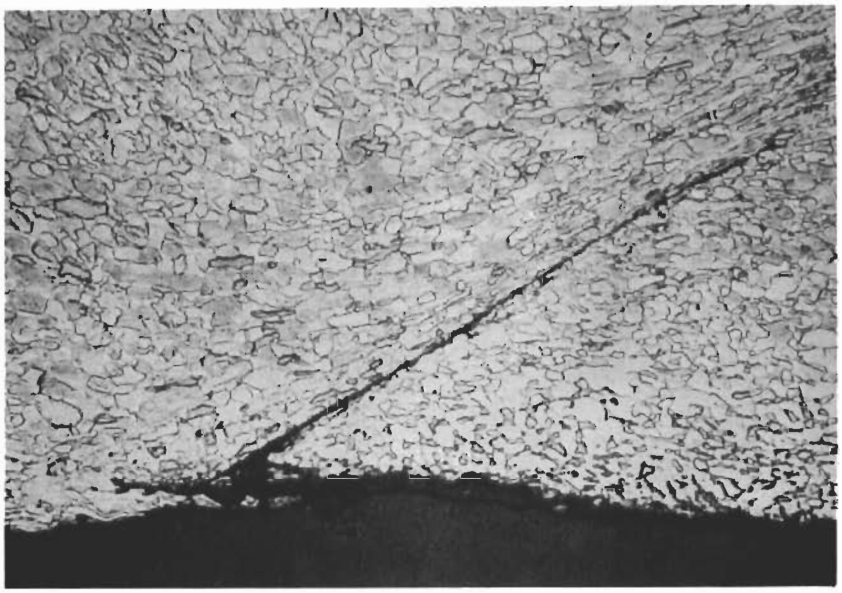
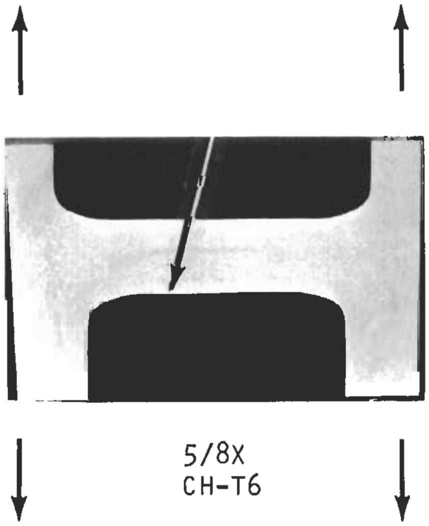


250X
CH-T6
(As-Forged)



5/8X
CH-T6

Figure 95. Small, Fine Crack in Web Surface of Ti 6Al-4V Fin Rib Forging Produced with the Hydraulic Press. Arrow in Small Section Indicates Actual Location of Photomicrograph. External Arrows Indicate Directions of Metal Flow at Die Parting Lines During Finish Forging Operation.

1404 C

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the impression as invariably occur during impression die forging, and the influence of these variations on interfacial friction at the different locations. The fact that only two of the ten forgings contained actual cracks near the surface along these bands of more intense deformation is probably indicative of a marginal chilling condition in this area from the standpoint of exceeding the ductility of the material.

The previously discussed indications of very slight surface tears at localized areas of rib sidewalls of several of the Ti 6Al-4V forgings produced with the mechanical press were confirmed by the fluorescent inspection and metallographic investigation. A 250X photomicrograph of the most severe of these noted is shown in Figure 96. Three of the ten forgings in this series contained this type of defect to a degree which could be detected by the fluorescent penetrant procedures. In addition, six of the ten forgings showed indications in certain fillet radii which appeared to be due to the same surface condition, shown at the left of Figure 93, found on the similar forgings produced with the hammer.

The more severe defects found in nine of the ten Ti 6Al-4V fin rib forgings produced with the CEFF machine have been shown in Figure 80. Forging PC-T2 (actually forged sixth of the series of eighteen produced to deliver ten) contained the most severe visual and penetrant indications, and was the subject of metallographic studies resulting in the photomacro- and photomicrographs in Figures 97 through 100.

The defect in Figure 97 can be seen to have been caused by a zone of intense shearing deformation between metal "locked" in the lower rib cavity and metal flowing from the web upward toward the parting line. In Figure 98, it can be observed that the lower side of the defect itself contains a zone of more highly deformed grains and no evidence of "alpha case"; whereas the upper side exhibits larger, more equiaxed alpha grains and evidence of considerable "alpha case". This suggests that the upper side of the defect actually represents exterior surface metal from the radius and web of the prior blocker shape which was forced to penetrate the rib sidewall to a depth of approximately 0.090 inch during the finish blow. The fact that the exterior surface of the finish forging, at the right of Figure 98, contains no evidence of "alpha case" is attributed to: 1) chemical conditioning of the Ti 6Al-4V forgings at Precision Metal Products with a reported removal of approximately 0.002 inch of surface metal; and 2) sandblasting of forging surfaces conducted at Precision Metal Products and later at TRW. This type of condition has been termed a "flow-through" defect(1,3). In this instance it is considered the result of a localized geometrical-thermal-friction environment such that, once the impression recess was filled, less energy was required to displace web and radius surface metal directly into the section than to initiate sliding along the die surface all the way around to the parting line.

The same mechanism is suggested as responsible for the inner rib sidewall defects in Figure 80 representing the upper die side of the forgings. Although the "alpha case" on the lower side only of the defects, Figure 99, could lend credence to a theory involving very severe "lapping", this would not explain the zone of more highly deformed metal on the upper side which can be observed to increase in severity in progressing from the

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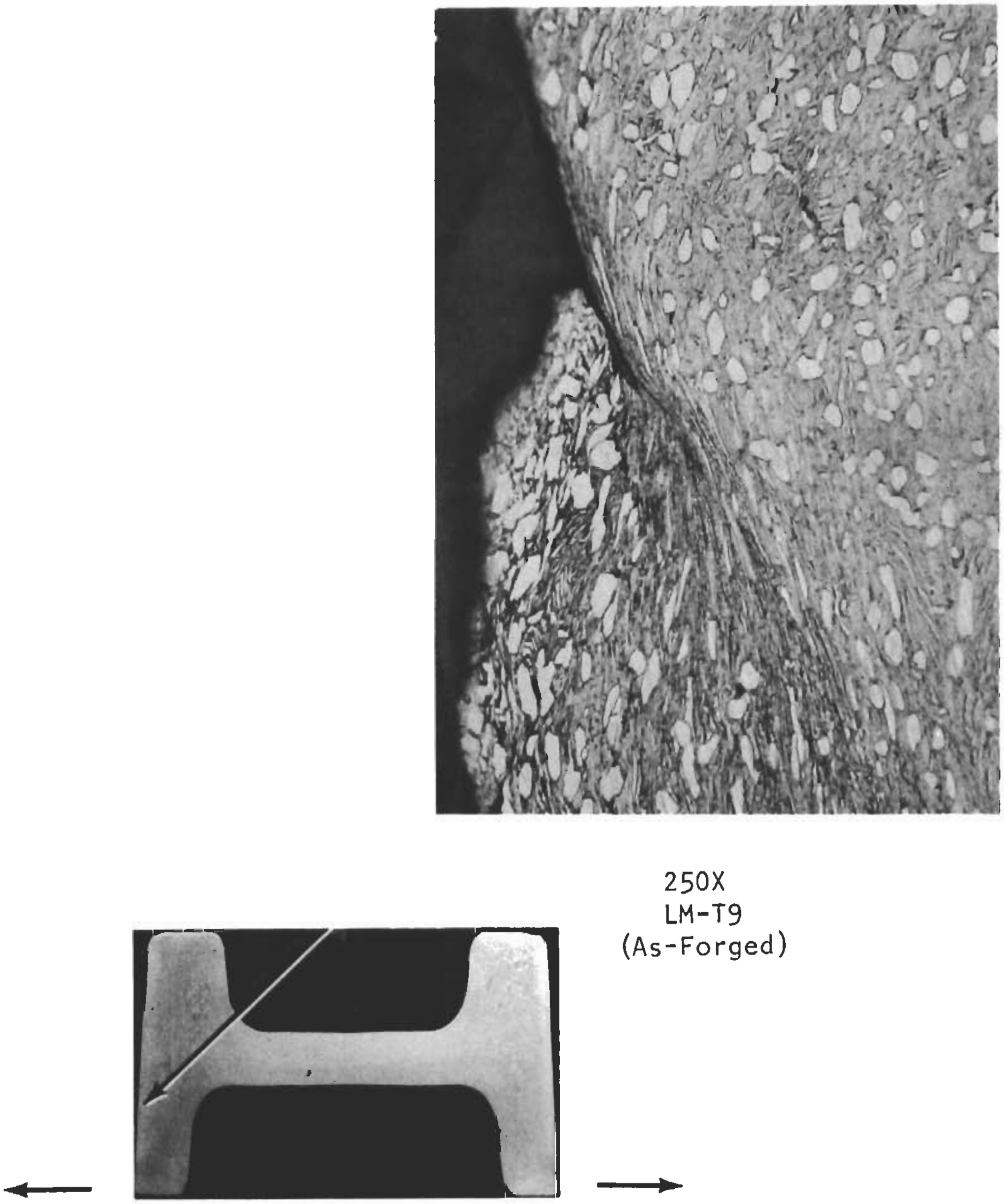
250X
LM-T9
(As-Forged)

5/8X
LM-T6

Figure 96. Small Defect in Outer Rib Wall of Ti 6Al-4V Fin Rib Forging Produced with the Mechanical Press. Arrow in Small Section Illustrates Typical Location Only. External Arrows Indicate Directions of Metal Flow at Die Parting Lines During Finish Forging Operation.

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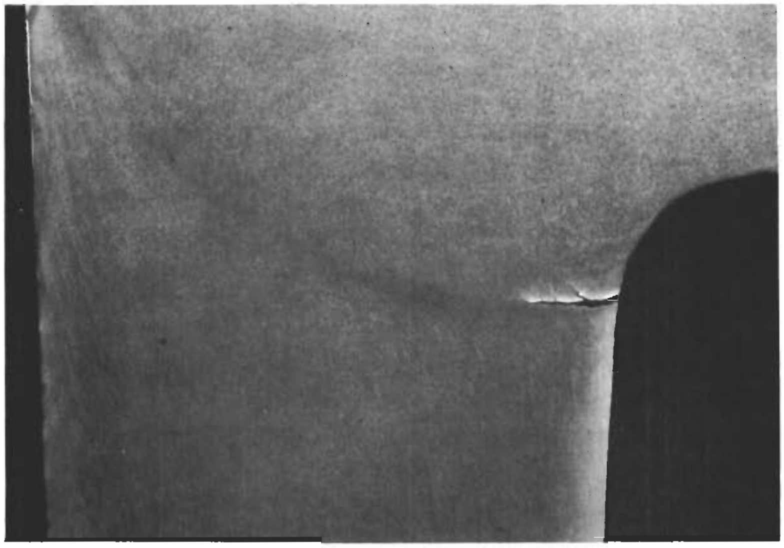
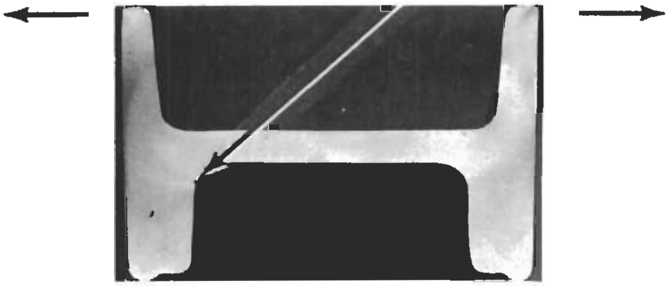


5X
PC-T2



5/8X
PC-T6

Figure 97. Severe Defect Near Fillet Radius of Ti 6Al-4V Fin Rib Forging Produced with the CEFF Machine. Arrow in Small Section Illustrates Location of Similar Defect in Different Forging. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. Note Band of More Severely Deformed Material which Initiates at the Defect Site. Also See Figure 80.

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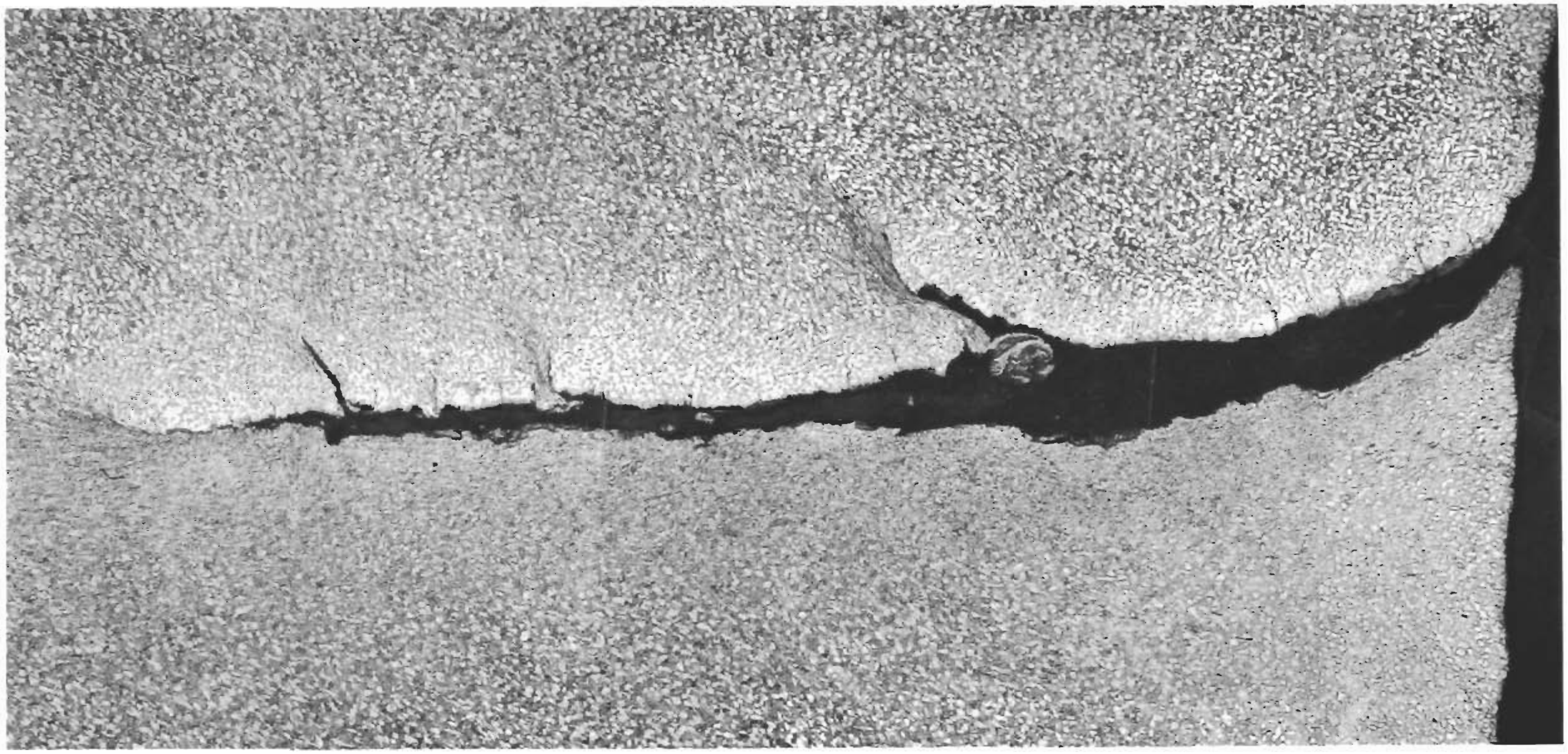
1407 C



75X
PC-T2
(Forged, Annealed 1-hour at 1500°F)

Figure 98. Composite Photomicrograph of Severe Defect Shown in Figure 97. Also See Figure 80.

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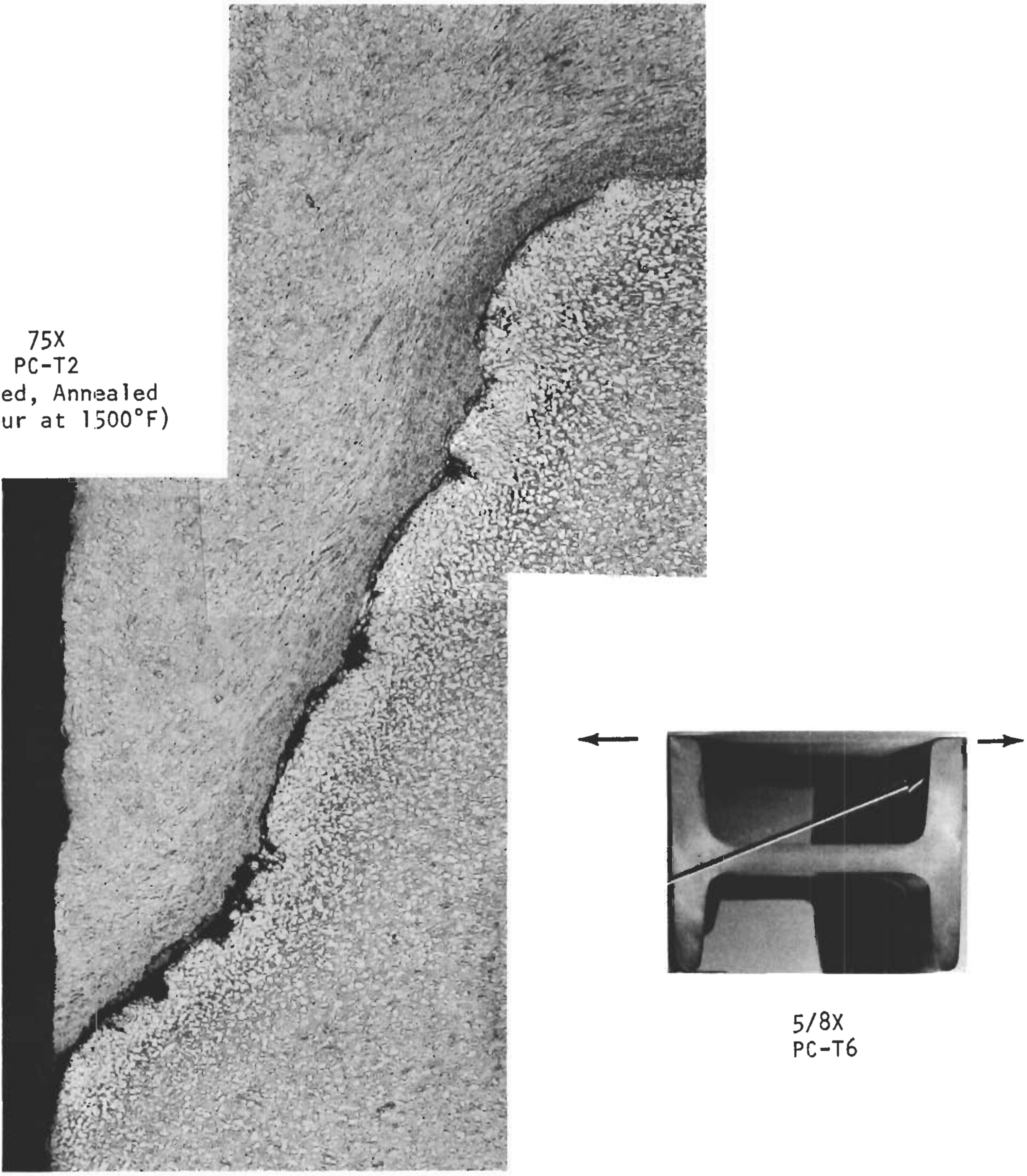

Figure 99. Composite Photomicrograph of Severe Defect in Inner Rib Wall of Ti 6Al-4V Fin Rib Forging Produced with the CEFF Machine. Arrow in Small Section Illustrates Typical Location Only. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. Also See Figure 80.

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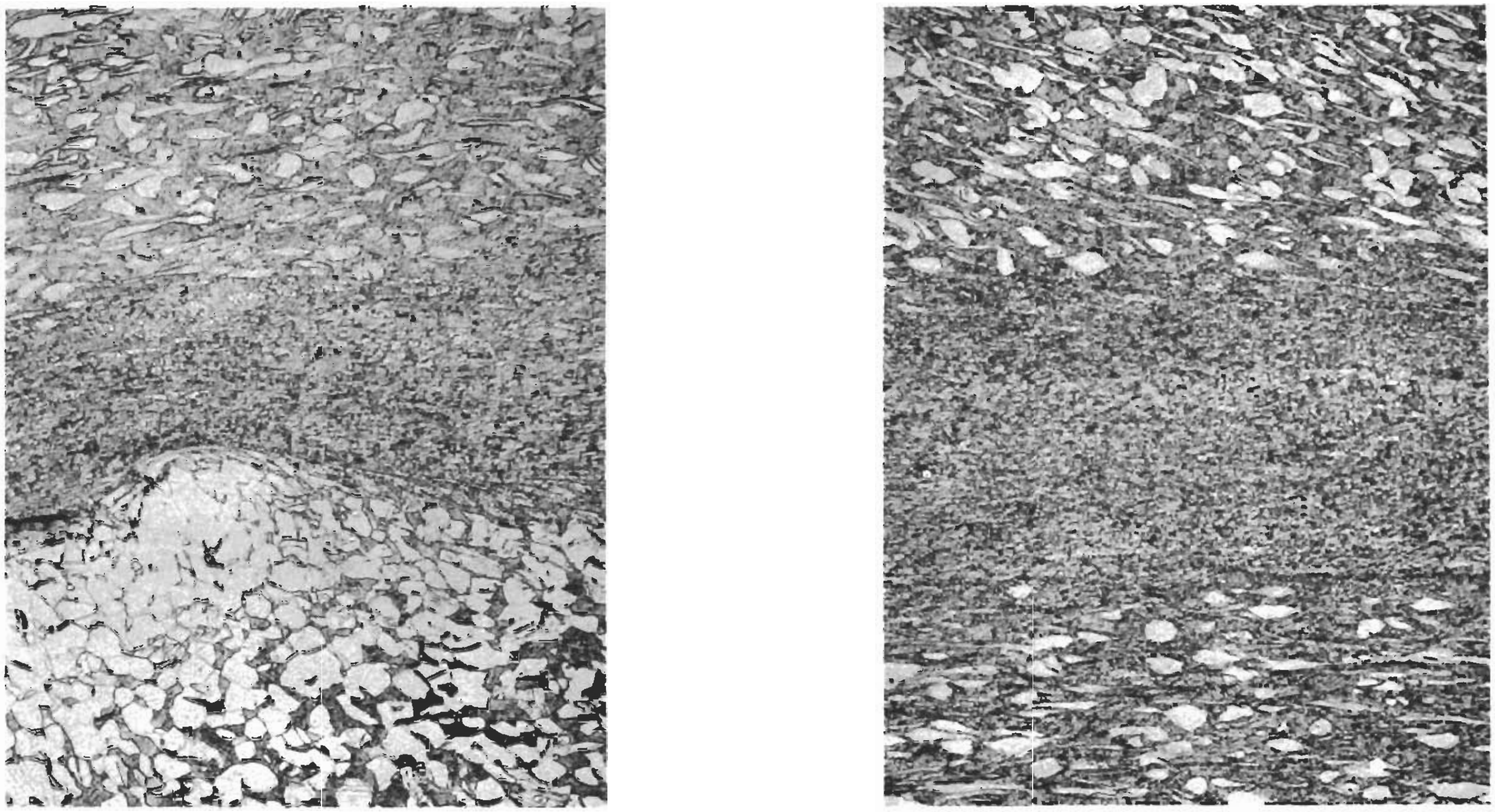
1408 C



250X
PC-T2
(Forged, Annealed 1-hour at 1500°F)

250X
PC-T2
(Forged, Annealed 1-hour at 1500°F)

Figure 100. Photomicrographs Showing Root of Severe Defect in Figure 99 (left) and 0.004 to 0.006 Inch Thick Band of More Severely Deformed Material (right) which Extended from the Upper Edge of the Defect to the Outer Corner of the Rib Corresponding to the Die Parting Line. Photomicrographs were Taken Approximately 1/8 Inch Apart.

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surface initiation site to the root of the defect. It appears that an approximately triangular cross section of metal became a "dead metal" zone in the upper die impression, and was "short circuited" by the remainder of the excess metal in the rib as it traveled to the parting line. This created a severe "shear band" which extended across to the parting line at the upper edge of the outer sidewall, and was responsible for the apparent surface metal penetration of the rib to a depth again approximating 0.090 inch at the angle shown. Details regarding the severity of the "shear band" itself are shown in Figure 100, and it can be noted that it was very narrow and represented material which appears to be highly deformed.

The previous major section of this report discussed visual identification of surface defects in Inconel 718 fin rib forgings produced with the hydraulic press, the mechanical press, and the CEFF machine. For the hydraulic press forgings, the defects involved only minor indications on the sides of the central locator pimple on three forgings. As shown in Figure 101, which illustrates the worst indication noted of the three, this condition proved to be of minimal severity. It appears to be the result of tearing of presumably chilled surface metal.

In contrast to the shallow surface tears on the three Inconel 718 forgings from the hydraulic press, the web surface defect in the Inconel 718 forgings produced with the mechanical press were, as previously discussed and shown (Figures 64, 65, and 66), particularly deep. Cracks of greater and lesser severity than the one shown in Figure 102 were found by visual and fluorescent penetrant section in nine of the ten forgings delivered of this series. These are also attributed to cold tearing, and their incidence and severity in comparison to those representing the hydraulic press effort is presumed at least partially due to the significantly lower heating temperature for forging; i.e., 1850°F for the mechanical press forgings (Table 6) versus 2050°F for the hydraulic press forgings (Table 4).

The very severe cracking difficulties experienced during forging of the Inconel 718 structurals with the CEFF machine have been shown in Figure 84. Photomicrographs of cross sections taken through selected crack areas are shown in Figures 103 and 104, and the small cross section photograph in Figure 104 serves to illustrate the severity of the problem. As previously indicated in Table 8, the five forgings produced before failure of the upper finish die occurred were multiple, low-energy-blow finish forged from a heating temperature of 2000°F. This produced the smaller cracks shown in Figure 103 and the upper photomicrograph in Figure 104 which again appeared to coincide with potential "shear band" locations due to web metal moving past a "dead metal" zone, the lower rib in this instance. Any microstructural evidence of the probable "shear band" itself has been lost due to recrystallization during the 1950°F solution annealing treatment given the forgings by Precision Metal Products. Also, the annealing treatment has resulted in oxidation and depletion of defect edges and in oxidation of adjacent grain boundaries to a degree which again masks the defect initiation mechanism. It is considered probable, however, that the defects occurred as a result of weakened grain boundaries, or possibly even incipient melting of grain boundary material, due to localized high temperatures within bands of more intense deformation.

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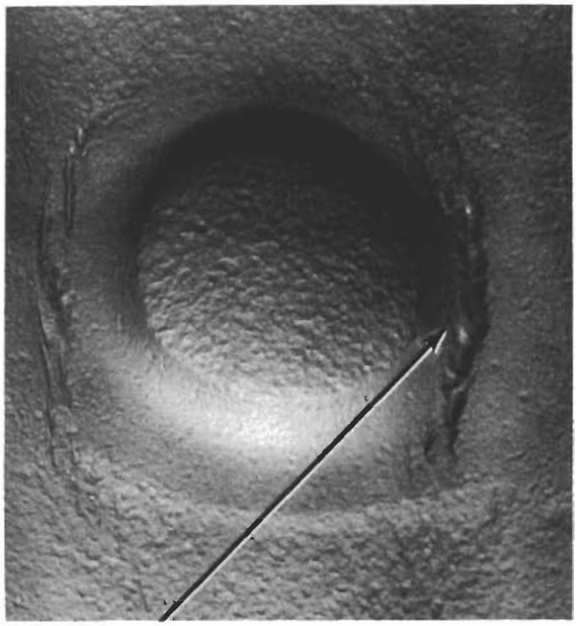
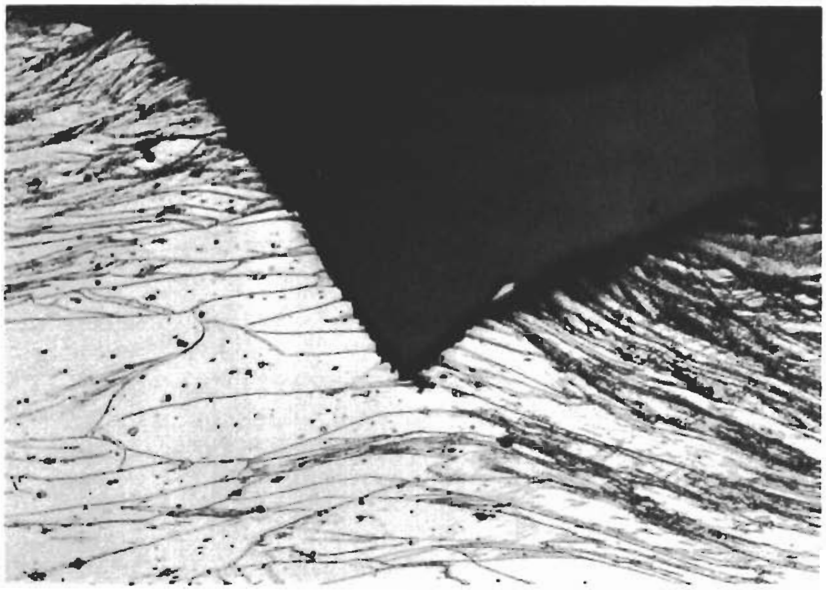


2X
CH-N5



75X
CH-N5
(As-Forged)

Figure 101. Small Defect in Web Surface Near Center Locator Pimple of Inconel 718 Fin Rib Forging Produced with the Hydraulic Press. Arrow in Photograph Indicates Actual Location of Photomicrograph. Also See Figure 46.

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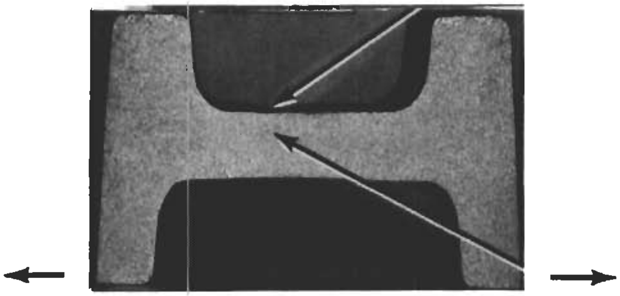
75X
LM-N6
(As-Forged)



5/8X
LM-N6

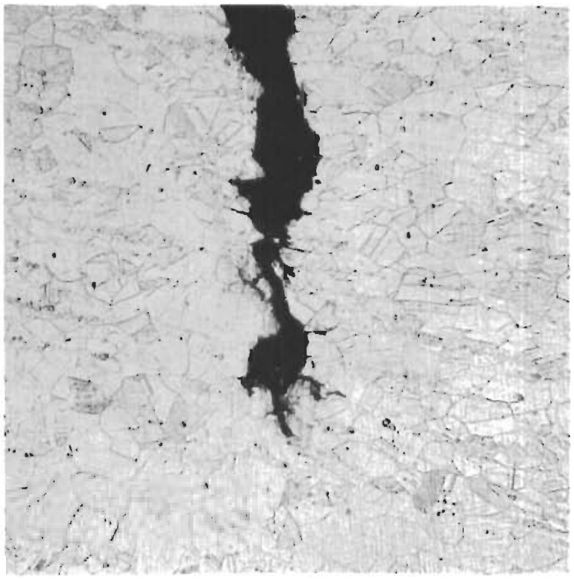


Figure 102. Severe Crack in Web Surface of Inconel 718 Fin Rib Forging Produced with the Mechanical Press. Arrows in Small Section Illustrate Typical Location and Depth Only. Crack in this Instance was Approximately 0.200 Inch Deep. External Arrows Indicate Directions of Metal Flow at Die Parting Line. Also See Figures 64, 65, and 66.

1430 C

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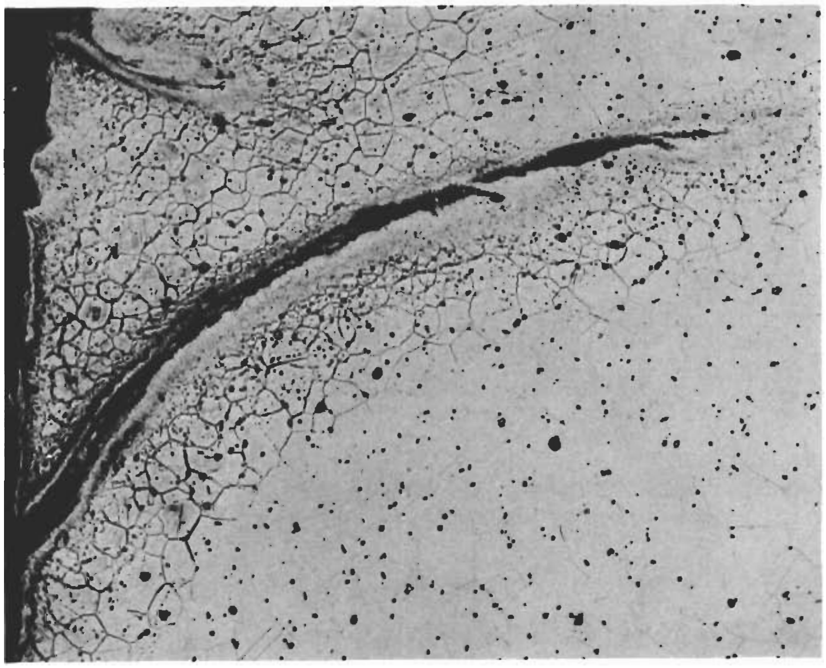
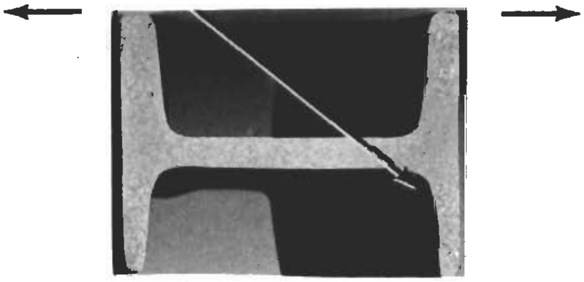


75X
PC-N3
(Forged, Annealed 1-hour at 1950°F)



5/8X
PC-N1

Figure 103. Severe Defect Near Fillet Radius of Inconel 718 Fin Rib Forging Produced with the CEFF Machine. Arrow in Small Section Illustrates Location of Similar, Less Severe Defect in Different Forging. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. Also See Figure 84.

1431 C

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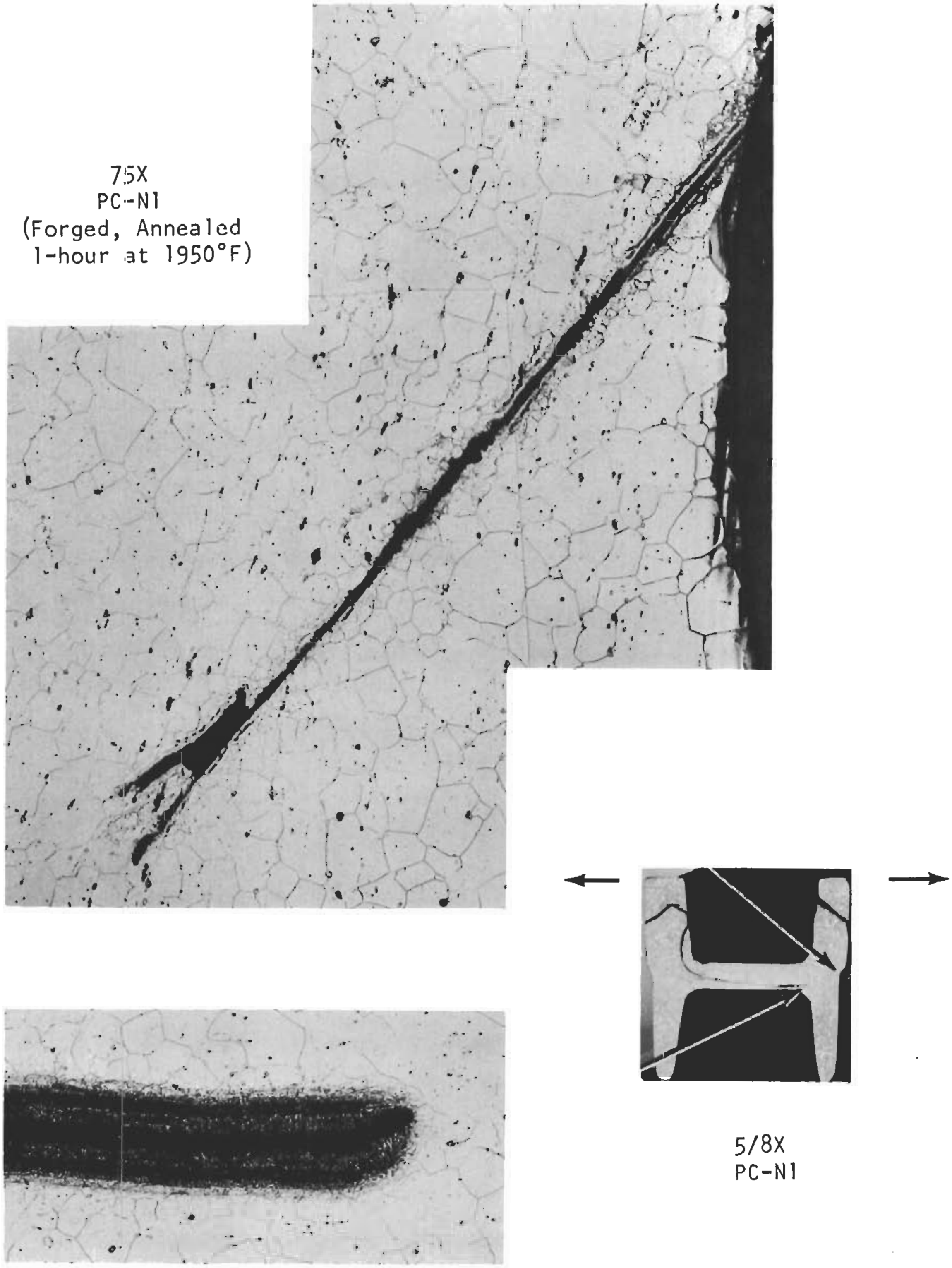

75X
PC-N1
(Forged, Annealed
1-hour at 1950°F)

5/8X
PC-N1

Figure 104. Severe Defects in Inconel 718 Fin Rib Forging Produced with the CEFF Machine. Arrows in Small Section Indicate Actual Locations of Photomicrographs. External Arrows Indicate Directions of Metal Flow at Die Parting Line During Finish Forging Operation. Also See Figure 84.

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2. Macro- and Microstructures

a) Procedures

Evaluation of macrostructural characteristics of the fin rib forgings was conducted by sectioning one forging of each of the twelve equipment-materials series at the same five transverse locations employed for dimensional inspection purposes, Figure 85, and by sectioning a second forging of each series longitudinally at the mid-width location. With but two exceptions, the forgings sectioned were the sixth (transverse) and the seventh (longitudinal) of the series of forgings delivered. The sixth and fifth, and the first and second forgings, respectively, were sectioned of the incomplete series of six and five Inconel 718 finish forgings from the hydraulic press and the CEFF machine. After sectioning with an abrasive cutoff wheel, the 60 transverse and 12 longitudinal cross sections were surface ground, polished, macro-etched, evaluated, and photographed in groups. Etchants employed were: D6ac, 60 percent hydrochloric acid plus 20 percent nitric acid plus 20 percent chromic acid; Ti 6Al-4V, 5 percent hydrofluoric acid plus 5 percent nitric acid in water; and Inconel 718, 90 percent hydrochloric acid plus 10 percent hydrogen peroxide.

Metallographic studies of the forgings in the as-received condition (as forged, except for the CEFF machine forgings) were then conducted by sectioning and preparing samples representing: 1) longitudinal and transverse mid-width web material at approximately the section C-C location, generally representing an area of high deformation; 2) longitudinal and transverse rib material half way between the web and the parting line at approximately the section C-C location, representing the general location from which mechanical test specimens were subsequently removed; 3) material at the center of the relatively large mass forming the "nose", representing the area which was observed during the studies of macro sections to generally contain the least deformation; and 4) material from the edge of the "nose" on the side away from the parting line, which was considered to represent more of a "dead metal" zone in comparison to other areas within the forging. For convenience, these samples were all sectioned from the reverse side of the surfaces which had been prepared for evaluation of macrostructures. In addition, the transverse microstructures of rib wall material were evaluated from the fifth forging of each series (the fourth of the Inconel 718 series from the hydraulic press and the CEFF machine). This furnished a check on reproducibility of microstructures at the same locations for two forgings within each series, and also served for direct comparison with the microstructure of subsequently heat treated material sectioned from this location for mechanical test specimens; i.e., as will be noted later, rib material from this location of the fifth forging of each equipment-materials category was scheduled for the major portion of the mechanical test program involving the fin rib forgings.

Metallographic techniques, etchants, etc., were the same as those employed during the previously discussed study of forging defects. Magnifications used for the photomicrographs were different, however. For the microstructural surveys of sound materials, a 250X magnification was used for all micrographs of D6ac and Ti 6Al-4V samples, and 100X was employed for the Inconel 718 samples.

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b) Results

Evaluation of the macrostructures of the 72 sections prepared revealed quality features among the forgings which differed relative to grain flow, grain size, and uniformity of grain size. The sections are shown in Figures 105 through 110 and, although the group photographs resulted in small reproductions of differing contrast, the pertinent comparisons can be observed. First, the degree of forging difficulty relative to detail and thinness attempted with the CEFF machine in comparison with the others is very apparent, particularly upon comparison of the longitudinal sections in Figures 106, 108, and 110.

The second feature which was noted in comparison of the macrostructures relates to the "chill zones" and their influence on interior metal in the steel and titanium alloy forgings produced with the hydraulic press. Bands representing material which was more highly deformed can be observed in the web and ribs of the sections from these forgings, particularly in the transverse sections in Figures 105 and 107. This occurred because the surface metal was more severely chilled and promoted preferential flow of interior metal to a greater degree than for the other forgings. The unusual tooling concept employed to produce the fin rib forgings with the hydraulic press was successful in providing uniform grain flow from the standpoint of avoiding disturbed metal, "shear bands", and "flow-through" defects resulting from "blind" impression recesses and their potential "dead metal" zones. However, it is apparent that this advantage in providing uniform flow is offset by the influence of these "chill zones" in forging of high temperature materials with slowly closing steel dies at conventional die temperatures.

Judging from a quality standpoint of a uniformly fine grained macrostructure throughout all sections, the hammer forgings appeared to be superior. This was particularly noticeable during the comparative evaluation of as-received macrostructures of the Ti 6Al-4V and Inconel 718 forgings, and can be noticed in Figures 107 through 110. Second, third, and fourth quality ratings, respectively, from this point of view were applied to the forgings from the mechanical press, the hydraulic press, and the CEFF machine.

The only inclusion type of defect found during destructive evaluation efforts involving fin rib forgings was found during preparation of transverse sections of Inconel 718 forgings from the CEFF machine. Two inclusions were actually noted but were unfortunately pulled out and lost during polishing of the fourth section from the left along the bottom row in Figure 109. The oval shaped voids left can still be observed in the web area of this section in the figure. In reviewing Tables 1, 3, 5, and 7; it is interesting that the starting stock for the Inconel 718 forgings from the CEFF machine was the only fin rib forging starting material in the program which had not received ultrasonic inspection.

Eighty-four photomicrographs were prepared, evaluated, and compared representing the longitudinal and transverse rib, longitudinal and transverse web, and center and edge longitudinal "nose" locations within D6ac, Ti 6Al-4V and Inconel 718 forgings from the four machines. Other than the previously mentioned variations in grain size, there were no microstructural indications of superiority of forgings from one machine over those from the others. Microstructures of rib material in the as-received condition will

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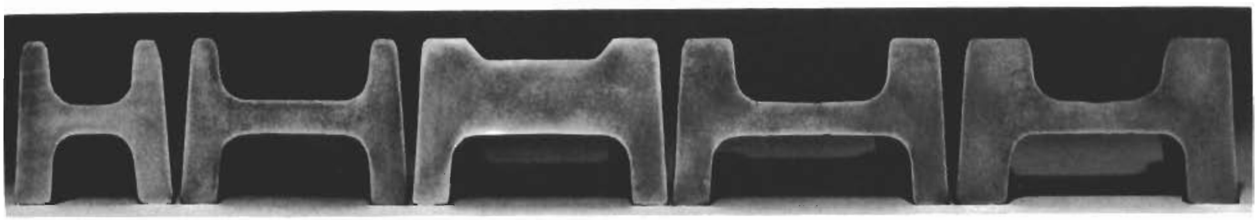
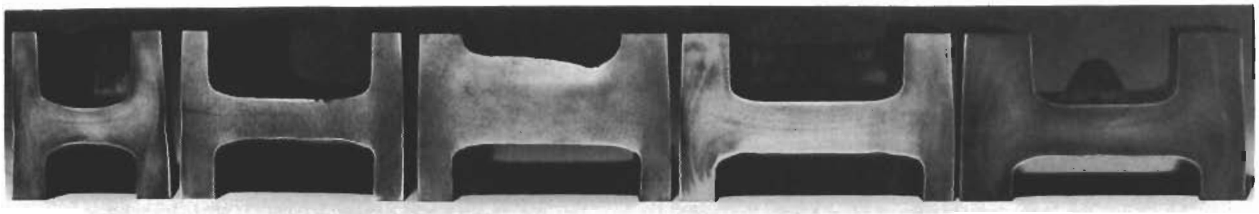
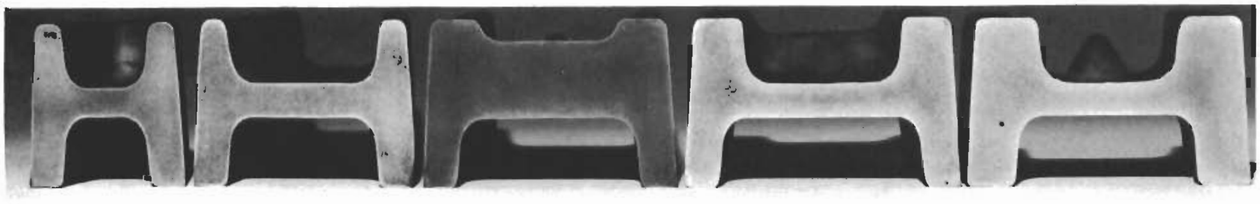


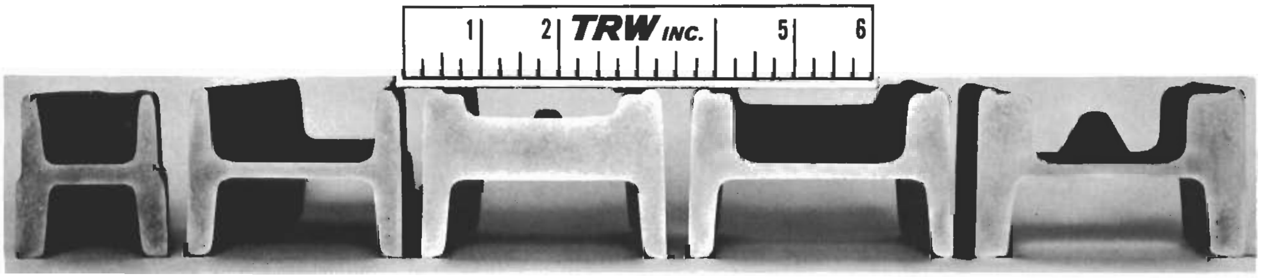
Steam Drop Hammer, Forging No. LH-S6



Hydraulic Press, Forging No. CH-S6



Mechanical Press, Forging No. LM-S6



CEFF Machine, Forging No. PC-S6

Figure 105. Transverse Sections Employed for Comparative Evaluation of Macrostructures of D6ac Fin Rib Forgings Produced with the Four Machine Types. Starting with Section B-B at Left in Each Instance, Section Locations are Identified in Figure 85. Photographed 5/8X - Further Reduced in Reproduction.

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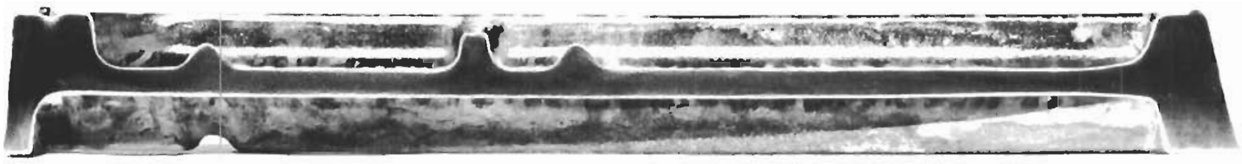
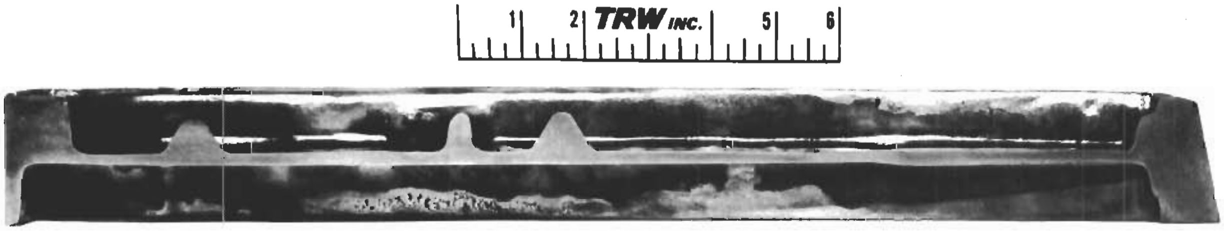


Steam Drop Hammer, Forging No. LH-S7

Hydraulic Press, Forging No. CH-S7

Mechanical Press, Forging No. LM-S7



CEFF Machine, Forging No. PC-S7

Figure 106. Longitudinal Sections Employed for Comparative Evaluation of Macrostructures of D6ac Fin Rib Forgings Produced with the Four Machine Types. Sectioned at the Mid-Width Location. Photographed 1/2X - Further Reduced in Reproduction.

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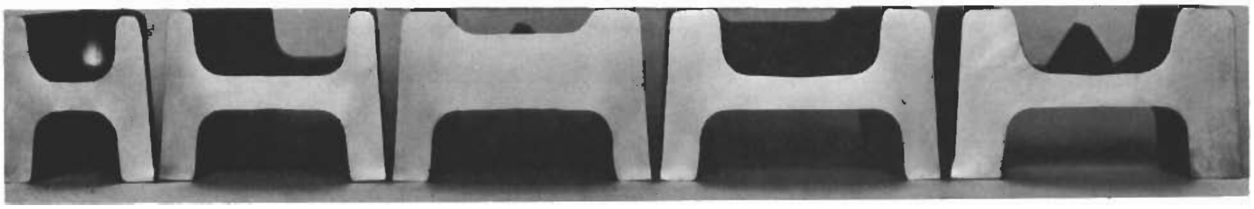
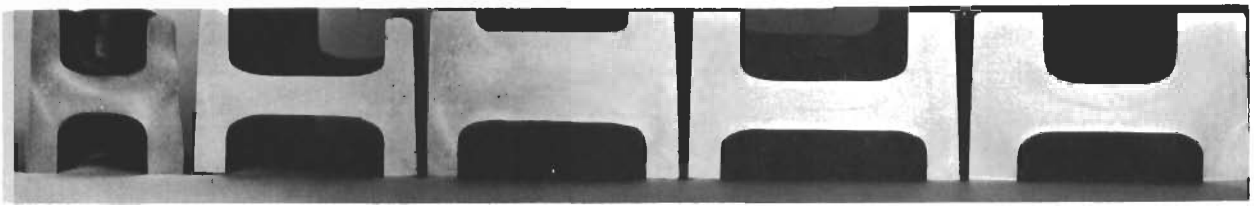
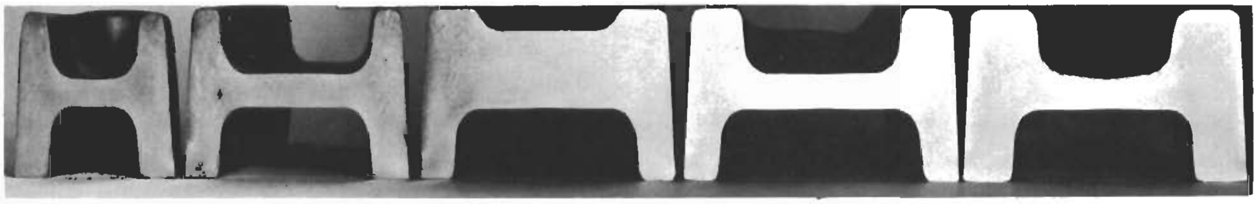


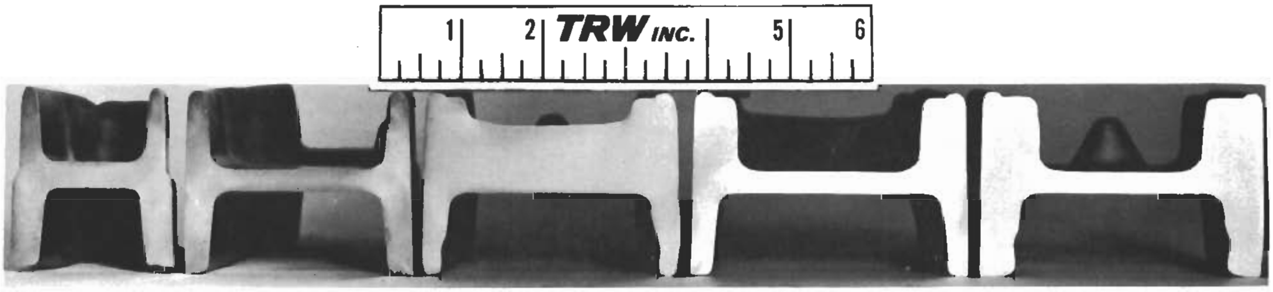
Steam Drop Hammer, Forging No. LH-T6



Hydraulic Press, Forging No. CH-T6



Mechanical Press, Forging No. LM-T6



CEFF Machine, Forging No. PC-T6

Figure 107. Transverse Sections Employed for Comparative Evaluation of Macrostructures of Ti 6Al-4V Fin Rib Forgings Produced with the Four Machine Types. Starting with Section B-B at Left in Each Instance, Section Locations are Identified in Figure 85. Photographed 5/8X - Further Reduced in Reproduction.

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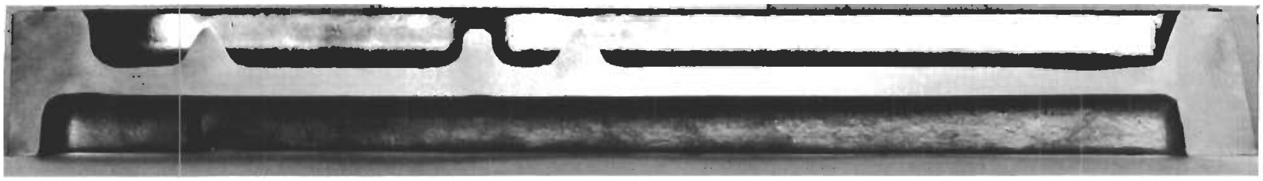

Steam Drop Hammer, Forging No. LH-T7

Hydraulic Press, Forging No. CH-T7

Mechanical Press, Forging No. LM-T7

CEFF Machine, Forging No. PC-T7

Figure 108. Longitudinal Sections Employed for Comparative Evaluation of Macrostructures of Ti 6Al-4V Fin Rib Forgings Produced with the Four Machine Types. Sectioned at the Mid-Width Location. Photographed 1/2X - Further Reduced in Reproduction.

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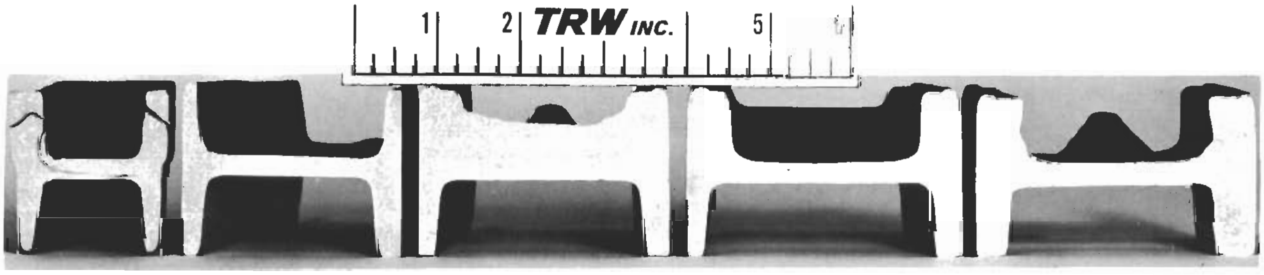
Steam Drop Hammer, Forging No. LH-N6

Hydraulic Press, Forging No. CH-N6

Mechanical Press, Forging No. LM-N6



CEFF Machine, Forging No. PC-N1

Figure 109. Transverse Sections Employed for Comparative Evaluation of Macrostructures of Inconel 718 Fin Rib Forgings Produced with the Four Machine Types. Starting with Section B-B at Left in Each Instance, Section Locations are Identified in Figure 85. Section B-B of CEFF Machine Forging Inadvertently Shown Inverted. Photographed 5/8X - Further Reduced in Reproduction.

1437 C

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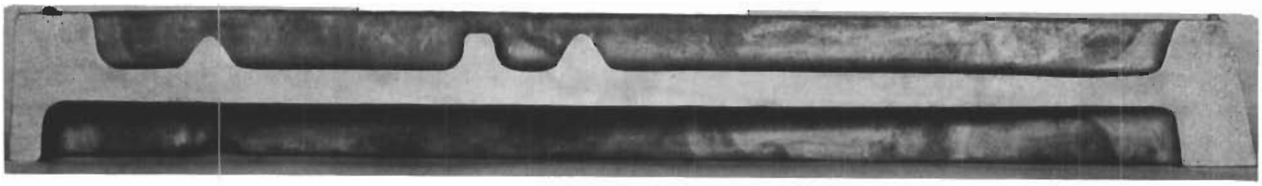
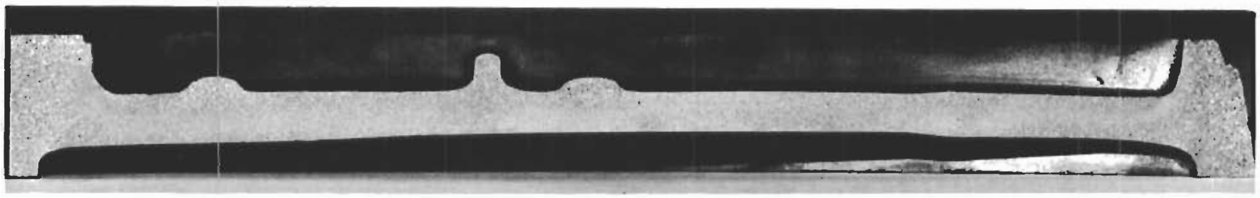
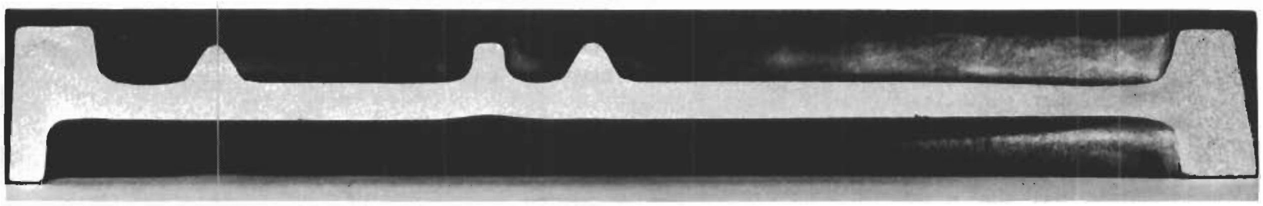


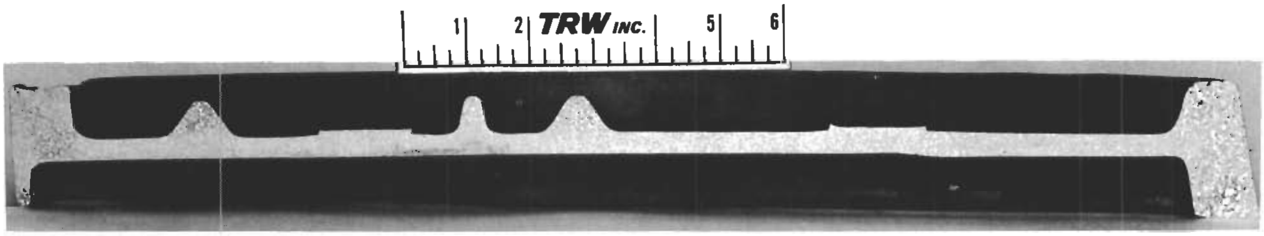
Steam Drop Hammer, Forging No. LH-N7



Hydraulic Press, Forging No. CH-N5



Mechanical Press, Forging No. LM-N7



CEFF Machine, Forging No. PC-N2

Figure 110. Longitudinal Sections Employed for Comparative Evaluation of Macrostructures of Inconel 718 Fin Rib Forgings Produced with the Four Machine Types. Sectioned at the Mid-Width Location. Photographed 1/2X - Further Reduced in Reproduction.

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be shown for comparison with microstructures of heat treated material from the same location during subsequent discussion of mechanical properties.

C. Mechanical Properties

Mechanical properties of the fin rib forgings were evaluated only for purposes of providing comparisons of equipment capabilities. All three of the materials from which the intermediate size forgings were produced are well characterized in the literature and in MIL Handbook 5A(12) in terms of their mechanical properties, and comprehensive mechanical testing of the 111 fin rib forgings evaluated was not a program objective. Nevertheless, the highly selective mechanical test program which was conducted resulted in preparation and testing of a total of 172 specimens to compare tensile, notch tensile (D6ac and Ti 6Al-4V only), notch impact (D6ac and Ti 6Al-4V only), and stress rupture (Inconel 718 only) properties of heat treated material representing each of the twelve equipment-materials categories.

For each of the above categories which included a complete series of ten fin rib forgings, the fifth forging in the series was selected for the majority of the mechanical testing and was sectioned to provide thirteen samples as shown in Figure 111. In addition, samples were removed from the number 4, 8, and 10 locations from the second and eighth forgings in those series involving D6ac and Ti 6Al-4V materials to serve as checks on reproducibility of tensile, notch tensile, and notch impact properties within the series; and from the number 4 and 6 locations from the second and eighth forgings in two complete series involving Inconel 718 forgings to check the reproducibility of tensile and stress rupture properties from forging to forging. In the instances involving Inconel 718 forgings from the hydraulic press and the CEFF machine where less than ten forgings made up the series, the fourth forging in the series was selected for sectioning as shown in Figure 111 and additional samples were prepared from only one "check" forging to evaluate reproducibility of properties.

All materials were tested after appropriate heat treatment for high strength as will be subsequently discussed. To insure that potential section size (as this determines heating and cooling rates) and heat treatment procedural variations could not influence the comparisons, two precautions were taken. First, all samples were machined to two common sizes prior to heat treatment. Samples scheduled for tensile, notch tensile, or stress rupture testing were turned to a diameter of 0.312 ±0.005 inch and those scheduled for heat treat response evaluations and notch impact testing were milled to a 0.260 ±0.005 inch square cross section. This provided an approximate 1/32 inch envelope over the eventually threaded ends of the cylindrical gage specimens employed for tensile, notch tensile, and stress rupture testing; and over the 0.197 inch square cross section of the subsize Charpy V-notch specimens employed for notch impact testing. The only exceptions to the above involved flat spots on several of the 0.312 inch diameter round samples from the CEFF machine forgings because the forging cross sections were so thin that the diameters did not "clean up".

The second precaution taken was that all samples representing one material were heat treated together at one time regardless of equipment origin, eventual test procedures scheduled, etc. In other words, heat treatment of samples from fin rib forgings was only performed three times; once for D6ac

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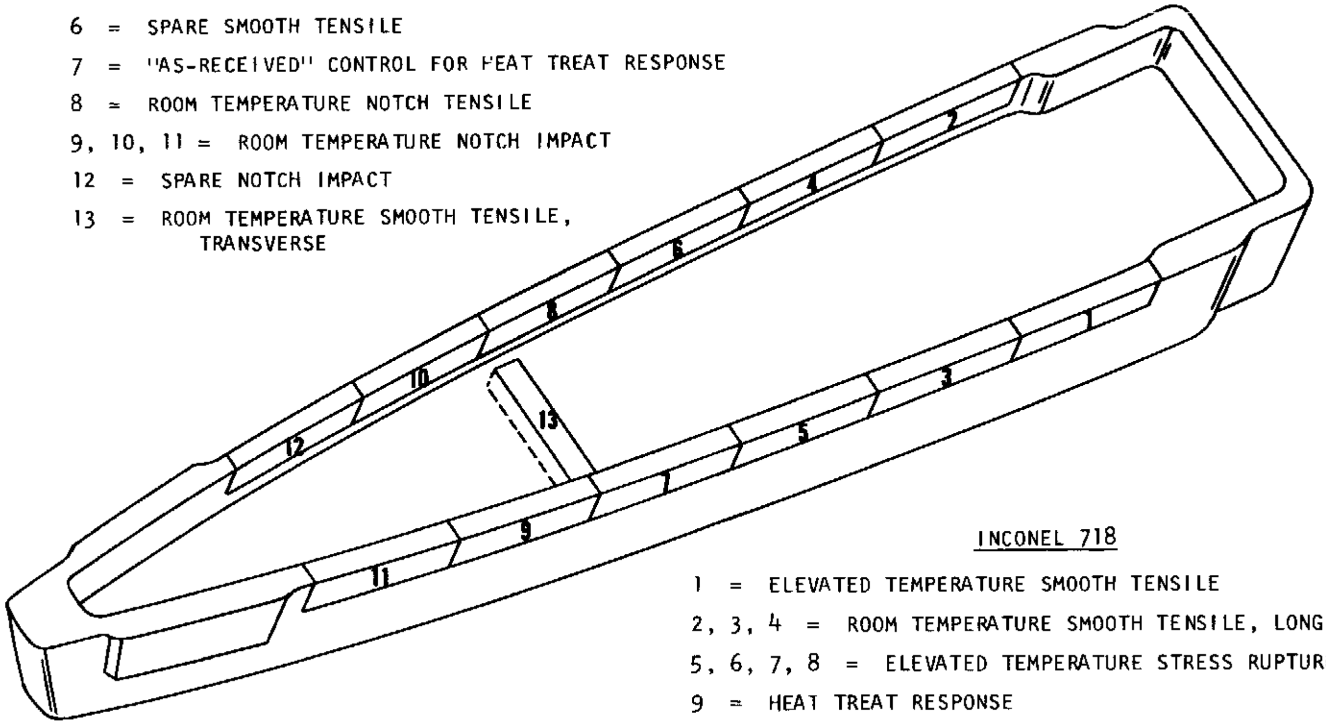
D6ac AND Ti 6Al-4V

1 = ELEVATED TEMPERATURE SMOOTH TENSILE
2, 3, 4 = ROOM TEMPERATURE SMOOTH TENSILE, LONGITUDINAL
5 = HEAT TREAT RESPONSE
6 = SPARE SMOOTH TENSILE
7 = "AS-RECEIVED" CONTROL FOR HEAT TREAT RESPONSE
8 = ROOM TEMPERATURE NOTCH TENSILE
9, 10, 11 = ROOM TEMPERATURE NOTCH IMPACT
12 = SPARE NOTCH IMPACT
13 = ROOM TEMPERATURE SMOOTH TENSILE, TRANSVERSE



INCONEL 718

1 = ELEVATED TEMPERATURE SMOOTH TENSILE
2, 3, 4 = ROOM TEMPERATURE SMOOTH TENSILE, LONGITUDINAL
5, 6, 7, 8 = ELEVATED TEMPERATURE STRESS RUPTURE
9 = HEAT TREAT RESPONSE
10 = SPARE SMOOTH TENSILE OR STRESS RUPTURE
11 = "AS-RECEIVED" CONTROL FOR HEAT TREAT RESPONSE
12 = UNUSED
13 = ROOM TEMPERATURE SMOOTH TENSILE, TRANSVERSE

Figure 111, Locations from Which Heat Treat Response and Mechanical Test Specimens were Taken from Fin Rib Forgings.

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samples, once for Ti 6Al-4V samples, and once for Inconel 718 samples. In this manner, any consideration of the effect of variations in heat treat procedures was avoided. Observed heat treat responses of materials from the four machine types are described in the next subsections of this report and the mechanical property comparisons then follow.

1. Heat Treat Response Characteristics

a) Procedures

The samples were heat treated according to the following procedures:

D6ac: austenitized by heating to 1625°F ±10° in a salt bath, holding for 1 hour and quenching in oil;

stress relieved by heating to 400° ±10°, holding for 1 hour and cooling in air;

tempered by heating to 1000°F ±15°, holding for 4 hours and cooling in air.

Ti 6Al-4V: solution heat treated by heating to 1750°F ±25° in a protective atmosphere, holding for 1 hour, and quenching in agitated water;

aged by heating to 1000°F ±15°, holding for 4 hours, and cooling in air.

Inconel 718: solution heat treated by heating to 1950°F ±25° in a vacuum, holding for 1 hour, and cooling at a rate equivalent to air cooling or faster by back filling the vacuum retort with argon;

precipitation heat treated (aged) by heating to 1400°F ±15°, holding for 10 hours, furnace cooling to 1200°F ±15°,holding until a total aging time of 20 hours was reached, and cooling in air.

Each of these heat treatments correspond to those defined in the applicable AMS specifications to which the materials were originally procured as starting stock. These heat treatments serve as "standard" procedures to evaluate heat treat response in terms of hardness and minimum room temperature tensile properties. As identified in Tables 1, 3, 5, and 7; all fin rib forging starting stock was ordered to AMS 6431, 4967A, and 5664A specifications, respectively, for D6ac, Ti 6Al-4V, and Inconel 718.

In one instance the samples were not heat treated in an identical manner. Since the Inconel 718 forgings produced with the CEFF machine were delivered after already having been solution treated for one hour at 1950°F, this material was actually subjected to two solution treatments for a total of 2 hours at 1950°F in comparison to 1 hour at the same temperature for the Inconel 718 samples from the other forgings.

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After heat treatment, the Figure 111 samples scheduled for heat treat response studies were surface ground to the 0.197 inch cross section, were checked for hardness, and were further sectioned to provide smaller samples for metallographic studies. Hardness testing was conducted using a Wilson Rockwell Model 3JR hardness tester with procedures conforming to ASTM E18. A minimum of five values were obtained in each instance. The metallographic samples were prepared to reveal microstructures transverse and longitudinal to each heat treated sample, corresponding to transverse and longitudinal orientations relative to the rib itself and also to the major axis of the forging, Figure 111. Metallographic procedures were identical to those previously discussed during the description of defects except for the magnifications at which the photomicrographs were taken. For the heat treated samples, 500X, 250X, and 100X magnifications, respectively, afforded the best comparisons of microstructural characteristics of the D6ac, Ti 6Al-4V, and Inconel 718 materials.

b) Results

Microstructures of transverse sections of D6ac rib materials "as-received"; i.e., the "control" samples for heat treat response, are shown in Figure 112. The hardness values beneath the photomicrographs represent the average of the individual values determined, subsequently rounded to the nearest whole number. No conclusive reasons can be advanced for the finer grained microstructure of the hydraulic press forged material, nor for the coarse microstructure and particularly for the high hardness level associated with the mechanical press forged material. In this latter regard, the high hardness confirmed the previous observation of the TRW technician responsible for trimming flash who indicated that this band sawing operation was much easier with the D6ac fin rib forgings produced with the hammer as compared to those produced with the mechanical press. The microstructure shown is also reasonably typical of those found in other locations of the companion mechanical press forgings (numbers LM-S6 and LM-S7) surveyed for as-forged microstructural characteristics, and neither the Ladish subcontract report nor discussions with Ladish personnel revealed the cause for the relatively high hardness levels. Drastic quenching by the dies is not a feature associated with the rapid ram advance and retraction characteristics of a mechanical press stroke, and all forgings from the four machines were reported to be air cooled; Tables 2, 4, 6, and 8.

The relative insensitivity of heat treated alloy steels to prior microstructure and hardness is well illustrated by comparing the photomicrographs and hardness levels in Figure 112 with those in Figures 113 and 114 representing microstructures of transverse and longitudinal sections of the same D6ac rib material after heat treatment. It can be observed that the microstructures of the heat treated materials are virtually identical replicas of uniform, fine-grained tempered martensite regardless of orientation or forging machine origin. The hardness levels were also virtually identical, and conformed to the AMS 6431 requirement of a minimum hardness of Rc 47 after the prescribed heat treatment.

Microstructures and hardness levels of the Ti 6Al-4V rib materials in the "as-received" condition are presented in Figure 115. Although the microstructures vary, they all appear typical of Ti 6Al-4V after

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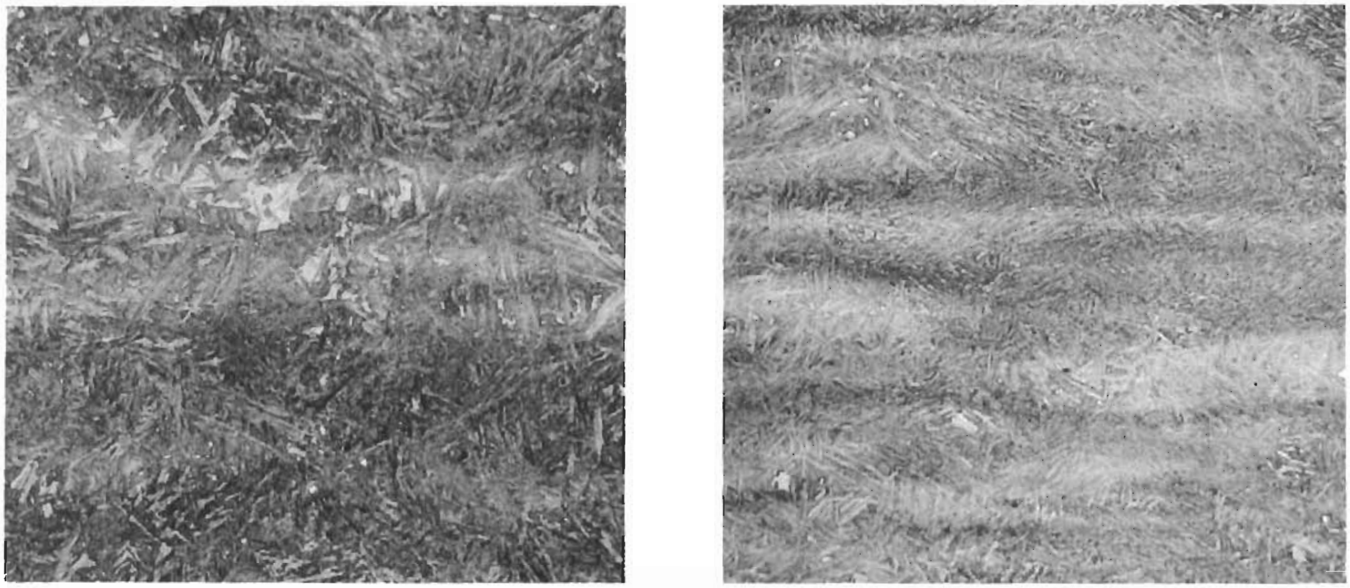
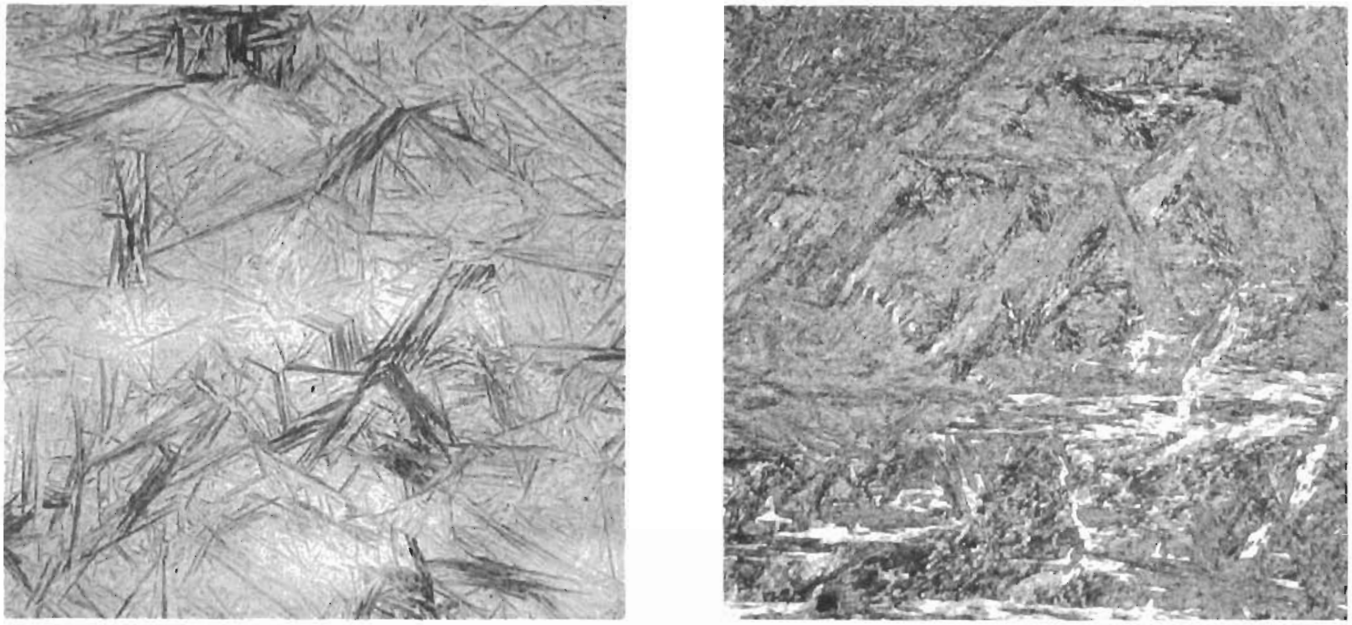


Steam Drop Hammer, LH-S5
Rc 45

Hydraulic Press, CH-S5
Rc 42



Mechanical Press, LM-S5
Rc 53

CEFF Machine, PC-S5
Rc 39

Figure 112. Microstructures of Transverse Sections of Rib Material from D6ac Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown "As-Received"; i.e., As-Forged Except for CEFF Machine Material which was Forged and Stress Relieved One Hour at 1200°F. All 250X. Representative Hardness Levels Indicated.

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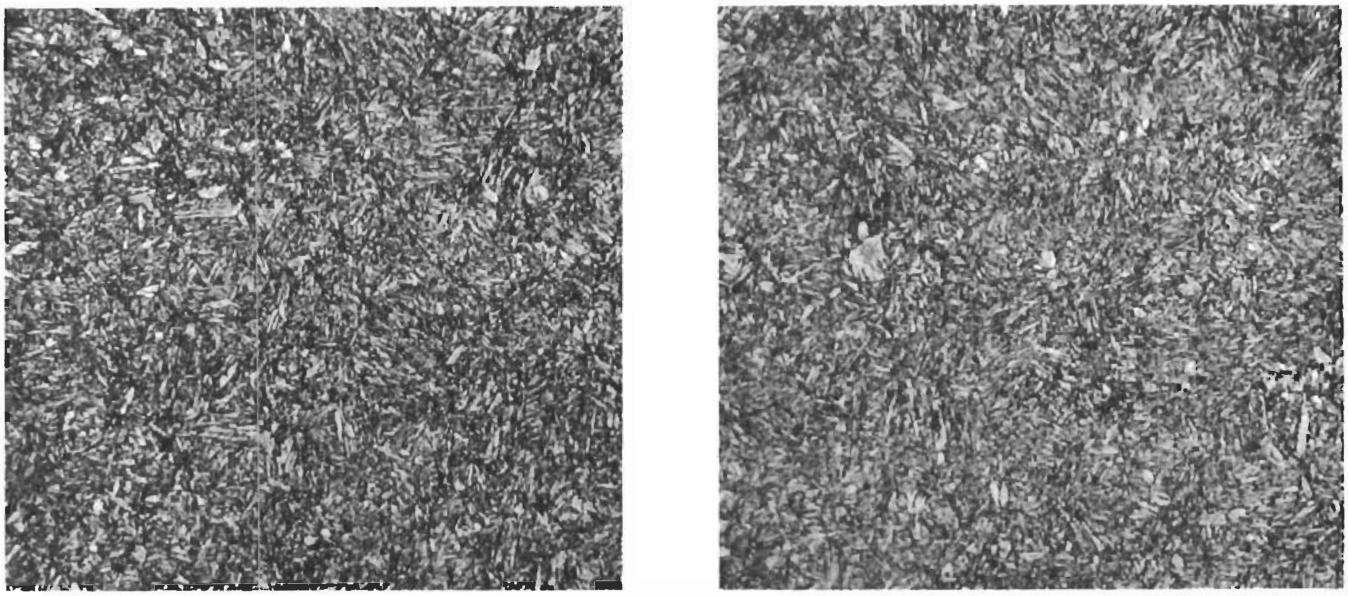
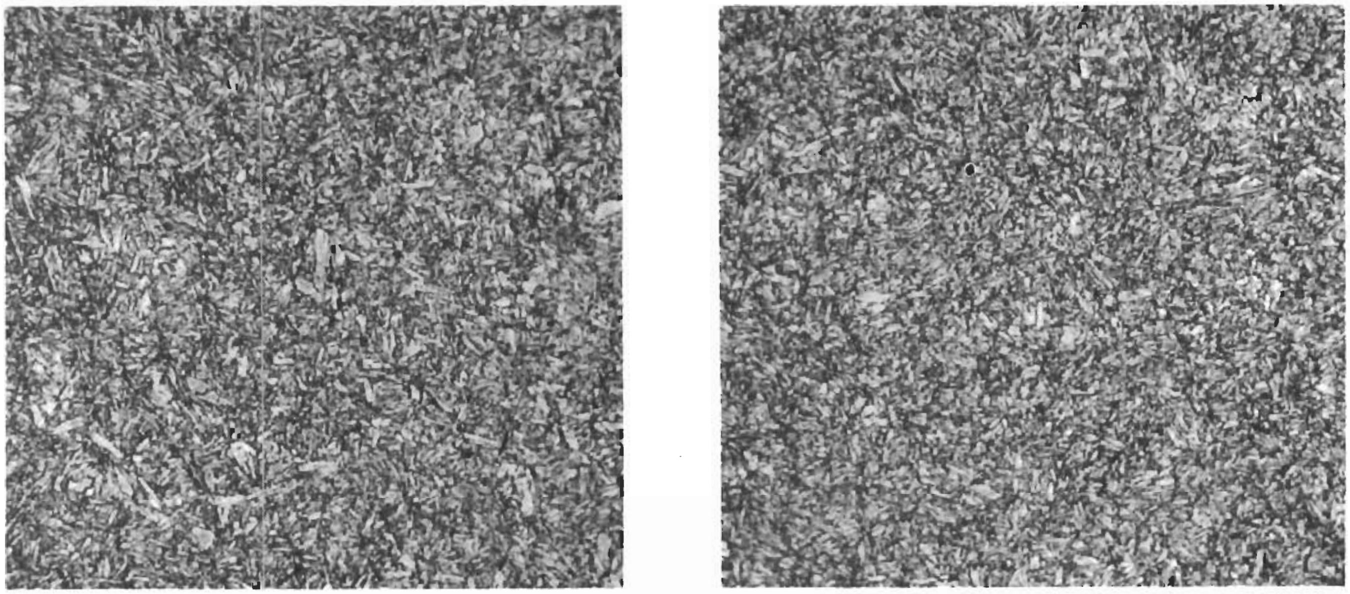


Steam Drop Hammer, LH-S5
Rc 47

Hydraulic Press, CH-S5
Rc 48



Mechanical Press, LM-S5
Rc 48

CEFF Machine, PC-S5
Rc 47

Figure 113. Microstructures of Transverse Sections of Rib Material from D6ac Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown in Heat Treated Condition - See Text. All 500X. Representative Hardness Levels Indicated.

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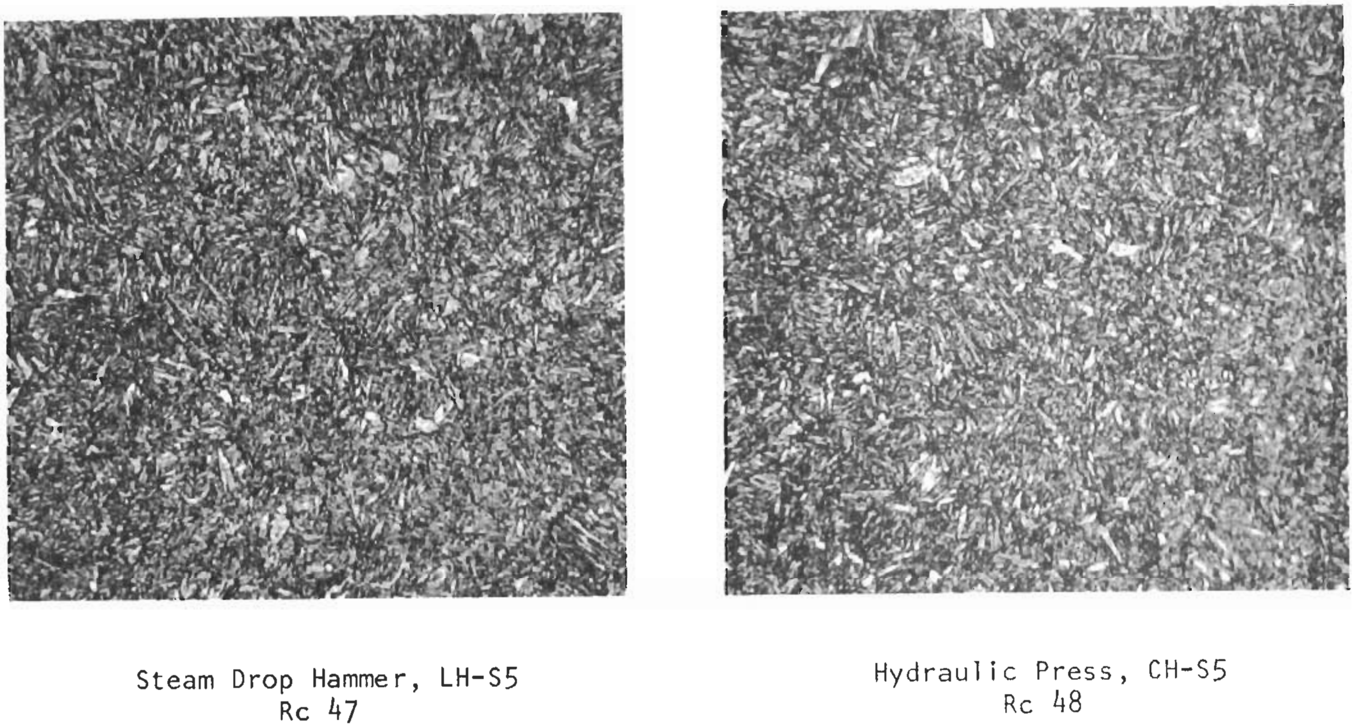
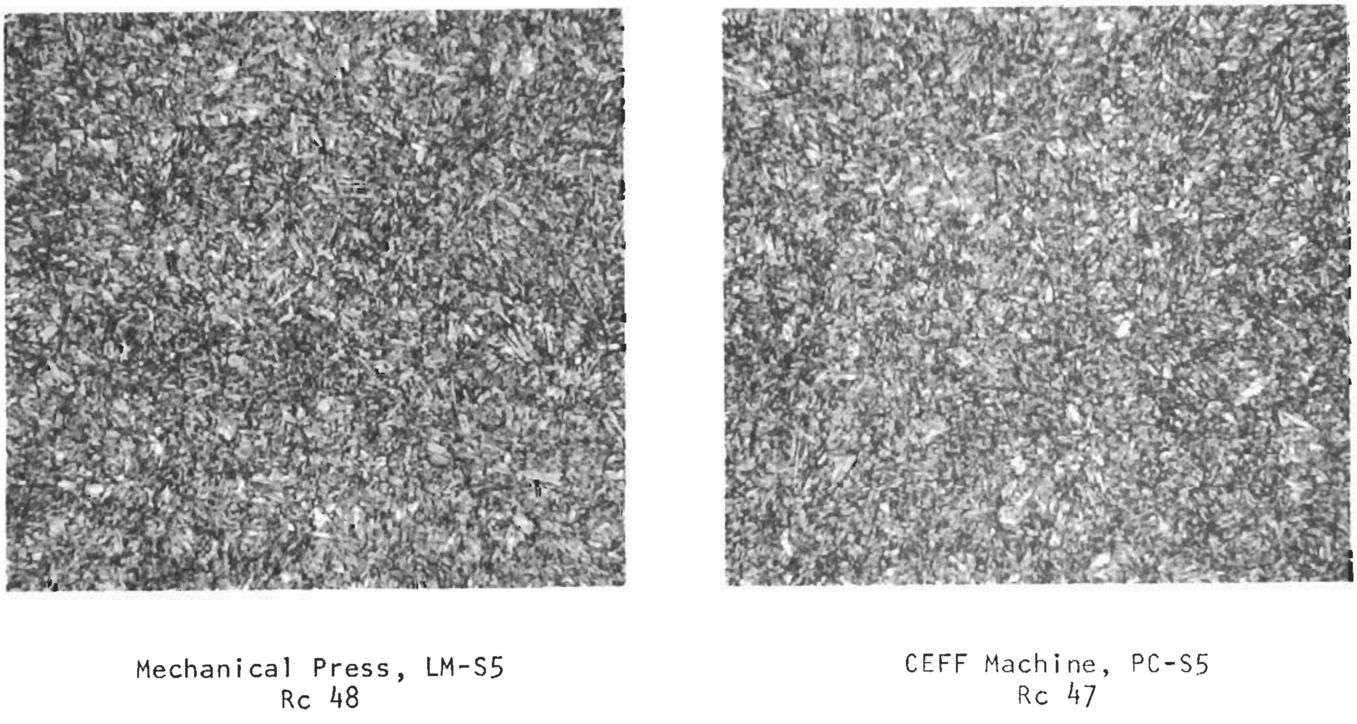


Steam Drop Hammer, LH-S5
Rc 47

Hydraulic Press, CH-S5
Rc 48



Mechanical Press, LM-S5
Rc 48

CEFF Machine, PC-S5
Rc 47

Figure 114. Microstructures of Longitudinal Sections of Rib Material from D6ac Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown in Heat Treated Condition - See Text. All 500X. Representative Hardness Levels Indicated.

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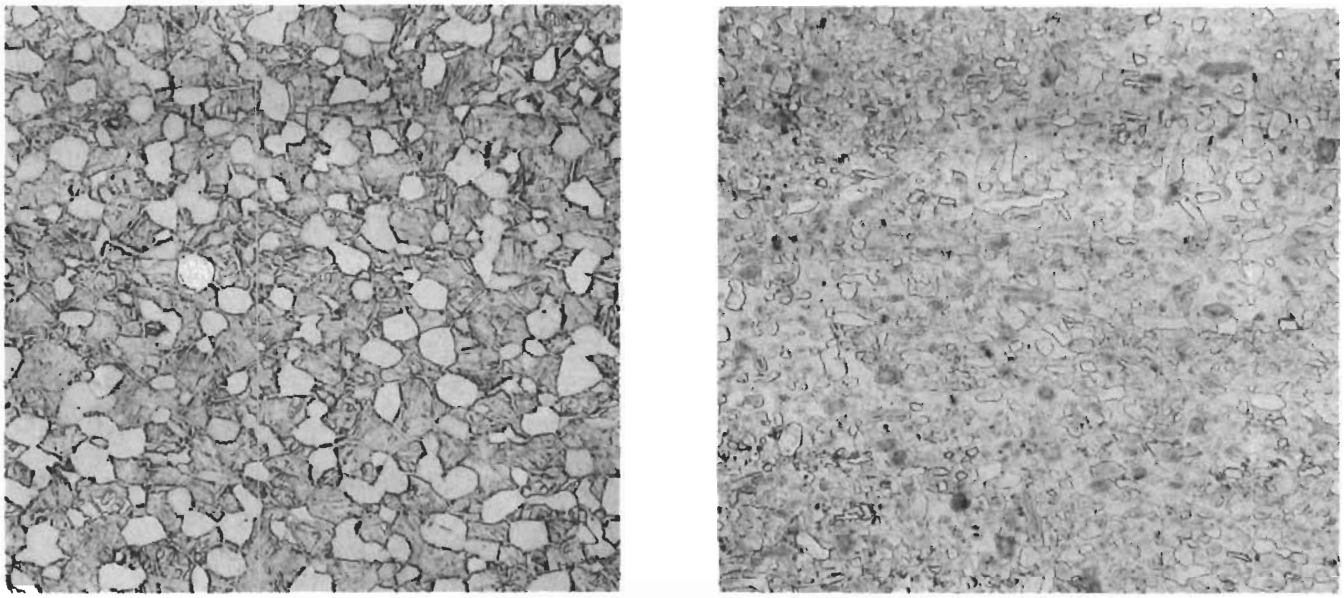
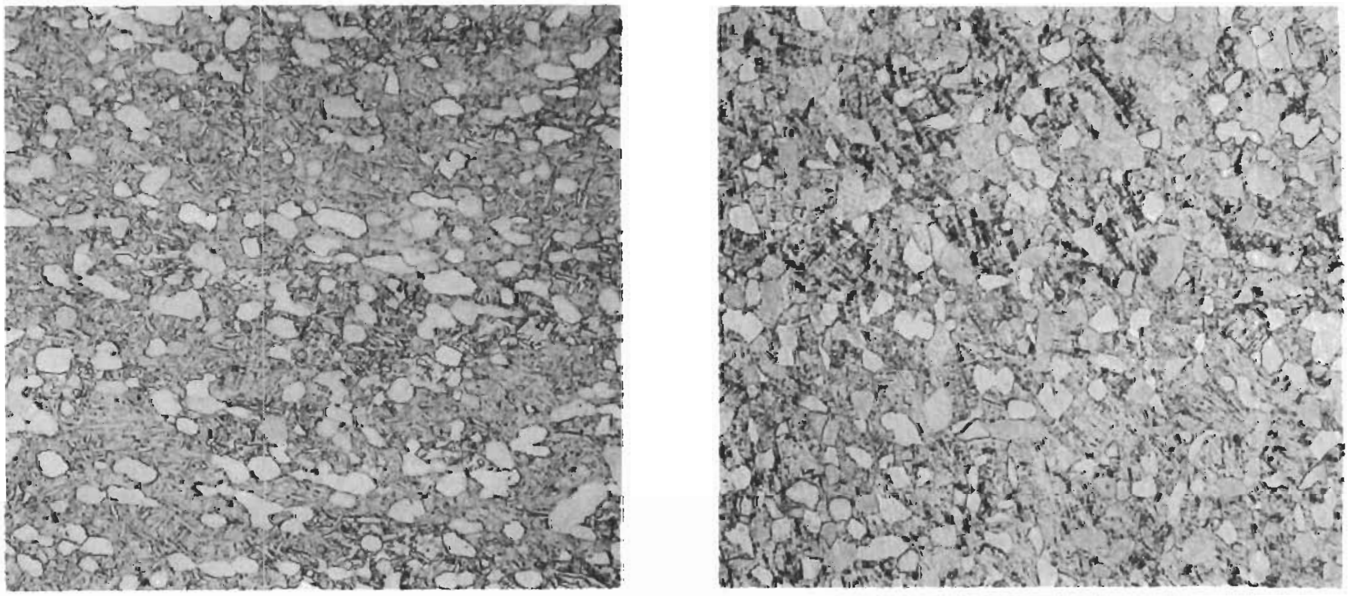


Steam Drop Hammer, LH-T5
Rc 34

Hydraulic Press, CH-T5
Rc 36



Mechanical Press, LM-T5
Rc 32

CEFF Machine, PC-T5
Rc 40

Figure 115. Microstructures of Transverse Sections of Rib Material from Ti 6Al-4V Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown "As-Received"; i.e., As-Forged Except for CEFF Machine Material which was Forged and Annealed One Hour at 1500°F. All 250X. Representative Hardness Levels Indicated.

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deformation in the alpha-beta field. It can be seen that the hydraulic press forged material contained the finest grain size in this rib area. However, as previously indicated, the grain size of companion hydraulic press forgings (CH-T6 and CH-T7) varied considerably in different areas. As with the D6ac material, but to a lesser degree, the heat treatment given the Ti 6Al-4V samples acted to equalize the microstructure and hardness levels representing the four machine types. This can be seen in Figures 116 and 117. Moderate variations in grain size can be observed, but all of the microstructures appear to consist of 20 to 30 percent primary alpha in aged alpha prime regardless of orientation or forging machine represented. The hardness levels were also virtually identical, and all conformed to the AMS 4967A requirements of "not higher than Rc 43" after the prescribed heat treatment.

A similar series of photomicrographs for the Inconel 718 materials are shown in Figures 118, 119, and 120. The differences observed between the fairly similar microstructures of the as-forged materials from the hammer and the mechanical press as compared to the dissimilar microstructure of the hydraulic press forged material, Figure 118, are probably more a result of the 200°F difference in latter stage heating temperatures for forging (2050°F for the hydraulic press forged material, Table 4; versus 1850°F for the other two, Tables 2 and 6) than of the minor variation in chemistry (Tables 1, 3, and 5). Surprisingly, the hardness values obtained from these three materials were close to each other. The lower hardness of the CEFF machine forged material is a reflection of the post-forging solution anneal given this material.

The solution and precipitation heat treatment given the Inconel 718 samples also served to partially equalize the microstructures as can be observed in Figures 119 and 120. The chief variations appear to consist of a somewhat finer grain size for the materials from the hammer and the mechanical press in comparison with those from the hydraulic press and the CEFF machine, and a tendency for orientation of the large precipitates in the longitudinal microstructures of the materials produced with the hammer and with both presses. The previously discussed double solution treatment given the material from the CEFF machine forging may have been responsible for the relative lack of precipitate orientation in this instance, but does not appear to have caused any other difference in microstructure which can be identified. The AMS 5664A specification states that the hardness of the Inconel 718 shall be Rc 36 or higher after the heat treatment given the samples, and it can be noted that all of the heat treated samples responded with hardness values considerably higher than this minimum, Figures 119 and 120.

2. Mechanical Testing

a) Procedures

After heat treatment, the mechanical test specimens were finished by grinding to the final dimensions. All smooth tensile and stress rupture specimens had cylindrical gage sections 0.113 inch diameter by 0.750 inch long which, with their radii, were form ground to a surface finish of 32 microinches or better. These corresponded in design to ASTM E8. Notch tensile specimens were of a TRW design and were ground in a similar manner to a 0.200 inch diameter by 0.750 inch long gage. A 60 degree included angle

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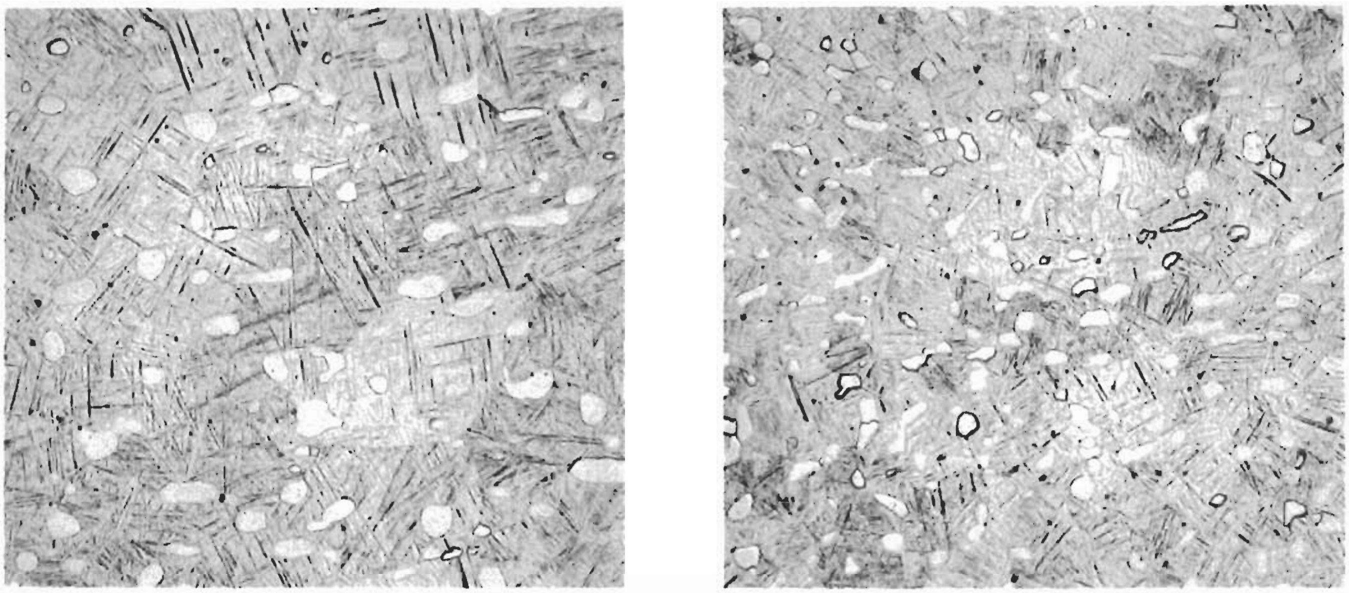
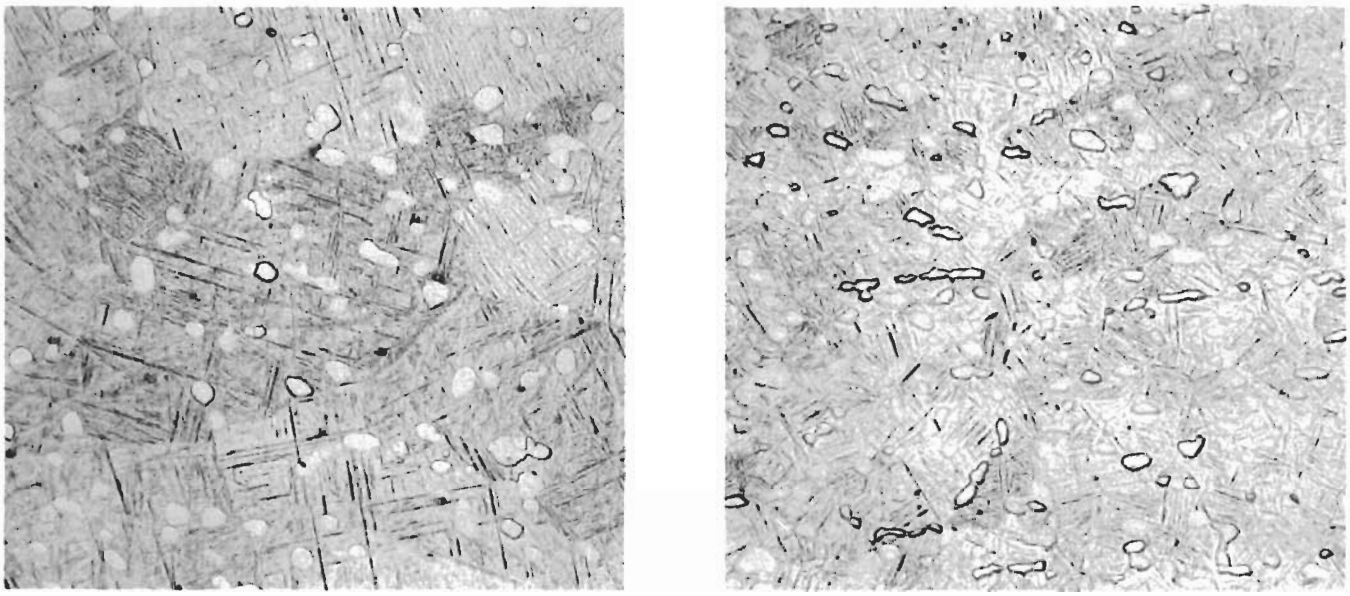


Steam Drop Hammer, LH-T5
Rc 43

Hydraulic Press, CH-T5
Rc 42



Mechanical Press, LM-T5
Rc 42

CEFF Machine, PC-T5
Rc 42

Figure 116. Microstructures of Transverse Sections of Rib Material from Ti 6Al-4V Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown in Heat Treated Condition - See Text. All 250X. Representative Hardness Levels Indicated.

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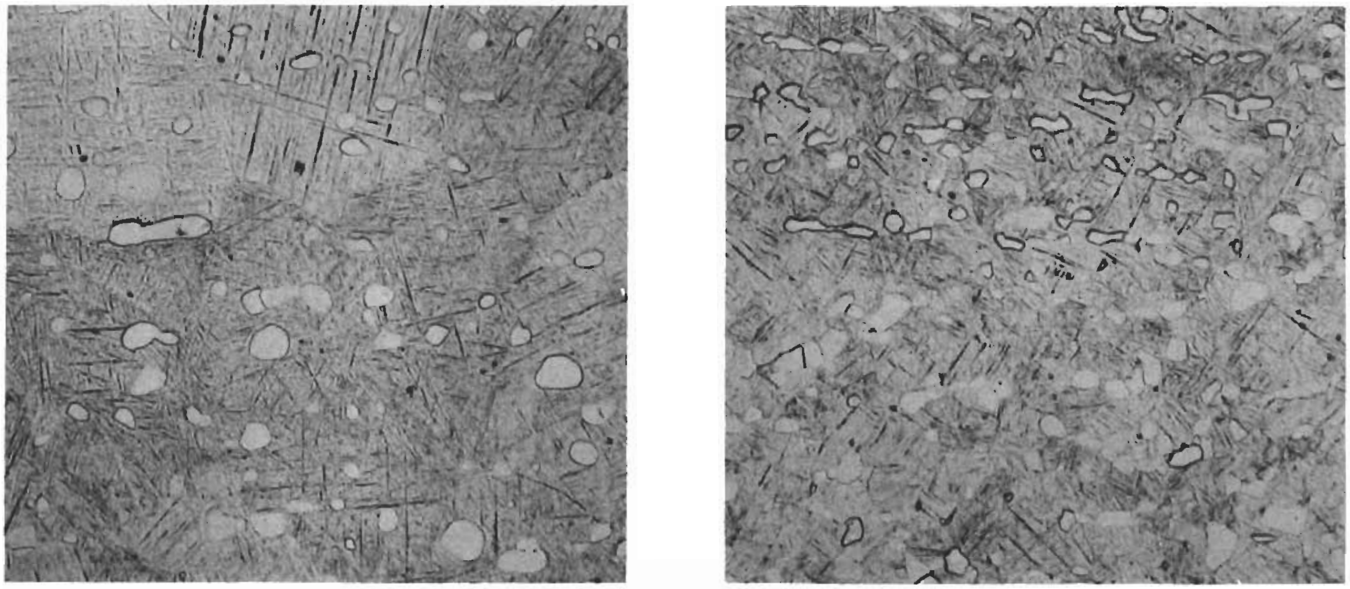
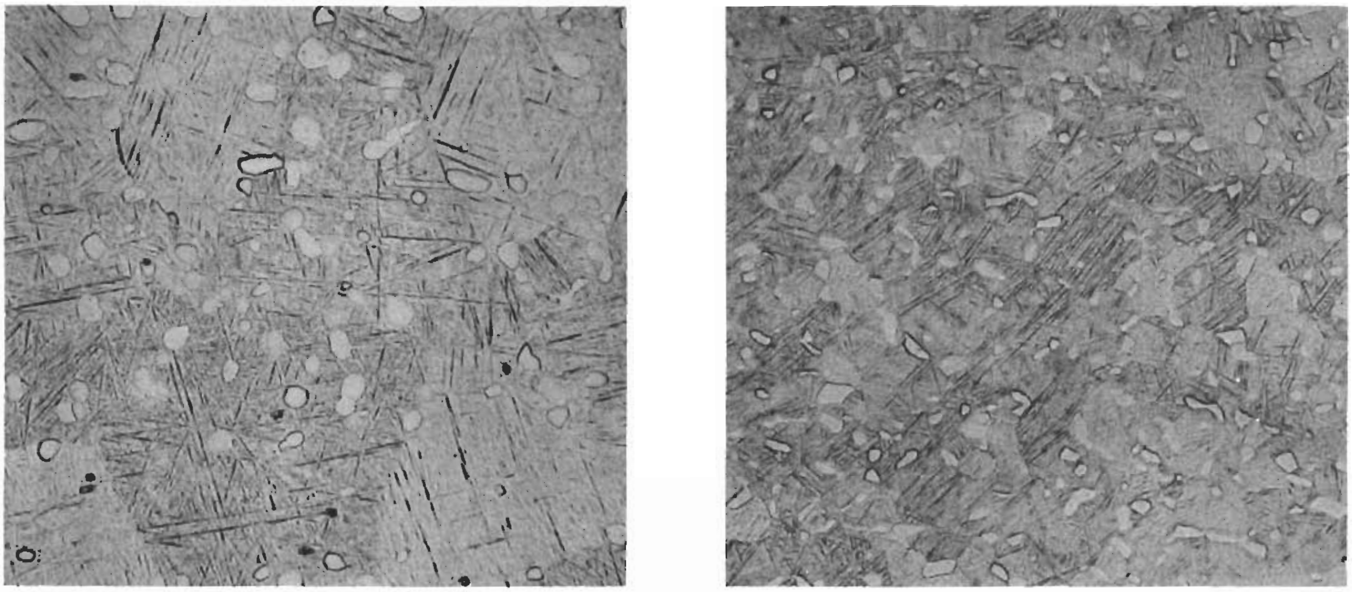


Steam Drop Hammer, LH-T5
Rc 43

Hydraulic Press, CH-T5
Rc 42



Mechanical Press, LM-T5
Rc 42

CEFF Machine, PC-T5
Rc 42

Figure 117. Microstructures of Longitudinal Sections of Rib Material from Ti 6Al-4V Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown in Heat Treated Condition - See Text. All 250X. Representative Hardness Levels Indicated.

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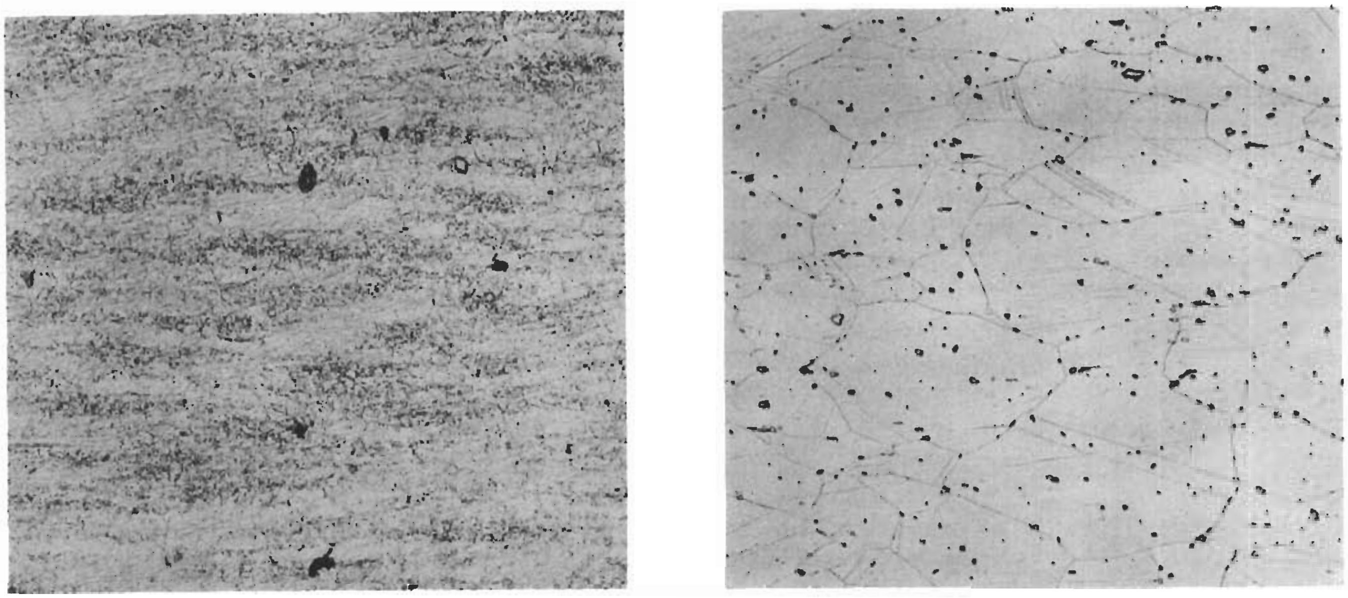
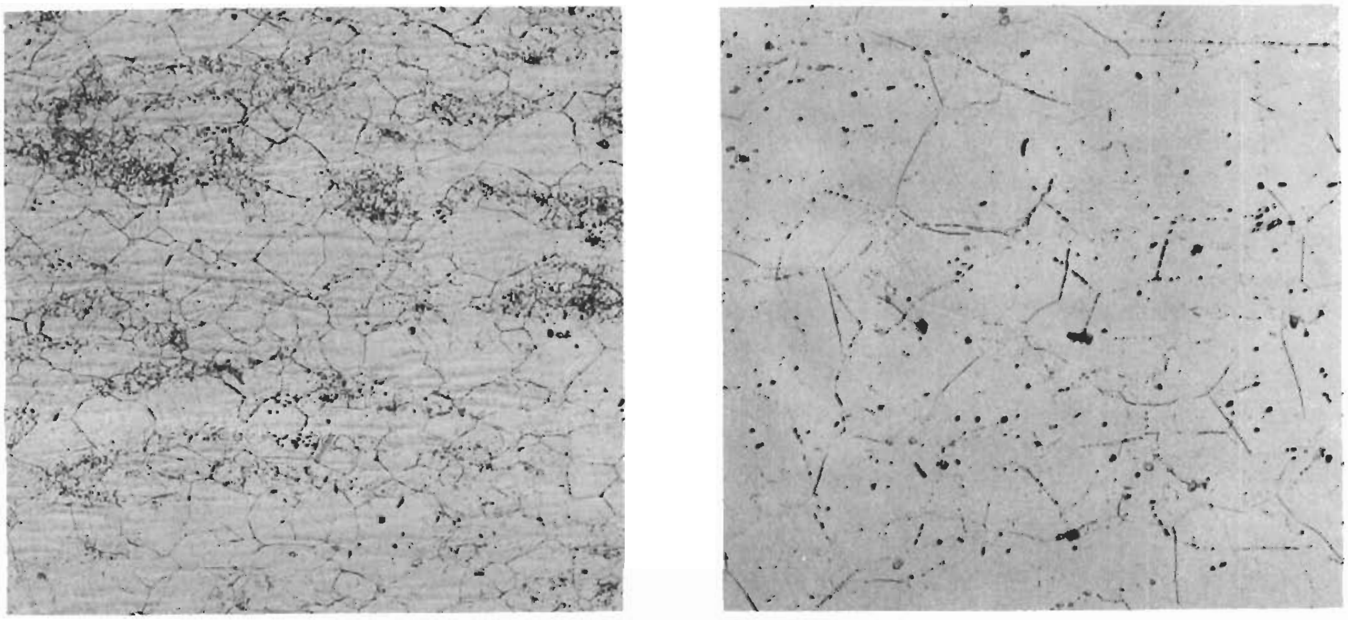


Steam Drop Hammer, LH-N5
Rb 97

Hydraulic Press, CH-N4
Rb 96



Mechanical Press, LM-N5
Rb 96

CEFF Machine, PC-N4
Rb 79

Figure 118. Microstructures of Transverse Sections of Rib Material from Inconel 718 Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown "As-Received"; i.e., As-Forged Except for CEFF Machine which was Forged and Solution Annealed One Hour at 1950°F. All 100X. Representative Hardness Levels Indicated.

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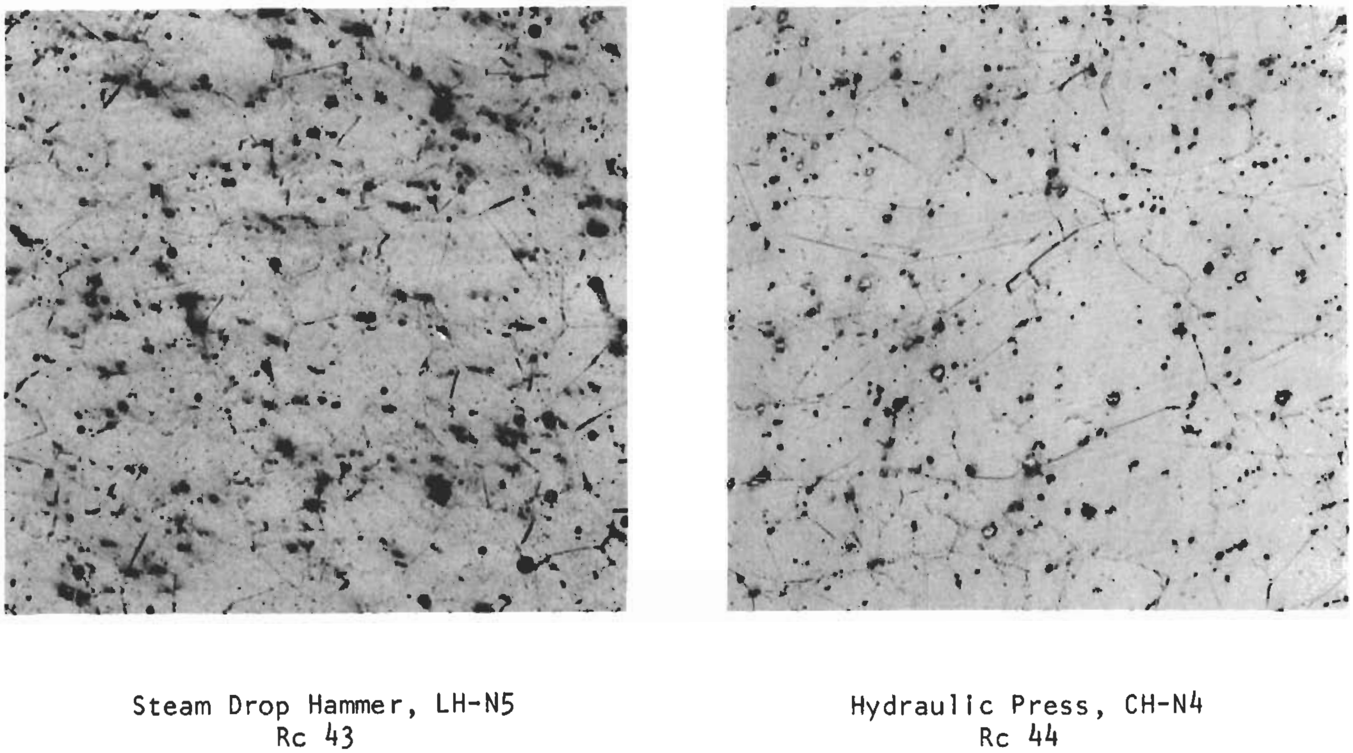
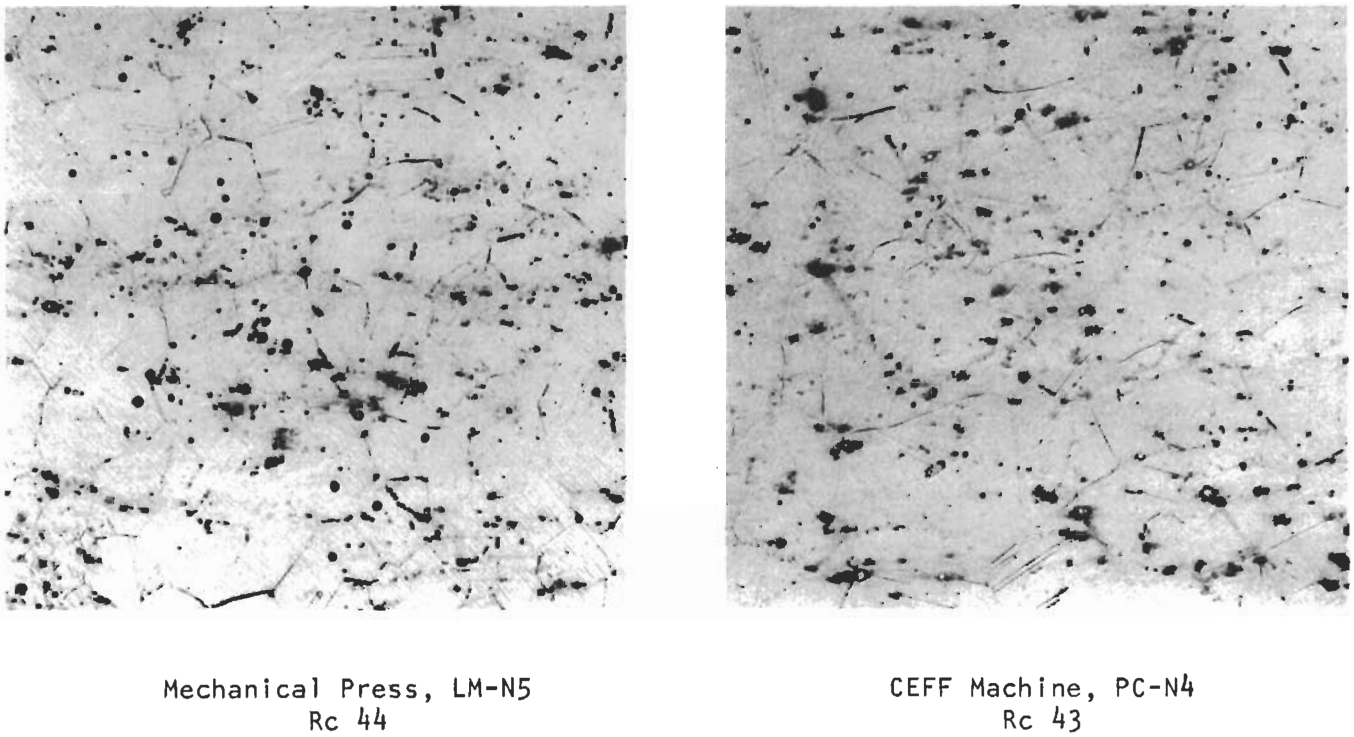


Steam Drop Hammer, LH-N5
Rc 43

Hydraulic Press, CH-N4
Rc 44



Mechanical Press, LM-N5
Rc 44

CEFF Machine, PC-N4
Rc 43

Figure 119. Microstructures of Transverse Sections of Rib Material from Inconel 718 Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Location. Shown in Heat Treated Condition - See Text. All 100X. Representative Hardness Levels Indicated.

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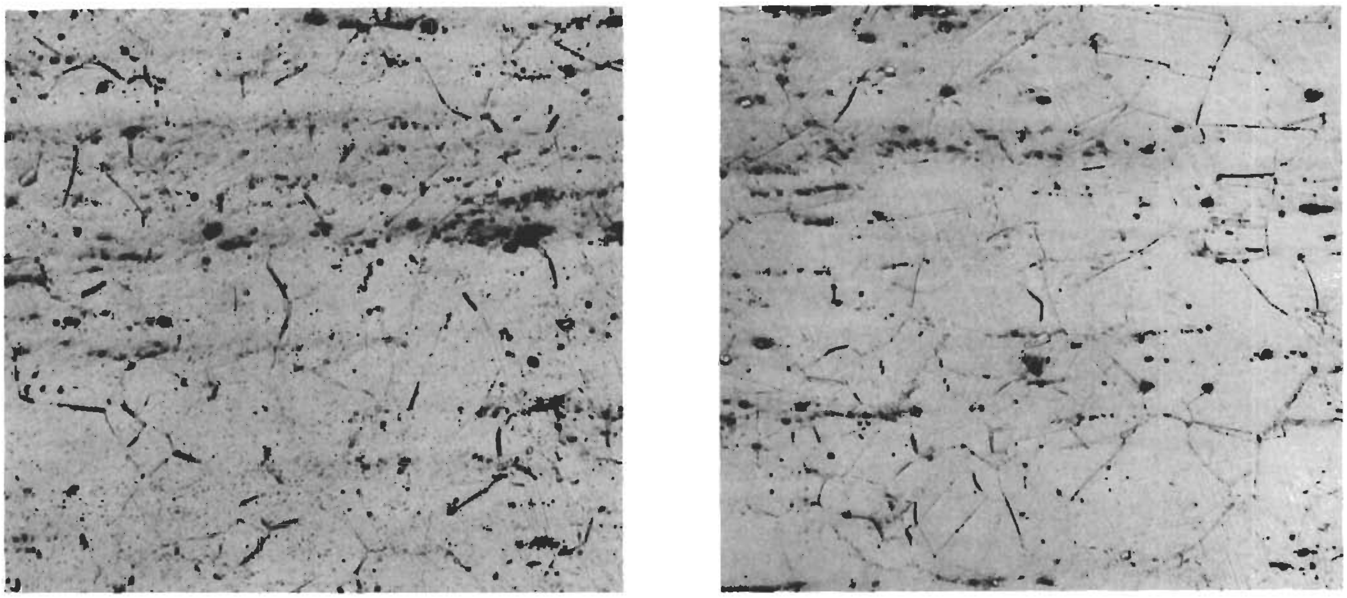
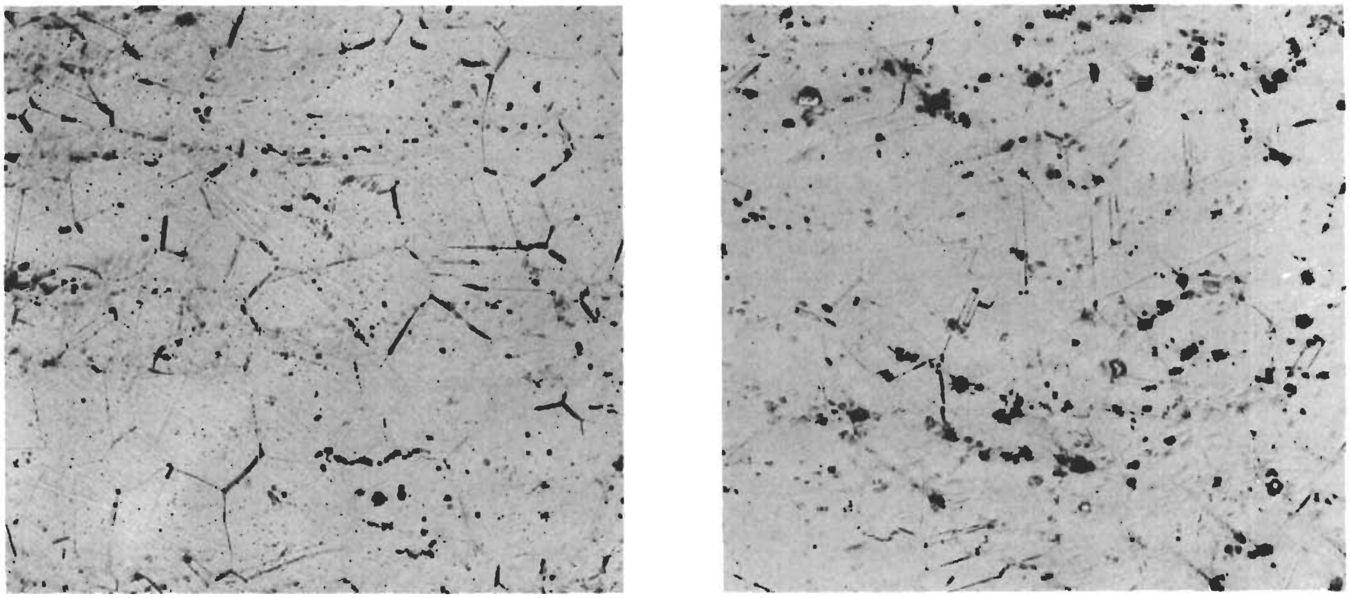


Steam Drop Hammer, LH-N5
Rc 43

Hydraulic Press, CH-N4
Rc 44



Mechanical Press, LM-N5
Rc 44

CEFF Machine, PC-N4
Rc 43

Figure 120. Microstructures of Longitudinal Sections of Rib Material from Inconel 718 Fin Rib Forgings from which Majority of Mechanical Test Specimens were Prepared. See Figure 111 for Specific Rib Locations. Shown in Heat Treated Condition - See Text. All 100X. Representative Hardness Levels Indicated.

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notch with a root diameter of 0.142 inch and a notch radius of 0.0015 ±0.0005 inch was then placed at mid-length of the gage by machine turning with a special, diamond-lapped carbide cutter. The 0.197 inch square subsize Charpy specimens were "cleaned up" by conventional surface grinding techniques, after which a 45 degree included angle notch with a notch radius of 0.010 ±0.001 inch was ground such that the specimen thickness at the root of the notch was 0.158 inch. These conformed to ASTM E23 in design. Finishing of all specimen gages and notches was the assignment of a single machine operator. This was to provide the greatest uniformity of dimensions and surface finish.

It was desired to conduct the limited number of elevated temperature tensile tests scheduled at the one temperature for each material which would represent the highest temperature at which the material might be used in structural service. A temperature of 600°F was selected for D6ac from the AMS 6431 specification for the material which lists this temperature as an applicable maximum for structural use. For the Ti 6Al-4V alloy, no such maximum useful temperature is listed in AMS 4967A. However, Section 5.4.6.0 of MIL Handbook 5A(12) indicates that Ti 6Al-4V possesses "excellent elevated temperature strength up to 750°F" and "can withstand prolonged exposure to temperatures up to 750°F without loss of ductility". A test temperature of 750°F was therefore selected in this instance.

Selection of the temperature for elevated temperature tensile and stress rupture testing of Inconel 718 was not so straightforward. Different AMS specifications cover forged products of the alloy, depending on whether short time (e.g., tensile) or long time (e.g., creep rupture) properties are most important. The Inconel 718 fin rib material was heat treated to the AMS 5664A specification which suggests, as does the MIL Handbook, good short time strength properties to 1000°F. Lower temperature solution and precipitation heat treatments provide Inconel 718 forgings to a different AMS specification which suggests good creep and stress-rupture properties to 1300°F. Since the TRW intent was to conduct limited tensile and stress-rupture testing at one temperature for comparative purposes only, a compromise was effected and 1200°F was selected as the common test temperature. This selection was reinforced on the basis of a recently reported study indicating that 1200°F was the highest temperature for which long time microstructural stability could be realized in the alloy(13).

Mechanical testing of fin rib forging materials was conducted in accordance with ASTM specified procedures; i.e., E8 for room temperature tensile tests, E21 for elevated temperature tensile tests, E23 for room temperature notch impact tests, and E139 for elevated temperature stress-rupture tests. All room and elevated temperature smooth tensile testing was conducted on an Instron Model TTC tensile tester and the 0.2% offset yield strengths were obtained using a 1/2 inch LVDT (linear variable differential transformer) extensometer. Cross head travel was 0.020 inch per minute through the yield point and 0.050 inch per minute from yield to failure. Notch tensile testing was conducted in the same Instron tester, but without the use of an extensometer and with a constant cross head travel of 0.050 inch per minute from application of the load until failure. Notch impact testing was conducted on a Sonntag Model SI-1 Universal Charpy impact tester with a pendulum velocity of 17 feet per second. The scale on this test machine provides graduations in 1/2 foot-pound increments and test values were

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interpolated to 1/4 foot pound. Stress rupture testing was conducted with multiple Satec Model J stress rupture testers.

To establish proper stress levels for stress rupture testing, the location number 5 and 6 specimens (see Figure 111) from the "majority of specimens" forgings representing each machine were loaded to 110,000 and 120,000 psi, respectively, and were tested. The correct stress levels for testing of the seventh and eighth specimens from each series were then extrapolated based on the results of the fifth and the sixth specimens. Finally, a stress level was extrapolated for the testing of the "spare" specimen in each case (number 10 - see Figure 111), and intermediate stress levels were also applied to the location number 6 specimens from the "check" forgings to evaluate reproducibility within the forging series.

b) Results

The room temperature smooth tensile data for the three materials are listed in Tables 14, 15, and 16. For each equipment-materials category, the data are listed such that the average of the three specimens from the rib of the "majority" forging is followed by the individual values for the rib material from the "check" forgings and by the value for the transverse web material (location number 13) from the "majority" forging. Each of the three tables thus provides an indication of reproducibility of room temperature tensile properties among: 1) different locations within the same forging; 2) different forgings within the same series produced by one machine; and 3) forgings produced by all four machines. In addition, each table contains the minimum room temperature tensile properties listed in the applicable AMS specification for the material. In this latter regard, however, it should be noted that the AMS 4967A specification lists the minimum yield strength for the titanium alloy as applicable after testing through the yield point at a strain rate of 0.005 inch per inch per minute. Since the 0.020 inch per minute cross head travel employed provides a greater strain rate than this, the yield strength values in Table 15 are not directly comparable with the specification minimum.

Review of the data from the D6ac specimens, Table 14, reveals that all values exceeded the minimums. The values within each category are very close to each other, indicating that specimen location, orientation and forging number within each series had little influence on the results. Hydraulic press forged material showed the highest ultimate strength, CEFF machine forged material showed the highest yield strength, and hammer forged material showed the highest ductility values. Although these results could be explained on the basis of the slightly higher carbon and vanadium contents of the D6ac starting stock used with the hydraulic press and the CEFF machine (see Tables 1, 3, 5, and 7), in practical terms the values are actually too close and represent too few specimens to validate such an explanation.

Review of the room temperature tensile data for the Ti 6Al-4V specimens revealed a marginal condition relative to meeting minimum ductility specifications. More than one specimen each from the CEFF machine and from mechanical press forgings fell beneath the 8 percent minimum elongation value, and none of the longitudinally oriented specimens from hammer forged material met this minimum value. Otherwise, all specification minimums were exceeded by a considerable margin in all instances. Strength values for the hammer

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TABLE 14

Room Temperature Smooth Tensile Properties(a) of D6ac Fin Rib Forgings(b)

Machine	Forging Number	Specimen Location(c)	Ultimate Strength (psi)	Yield Strength(d) (psi)	Elong. (%)	Reduct. of Area (%)
Hammer	LH-S5	2	224,800	203,100	12.6	56.3
	"	3	226,300	204,100	12.4	54.0
	"	4	224,300	202,900	12.1	53.6
		Ave.	225,100	203,400	12.4	54.6
	LH-S2	4	226,800	204,400	11.1	57.1
	LH-S8	4	225,300	203,900	12.1	51.1
	LH-S5	13	228,800	206,000	12.9	51.6
H. Press	CH-S5	2	230,700	209,500	11.6	55.2
	"	3	227,300	206,500	11.8	55.2
	"	4	229,200	208,500	11.5	52.8
		Ave.	229,100	208,200	11.6	54.4
	CH-S2	4	229,800	207,900	11.1	53.6
	CH-S8	4	230,300	208,900	11.4	53.6
	CH-S5	13	228,800	207,400	10.9	53.6
M. Press	LM-S5	2	228,300	207,500	10.3	49.1
	"	3	227,800	206,400	11.2	56.0
	"	4	227,300	206,000	11.1	54.6
		Ave.	227,800	206,600	10.9	53.2
	LM-S2	4	226,800	205,500	12.3	55.2
	LM-S8	4	225,800	205,000	11.6	55.2
	LM-S5	13	229,700	208,500	11.1	49.1
CEFF	PC-S5	2	226,800	208,000	12.0	58.6
	"	3	225,300	207,500	10.2	45.2
	"	4	230,300	209,400	11.5	54.8
		Ave.	227,500	208,300	11.2	52.9
	PC-S2	4	228,800	210,400	13.2	58.3
	PC-S8	4	229,300	210,900	11.3	54.8
	PC-S5	13	230,300	212,400	11.8	56.0
AMS(b)	Spec.	Min.	224,000	195,000	7.0	30.0

(a) - Specimen design and test procedures in accordance with ASTM E8. Specimen gage diameter 0.113 inch.

(b) - Heat treated in accordance with AMS 6431. Minimum tensile properties in specification after such heat treatment are listed above.

(c) - See Figure 111.

(d) - 0.2% Offset.

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TABLE 15

Room Temperature Smooth Tensile Properties(a) of Ti 6Al-4V Fin Rib Forgings(b)

Machine	Forging Number	Specimen Location(c)	Ultimate Strength (psi)	Yield Strength(d) (psi)	Elong. (%)	Reduct. of Area (%)
Hammer	LH-T5	2	187,100	175,500	7.2	37.4
	"	3	191,500	179,500	6.9	31.7
	"	4	188,300	175,700	6.5	30.2
		Ave.	189,000	176,900	6.9	33.1
	LH-T2	4	197,000	185,700	7.9	34.6
	LH-T8	4	191,100	178,300	6.9	29.5
	LH-T5	13	189,000	175,500	9.5	29.3
H. Press	CH-T5	2	182,700	168,000	11.5	51.5
	"	3	177,100	165,100	9.1	52.4
	"	4	177,100	165,700	11.1	51.5
		Ave.	179,000	166,300	10.6	51.8
	CH-T2	4	179,700	167,000	11.1	57.5
	CH-T8	4	182,700	171,700	10.6	52.4
	CH-T5	13	179,100	168,300	9.2	48.6
M. Press	LM-T5	2	187,400	175,200	9.9	37.2
	"	3	183,400	170,300	6.7	27.8
	"	4	185,300	173,600	8.2	29.8
		Ave.	185,400	173,000	8.3	31.6
	LM-T2	4	186,800	172,900	8.4	29.3
	LM-T8	4	189,200	175,700	8.4	33.7
	LM-T5	13	187,200	172,300	6.8	24.8
CEFF	PC-T5	2	183,400	170,000	12.0	49.9
	"	3	184,800	170,600	9.8	51.5
	"	4	184,400	172,500	7.7	44.7
		Ave.	184,200	171,000	9.8	48.7
	PC-T2	4	186,900	171,500	12.8	49.9
	PC-T8	4	183,900	170,000	7.8	46.1
	PC-T5	13	185,900	171,500	10.8	49.9
AMS(b)	Spec.	Min.	165,000	155,000	8.0	20.0

(a) - Specimen design and test procedures in accordance with ASTM E8. Specimen gage diameter 0.113 inch.

(b) - Heat treated in accordance with AMS 4967A. Minimum tensile properties in specification after such heat treatment are listed above.

(c) - See Figure 111.

(d) - 0.2% Offset.

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TABLE 16

Room Temperature Smooth Tensile Properties(a) of Inconel 718 Fin Rib Forgings(b)

Machine	Forging Number	Specimen Location(c)	Ultimate Strength (psi)	Yield Strength(d) (psi)	Elong. (%)	Reduct. of Area (%)
Hammer	LH-N5	2	196,700	169,200	25.2	43.9
	"	3	194,500	166,000	23.2	46.5
	"	4	196,000	165,900	24.5	46.1
		Ave.	195,400	167,000	24.3	45.5
	LH-N2	4	195,700	168,000	23.1	45.2
	LH-N8	4	192,500	167,400	24.8	46.5
	LH-N5	13	196,200	169,200	24.7	42.6
H. Press	CH-N4	2	195,500	169,200	24.2	39.9
	"	3	195,700	168,800	24.2	39.9
	"	4	195,200	168,300	22.1	40.7
		Ave.	195,500	168,800	23.5	40.2
	CH-N2	4	195,700	169,400	23.9	41.3
	CH-N4	13	190,500	166,600	21.1	41.3
M. Press	LM-N5	2	193,700	167,800	25.7	47.8
	"	3	193,700	163,800	21.9	45.2
	"	4	194,100	167,000	24.1	46.5
		Ave.	193,800	166,200	23.9	46.5
	LM-N2	4	193,900	168,800	23.6	43.9
	LM-N8	4	194,500	167,000	23.5	42.6
	LM-N5	13	197,400	170,200	22.1	43.9
CEFF	PC-N4	2	194,300	166,100	26.8	43.1
	"	3	195,200	170,300	21.5	39.4
	"	4	194,800	166,900	23.9	39.4
		Ave.	194,800	167,800	24.1	40.6
	PC-N3	4	190,900	167,000	17.8	45.2
	PC-N4	13	196,900	171,000	23.4	40.4
AMS(b)	Spec.	Min.	180,000	150,000	12.0	15.0

(a) - Specimen design and test procedures in accordance with ASTM E8. Specimen gage diameter 0.113 inch.

(b) - Heat treated in accordance with AMS 5664A. Minimum tensile properties in specification after such heat treatment are listed above.

(c) - See Figure 111.

(d) - 0.2% Offset.

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forged material can be noted to be approximately 10,000 psi higher than those for the hydraulic press forged material, with intermediate values representing the materials from the other two machines. Ductility levels are in reverse order of the strength levels, as would be expected. These moderate differences can probably be explained as a result of the combined influence of minor variations in chemistries (Tables 1, 3, 5, and 7) and in microstructures (Figures 116 and 117) with one exception. The hammer and mechanical press forging were produced from the same heat of bar stock and were forged to an identical finish shape through identical impressions. No differences can be observed in the microstructures of the heat treated rib materials from the two types of forgings. The slight differences in room temperature strength and elongation between these two series in Table 15 could be attributed to an invalid statistical sampling (too few samples) or to the influence of an unidentified factor.

The room temperature tensile data in Table 16 indicate that the Inconel 718 material from all four machines exceeded the AMS 5664A minimums by a considerable margin relative to both strengths and ductility levels. Also, all values in the table can be seen to be very close to each other regardless of the minor variation in starting stock chemistries, the moderate differences in appearance of the heat treated microstructures, the different specimen locations and orientations, and the very significant differences in thermal-mechanical histories prior to heat treatment afforded by the different die designs and forging machines.

Results of elevated temperature smooth tensile testing are listed in Table 17. For the D6ac and Ti 6Al-4V materials, the values decrease in strength and increase in ductility levels from their room temperature counterparts as would be expected. Also, the same general orders of strengths and ductilities were maintained; i.e., the strongest at room temperature was also the strongest at the elevated temperature, etc. Although the strength levels of the Inconel 718 materials decreased from room temperature to 1200°F, it can be observed that the ductility levels also decreased significantly. Further interpretation of the data is unjustified due to the limited number of specimens, but it is obvious that the data do not suggest rating the forging machines in terms of promoting significantly different elevated temperature tensile properties.

Fracture toughness testing as defined by the recently issued ASTM E399 method, affords the best measure of toughness characteristic of materials. Unfortunately, specimen preparation is costly and thicker material sections than were available from the fin rib forgings are required for valid toughness tests. Toughness characteristics of D6ac and Ti 6Al-4V materials from the fin rib forgings were therefore evaluated and compared at room temperature using older techniques involving the V-notch tensile and Charpy impact specimens. Data from the tests are listed in Tables 18 and 19.

Tensile testing of notched, cylindrical gage specimens is not defined by an ASTM procedure. In general, however, a notched-to-unnotched strength ratio significantly higher than 1.0 is an indication of good toughness characteristics, particularly when the notched specimen has a high theoretical stress concentration factor (a large K_T)(14) as is afforded by the sharp notch root radius of the TRW specimen design. The results in Table 18, therefore, indicate good toughness characteristics for all of the

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TABLE 17

Elevated Temperature Smooth Tensile Properties(a) of Fin Rib Forgings

Material(b)	Machine	Forging Number	Specimen Location(c)	Test Temp. (°F)	Ultimate Strength (psi)	Yield Strength(d) (psi)	Elong. (%)	Reduct. of Area (%)
D6ac	Hammer	LH-S5	1	600	202,400	155,500	13.3	58.3
	H. Press	CH-S5	"	"	206,900	162,500	13.7	64.8
	M. Press	LM-S5	"	"	202,600	157,600	14.8	60.9
	CEFF	PC-S5	"	"	203,400	166,000	15.9	67.9
Ti 6Al-4V	Hammer	LH-T5	1	750	133,000	109,300	10.4	63.8
	H. Press	CH-T5	"	"	127,900	101,700	11.1	66.3
	M. Press	LM-T5	"	"	132,400	108,600	11.4	67.3
	CEFF	PC-T5	"	"	129,900	105,800	10.7	72.2
Inconel 718	Hammer	LH-N5	1	1200	161,400	137,900	12.6	23.1
	H. Press	CH-N4	"	"	158,100	136,000	12.0	14.4
	M. Press	LM-N5	"	"	160,300	136,400	12.2	25.5
	CEFF	PC-N4	"	"	155,700	136,200	12.0	22.4

(a) - Specimen design and test procedures in accordance with ASTM E8 and E21, respectively. Specimen gage diameter 0.113 inch.

(b) - Heat treated in accordance with AMS 6431 for D6ac, AMS 4967A for Ti 6Al-4V, and AMS 5664A for Inconel 718.

(c) - See Figure 111.

(d) - 0.2% Offset.

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TABLE 18

Room Temperature Notch Tensile Properties(a) of D6ac and Ti 6Al-4V Fin Rib Forgings

Material(b)	Machine	Forging Number	Specimen Location(c)	Ultimate Strength (psi)	Notch Strength Ratio(d)
D6ac	Hammer	LH-S2	8	320,100	1.41
	"	LH-S5	"	308,700	1.38
	"	LH-S8	"	313,100	1.39
"	H. Press	CH-S2	8	319,700	1.39
	"	CH-S5	"	315,400	1.38
	"	CH-S8	"	302,400	1.31
"	M. Press	LM-S2	8	304,500	1.34
	"	LM-S5	"	317,200	1.40
	"	LM-S8	"	305,700	1.35
"	CEFF	PC-S2	8	332,700	1.45
	"	PC-S5	"	317,100	1.40
	"	PC-S8	"	323,800	1.41
Ti 6Al-4V	Hammer	LH-T2	8	224,200	1.14
	"	LH-T5	"	231,100	1.23
	"	LH-T8	"	234,600	1.23
"	H. Press	CH-T2	8	241,200	1.34
	"	CH-T5	"	249,300	1.41
	"	CH-T8	"	245,400	1.34
"	M. Press	LM-T2	8	217,800	1.17
	"	LM-T5	"	214,300	1.16
	"	LM-T8	"	235,100	1.24
"	CEFF	PC-T2	8	238,300	1.28
	"	PC-T5	"	236,900	1.28
	"	PC-T8	"	232,000	1.26

(a) - TRW specimen design. Specimen gage diameters 0.200 inch outside of notch and 0.142 inch at root of 60 degree included angle notch. Notch root radius 0.0015 ±0.0005 inch.

(b) - Heat treated in accordance with AMS 6431 for D6ac and AMS 4967A for Ti 6Al-4V.

(c) - See Figure 111.

(d) - The ultimate strength value from the notch tensile specimen from location 8 divided by the ultimate strength value from the smooth tensile specimen from location 4 of the same forging (Table 14 for D6ac and Table 15 for Ti 6Al-4V).

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TABLE 19

Room Temperature Notch Impact Properties[a] of D6ac and Ti 6Al-4V Fin Rib Forgings

	D6ac[b]			Ti 6Al-4V[b]		
Machine	Forging Number	Specimen Location[c]	Energy Absorbed (foot-pounds)	Forging Number	Specimen Location[c]	Energy Absorbed (foot-pounds)
Hammer	LH-S5	9	3 1/2	LH-T5	9	1 1/4
	"	10	3 1/2	"	10	1 1/2
	"	11	3 1/4	"	11	1 1/4
		Ave.	3 1/2		Ave.	1 1/4
	LH-S2	10	3	LH-T2	10	1 1/2
	LH-S8	10	3	LH-T8	10	1 1/4
H. Press	CH-S5	9	3 1/2	CH-T5	9	1 1/4
	"	10	3 1/2	"	10	2
	"	11	3	"	11	2
		Ave.	3 1/4		Ave.	1 3/4
	CH-S2	10	3 1/4	CH-T2	10	1 1/2
	CH-S8	10	3	CH-T8	10	2
M. Press	LM-S5	9	3	LM-T5	9	1
	"	10	3	"	10	1 1/4
	"	11	3	"	11	1 1/4
		Ave.	3		Ave.	1 1/4
	LM-S2	10	2 1/2	LM-T2	10	1 1/4
	LM-S8	10	3 1/4	LM-T8	10	1 1/2
CEFF	PC-S5	9	3	PC-T5	9	1 1/2
	"	10	4 1/2	"	10	2
	"	11	4	"	11	1 1/2
		Ave.	3 3/4		Ave.	1 3/4
	PC-S2	10	4	PC-T2	10	1 3/4
	PC-S8	10	3	PC-T8	10	1 1/4

(a) - Specimen design (Charpy sub-size of 0.197 inch square cross section) and test procedures in accordance with ASTM E23.

(b) - Heat treated in accordance with AMS 6431 for D6ac and AMS 4967A for Ti 6Al-4V.

(c) - See Figure 111.

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heat treated D6ac materials, with little variation from forging to forging as related to machine origin. A very slight trend favoring the CEFF machine and hammer forged materials can be noted. The test results also indicate moderate variations in toughness of the Ti 6Al-4V material as a function of machine origin. The ratings in this instance are inversely and directly proportional, respectively, to the smooth tensile strength and ductility ratings, Table 15. This suggests that the heat treatment given the titanium alloy can result in a marginal favoring of strength over toughness within the compositional limits of the specification.

The notch tensile results are generally confirmed by the notch impact data in Table 19. Although some scatter in the data is apparent and the small size of the specimens employed resulted in absorbed energy values which were all quite low, the results moderately favor the CEFF machine, hammer, hydraulic press, and mechanical press forged D6ac materials in that order; and the hydraulic press and CEFF machine forged Ti 6Al-4V materials over those from the hammer and the mechanical press.

The stress rupture data obtained from the Inconel 718 specimens, Table 20 and Figure 121, illustrate an apparent result of long time testing of the alloy heat treated to the AMS 5664A (short time) specification. "Notch sensitivity" of Inconel 718 in the 1100 to 1300°F range has been reported(15), and is presumed responsible for the erratic elongation and reduction of area values obtained from the "smooth" specimens, Table 20, as well as for the difficulties in providing good curve "fits" for the plotted stress versus life data in Figure 121 representing the hammer and CEFF machine forged materials. Although the tensile ductility levels were less at 1200°F than at room temperature, Tables 17 and 16, typical elongation and reduction of area values of 12 percent and 20 to 25 percent, respectively, at 1200°F are hardly indicative of brittle behavior.

Because of the difficulty in plotting the stress rupture data, all values representing one type of forging equipment were combined for curve fitting purposes in preference to fitting the curve to the five values from the "majority" forging and noting the distance of the "check" values from the curve. This procedure provided seven values each for the hammer and the mechanical press forged materials, and six values each for the hydraulic press and the CEFF machine forged materials. A computer was employed to perform the curve fitting and, after reviewing the results of several "straight line" and "curve" programs, a hyperbolic sine function program was selected to provide the computer recalculated data points (not shown) which actually defined the curves.

The curves in Figure 121 show moderate superiority in stress rupture properties of the mechanical press and the hammer forged Inconel 718 materials up to approximately 50 to 100 hour life and indications of superiority of the hydraulic press and the CEFF machine forged materials for longer time service. Although possibly influenced by variations in chemistry (Tables 1, 3, 5, and 7), this behavior would be expected from comparison of grain size (Figures 119 and 120) and is considered principally a result of the lower forging temperature employed with the hammer and the mechanical press. Reasons for the indications of slight superiority of press forged materials over their respective impact energy machine forged counterparts having the same type of curve are not apparent from comparison of chemistries or microstructural features.

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TABLE 20

Stress Rupture Properties(a) of Inconel 718 Fin Rib Forgings(b) at 1200°F

Machine	Forging Number	Specimen Location(c)	Applied Stress (psi)	Time to Rupture (hrs)	Elong. (%)	Reduct. of Area (%)
Hammer	LH-N5	10	105,000	109.3	1.7	13.7
	"	5	110,000	45.1	3.0	15.6
	"	7	115,000	40.1	3.1	17.9
	"	6	120,000	28.3	4.0	8.7
	"	8	125,000	34.0	2.0	15.3
	LH-N2	6	120,000	21.0	1.2	12.7
	LH-N8	6	120,000	27.1	3.1	6.1
H. Press	CH-N4	5	110,000	164.5	3.8	5.3
	"	8	112,500	164.8	1.9	7.0
	"	7	115,000	81.5	3.5	15.3
	"	10	117,500	47.5	3.5	8.7
	"	6	120,000	8.7	5.9	18.4
	CH-N2	6	115,000	79.0	2.2	11.9
M. Press	LM-N5	5	110,000	118.7	4.1	13.7
	"	10	115,000	103.0	0.9	12.0
	"	6	120,000	51.3	6.2	12.0
	"	8	125,000	32.9	4.7	8.7
	"	7	130,000	3.7	3.5	16.7
	LM-N2	6	125,000	18.3	1.6	13.7
	LM-N8	6	125,000	16.9	4.3	12.7
CEFF	PC-N4	5	110,000	137.0	3.9	8.7
	"	8	112,500	35.3	0.4	7.0
	"	7	115,000	75.7	2.2	15.2
	"	10	117,500	11.9	1.6	11.9
	"	6	120,000	8.6	3.6	20.0
	PC-N3	6	115,000	43.7	4.1	13.7

(a) - Specimen design and test procedures in accordance with ASTM E139. Specimen gage diameter 0.113 inches.

(b) - Heat treated in accordance with AMS 5664A.

(c) - See Figure 111.

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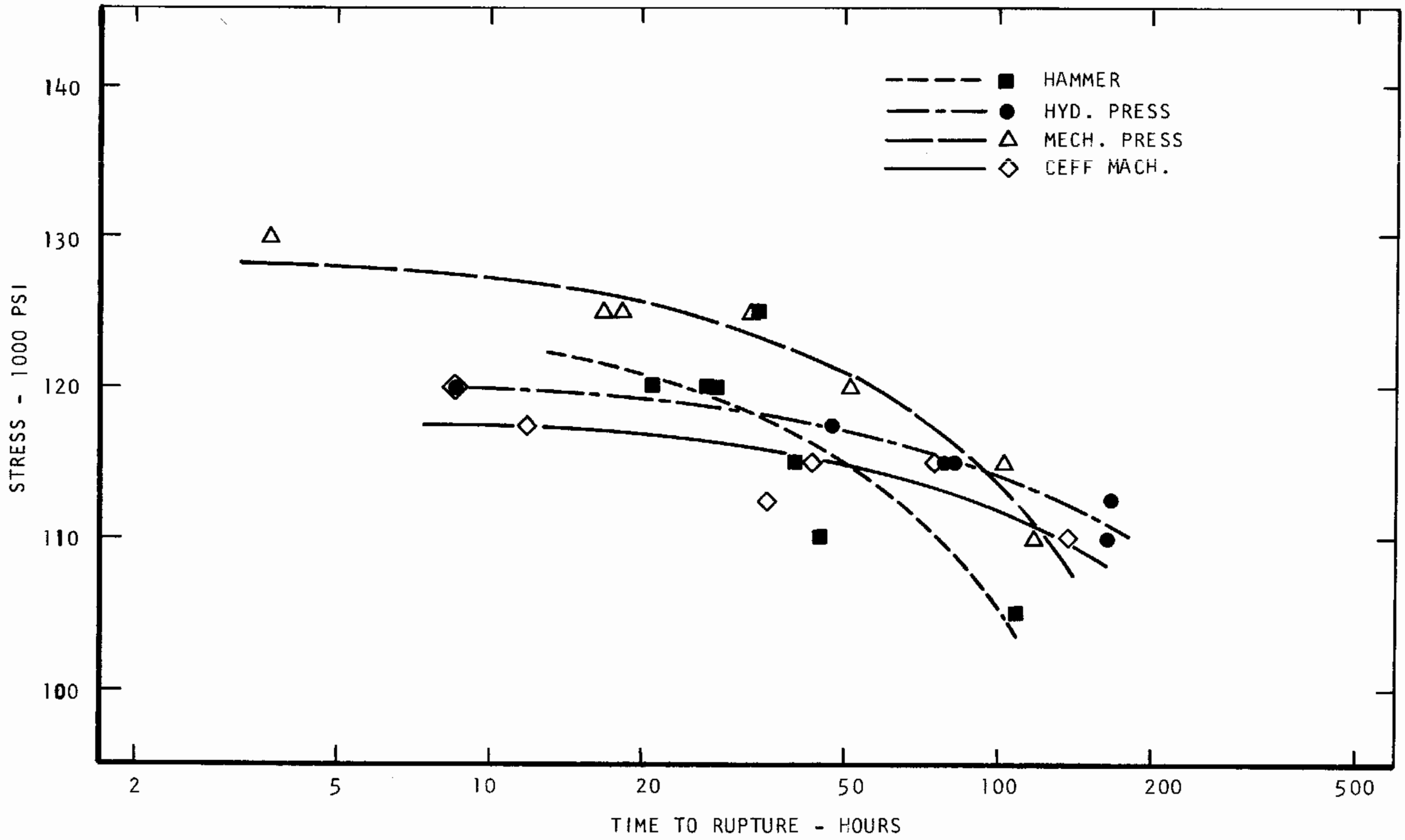

Figure 121. Stress Rupture Properties of Inconel 718 Fin Rib Forgings at 1200°F. Note Difficulty in Providing Appropriate Curves for Data from Hammer Forged and CEFF Machine Forged Materials - See Text and Table 20.

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To summarize, the results of the 172 mechanical tests performed on materials representing 34 of the 111 finish fin rib forgings evaluated indicate that none of the four forging machines under study provided D6ac, Ti 6Al-4V, or Inconel 718 forgings having significantly superior mechanical properties. The moderate variations in certain mechanical properties which were observed appear to be the result of minor variation in starting stock chemistries, minor variations in microstructural responses to heat treatment, and possible lack of statistical validity of the actual values in some instances due to the limited number of tests performed representing a single set of variables.

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VI PRODUCTION OF LARGE FORGINGS

Section IV of this report described the subcontracted design, tooling, and manufacturing efforts necessary to produce the intermediate size fin rib forgings. This section will review and discuss results of similar subcontract activities which were necessary to produce the large bulkhead forgings for TRW evaluation and comparison of particularly large press and hammer equipment. Each of the two sources, Aluminum Company of America (Alcoa) and Ladish Company, were required by the common work statement for large forgings to produce a minimum of two bulkhead forgings in D6ac high strength steel during tooling try-outs, to section them for grain flow studies and defect analyses to establish suitability of sequence and tooling designs, and to deliver the sections to TRW for further evaluation. Subsequently, each source was required to produce sufficient Ti 6Al-4V bulkhead forgings to deliver to TRW five forgings from each of the two machines.

In addition to necessary forging development trials to establish correct preform shapes, each subcontractor produced ten bulkhead forgings to meet the delivery requirements. Alcoa produced three D6ac and seven Ti 6Al-4V bulkhead forgings to result in the two steel and the five titanium alloy forgings which were delivered. Ladish produced the number required in the high strength steel, but delivered five of eight titanium alloy forgings produced. The design and tooling details, and the forging efforts which resulted in the large bulkhead shapes enveloping the Figure 2 component are described in the report sub-sections A and B which follow. Results of the TRW evaluation of the forgings are then given in Section VII.

A. Hydraulic Press - Aluminum Company of America (Alcoa)

1. Forging Equipment

The general characteristics of hydraulic presses employed for forging have been outlined in Section IV-B-1. The specific machine employed to produce the press forged bulkhead forgings was the 50,000 ton "push down" type hydraulic press operated by Alcoa and shown in Figure 122. Installation was completed in 1955, and the press is one of only two with this force rating in the United States. The single larger machine is in Russia(16). The press is capable of a maximum working stroke of 72 inches, and the pumping system is of the air-water accumulator type. Alcoa reported that the ram approach speed ranges from 4 to 6 inches per second and that the maximum pressing velocity ranges from 2 to 3 inches per second at the rated ram force for the press.

2. Tooling Concept and Finish Forging Design

The die parting line concept and details of the finish bulkhead forging designed by Alcoa are schematically represented in Figures 123 and 124. (Illustrations are only in partial section due to the difficulty in presenting detail in a full section suitably reduced for report reproduction.) A "straight"(1-3) horizontal parting line was employed. This can be observed in Figure 123 to correspond to a horizontal reference plane formed by one

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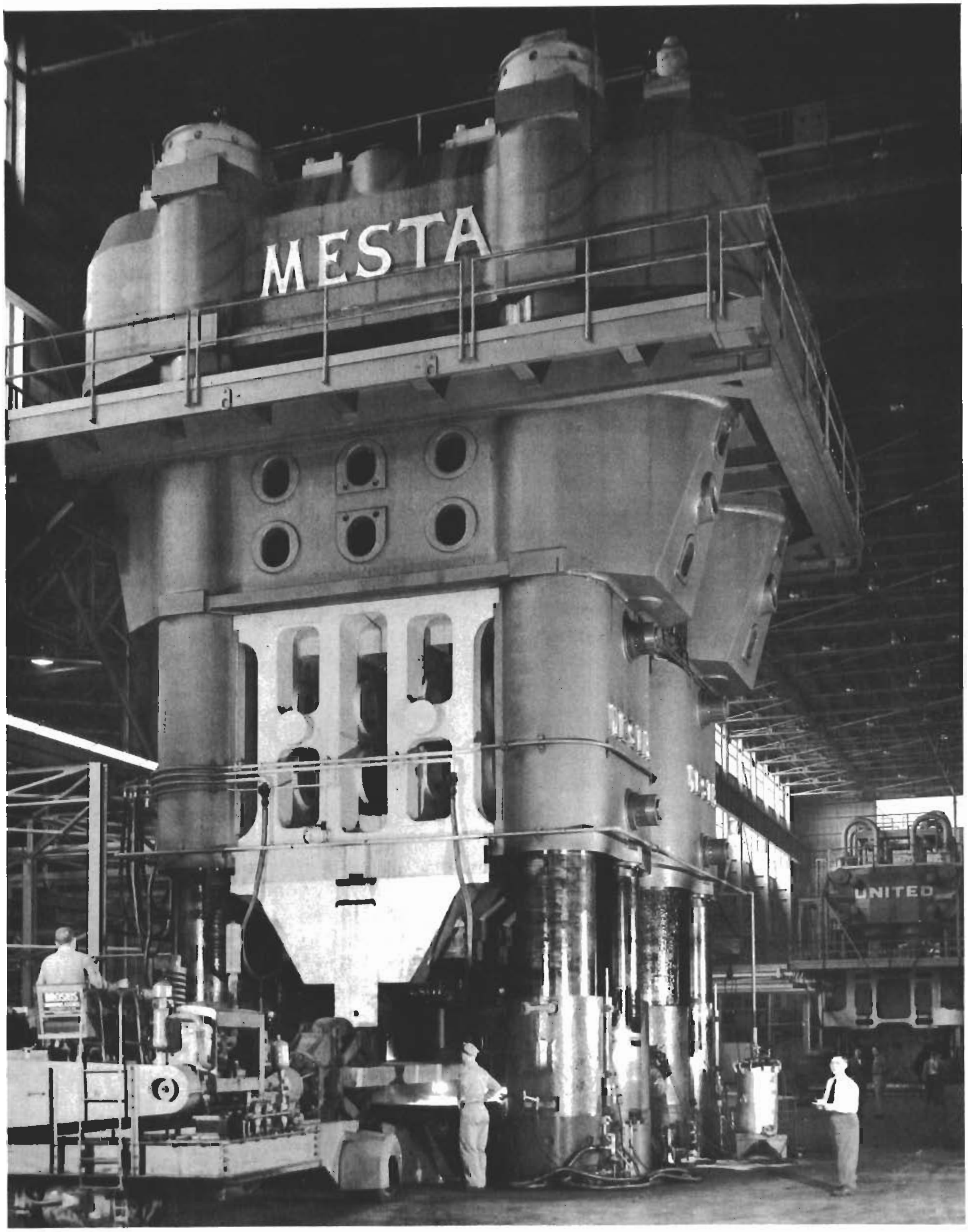

Figure 122. "Push-Down" Type Single Action Hydraulic Forging Press Rated at 50,000 Tons of Force and Employed by Aluminum Co. of America to Produce Bulkhead Forgings. Operation Shown is Not Pertinent to Program.

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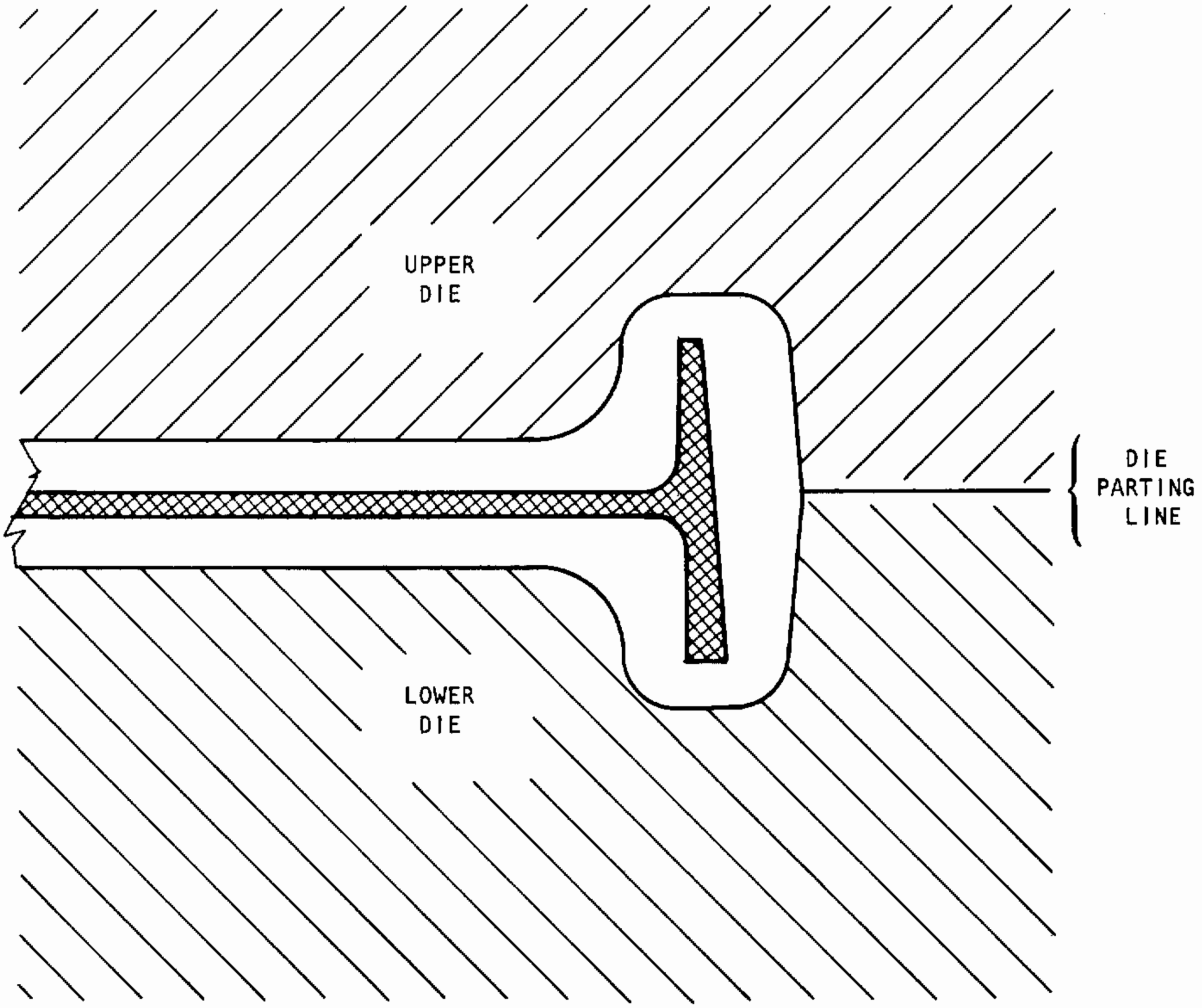

Figure 123. Schematic Illustration of Bulkhead Cross Section (at one end) and Die Parting Line Concept with Finish Forging Die Impression for 50,000 Ton Hydraulic Press Superimposed to Target Closure. Approximately Full Scale.

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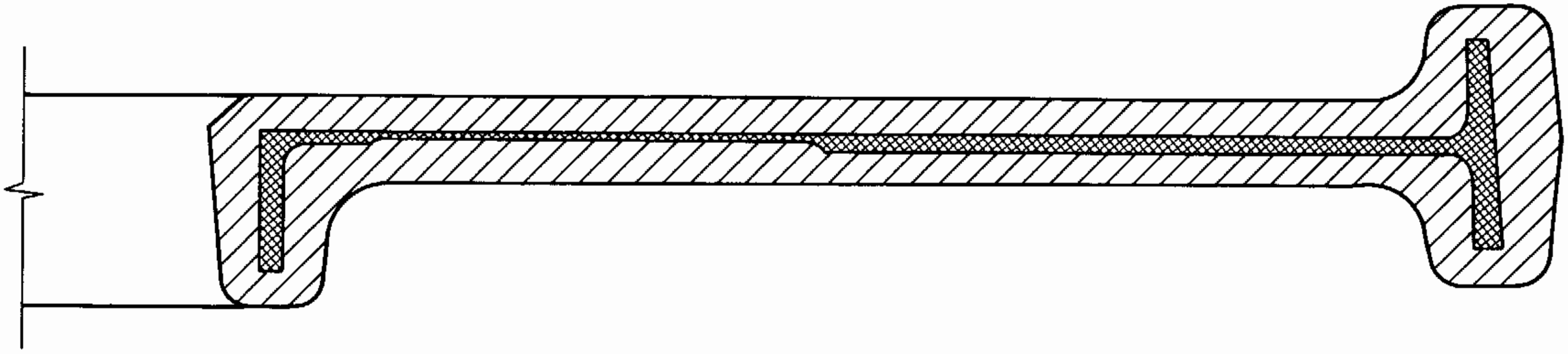

Figure 124. Illustration of Bulkhead Longitudinal Section (at one end) with Target Finish Forged Shape for 50,000 Ton Hydraulic Press Superimposed. Approximately Six-Tenths Scale.

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side of the machined bulkhead web surface. It should be noted that the Figure 2 view of the machined bulkhead represents the most complex side, and that the reverse side includes: 1) only two partial cross ribs, 2) no rib detail around the periphery of the central rectangular hole, and 3) rib detail along the two sides and one end only of the outer periphery of the bulkhead. The Figure 124 section illustrates the lack of rib detail along the edge of the one side of the hole, and it can be appreciated that the interior parting line of the forging also corresponded to the intersection of the lines representing draft and lay along the same reference plane formed by the machined web surface.

Other characteristics of the finish forging design for the 50,000 ton press included the following:

a) typical five degree external and internal draft allowances, with "matching draft"(1-3) as required to make forging surfaces meet at the parting line;

b) typical rib-web fillet and rib edge corner radii of 0.500 and 0.312 inch, respectively, and

c) a target thickness of 0.75 inch (with die closure tolerances of plus 0.25, minus 0.03 inch) at all web areas of the forging.

These features are illustrated in correct proportion in Figure 124. The sketch also shows the correct orientation of the finish forging with respect to the position in which it was forged; i.e., Alcoa elected to forge the side representing the majority of the rib detail (Figure 2 view) in the lower die impression.

3. Staging Sequence and Starting Stock

The large bulkhead forging staging sequence designed by Alcoa is illustrated in Figure 125. Round-corner-square billet stock was open-die forged to the preform shape using a 3000 ton hydraulic press. The technique involves use of several flat, relatively small dies with generously radiused edges. The billet was first lengthened by working the center section only, and was then progressively forged to the preform shape by operating the press as a multiple stroke machine and manipulating the workpiece as required between strokes. Die changes (for different sizes) and reheats were inserted as necessary during this operation. A skilled crew can produce a large semi-impression shape with non-impression dies in a relatively small hydraulic press (or an open frame hammer) in this manner. Other than changes required in starting billet length and in the shape and thickness of this preform, described during subsequent discussion of forging results, the Figure 125 sequence did not require modification; i.e., the impression dies which produced the intermediate shapes which followed did not require extensive shape adjustment.

After preforming, the workpieces were trimmed to appropriate exterior dimensions by torch cutting and were forged through three separate sets of impression dies in the 50,000 ton hydraulic press in progressing

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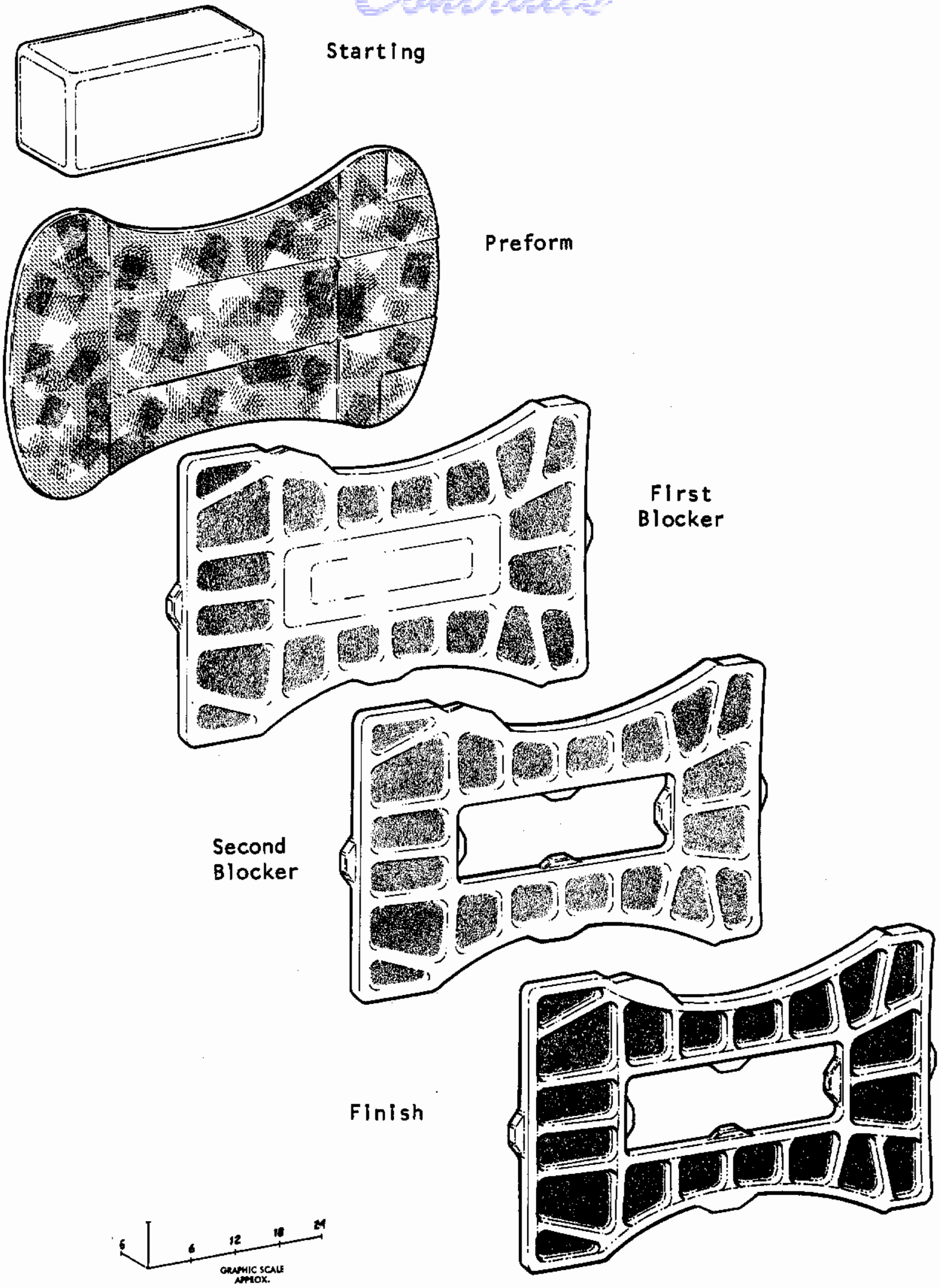

Figure 125. Illustration of Bulkhead Forging Staging Sequence Employed During Forging Efforts with 50,000 Ton Hydraulic Press (First Blocker Through Finish).

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through the Figure 125 first blocker and second blocker shapes and arriving at the finish shape. Intermediate and final trimming, abrasive blasting, and chemical conditioning (titanium alloy workpieces only were chemically conditioned by pickling to remove approximately 0.015 inch of stock from preform surfaces and approximately 0.010 inch of stock from all surfaces of the blocker and finish shapes) were conducted in all instances; further intermediate conditioning by grinding was conducted as required; and the center section was removed by torch cutting between the first blocker and the second blocker operations.

It should be noted that the preform and both blocker shapes, as represented in Figure 125, were drawn by TRW on the basis of general information and sketches supplied by Alcoa which included major dimensions, but virtually no rib or web thickness or radius detail. This was because Alcoa considered detailed dimensional data for intermediate shapes in the staging sequence to be proprietary, as allowed by the common work statement. Eight projections can be noted along the interior (hole) and exterior edges of the forging designs. The two larger of these represent excess stock for material property evaluations. The remaining six were designed as "hold down tabs" for subsequent machining operations. Although not requirements of this program since the finish forgings were not machined and several were destructively evaluated, Alcoa chose to include these details as representative of their current practices in production of such forgings for actual airframe service.

Data for the 12 inch, round-corner-square D6ac and Ti 6Al-4V starting stock procured by Alcoa are listed in Table 21.

4. Forging Tooling

Separate sets of upper and lower dies were employed in the 50,000 ton hydraulic press for each of the impression die operations in Figure 125. Each set was similar except for the impressions, and each upper and lower block had exterior dimensions of 70 inch length by 52 inch width by 14 inch height.

Design concepts for the large press dies are represented in Figure 126 by an illustration of the upper and lower impressions for the finish forging operation. Flash land detail was equally divided between the upper and lower dies, and encompassed all interior (hole) and exterior edges of the impressions. "Kissing" surfaces were provided surrounding the exterior gutter, which was machined only in the upper die, and two cylindrical guide posts were included to minimize mismatch at closure.

All bulkhead forging impression dies for the 50,000 ton press were prepared by conventional machining of wrought blocks of Finkl "FX" die steel (nominal analysis: 0.55C, 0.75Mn, 0.30Si, 0.95Cr, 0.35Mo, 0.95Ni, bal. Fe). These were procured prehardened to the "Finkl No. 2" temper (Rc 37 to 40). The finish dies are shown in Figures 127 and 128. It can be observed that the flash lands were quite narrow, allowing relatively little restraint, and that the transition areas from the lands to the gutters were generously inclined. These features indicate that the previous dies provided a shape

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TABLE 21

Material Data for Large Bulkhead Forgings Produced with a 50,000-Ton Hydraulic Press

Chemical Analysis	C	Si	Mn	S	P	N	Cr	V	Ni	Mo	Cu	Fe	Al	O	H	Ti
D6ac	0.48	0.25	0.61	0.003	0.005		1.05	0.07	0.54	0.99	0.06	Bal.				
Ti 6Al-4V	0.02					0.009		4.2				0.17	6.3	0.167- 0.135	0.0023- 0.0077	Bal.

	D6ac	Ti 6Al-4V
Material Source	Latrobe Steel Co.	Reactive Metals Inc.
Heat Number	C 13304	310523
Starting Stock Form	12 inch RCS Billets by 25-5/8 inches long.	12 inch RCS Billets by 29-1/2 inches long.
Starting Stock Weight	1043 pounds	679 pounds
Procurement Specifications	AMS-6431A	AMS-4967A
Other Inspection Procedures	-	Ultrasonically Inspected

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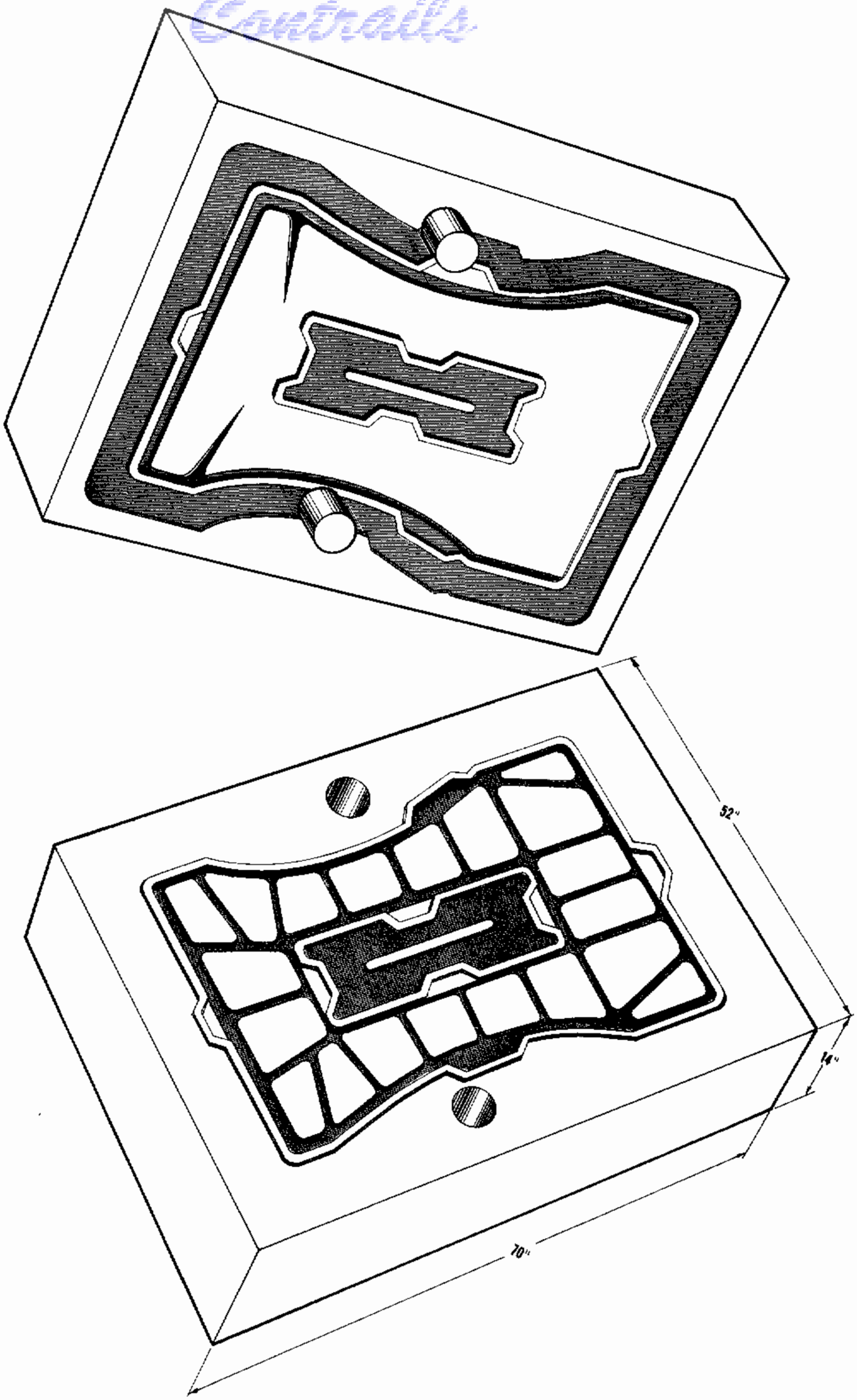

Figure 126. Schematic Illustration of Impression Dies for Finish Bulkhead Forging Operation with 50,000 Ton Hydraulic Press.

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Figure 127. Lower Die for the Finish Bulkhead Forging Operation with the 50,000 Ton Hydraulic Press. Impression Polished and Photograph Taken after Completion of All Program Forging Efforts with the Press.

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Figure 128. Upper Die for the Finish Bulkhead Forging Operation with the 50,000 Ton Hydraulic Press. Impression Polished and Photograph Taken after Completion of All Program Forging Efforts with the Press.

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which had been correctly proportioned, and that the principal function of the finish dies was to uniformly remove excess metal along the flashlines in accomplishing vertical sizing of the forging. It might be noted here that, when forging with flash, some measure of control of preferential metal flow within the impression is conventionally afforded the press forging engineer by machining dies to include wide flash lands which are uniformly stepped or inclined to meet relief area surfaces or gutters. These wide lands are then relieved by grinding with a manually operated rotary tool during concurrent "development" of the dies and of the forging operation itself. Variable land width and variable "ramp" geometries in leading to the gutters of such "developed" dies are therefore indicative of a desire to nonuniformly restrict flash and thereby accomplish re-proportioning of metal within the impression.

5. Forging Results

Processing data recorded by Alcoa in forging the high strength steel and the titanium alloy bulkheads are listed in Table 22. The 12 inch round-corner-square by 25-5/8 inch long D6ac starting billets were preformed on the 3000 ton press and subsequently progressed through the blocker and finish shapes without incident. The proprietary coating noted in the table was applied to the starting stock to reduce scaling during heating. Intermediate operations included trimming, abrasive blasting, conditioning as required, and reapplication of the coating. Post forging operations included the thermal stress relief also noted in Table 22, trimming, and abrasive blasting.

The evidence of slight lack of fill and the incomplete die closure obtained during forging of the steel bulkheads were not subjects of major concern since the effort represented the initial try-out of the tooling and since the results indicated that the deficiencies could be corrected through revision of the preform design; i.e., reworking of the impression dies for the 50,000 ton press was not required. One of the three D6ac forgings produced during this initial effort is shown in Figure 129. The other two were sectioned, one longitudinally at three locations and the other in the transverse direction at three locations for the studies involving grain flow and location of potential defects as might be characteristic of forgings produced by the dies. Upon examination at TRW, the grain flow was observed to be uniform and it was also noted that the two sectioned forgings contained no visible defects.

Three separate forging trials were conducted with Ti 6Al-4V stock before the starting volume was correct and the preform design was sufficiently developed to allow production of the titanium alloy forgings for delivery to TRW. The first trial was conducted concurrently with the die try-out for the D6ac material and utilized three Ti 6Al-4V starting billets of the same size (12 inch RCS by 25-5/8 inch long) as those of the steel. Processing conditions were identical except for heating times and temperatures (see Table 22), the use of intermediate and post forging pickling operations to chemically remove surface material from the titanium alloy workpieces after trimming and abrasive blasting, and the lack of a post forging stress relief for the titanium alloy forgings. The first Ti 6Al-4V bulkhead forgings were reported to be much more severely unfilled than their steel counterparts.

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TABLE 22

Processing Data for Large Bulkhead Forgings Produced with a 50,000 Ton Hydraulic Press(a)

	Material	
	D6ac	Ti 6Al-4V
Furnace Type	Gas Fired	Gas Fired
Furnace Atmosphere	Air	Air
Furnace Temperature	2250°F ±25°F All Stages	1725°F ±25°F All Stages
Protective Workpiece Coating	XL 1167 - Alcoa Proprietary	XL 1167 - Alcoa Proprietary
Heating Times	5.0 Hours-Preform 3.0 Hours-First Blocker 2.5 Hours-Second Blocker 6.0 Hours-Finish	4.0 Hours-Preform 4.0 Hours-First Blocker 2.0 Hours-Second Blocker & Finish
Transfer Times	20 Seconds-Preform 35 Seconds-First Blocker 30 Seconds-Second Blocker & Finish	25 Seconds-Preform 35 Seconds-First and Second Blocker 30 Seconds-Finish
Die Lubricant	PL 488 - Alcoa Proprietary-Spray	PL 488 - Alcoa Proprietary-Spray
Die Temperature	Heated-Die Temperature Proprietary	Heated-Die Temperature Proprietary
Number of Strokes per Stage	One	One
Number of Reheats per Stage	None	None
Cooling Method	Air	Air
Post Forging Thermal Treatment	Stress Relieve 1 Hour at 1200°F after Finish Operation	None
Contact Velocity (in./sec.)	4 to 6	4 to 6
Pressing Velocity (in./sec.)	2 to 3	2 to 3

(a) - Preform operation conducted with 3000 ton hydraulic press - see text.

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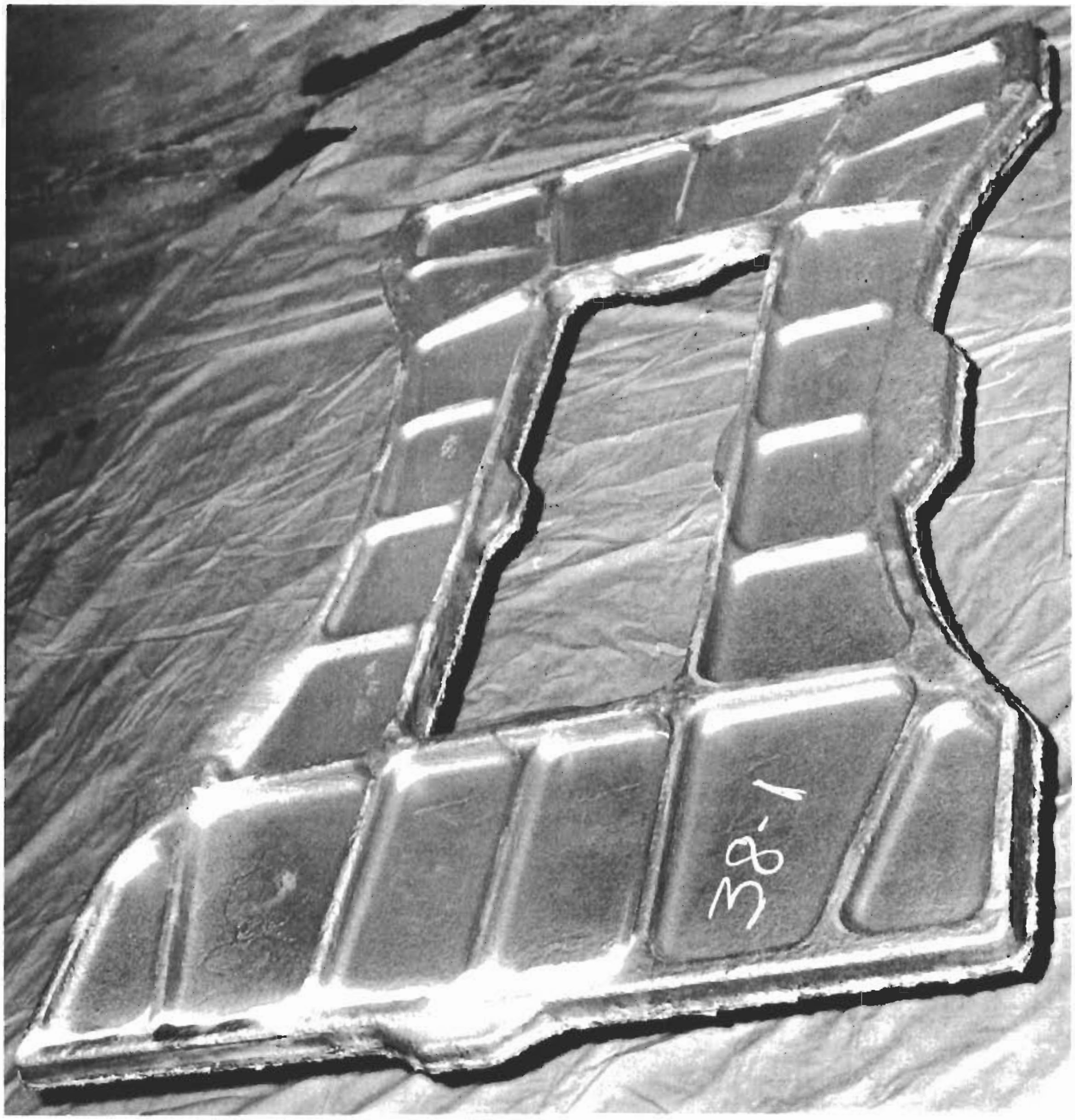

Figure 129. One of Three High Strength Steel (D6ac) Bulkhead Forgings Produced During Initial Die Try-Outs with 50,000 Ton Hydraulic Press. Surface Shown Represents Lower Die Impression. Shown after Trimming (Torch Cut, but in this Case, not Ground Along Flashlines) and Abrasive Blasting.

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Two billets were then scrapped due to cracking during the "multiple stroke-open die" preforming operation with the 3000 ton press. The significance of this will be briefly touched upon during subsequent discussion of similar difficulties experienced by Ladish during preforming prefatory to forging of the Ti 6Al-4V bulkheads with the large counterblow hammer. A subsequent third trial with two additional billets of Ti 6Al-4V, although resulting in finish bulkhead forgings which were slightly unfilled and overly thick in web areas, nevertheless was successful in establishing the correct length billets (29-1/2 inches, Table 21) of the 12 inch round-corner-square stock and the correct preform design for production of the titanium alloy forgings for TRW evaluation.

Seven Ti 6Al-4V bulkhead forgings were successfully produced during the final effort at Alcoa. Of these the first, third, fourth, fifth and sixth were delivered to TRW after trimming, abrasive blasting, chemical conditioning, and dimensional and ultrasonic inspection. The five forgings delivered; which were subsequently re-serialized as Al-Tl, AL-T2, AL-T3, AL-T4, and AL-T5, respectively; are shown in Figures 130 and 131. Alcoa assured TRW that, in production of these forgings, the 50,000 ton press was employed using maximum ram speed and ram force capabilities. Adding the approximately 100 square inch peripheral forging envelope (inner hole and outer rib edges) of excess metal to the bulkhead component plan area of 1265 square inches, 50,000 tons of press force provided an average unit pressure of approximately 36.6 tons per square inch.

Upon visual examination, none of the five titanium alloy forgings produced with the 50,000 ton press and delivered to TRW contained any apparent defects. Number AL-T5, however, exhibited two types of surface effects which could be considered as marginally undesirable conditions. The first is the localized, but severely pitted surface shown in Figure 132. This was attributed to a build-up of workpiece coating material on the die surface in this area, or to sticking and "carry over" of refractory furnace hearth material which subsequently could have been pressed into the forging surface. The former was considered more likely since the condition was also observed, but to a lesser extent, on the previous forging produced. The second marginal condition exhibited by this forging is shown in Figure 133. This appears to represent the onset of a tendency to form laps at fillet and corner radii of the lower die side. The fillet radius condition was noted to exist to a lesser degree at localized areas on all of the titanium alloy forgings and was the subject of more comprehensive TRW investigation during the fluorescent penetrant studies described in the next major section of this report.

B. Counterblow Hammer - Ladish Company

1. Forging Equipment

The essential principles upon which large steam powered counterblow hammers operate are illustrated in Figure 134. Steam is admitted to the upper cylinder and drives the upper ram downward. At the same time, pistons connected to the upper ram act through a hydraulic linkage in forcing the lower ram upward. Since the weight of the lower ram and piston

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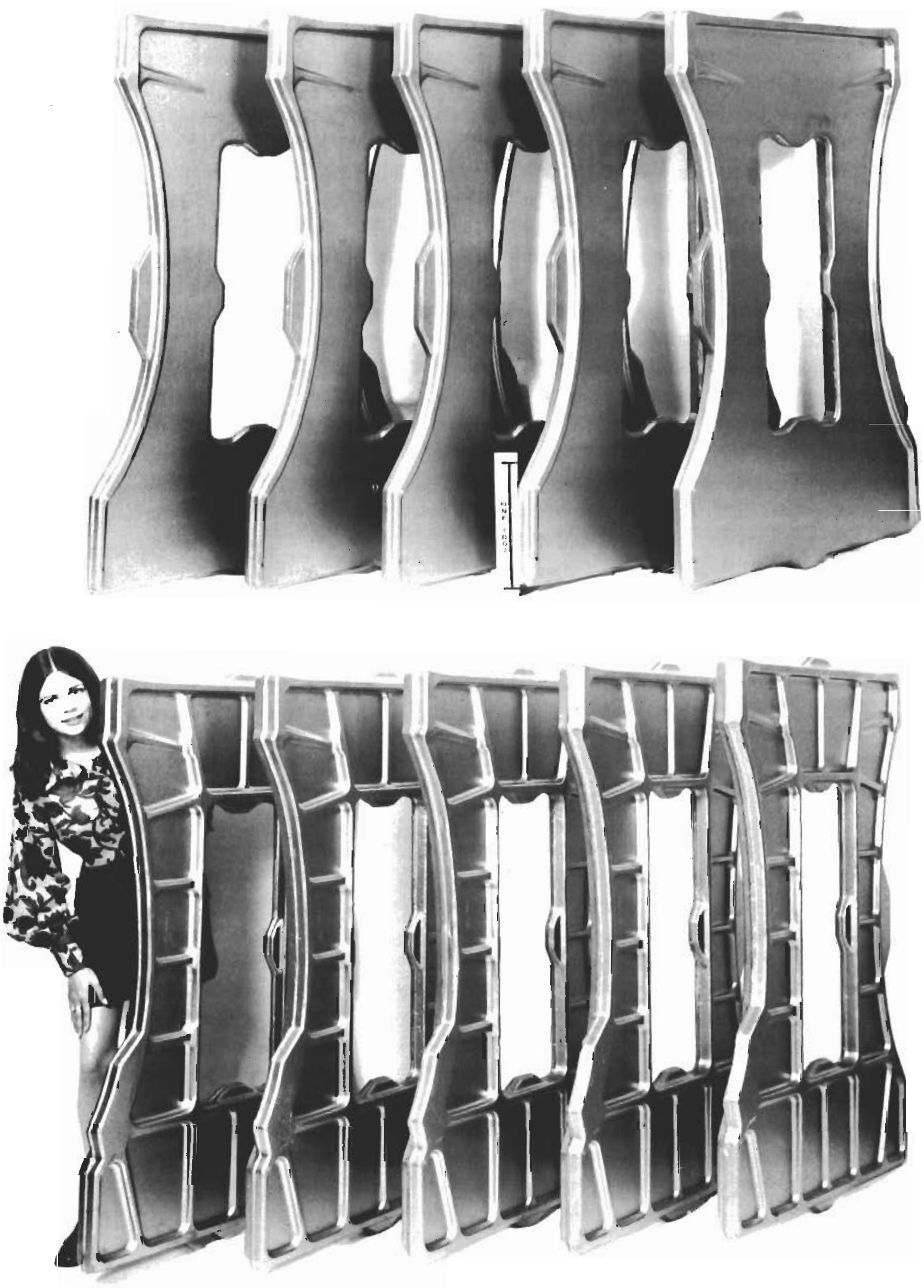

Figure 130. Five Titanium Alloy (Ti 6Al-4V) Bulkhead Forgings Produced with 50,000 Ton Hydraulic Press for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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Figure 131. Close-Up of Two of the Ti 6Al-4V Bulkhead Forgings Produced with the 50,000 Ton Hydraulic Press and Delivered to TRW.

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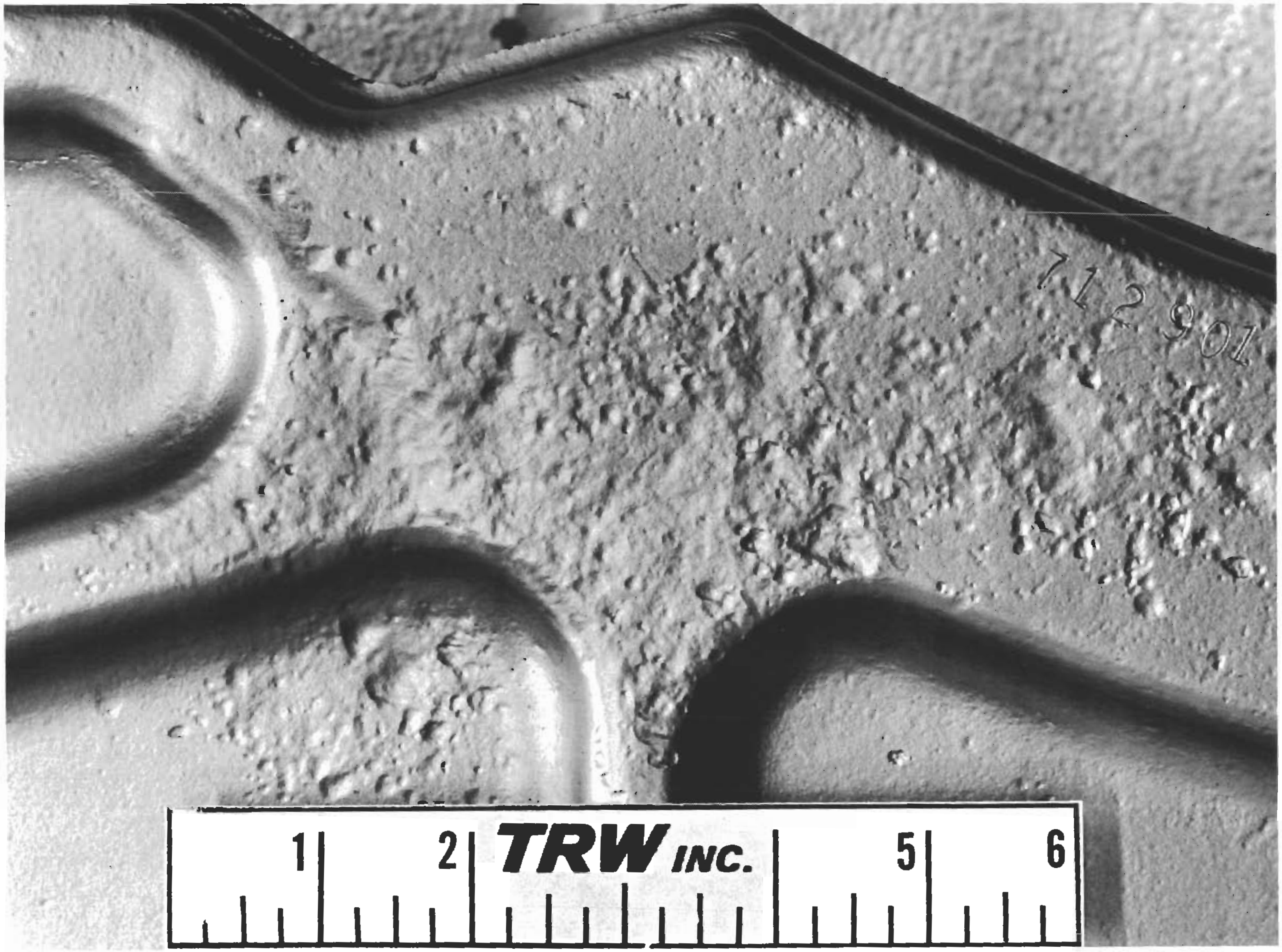

Figure 132. Pitted Surface Condition Exhibited in Localized Areas of the Lower Die Side of the Sixth Ti 6Al-4V Bulkhead Forging Produced (of Seven Forgings Total, the Fifth of the Five Delivered to TRW) with the 50,000 Ton Hydraulic Press.

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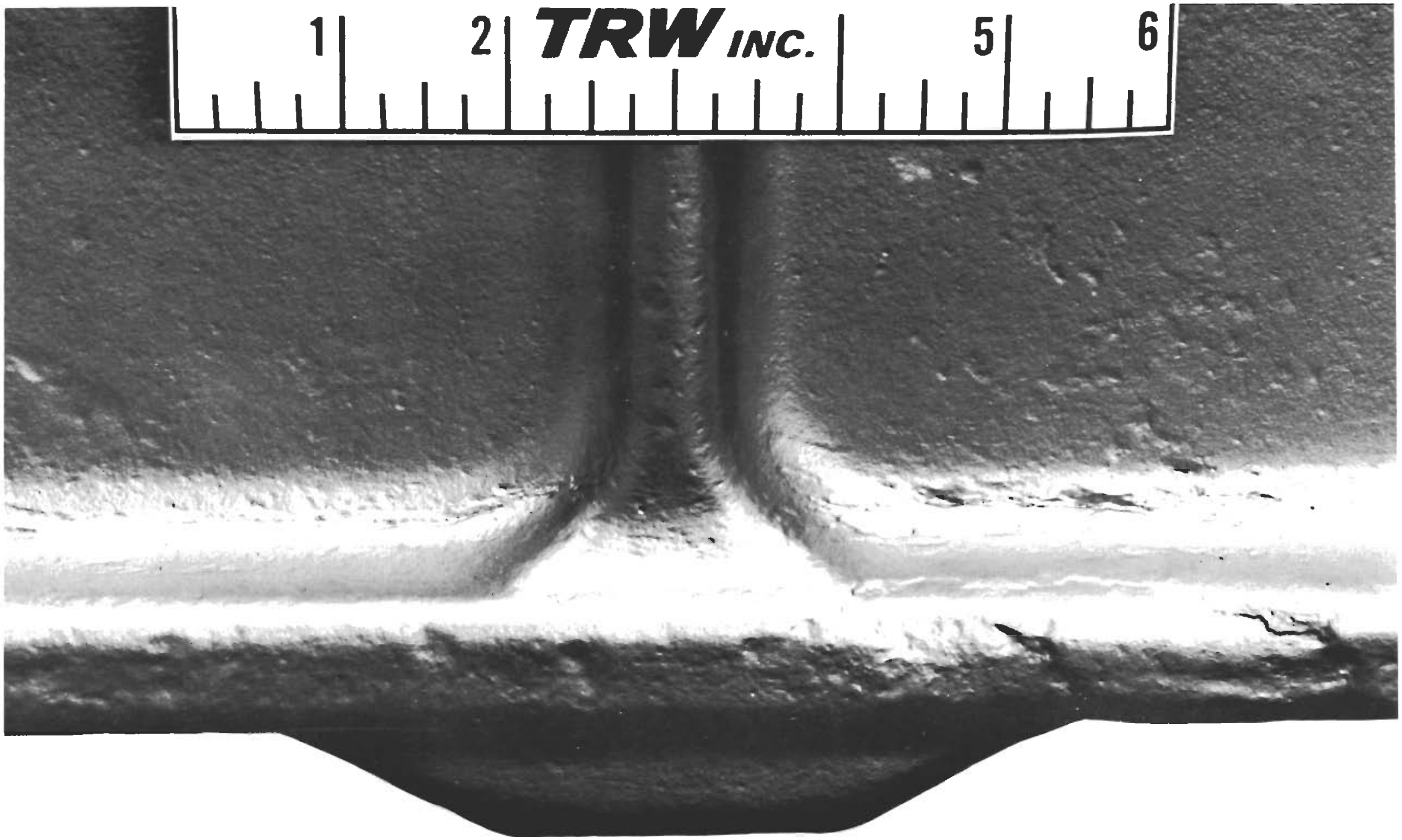

Figure 133. Indications of the Initiation of Laps at Fillet and Corner Radii on the Lower Die Side of the Sixth Ti 6Al-4V Bulkhead Forging Produced (of Seven Forgings Total, the Fifth of the Five Delivered to TRW) with the 50,000 Ton Hydraulic Press.

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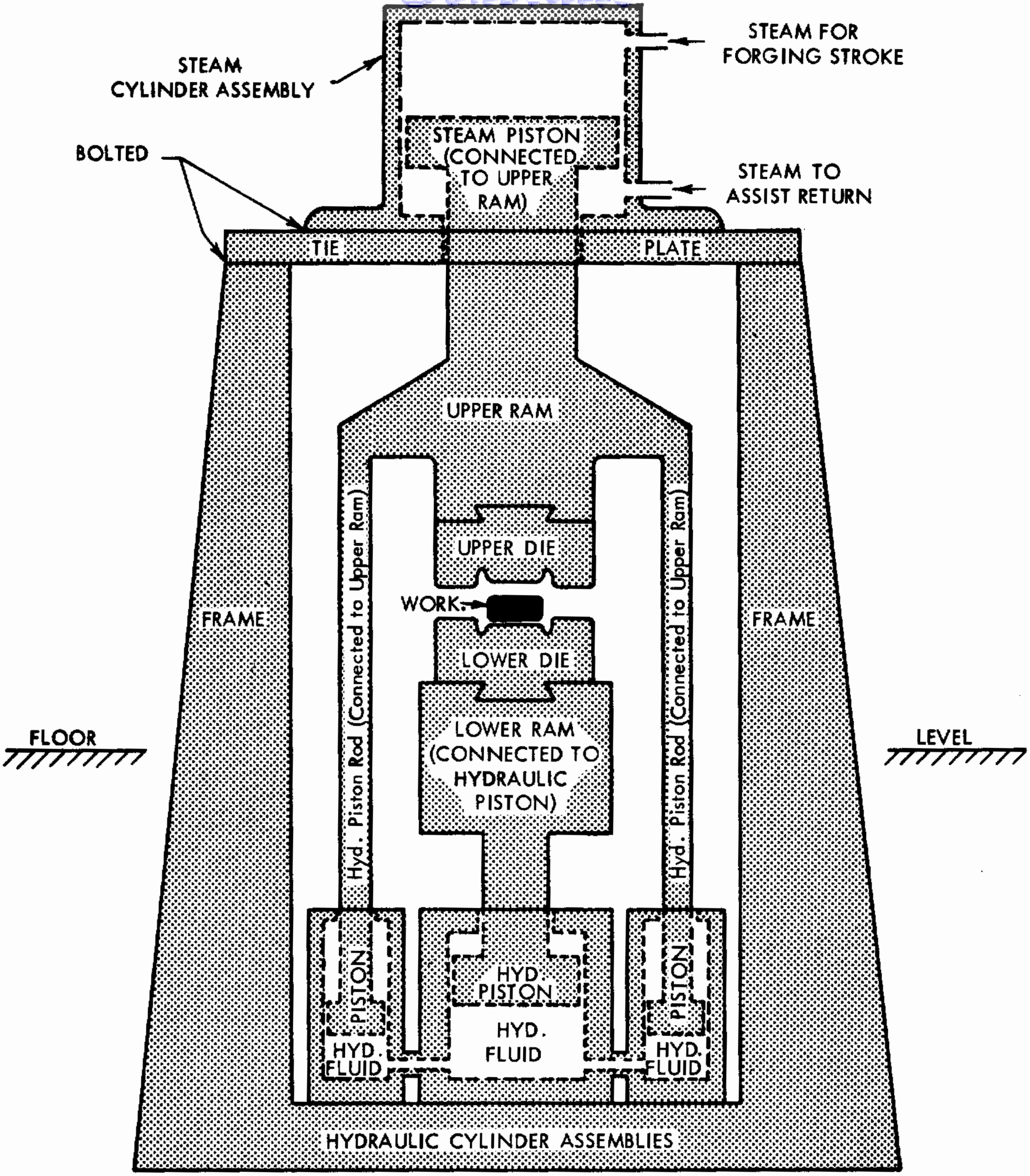

Figure 134. Highly Simplified Illustration of Large Counterblow Forging Hammer Construction Showing Major Components. Frame Actuall Envelops Hydraulic Piston Rods and Provides "Four Corner" Guiding for Upper and Lower Rams.

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assembly is slightly greater than that of the upper assembly, the rams retract automatically after the blow. Retraction speed is increased in operation by steam pressure acting upward on the lip of the steam piston as indicated.

Through proper design relative to weights (including tooling and workpiece, which rides up on the lower die) and hydraulics (slightly slower lower assembly velocity), the kinetic energies of the upper and lower assemblies of the counterblow hammer may be balanced at impact. Such balancing reduces energy losses to those caused by friction during die closure and by deflection during the blow; i.e., counterblow hammers do not transmit an appreciable degree of their impact energy to the ground as do steam drop hammers. Although conventionally employed as multiple blow machines, current counterblow hammers have been designed for somewhat slower cycle rates and impact velocities than steam drop hammers.

The hydraulic linkage and greater weight of the lower assembly results in a slightly negative "falling weight". All of the impact energy delivered is supplied by the steam pressure, which must also overcome the greater lower weight and friction losses. Thus, it can be appreciated that counterblow hammers are rated on the basis of impact energy alone as a function of weights and velocities of the upper and lower assemblies. As with steam drop hammers, die weight and thickness (stroke) affect the impact energy available due to their influences on mass and impact velocity in the MV^2 relationship. These effects are less significant to counterblow hammer ratings, however, due to the relatively much larger weights of the rams (as compared to the weights of the dies) and the slower die closure velocity at impact.

In 1959 the Ladish Company completed the design and construction of the largest hammer in the world. This is the counterblow hammer shown in Figure 135 which is conservatively rated at 125,000 meter kilograms (equivalent to 903,000 foot pounds) of energy per blow. Ladish has indicated that the average stroke per ram is 40 inches and that, when "stroked to capacity", the hammer provides thirty 1,080,000 foot-pound (approximately 150,000 MKG) blows per minute under "nominal", or average, conditions of steam pressure (120 psi) and die weight (56,600 pounds total). The combined ram velocities under these conditions provide a die contact velocity of approximately 18 feet per second. A 72 inch by 200 inch rectangular die space is provided, and 96 inch diameter circular dies can also be accommodated. The hammer is powered by steam acting in an 80 inch diameter cylinder to actuate a total upper and lower design "mass in motion" of 819,000 pounds, not including the weight of the dies.

2. Tooling Concept and Finish Forging Design

The Ladish parting line concept and finish bulkhead forging design, illustrated as partial section drawings in Figures 136 and 137, present two significant contrasts with the tooling and design concepts employed for the large press effort. First, it can be observed in Figure 137 that the finish bulkhead forgings were hammer forged with the side representing the greatest rib detail (Figure 2 view) produced by the upper die impression. This was done to minimize the effects of chilling on rib

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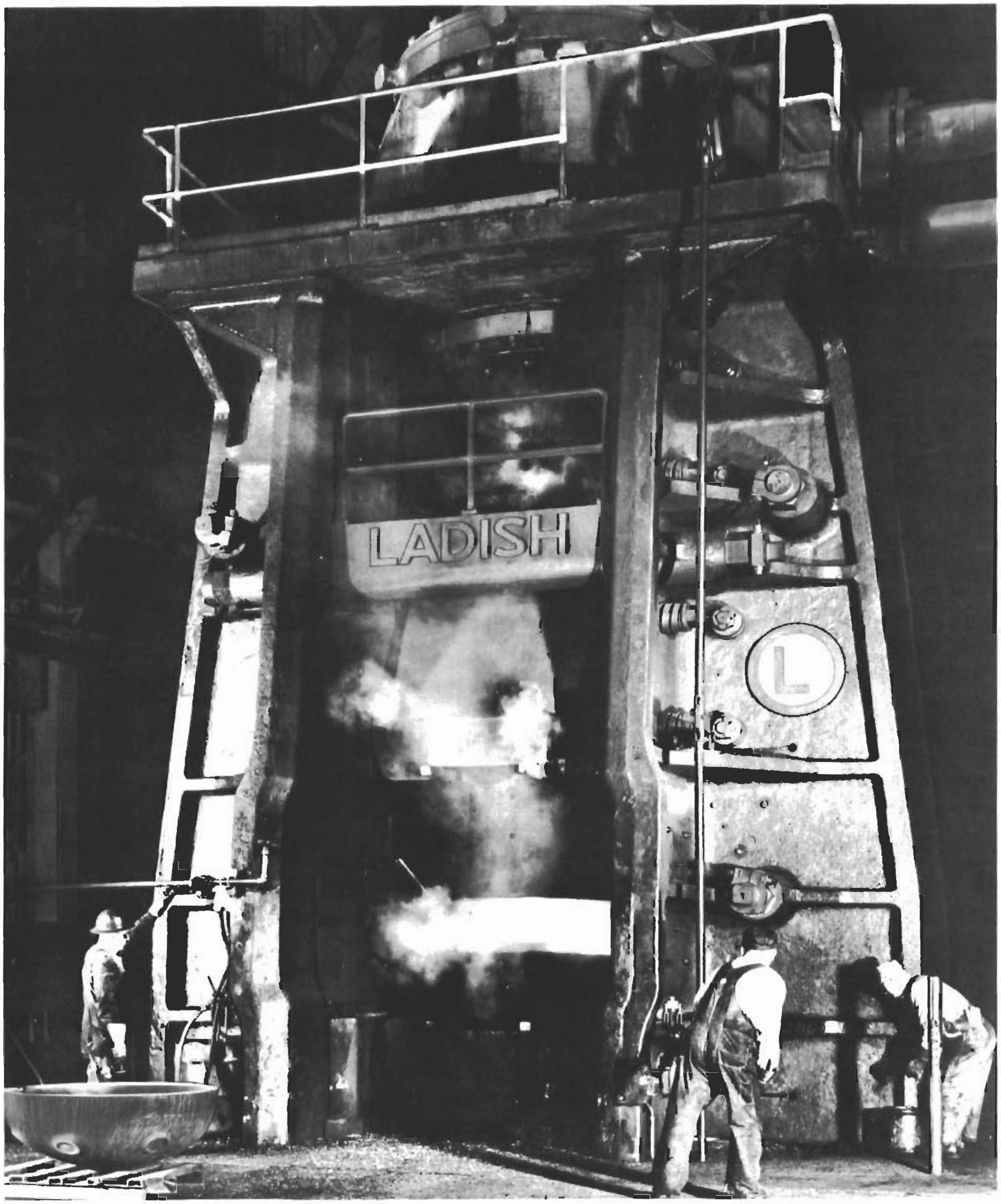

Figure 135. Counterblow Forging Hammer Rated at 125,000 MKG per Blow and Employed by Ladish Co. to Produce Bulkhead Forgings. Forging Operation Shown is Not Pertinent to Program.

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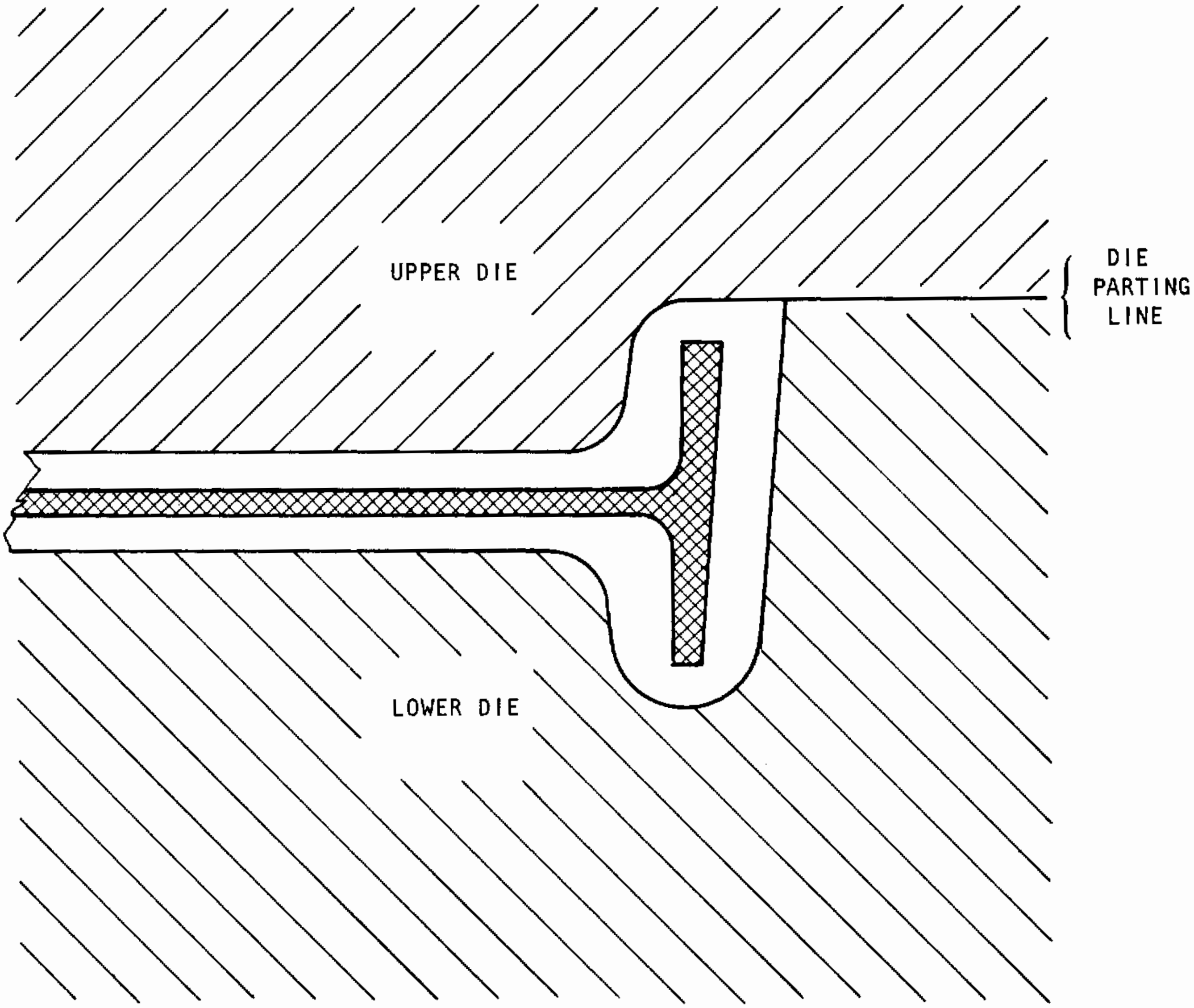

Figure 136. Schematic Illustration of Bulkhead Cross Section (at one end) and Die Parting Line Concept with Finish Forging Die Impression for 125,000 MKG Counterblow Hammer Superimposed to Target Closure. Approximately Full Scale.

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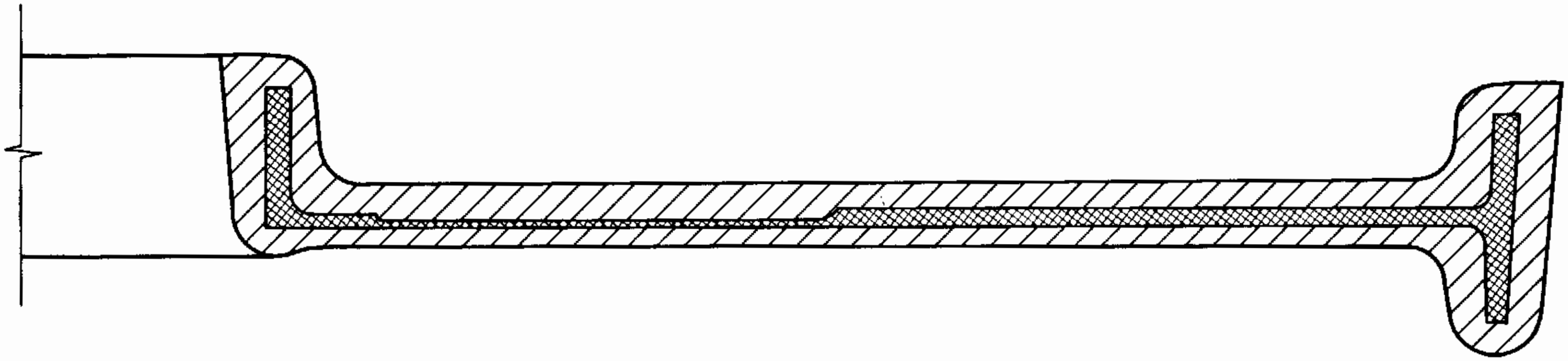

Figure 137. Illustration of Bulkhead Longitudinal Section (at one end) with Target Finish Forged Shape for 125,000 MKG Counterblow Hammer Superimposed. Approximately Six-Tenths Scale.

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fill. Second, rather than reflecting a web plane location, the hammer forging parting line placement was at the upper edges of the interior (hole) and exterior bulkhead ribs. Since the height of the exterior rib varied in circumscribing the bulkhead, and also since the interior rib height was slightly greater than that of the major portion of the same side of the exterior rib; the parting line was moderately "irregular"(1-3) in terms of reference from a horizontal plane.

Specific features of the finish bulkhead forging designed for the 125,000 MKG counterblow hammer were as follows:

a) typical five degree external and internal draft allowances;

b) typical rib-web fillet and rib edge corner radii of 0.375 inch and 0.312 inch, respectively; and

c) target web thicknesses of 0.575 inch and 0.500 inch at areas representing correspondingly thicker and thinner areas of the bulkhead component web.

These features are illustrated in correct proportion for the thinner web sections in Figure 137.

3. Staging Sequence and Starting Stock

The staging sequence employed by Ladish to produce the large bulkhead forgings of the Ti 6Al-4V alloy is illustrated in Figure 138. A rectangular section of 2 inch thick plate stock was torch cut to the approximate exterior and interior (hole) shape and was single-stroke forged to the preform shape in a 15,000 ton hydraulic press. An intermediate shape representing a partial preform shape, not shown, was provided by fullering of a smaller section of plate starting stock in producing the D6ac bulkhead forgings required. As will be noted subsequently, however, this technique was not successful in improving overall material yield for the titanium alloy due to cracking of the Ti 6Al-4V material during the fullering operation.

After preforming to the Figure 138 shape, all steel and titanium alloy workpieces progressed through separate blocker and finish impression dies in the 125,000 MKG counterblow hammer. Also, reheats and restrikes were employed during the multiple-blow hammer forging efforts in producing both of the lower two shapes in the Figure 138 sequence. Intermediate operations included trimming, abrasive blasting, and conditioning by grinding as required. Trimming was accomplished by torch cutting, and was also conducted prior to the reheat-restrike operations involved in producing the blocker and the finish forgings. As with the effort involving the large press, none of the impression dies which produced the Figure 138 shapes required modification during the program.

Table 23 lists pertinent data for the 2 inch thick D6ac and Ti 6Al-4V plate materials utilized as starting stock for the efforts with the large counterblow hammer. The 27 by 45 inch dimensions for the D6ac stock were the same for the initial pieces of the titanium alloy which cracked

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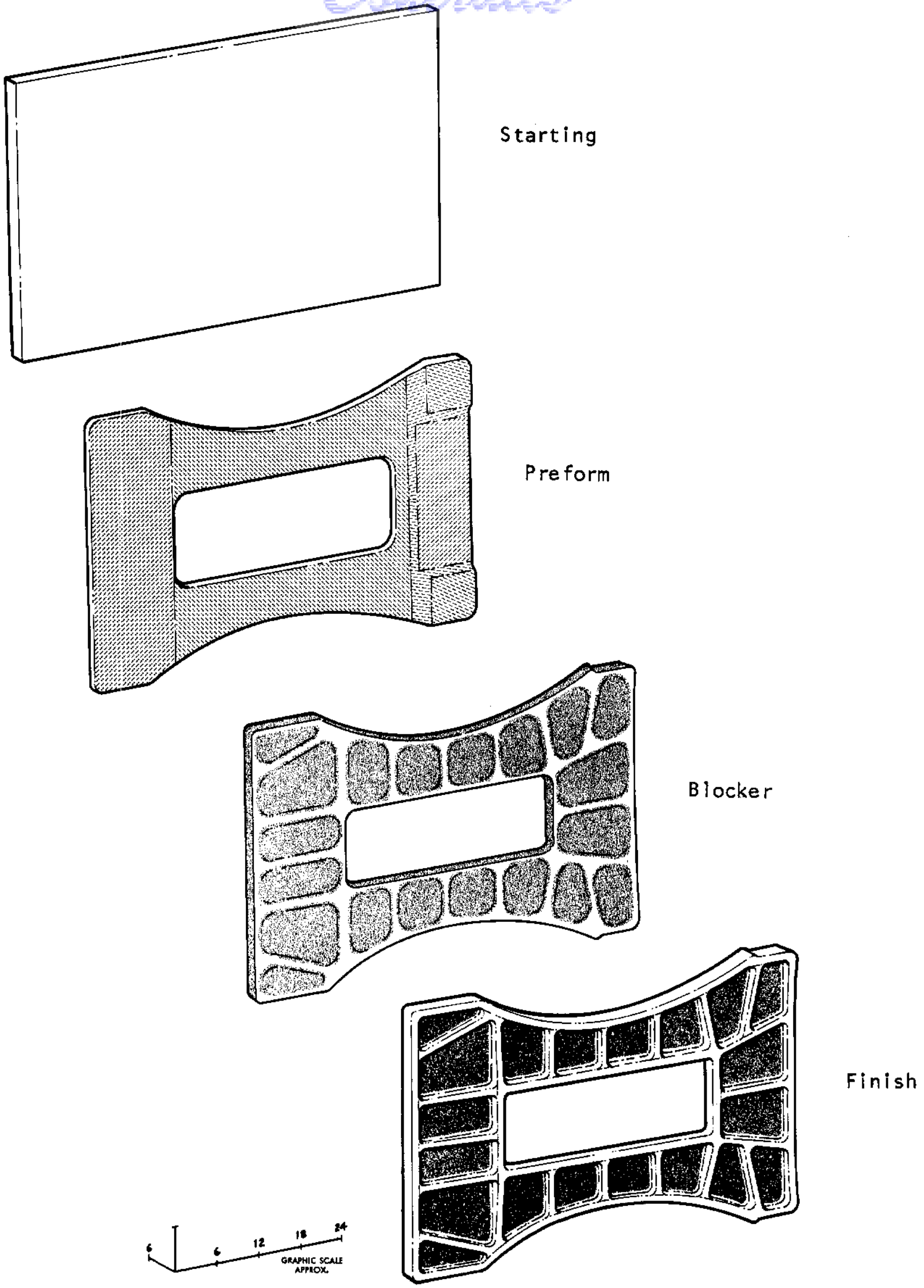

Figure 138. Illustration of Bulkhead Forging Staging Sequence Employed During Forging Efforts with 125,000 MKG Counterblow Hammer (Blocker and Finish).

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TABLE 23

Material Data for Large Bulkhead Forgings Produced with a 125,000 MKG Counterblow Hammer

Chemical Analysis	C	Si	Mn	S	P	N	Cr	V	Ni	Mo	Fe	Al	O	H	Ti
D6ac (3952187)	0.48	0.19	0.63	0.005	0.007		1.06	0.10	0.55	1.00	Bal.				
(3952188)	0.47	0.20	0.72	0.005	0.007		1.06	0.10	0.55	0.98	Bal.				
Ti 6Al-4V	0.037					0.010		3.90			0.11	6.10	0.18	0.0026	Bal.

	D6ac	Ti 6Al-4V
Material Source	Republic Steel Corp.	Oregon Metallurgical Corp.
Heat Number	Airmelt No. 3323289 VAR No. 3952187 and 3952188	4608-RD-16
Starting Stock Form	Plate-2 by 27 by 45 inches	Plate-2 by 35 by 59 inches
Starting Stock Weight	690 Pounds	661 Pounds
Procurement Specifications	AMS-6438A	The material was originally procured as 24 inch diameter ingot to Ladish specification 2T-400-R1 and requalified to AMS-4911B after Ladish conversion to 18 inch round. This billet size was subsequently converted to plate at Ladish Co., see text.
Other Inspection Procedures	Ultrasonically Inspected	Ultrasonically Inspected (as plate)

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during the fullering operation, and resulted in a Ti 6Al-4V starting stock weight of only 389 pounds for the early trial. The increase to a nominal 661 pounds which was necessary during the later forging efforts involving single operation preforming from 2 inch thick by 35 inch width by 59 inch length stock can be noted to have very significantly influenced the overall yield. The 59 inch length was torch cut to approximately 55 inches prior to preforming. The excess length is an indication that sufficient billet stock was available to back extrude to a cup shape and to ring roll a 118 inch circumference ring by the time the desired 2 inch ring wall thickness was achieved. Four such rings were produced and were cut to semi-cylindrical segments which were straightened to form eight 59 inch long sections of 2 inch thick plate stock.

4. Forging Tooling

The dies designed to produce the Figure 138 preform shape in the 15,000 ton hydraulic press were considerably different from those which were subsequently employed in the large counterblow hammer to forge the remaining shapes in the staging sequence for the bulkhead forging. The impression detail of the dies for the preform operation, Figure 139, was quite meager and no flash or gutter details were provided. Basic block sizes were 75 inch length by 42 inch width by 12 inch height each for the upper and lower dies, and the dies were of Finkl "FX" material (nominal analysis previously given) at a hardness level within the range Rc 37 to 40.

Basic block dimensions for upper and lower dies employed for blocker and finish forging operations in the 125,000 MKG counterblow hammer were 70 inch length by 56 inch width by 26 inch height. The actual dies are shown installed in the hammer in Figures 140 and 141, and design detail for the finish forging dies is illustrated in Figure 142. Interior and exterior flash lands approximately 1 inch wide were designed to provide approximately 1/8 inch thick flash at the trimlines of the bulkhead forgings. Gutter widths ranged from approximately 2 inches (interior) to 2-1/2 inches (exterior), and the exterior gutters were surrounded by "kissing" surfaces which extended to the edges of the blocks. It can be observed that the majority of the interior and exterior gutter detail was in the upper and lower die, respectively, in this instance. The two integral rectangular guide posts, which can also be observed in the three figures, assisted the counterblow hammer guiding in minimizing mismatch during closure of the dies for both operations.

All forging dies for the counterblow hammer were machined from wrought blocks of Heppenstall "Hardtem C" die steel (analysis range: 0.50 to 0.60C, 0.60 to 0.95Mn, 0.20 to 0.35Si, 0.85 to 1.15Cr, 0.38 to 0.48Mo, 0.45 to 0.60Ni, 0.03V added, bal. Fe). These were procured in the prehardened condition to a specification which allowed slightly greater latitude on the high side of the hardness range than is conventional for "Hardtem C". Hardness was within the range Rc 32 to 37.

5. Forging Results

The two D6ac bulkhead forgings produced by Ladish during the initial die try-outs are shown in Figure 143. The 2 by 27 by 45 inch starting plates were first heated to 2000°F, Table 24, and were subjected

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Figure 139. Dies for the Preform Operation in a 15,000 Ton Hydraulic Press Prior to Blocker and Finish Forging of the Bulkhead Shape in the 125,000 MKG Counterblow Hammer. Lower Die Contains the Impression. Flat-Faced Upper Die is Shown on Edge at Left from the "Dovetail" Side which Attaches to the Press Ram.

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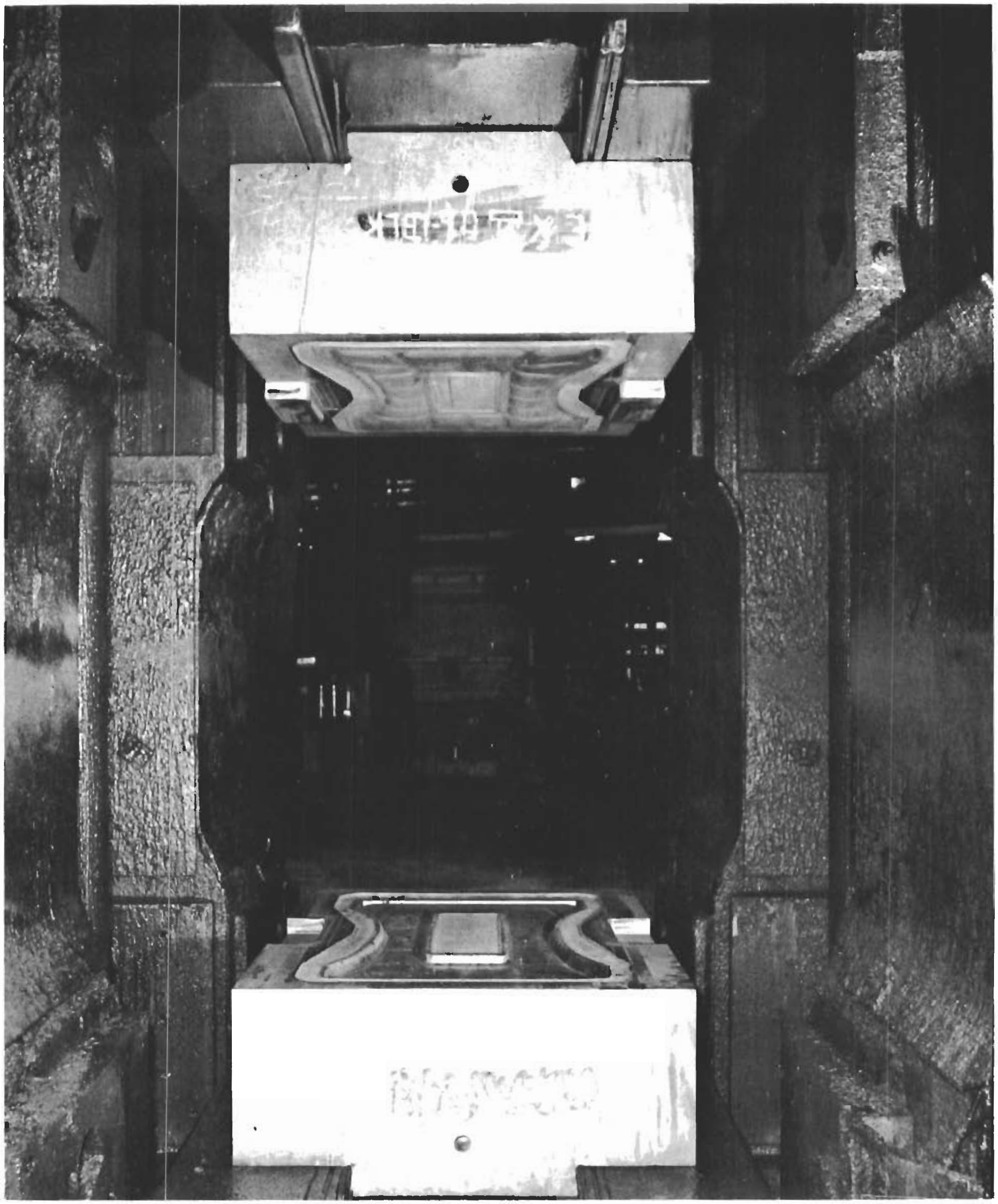

Figure 140. Dies for the Blocker Forging Operation with the 125,000 MKG Counterblow Hammer. Shown Installed in the Hammer.

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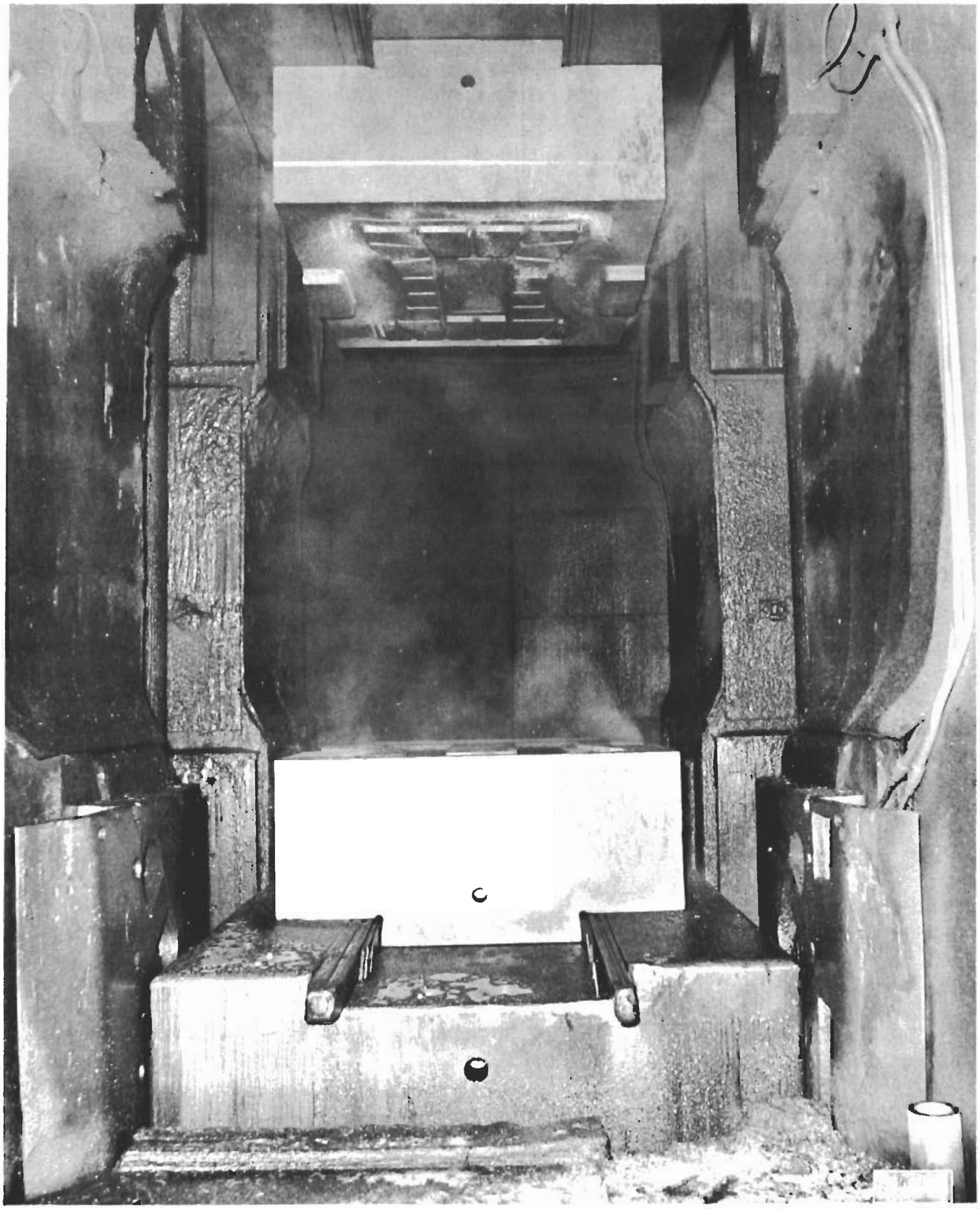

Figure 141. Dies for the Finish Bulkhead Forging Operation with the 125,000 MKG Counterblow Hammer. Shown Installed in the Hammer.

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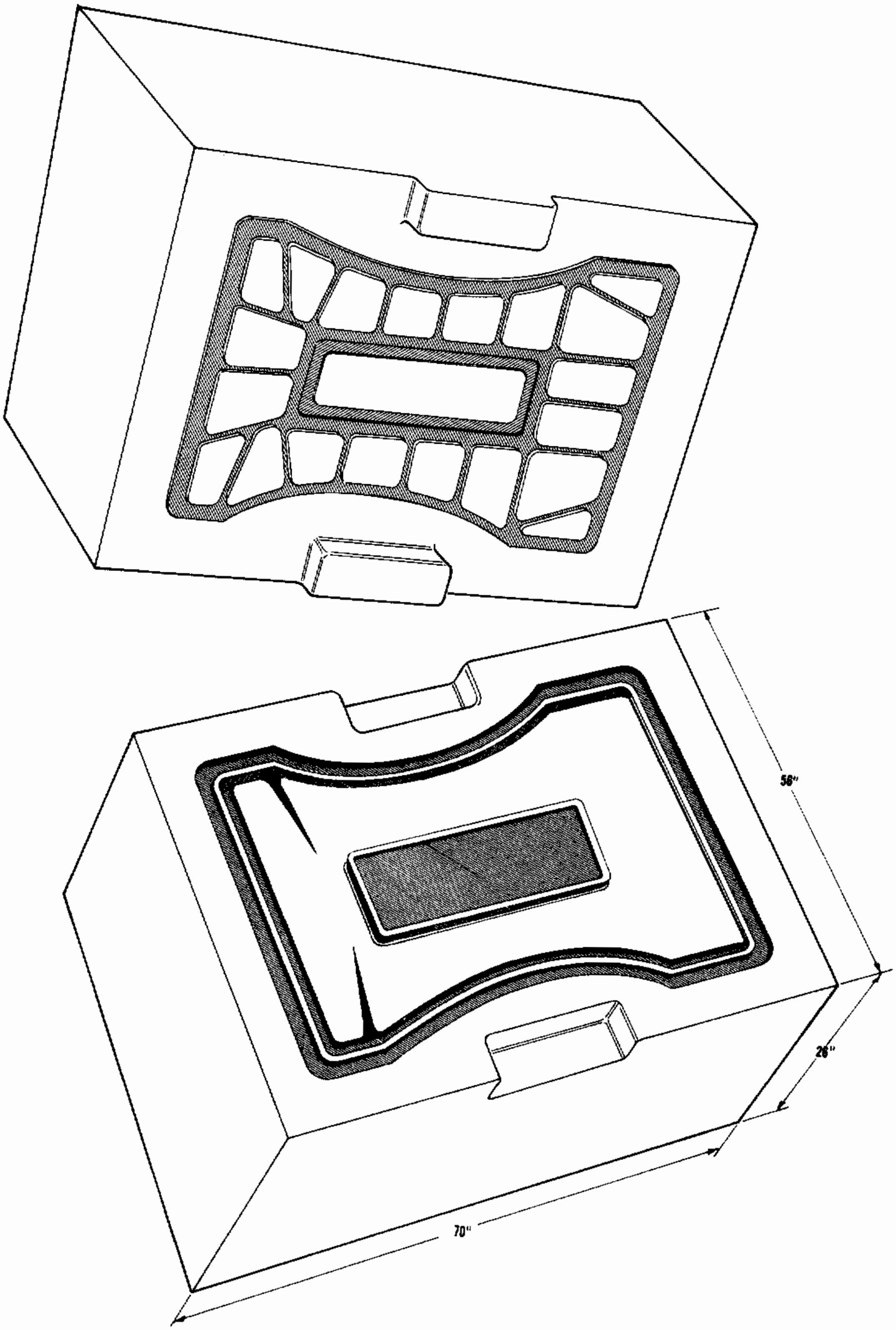

Figure 142. Schematic Illustration of Impression Dies for Finish Bulkhead Forging Operation with 125,000 MKG Counterblow Hammer.

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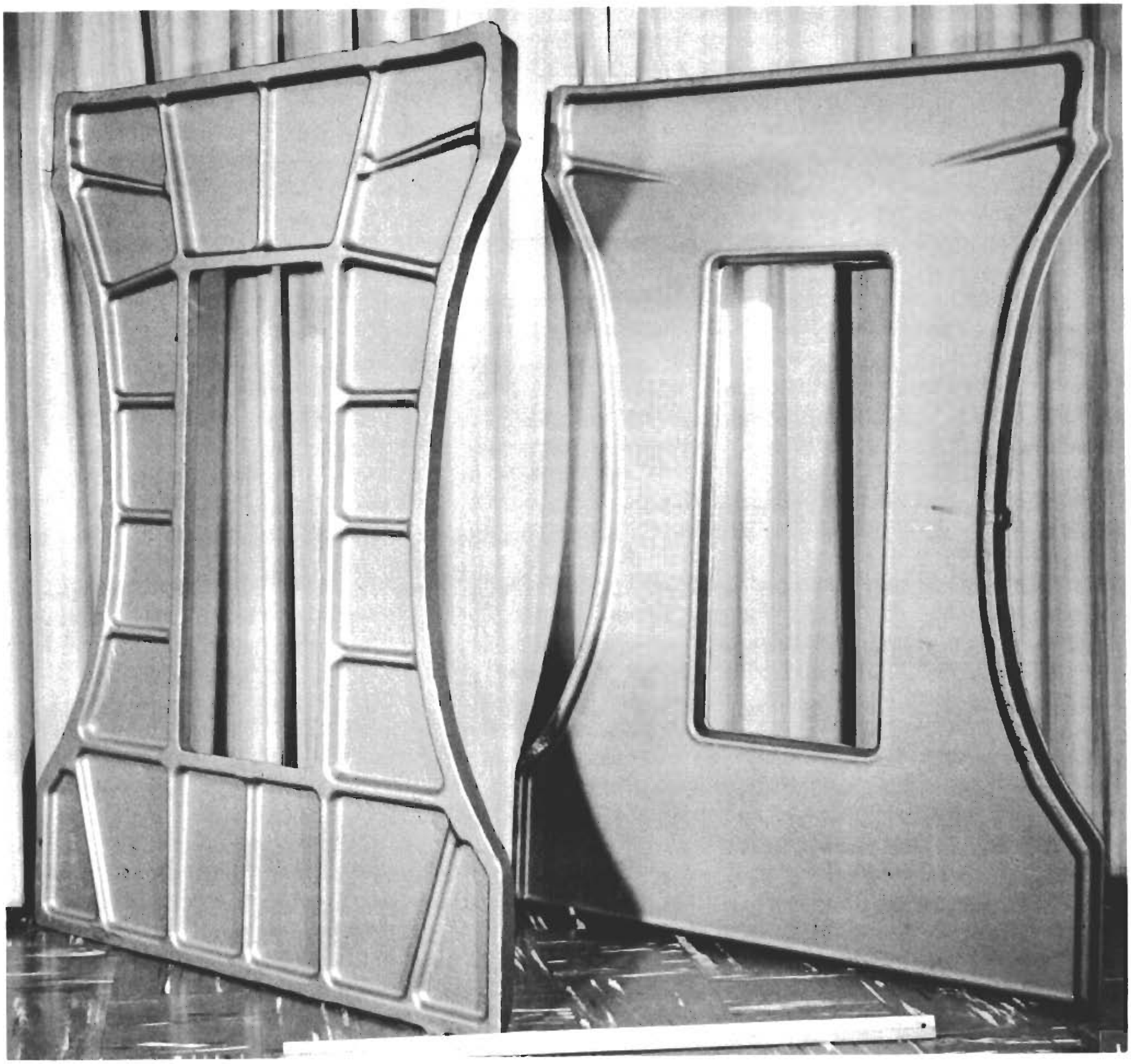

Figure 143. Two High Strength Steel (D6ac) Bulkhead Forgings Produced During Initial Die Try-Outs with 125,000 MKG Counterblow Hammer. Surfaces Shown for Forgings at Left and Right Represent Upper and Lower Die Impressions, Respectively, Shown after Trimming and Abrasive Blasting.

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TABLE 24

Processing Data for Large Bulkhead Forgings Produced with a 125,000 MKG Counterblow Hammer (a)

	Material	
	D6ac	Ti 6Al-4V
Furnace Type	Gas Fired	Gas Fired
Furnace Atmosphere	Neutral to slightly oxidizing-products of combustion	Neutral to slightly oxidizing-products of combustion
Furnace Temperature	2200°F ±25°F Final Three Stages (a)	1750°F ±25°F All Three Stages (a)
Protective Workpiece Coating	None	Proprietary
Heating Times	One Hour Maximum	One Hour Maximum
Transfer Times	30 Seconds Maximum	30 Seconds Maximum
Die Lubricant	Proprietary - Spray	Proprietary - Spray
Die Temperatures	300°F Minimum 800°F Maximum	300°F Minimum 800°F Maximum
Number of Blows per Stage (b)	15-Blocker 15-Blocker (Reheat) 20-Finish	24-Blocker 36-Blocker (Reheat) 9-Finish 17-Finish (Reheat) 15-Finish (Reheat)
Number of Reheats per Stage	One-Blocker None-Finish	One-Blocker Two-Finish
Cooling Method	Air	Air
Post Forging Thermal Treatment	None	Fg. No. LA-T2 annealed, Others none
Contact Velocity (in./sec.)	216	216

(a) - D6ac was fullered after heating to 2000°F, and was preformed with a 15,000 ton hydraulic press after heating to 2200°F. Ti 6Al-4V could not be successfully fullered and was directly preformed from starting stock. Blocker and finish operations were conducted with the 125,000 MKG counterblow hammer - see text.

(b) - Reported as an average per piece forged, plus or minus one or two blows for individual pieces.

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to the fullering operation to locally reduce the section thickness of the plate prior to torch cutting to shape and preforming. The tooling consisted of two identical, semi-cylindrical "fuller bars" mounted in a 4500 ton hydraulic press, the bed space of which was quite large to permit the plate to be manipulated from left to right and from front to back between strokes as the multiple-stroke operation progressed. Preforming was then completed for the two steel workpieces with the Figure 139 dies in the 15,000 ton hydraulic press. The pieces were heated to 2200°F in this instance and the operation was performed with a single stroke of the press.

Table 24 also lists the processing conditions employed during blocker and finish forging of the Figure 143 forgings with the 125,000 MKG counterblow hammer. After abrasive blasting and conditioning, the preforms: 1) were heated to 2200°F and struck an average of 15 blows each in the Figure 140 blocker dies; 2) were trimmed, blasted, conditioned, reheated, and again were struck an average of 15 blows each in the blocker dies; and, 3) were trimmed, blasted, conditioned, heated to 2200°F and finish forged with 20 blows in the Figure 141 dies. Post forging operations included only trimming and abrasive blasting prior to taking the Figure 143 photograph. A slight lack-of-fill condition can be observed on the outer rib of the forging on the right. The Ladish report to TRW attributed this to incorrect proportioning during the original fullering operation which was not corrected during subsequent impression die preforming.

The two D6ac bulkhead forgings were sectioned and examined for longitudinal and transverse grain flow characteristics and indications of defects. As with the steel try-out forgings produced with the large hydraulic press dies, TRW examination of the sectioned Figure 143 forgings revealed uniform grain flow and no visible evidence of defects.

At the same time the two 2 by 27 by 45 inch pieces of D6ac plate were started through the sequence, two pieces of Ti 6Al-4V plate of the same size were also started. As previously discussed, these each weighed a calculated 389 pounds and, had the results of the initial fullering operation been different, their successful use would have resulted in two significant effects on the overall forging effort. First, the forging yield in producing the titanium alloy forgings would have been much greater. Second, the blocker and/or finish operations with the large hammer would have required less reheat and restrike operations as subsequently proved necessary to remove excess metal by repetitive forging and trimming operations. However, Ladish reported that severe shear cracking occurred due to excessive localized chilling during attempts to fuller the first piece of starting plate from a heating temperature of 1750°F. Subsequent efforts with different fuller bar tooling sizes and configurations were also reported to provide the same results, and the two pieces were scrapped. These results, coupled with the similar results initially experienced by Alcoa during preforming of billet stock, illustrate the difficulties in multiple-stroke preforming of large thin shapes as are required for the bulkhead forgings and suggest use of higher temperature tooling and/or more rapid acting equipment during similar operations in future efforts involving a desire for thin titanium alloy structural forgings.

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In view of the above results, the procedure was changed to direct, single-stroke preforming of 2 by 35 by 59 inch starting plates with the Figure 139 dies in the 15,000 ton press. Two pieces were selected as trial forgings, and the other six were reserved as a six-piece "production run" to yield the five forgings to be delivered to TRW. After torch cutting to size, painting with a proprietary protective coating, and heating under the conditions in Table 24; the "trial" pieces and the "production" pieces were then successively preformed. It was noted that the 15,000 tons of force applied did not result in complete filling of the Figure 139 cavity. However, the eight Ti 6Al-4V preforms were free of defects and were considered suitably proportioned to commence with the blocker operation in the 125,000 MKG counterblow hammer.

After abrasive blasting, conditioning, and brush application of the protective coating; the two "trial" and six "production" preforms:

a) were heated to 1750°F and struck an average of 24 blows each in the Figure 140 blocker dies;

b) were trimmed and recoated;

c) were reheated to 1750°F and struck an average of 36 blows in the blocker dies;

d) were blasted, trimmed, conditioned, and coated;

e) were heated to 1750°F and struck an average of 9 blows in the Figure 141 finish dies;

f) were trimmed and recoated;

g) were heated to 1750°F and struck an average of 17 blows in the finish dies;

h) were blasted, trimmed, dimensionally checked for thickness, conditioned, and recoated;

i) were heated to 1750°F and struck an average of 15 blows in the finish dies; and

j) were blasted, trimmed, and subjected to dimensional and ultrasonic inspection.

Of the eight Ti 6Al-4V forgings successfully produced by the above efforts, the second, third, fourth, fifth, and sixth were delivered to TRW and are shown in Figures 144 and 145. These were subsequently re-serialized as LA-T1, LA-T2, LA-T3, LA-T4, and LA-T5, respectively.

Two surface conditions were observed on the titanium alloy forgings produced with the 125,000 MKG counterblow hammer. The first of these is the wrinkled appearance which was noted in the fillet radii of the lower die surface of forging LA-T5 as shown in Figure 146 and, to a lesser extent, the other four forgings. No reason was advanced for this condition. Second, all of the forgings contained localized indications of laps in fillet radii representing the upper die surface. The worst such indications noted can be seen in Figure 147. Ladish, in the subcontract report to TRW, attributed these "to the shallow draft angle in conjunction with die shift"; and it

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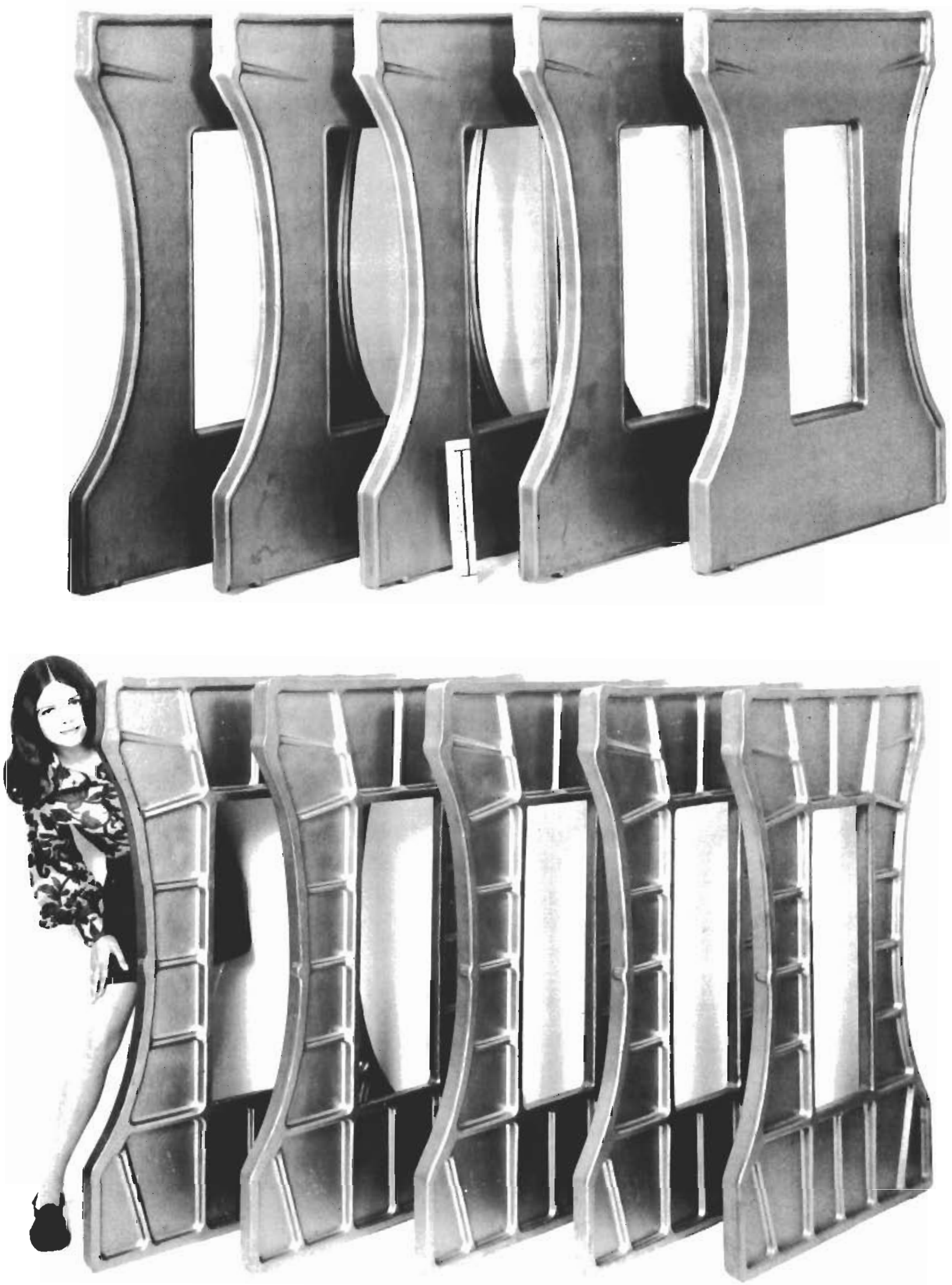

Figure 144. Five Titanium Alloy (Ti 6Al-4V) Bulkhead Forgings Produced with 125,000 MKG Counterblow Hammer for TRW Evaluation. Upper and Lower Views Represent Upper and Lower Die Impressions, Respectively, for the Finish Forging Operation. Shown after Trimming and Abrasive Blasting.

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Figure 145. Close-Up of Two of the Ti 6Al-4V Bulkhead Forgings Produced with the 125,000 MKG Counterblow Hammer and Delivered to TRW.

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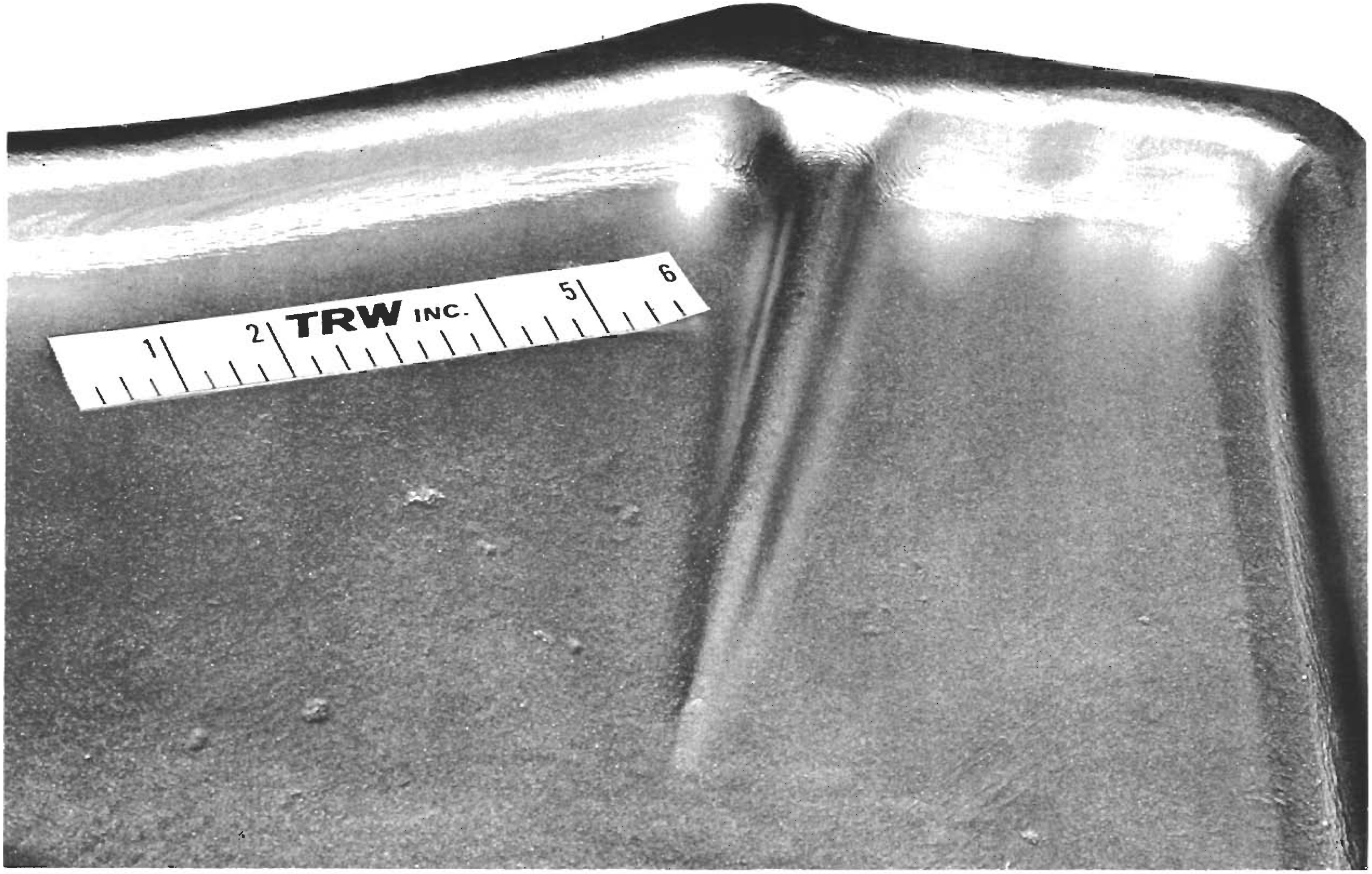

Figure 146. Wrinkled Surface Condition Exhibited in Fillet Radii of the Lower Die Side of the Seventh Ti 6Al-4V Bulkhead Forging Produced (of Eight Forgings Total, the Fifth of the Five Delivered to TRW) with the 125,000 MKG Counterblow Hammer.

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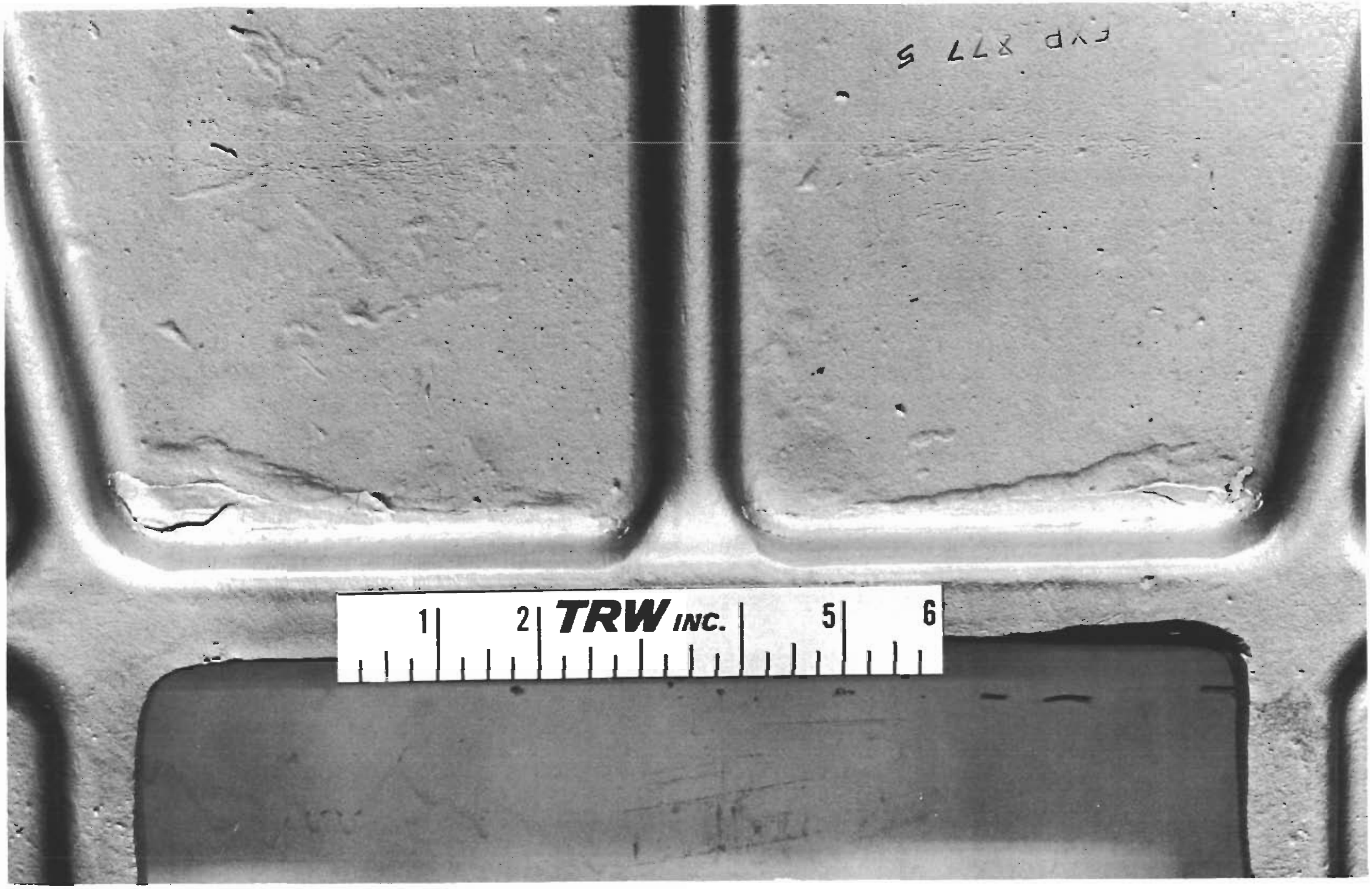

Figure 147. Laps in Fillet Radii on the Upper Die Side of the Fith Ti 6Al-4V Bulkhead Forging Produced (of Eight Forgings Total, the Fourth of the Five Delivered to TRW) with the 125,000 MKG Counterblow Hammer.

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was observed at TRW that virtually all of the indications lay on the same side of cross and end rib fillets, supporting a theory of a reproducible die shift condition. Ladish inspection, using ultrasonic and "local probe grinding" techniques, indicated that the defects were shallow and would not affect Figure 2 bulkhead components if machined from the forgings. The Ladish report further pointed out that the defects were left in the forgings for the purposes of the program and that "under any other circumstances, all defects are removed and appropriate nondestructive inspection methods are employed to verify removal prior to shipment". The defects were, of course, a subject of TRW evaluation as will be described later. It is noteworthy that the more easily deformed D6ac forgings exhibited no indications of a tendency to form laps in the fillet areas.

Ladish indicated that; in dealing with large surface area, thin section configurations that cool rapidly (as exemplified by the bulkhead forgings); the large hammer is generally "stroked to capacity" for virtually all of the blows required. This was verified in the opinions of TRW personnel who observed forging operations during production of the titanium alloy pieces. This indicates that of the order of 100,000,000 foot-pounds of energy were expended in accumulating the average total number of blows (101, see Table 24) required to process each titanium alloy forging through the two blocker and three finish operations. Hammer forging of the bulkheads was discontinued at this point because Ladish dimensional inspection indicated that the goal of a "two machining pass" forging envelope (see Figure 5) had been attained. In-process dimensional inspection before and after the final reheat and restrike effort showed thickness reductions of 0.050 inch to 0.070 inch per side, or an average thickness reduction of 0.120 inch as a result of the average of 15 blows struck.

It is coincidental that the two opposed ram impact energy machines represented in the program; the Model HE-55, CEFF-type HERF machine and the 125,000 MKG counterblow hammer; both achieved average forging thickness reductions of 0.12 inch (0.01 foot) during final restrike efforts. The coincidence provides an interesting and useful parallel, however, because it illustrates that average unit force calculated for hard blows with an impact energy machine without consideration of tooling and ram deflections are incorrect to the point of being meaningless. For the CEFF machine in forging of the Inconel 718 alloy, it has previously been discussed that the average unit force in the absence of an elastic response by the dies and rams would have been 463,000 psi over the 54 square inch fin rib forging. It has also been pointed out that the upper die cracked during final production of the fifth Inconel 718 forging. During the final 15 blow (average) effort in production of the 1350 square inch Ti 6Al-4V bulkhead forgings, it appears reasonable to assume that the large hammer was delivering blows averaging at least 1,000,000 foot pounds each, considering that the hammer provides as much as 1,080,000 foot pounds per blow under "nominal" conditions. If it could also be considered that each blow was responsible for 1/15 of the 0.01 foot total deformation experienced (any other consideration would provide an even higher value of force for at least one blow), then the total force expressed as energy divided by distance would be 1,500,000,000 pounds for each of the 15 blows under conditions of completely rigid dies

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and rams. This would represent repeated average unit forces of 1,110,000 psi on the Figure 141 die impressions, which were inspected by TRW personnel and which showed virtually no deterioration after all forging efforts were completed.

On the basis of the above comparison, it is obvious that elastic effects on dies and die support members of impact energy machines must be increasingly taken into account as the forging becomes thinner until finally the elastic response alone must be considered in attempting to define forces on die impressions and undeformable workpieces. This subject will be reviewed in greater depth in the general discussion of program results provided in Section VIII of this report.

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VII EVALUATION AND COMPARISON OF LARGE FORGINGS

The evaluation schedule for the large bulkhead forgings was patterned after that employed to establish the comparative precision, quality, and mechanical property levels of the smaller fin rib forgings. After delivery to TRW, the Ti 6Al-4V bulkhead forgings from the large press and the large counterblow hammer were identified, re-serialized, sandblasted, visually inspected for unfilled areas and surface defects, and photographed as described in the previous report section. They were then weighed, dimensionally inspected, and subjected to fluorescent penetrant inspection. Following these procedures, the forgings were selectively sectioned for further investigation of defects and for evaluation of macro- and microstructural characteristics, response to heat treatment, and mechanical properties.

Although scheduled in a similar manner, the techniques employed in evaluating the large bulkhead forgings were, in certain instances, different from those used with the fin rib forgings. This was due to the size of the large forgings (e.g., the Sheffield Ferranti machine used for dimensional inspection of fin rib forgings could not provide the probe travel required to inspect the bulkhead forgings) and also because there were comparatively few of the large forgings. Fourteen bulkhead forgings were received by TRW and, of these, only the ten Ti 6Al-4V forgings were completely evaluated. The four sectioned D6ac forgings were evaluated and compared relative to heat treat response and mechanical properties. Detailed comparisons of precision and quality levels were not considered appropriate in this instance because the four forgings were produced during initial die try-out efforts.

A. Precision

1. Weights

a) Procedures

Each of the ten Ti 6Al-4V bulkhead forgings were weighed on a large platform scale which has a dial graduated in two-pound increments. The forgings weights were interpolated to the closest pound.

b) Results

Weights of the Ti 6Al-4V bulkhead forgings are listed in Table 25. As noted, the values listed for the hydraulic press forgings are each 12 pounds less than the values actually recorded. This was to achieve more valid comparisons by removing the calculated weight of the projections added by Alcoa representing their standard practice in providing material control samples and "hold down tabs" for machining of forgings. It can be observed that, even after this adjustment, the press forgings were much heavier than the hammer forgings. In terms of forging-to-forging consistency in weight, however, the two groups of forgings were quite similar.

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TABLE 25

Weights of Ti 6Al-4V Bulkhead Forgings

Machine	Forging Number	Weight (pounds)
50,000 Ton Hydraulic Press	AL-T1	311(a)
	AL-T2	311(a)
	AL-T3	314(a)
	AL-T4	308(a)
	AL-T5	307(a)
	Average	310
	Variation	7
125,000 MKG Counterblow Hammer	LA-T1	236
	LA-T2	237
	LA-T3	232
	LA-T4	232
	LA-T5	231
	Average	234
	Variation	6

(a) - Hydraulic press forgings were each actually 12 pounds heavier. Values listed represent adjusted weights after removal of calculated weight of extra projections for "hold-down tabs", etc. = see text.

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2. Dimensions

a) Procedures

The conventional techniques employed for dimensional inspection of the ten Ti 6Al-4V bulkhead forgings can best be appreciated by reviewing the photograph in Figure 148. A holding fixture was prepared and placed on a large granite top inspection table. The fixture was equipped with an adjustable lower locating pad at one end and adjusting screws as shown such that lateral and vertical reference planes on the forging could be accurately established relative to the granite surface and to ground steel rails on the sides of the fixture. This allowed correct, repeatable location of dial indicator probes for measurement of rib height and web thickness (as shown) at any inspection data point desired. Inspection data were taken from both sides of the forging, were referenced from both rails, and the desired height or thickness value was determined by subtracting both balues from the known distance between the two rail surfaces.

Each forging was inspected at the forty web thickness and twenty-eight rib height locations illustrated in Figure 149. The reference planes employed to correctly locate the forging in the fixture and to afford dimensional reference for the data points are also indicated. It can be noted that the data were actually taken in linear longitudinal and transverse patterns which corresponded to the dimensional inspection planes A-A through G-G shown.

In addition to the above, fillet and corner radii were measured at the eighty-four locations and rib thickness values were obtained at the twenty-eight locations intersecting the inspection section planes in Figure 149. Radius gages and ball micrometers were employed for these measurements.

b) Results

Typical design fillet radii for the press and hammer forgings were 0.500 and 0.375 inch respectively. Typical design corner radii were 0.312 inch for both types of forgings. Results of dimensional inspection indicated that, within the accuracy levels afforded by radius gages, the press and the hammer forgings met their design targets relative to radii. Review of the rib thickness data also revealed no significant information. The ribs of the hammer forgings were designed to be moderately thinner at most locations, and comparison of the inspection results confirmed that this was the case.

Comparison of the rib height and the web thickness data taken at the sixty eight Figure 149 locations revealed the significant dimensional differences between the forgings from the two types of machines. The web thickness data are presented in terms of average (mean), minimum, maximum, maximum minus minimum (range), and standard deviation values in Table 26. Each press die impression was prepared with all web forming surfaces flat and in a single plane to provide a target thickness of 0.750 inch (without tolerances) at all web pockets of the bulkhead forgings. All forty values obtained from each forging were therefore employed in calculating the Table 26 data for the hydraulic press forgings. The hammer forging dies,

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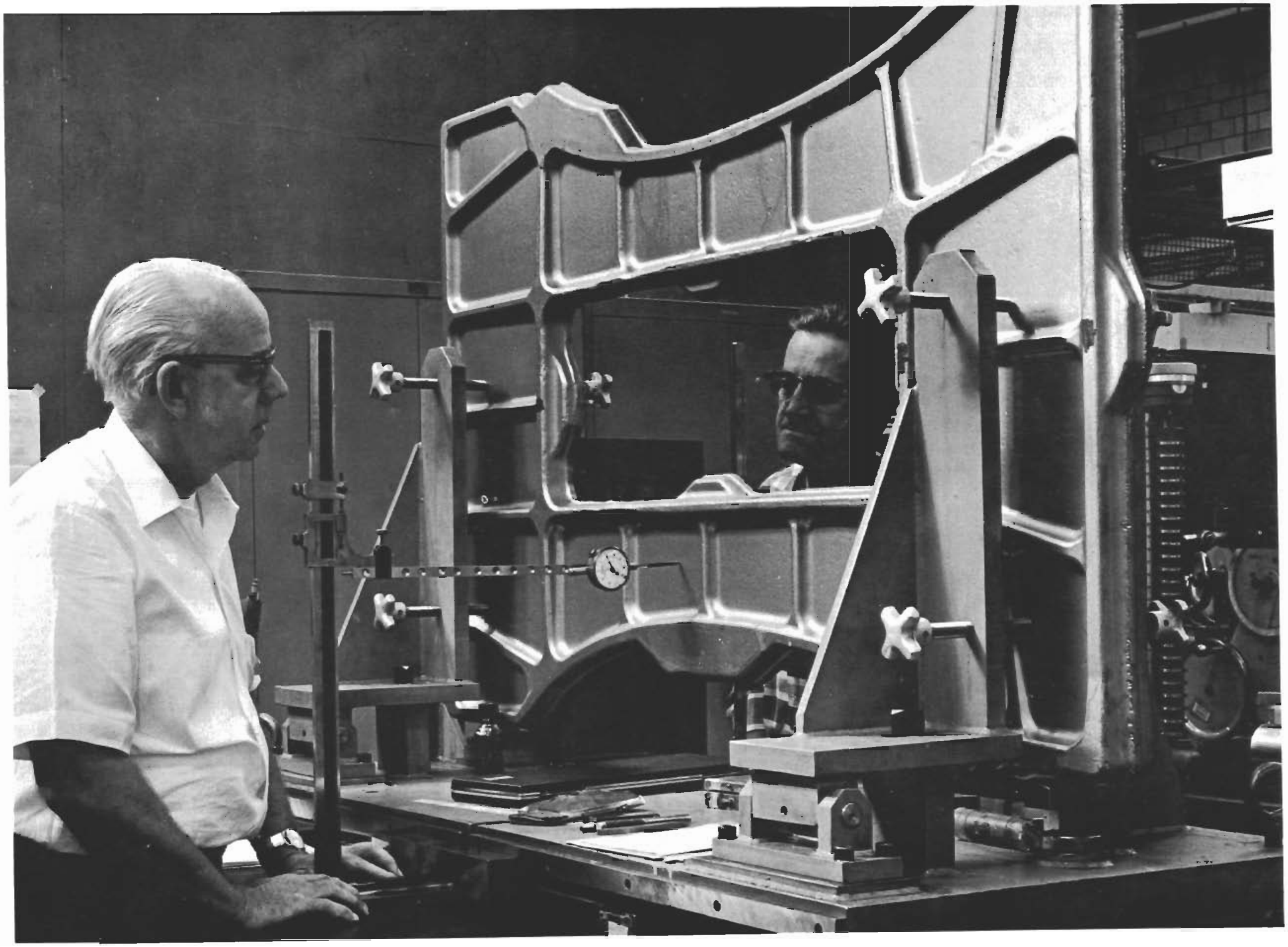

Figure 148. Dimensional Inspection of Ti 6Al-4V Bulkhead Forging Showing Details of Holding Fixture and Gaging Employed.

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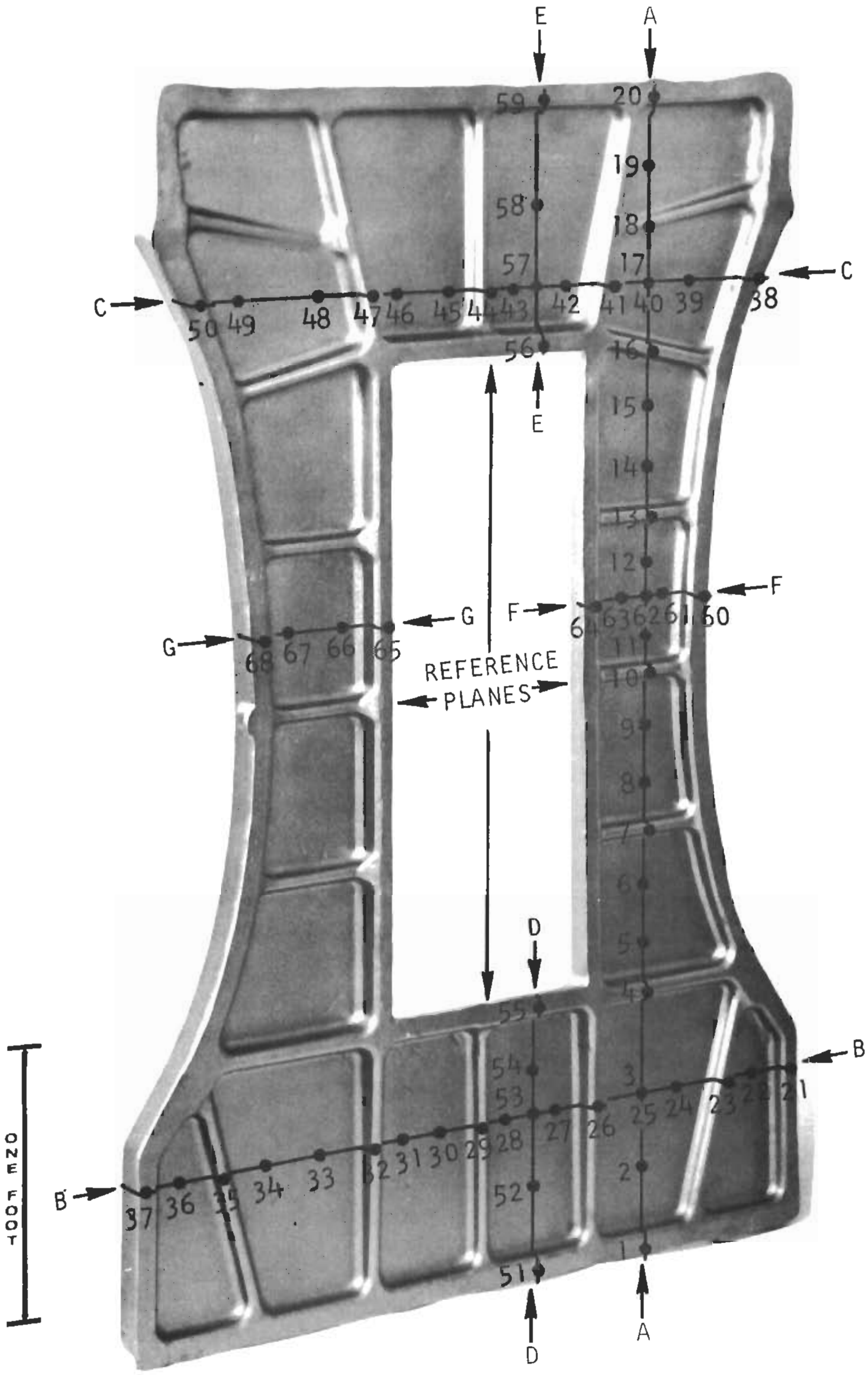

Figure 149. Locations of Inspection Section Planes and Data Measurement Points Employed for Dimensional Evaluation of Rib Height and Web Thickness Characteristics of Ti 6Al-4V Bulkhead Forgings.

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TABLE 26

Web Thickness Characteristics of Ti 6Al-4V Bulkhead Forgings

Machine	Forging Number	Number of Values in Average	Average Thickness (inches)	Lowest Value (inches)	Highest Value (inches)	Total Variation (inches)	Standard Deviation (inches)
50,000 Ton Hydraulic Press	AL-T1	40[(a)]	1.081	1.019	1.138	0.119	0.022
	AL-T2	40[(a)]	1.079	1.020	1.138	0.118	0.020
	AL-T3	40[(a)]	1.084	1.019	1.126	0.107	0.026
	AL-T4	40[(a)]	1.052	0.940	1.104	0.154	0.029
	AL-T5	40[(a)]	1.056	0.983	1.086	0.103	0.024
	All Five	200	1.070	0.940	1.138	0.198	0.028
125,000 MKG Counterblow Hammer	LA-T1	34[(b)]	0.723	0.703	0.763	0.060	0.017
	LA-T2	34[(b)]	0.749	0.681	0.788	0.107	0.022
	LA-T3	34[(b)]	0.715	0.680	0.748	0.068	0.019
	LA-T4	34[(b)]	0.725	0.700	0.749	0.049	0.015
	LA-T5	34[(b)]	0.716	0.691	0.755	0.064	0.017
	All Five	170	0.726	0.680	0.788	0.108	0.028
125,000 MKG Counterblow Hammer	LA-T1	6[(c)]	0.789	0.773	0.796	0.023	0.008
	LA-T2	6[(c)]	0.822	0.808	0.832	0.024	0.011
	LA-T3	6[(c)]	0.800	0.783	0.809	0.026	0.009
	LA-T4	6[(c)]	0.795	0.783	0.810	0.027	0.011
	LA-T5	6[(c)]	0.784	0.772	0.813	0.041	0.015
	All Five	30	0.798	0.772	0.832	0.060	0.017

(a) - Uniform target thickness of 0.750 inch at all forty web locations in Figure 149.

(b) - Target thickness of 0.500 inch at thirty-four web locations in Figure 149.

(c) - Target thickness of 0.625 inch at Figure 149 location numbers 17, 19, 39, 40,48, and 49.

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however, were prepared to provide a target 0.625 inch web thickness at the corner web pockets dimensionally identified by data point numbers 17, 19, 39, 40, 48, and 49 in Figure 149; and a target thickness of 0.500 inch at all other web areas. For this reason, the Table 26 data for the hammer forgings were calculated separately for the thirty-four thinner and the six thicker web locations on each forging.

Upon analyzing the data in Table 26, several dimensional characteristics of the bulkhead forgings become apparent. The forgings produced by the counterblow hammer were not only considerably thinner, but were also characterized by less variation in web thickness. Comparison of the standard deviation values for the individual forgings also indicates less variation in web thicknesses of individual forgings produced with the hammer. However, the fact that both large groups of values representing all five forgings in each case resulted in the same standard deviation suggests statistically equivalent control of combined accuracy and reproducibility tolerance factors through each of the two forging runs. Further review of the individual data values revealed that only five of the 200 values from the press forgings fell below 1.000 inch and that only twenty-one values exceeded 1.100 inch; i.e., thirteen percent of the values were responsible for doubling the total variation range to the 0.198 inch value listed in Table 26. In contrast, the majority of the 170 web thickness values listed for the hammer forgings were closer to the low and the high limits listed, thus the 0.108 inch total variation range is more representative in this instance. Unfortunately, the occasional low and high values from the press forgings appeared to be random and could not be correlated with forging process data or particular forging locations. For this reason recommendations regarding press forging practices or conclusions relative to comparative die deflection characteristics afforded by the two machines cannot be given.

The average web thickness values for the bulkhead forgings are compared with their targets (without tolerances) in Table 27. The data indicate that the hammer forgings were produced closer to their nominal target thicknesses in spite of the fact that both targets for the hammer forgings were thinner than was the single target thickness value for the press forgings. It is also interesting to note that the two groups of average thickness values for the hammer forgings do not reflect the total 0.125 inch difference in the target values. Assuming that the die impressions were accurately machined to provide the 0.125 inch difference, the fact that the thicker areas only showed an approximately 0.075 inch increase in thickness must be indicative of differences in deflection between those portions of the impressions which formed the thinner and the thicker web pockets.

It can be observed in Figure 2 that the web pockets of the very sophisticated machined bulkhead are "sculptured" to different thicknesses. The central, thinner areas of different pockets vary in nominal thickness from 0.040 to 0.075 inch and the thicker areas near the fillet radii range upward in thickness to nominal values as high as 0.200 inch. For convenience, a single (0.075 inch) thickness value was employed in calculating the average envelope thicknesses listed in Table 27. It can be observed from the data that web areas of the hammer forgings met the Figure 5 program target of a "two machining pass", 0.375 inch maximum

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TABLE 27

Web Thickness Characteristics of Ti 6Al-4V Bulkhead Forgings

Machine	Forging Number	Number of Values in Average	Average Thickness (inches)	Target Thickness (inches)	Average Off-Target (inches)	Average Envelope (inches)(d)
50,000 Ton Hydraulic Press	AL-T1	40(a)	1.081	0.750	+0.331	0.503
	AL-T2	40(a)	1.079	0.750	+0.329	0.502
	AL-T3	40(a)	1.084	0.750	+0.334	0.505
	AL-T4	40(a)	1.052	0.750	+0.302	0.489
	AL-T5	40(a)	1.056	0.750	+0.306	0.491
	All Five	200	1.070	0.750	+0.320	0.498
125,000 MKG Counterblow Hammer	LA-T1	34(b)	0.723	0.500	+0.223	0.324
	LA-T2	34(b)	0.749	0.500	+0.249	0.337
	LA-T3	34(b)	0.715	0.500	+0.215	0.320
	LA-T4	34(b)	0.725	0.500	+0.225	0.325
	LA-T5	34(b)	0.716	0.500	+0.216	0.321
	All Five	170	0.726	0.500	+0.226	0.326
125,000 MKG Counterblow Hammer	LA-T1	6(c)	0.789	0.625	+0.164	0.357
	LA-T2	6(c)	0.822	0.625	+0.197	0.374
	LA-T3	6(c)	0.800	0.625	+0.175	0.363
	LA-T4	6(c)	0.795	0.625	+0.170	0.360
	LA-T5	6(c)	0.784	0.625	+0.159	0.355
	All Five	30	0.798	0.625	+0.173	0.362

(a) - Uniform target thickness of 0.750 inch at all forty web locations in Figure 149.

(b) - Target thickness of 0.500 inch at thirty-four web locations in Figure 149.

(c) - Target thickness of 0.625 inch at Figure 149 location numbers 17, 19, 39, 40, 48, and 49.

(d) - Nominal values for web thickness of the finished (Figure 2) bulkhead vary from 0.040 to 0.200 inch, with several intermediate values including 0.075 inch. The latter was chosen as a common base for calculation of average envelope thickness values in this column.

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thickness of excess material in enveloping a 0.075 inch thick component web; whereas the average envelopes of web areas of the press forgings were approximately 1/8 inch thicker than the target maximum.

In reviewing the results of dimensional evaluation of the large Ti 6Al-4V bulkhead forgings, the comparison of greatest significance involves the capability of the large counterblow hammer to produce such forgings with thinner envelopes of excess metal when conditions of use of conventional die steels and heating and forging temperatures below the beta transus are imposed. The difference is illustrated in Figures 150 and 151, which show section A-A (longitudinal) and section B-B (transverse) profiles drawn from forging inspection data and superimposed over the component profiles for the same section planes. Although comparisons relative to other "precision" factors are less apparent, the Tables 26 and 27 data also indicate that the large counterblow hammer is capable of providing the thinner forgings to combined reproducibility and accuracy tolerances at least equivalent to those afforded by the 50,000 ton hydraulic press.

B. Quality

1. Freedom from Defects

a) Procedures

The ten Ti 6Al-4V bulkhead forgings were inspected for surface defects using post emulsification fluorescent penetrant procedures in accordance with specification MIL-I-6866B, Type I, Method B. A small section was then taken through a typical area of the only type of defect identified, the apparently "lapped" condition in certain fillet radii of the hammer forgings. This sample was mounted, polished, and etched with 2 percent hydrofluoric acid plus 2 percent nitric acid in water.

b) Results

Results of fluorescent penetrant inspection indicated that the five Ti 6Al-4V forgings produced with the 50,000 ton press contained no surface defects. The surface condition noted at localized fillet and corner radii areas, Figure 133, did not retain penetrant.

Fluorescent penetrant inspection also confirmed that all five of the Ti 6Al-4V forgings from the 125,000 MKG counterblow hammer contained defects at the localized areas in fillet radii which had been observed visually. The most severe visual indication has been shown in Figure 147. A photomacrograph and a photomicrograph of a cross section through a more typical (less severe) example of this type of defect are shown in Figure 152. The progressive "lapping" that occurred as a result of the multiple blow action of the hammer is very apparent. The normal-to-surface depth of this defect is 0.040", and it can be noted in the photomacrograph that the grain flow in the radius has not been seriously disturbed. These features, in conjunction with the degree of excess metal in the bulkhead forgings, Figures 150 and 151, support the previously discussed Ladish indication that "the defects were shallow and would not affect Figure 2 bulkhead components if machined from the forgings". However, such "lapping" indications cannot be as easily tolerated in circumstances where forged shapes more closely envelop component designs.

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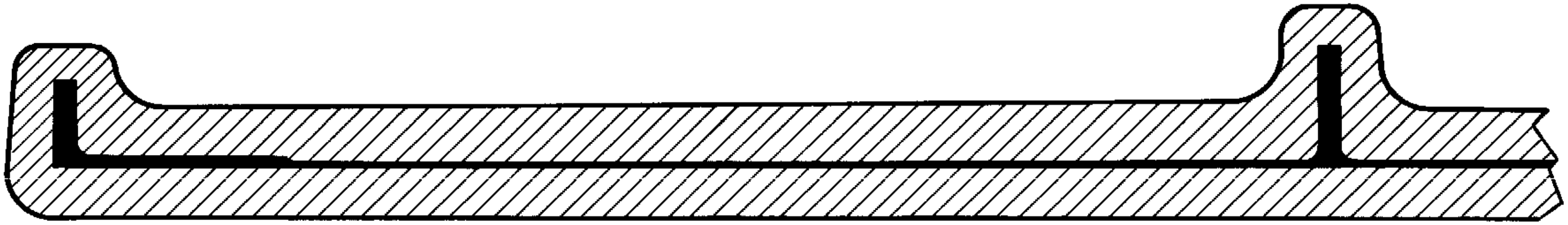
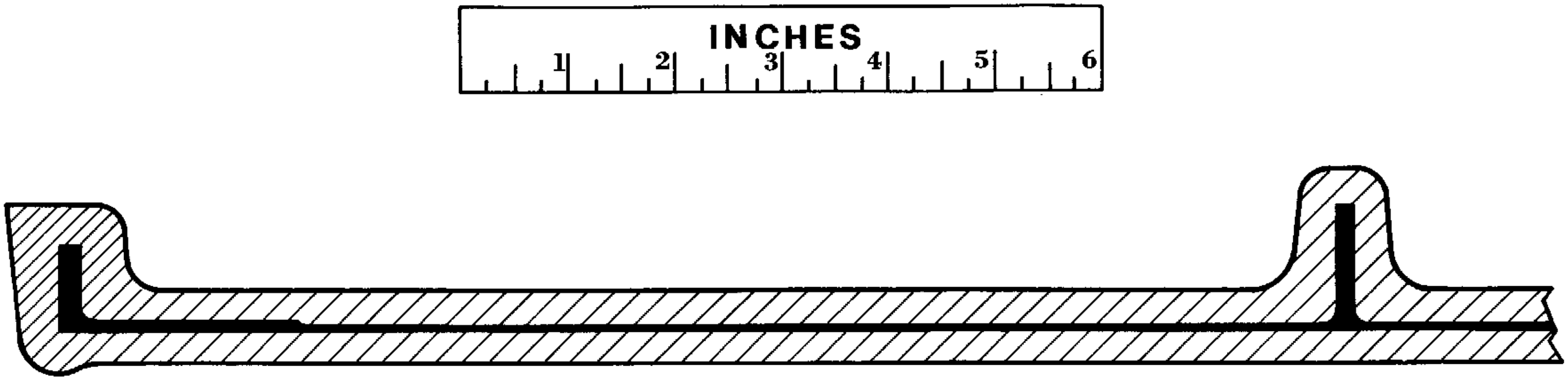


(a) 50,000 Ton Hydraulic Press



(b) 125,000 MKG Counterblow Hammer

Figure 150. Ti 6Al-4V Bulkhead Forging Cross Section Profiles Prepared from Dimensional Inspection Data and Superimposed Over the Figure 2 Component Cross Section Profile at the Same Location. Inspection Data from Forging Numbers AL-T3 (top) and LA-T3 (bottom). Location Corresponds to Section A-A, Points 1 Through 5 in Figure 149.

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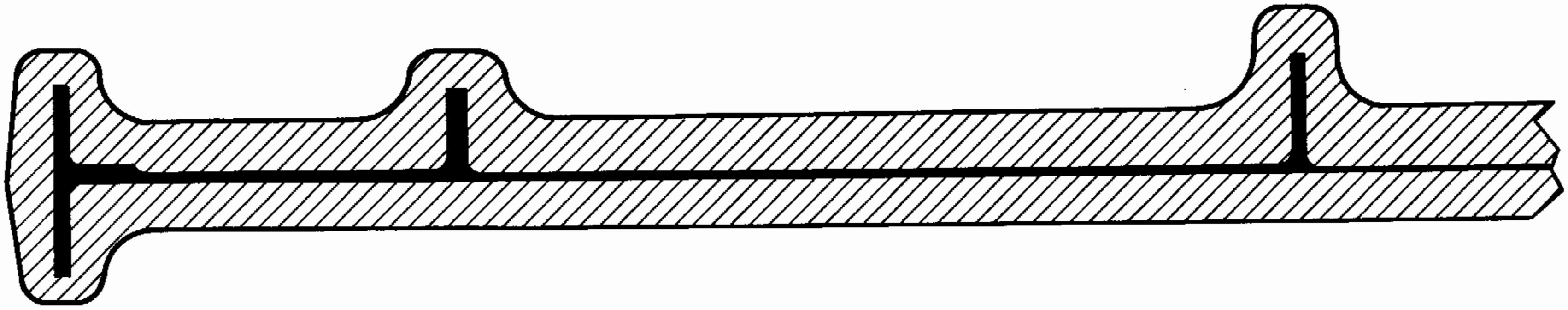
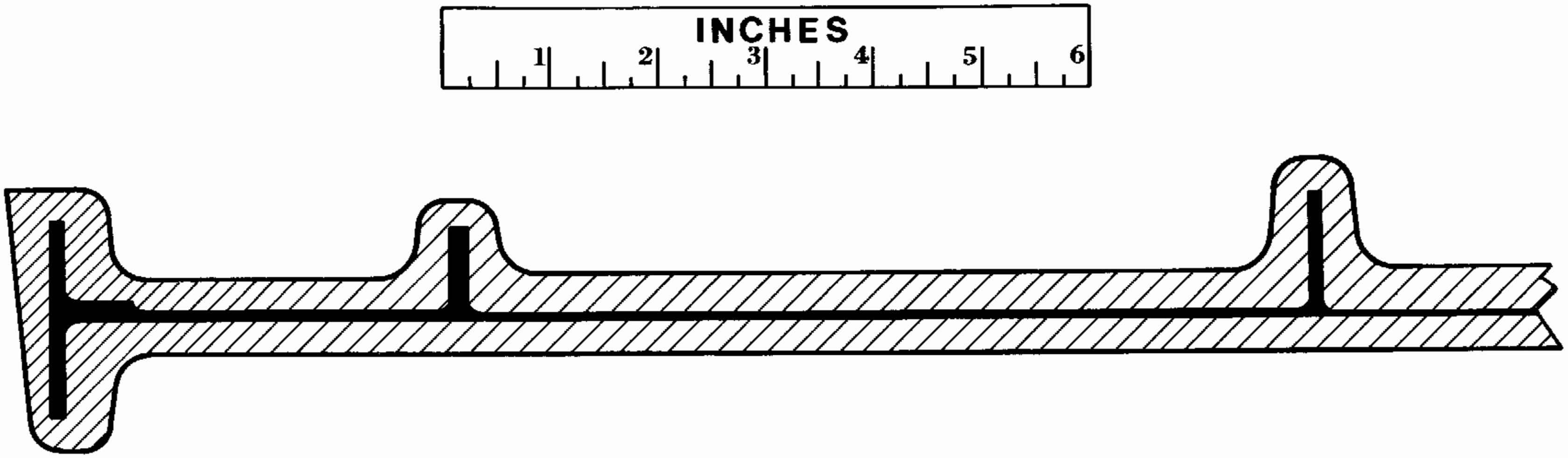


(a) 50,000 Ton Hydraulic Press



(b) 125,000 MKG Counterblow Hammer

Figure 151. Ti 6Al-4V Bulkhead Forging Cross Section Profiles Prepared from Dimensional Inspection Data and Superimposed Over the Figure 2 Component Cross Section Profile at the Same Location. Inspection Data from Forging Numbers AL-T1 (top) and LA-T1 (bottom). Location Corresponds to Section B-B, Points 31 Through 37 in Figure 149.

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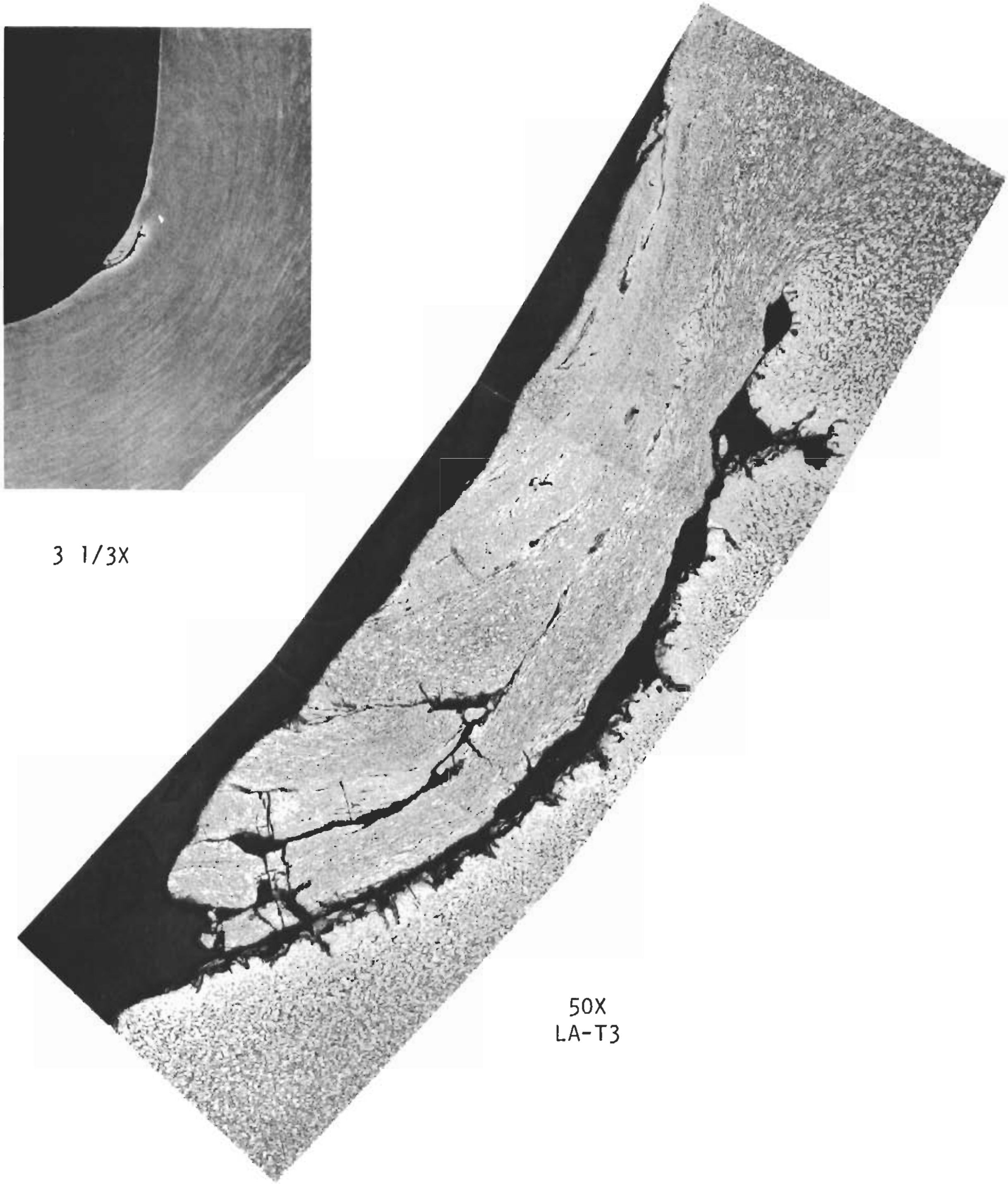

3 1/3X

50X
LA-T3

Figure 152. Photomacrograph and Composite Photomicrograph of Progressive Lap in Rib-Web Fillet of Ti 6Al-4V Bulkhead Forging Produced with the 125,000 MKG Counterblow Hammer. Also See Figure 147.

1449 c

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Rather than the ultimate reduction in section thickness which can be achieved, the "lapping" tendency discussed above appears to limit the effectiveness of multiple-blow techniques in furnishing highly detailed structural forgings with cross sections which require ribs to be precisely formed by the upper die.

2. Macro- and Microstructures

a) Procedures

The macrostructural features of the Ti 6Al-4V bulkheads were representatively evaluated from longitudinal sections of the third forging and transverse sections of the first forging of each series. For forging nembers AL-T3 and LA-T3, the sections were taken along plane A-A in Figure 149. For forgings AL-T1 and LA-T1, the sections corresponded to plane B-B. After sectioning approximately 1-1/4 inch wide strips at these locations with an abrasive cutoff wheel, the strips were further sectioned to shorter length segments to facilitate finishing and etching.

All segments were milled to a uniform 3/4 inch width. This operation removed approximately 1/4 inch from all section surfaces and was conducted to avoid the possible influence of thermal effects from the cut-off operation on the macrostructures. After finishing by surface grinding, the sections were etched with 5 percent hydrofluoric acid in water.

Metallographic studies of "as-received" D6ac and Ti 6Al-4V materials from bulkhead forgings were conducted by further sectioning and removal of samples from web areas close to data points 2 and 11 in Figure 149, and from the large rib identified by data point 20 in the same figure. These were all from D6ac forging numbers AL-S2 (stress relieved at 1200°F, see Table 22) and LA-S2 (as-forged), from Ti 6Al-4V forging numbers AL-T3 and LA-T3 (both as-forged). The three samples from each of the four forgings were then further sectioned, mounted, polished, and etched to reveal: 1) longitudinal and transverse microstructures of mid-thickness web material at the point 2 location, 2) longitudinal and transverse microstructures of mid-thickness web material at the point 11 location, 3) transverse microstructures of near-surface material at the point 11 location, 4) longitudinal and transverse microstructures of mid-thickness rib material at the point 20 location, and 5) longitudinal microstructures of near surface rib material at the point 20 location (close to the parting line for the press forgings). Metallographic samples were also sectioned and prepared from mid-thickness web material (point 11) of D6ac forging numbers AL-S1 and LA-S1 and of Ti 6Al-4V forging numbers AL-T1, AL-T5, LA-T1, and LA-T5 to allow observation of forging-to-forging consistency of microstructural features within the four small groups of forgings represented.

The etchants used were 2 percent Nital for D6ac samples and 2 percent hydrofluoric acid plus 2 percent nitric acid in water for the Ti 6Al-4V samples. Photomicrographs were taken at 100X for the steel samples and 250X for the titanium alloy samples.

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b) Results

Differences relating to uniformity of grain flow and of grain size were noted upon comparison of the macrostructures of the Ti 6Al-4V bulkhead forgings from the large press and the counterblow hammer. Segments of longitudinal sections are shown for comparison in Figure 153, and comparisons of segments of transverse sections are provided in Figure 154. The macrostructures of the hammer forgings can be observed to represent more consistent grain size, particularly in the longitudinal section. Although the largest area of coarse grains noted during the study can be seen at the left of Figure 153(a), several other press forging cross section segments contained smaller areas of similar coarse grained material.

The grain flow characteristics exhibited by both types of forgings were generally uniform. The sectioned segments shown in Figures 153 and 154 are typical of the grain flow observed for all segments, and it can be noted that there is no evidence of severely disturbed metal flow at radii, die parting lines, etc. However, the flow lines of the press forged material can be seen to represent more pronounced bands which are aligned in a slightly wavy pattern throughout the web area. The flow lines of the hammer forged material appear straight and uniform from surface to surface in the same areas.

The slight waviness in the flow lines of the press forged material can probably be attributed to the preforming technique employed. The multiple-stroke, open die operation used, described in report Section VI, represents a selective "step forging" practice and would not be expected to provide uniform thermal and deformation profiles in working a 12 inch thick section to the preform shape in Figure 125. In contrast, the preforms for the hammer forging effort were prepared by rolling of billet to plate, followed by single stroke preforming within impression dies. This practice would be expected to provide preforms with more uniform grain flow patterns as a result of a more uniform thermal-deformation environment.

The indications of moderately greater surface-to-surface uniformity of flow for the hammer forged Ti 6Al-4V material are probably the result of a more uniform surface-to-surface temperature profile during the blocker and finish operations. Surface chilling to a significant depth is not characteristic of multiple-blow forging. Instead, the chilling occurs in small increments corresponding to very small pressure-contact intervals during the incremental steps of deformation, and the relatively long interval after each blow tends to allow equalization of the thermal profile prior to the next blow as the hotter interior supplies heat to the surface by conduction. This comparison is, of course, no longer valid in forging of materials under conditions where the workpiece and the die temperatures approach each other, as in forging of aluminum alloys or as recently exemplified by an Air Force sponsored study involving isothermal forging of a titanium alloy with a high temperature die system(17).

Several small and one larger inclusion-type defects were noted after macroetching the segments representing the transverse section of hammer forging number LA-T1. All appeared to be alpha segregation defects of the aluminum rich, medium high hardness type classified as "Type II"(18).

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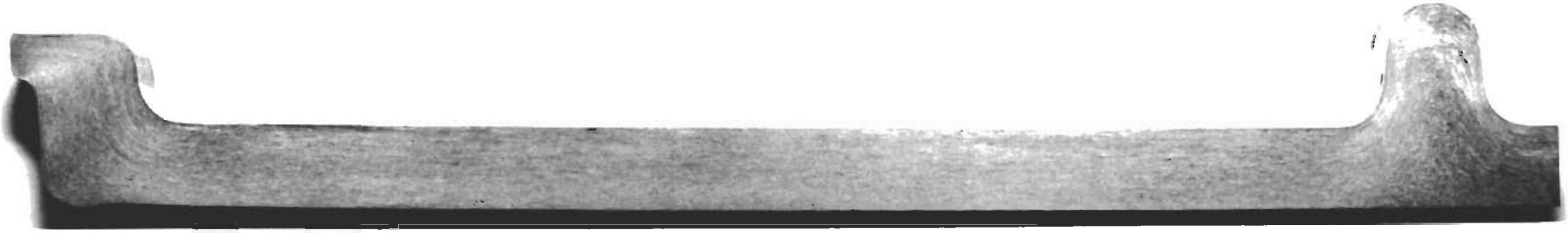
1450 C

(a) 50,000 Ton Hydraulic Press, Forging No. AL-T1



(b) 125,000 MKG Counterblow Hammer, Forging No. LA-T1

Figure 153. Segments of Longitudinal Sections Employed for Comparative Evaluation of Macrostructures of Ti 6Al-4V Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section A-A, Points 1 Through 5 in Figure 149.

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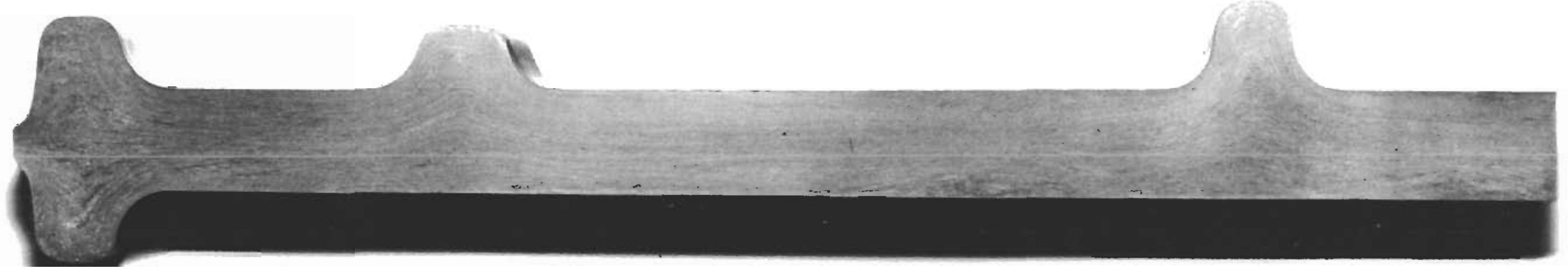
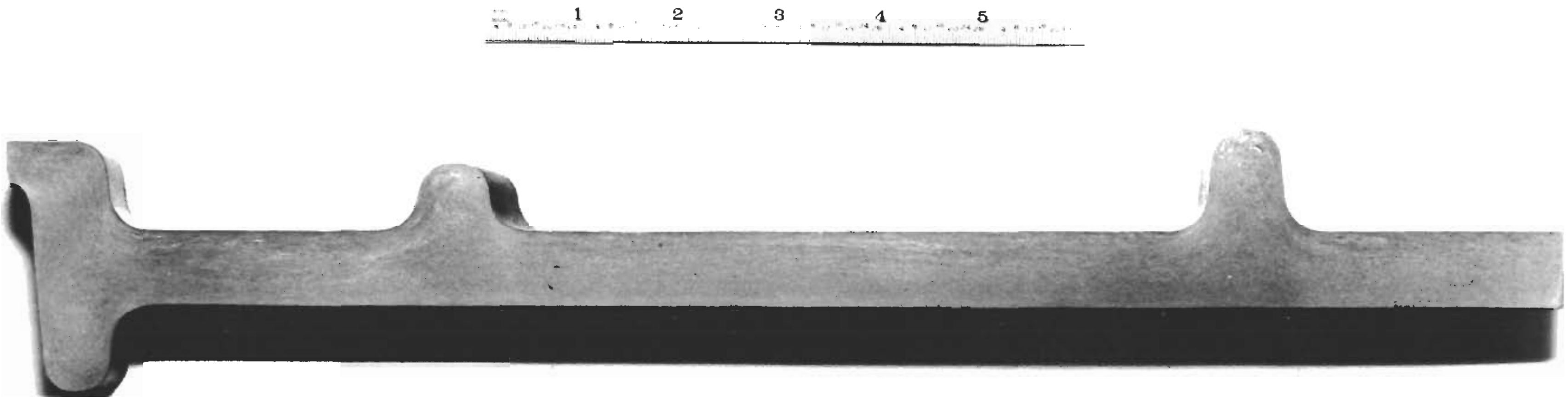
1451 C



(a) 50,000 Ton Hydraulic Press, Forging No. Al-T3



(b) 125,000 MKG Counterblow Hammer, Forging No. LA-T3

Figure 154. Segments of Transverse Sections Employed for Comparative Evaluation of Macrostructures of Ti 6Al-4V Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section B-B, Points 21 Through 27 in Figure 149.

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The larger of these defects is shown in Figure 155. The trench-like depressions and the coarse apparent grain boundaries in the 50X "photomacrograph" are considered the result of the macroetchant employed; i.e., it is believed that the defect was a sound, segregation-type inclusion with its own grain boundary network prior to application of the strong etchant used to reveal flow lines. Such inclusion-type defects are very difficult to detect by ultrasonic techniques. It is presumed that Ladish ultrasonic inspection did not reveal this one because of its chance location directly beneath a cross rib and because the inspection was conducted with all forging surfaces in the forged and blasted condition to conform with the delivery requirements of the work statement.

Microstructures of the "as-received" D6ac bulkhead forgings at mid-thickness web and rib locations are shown in Figures 156 and 157. It should be noted that the longitudinal and transverse captions under the photomicrograph relate to the major axis of the forging in all cases; not, for example, to that of the rib in Figure 157. The microstructures of the press forged and hammer forged material cannot be directly compared because of the post forging stress relief given the D6ac forgings from the press, Table 22. However, it can be observed that the "as-received" microstructures of the hammer forged material appeared to vary less from the web location (Figure 156) to the rib location (Figure 157) than do those of the press forged material. The microstructures shown are also representative of those evaluated from the other locations in the same forgings and from the other D6ac forging in each case.

In spite of the differences in microstructures and post forging thermal treatment, the hardness values for the press forged and hammer forged materials were identical. These are given in Figure 156 and are averages rounded to the nearest whole number. The individual hardness values were actually determined from heat treat response samples prior to heat treatment. These samples were taken from a different web area, described later.

Photomicrographs taken at the mid-thickness web and rib locations of Ti 6Al-4V bulkhead forgings from the large press and the counterblow hammer are shown in Figures 158 and 159. Comparison of these microstructures indicates: 1) different microstructural responses to the press and the hammer operations (comparisons between forgings produced by both machines are, in this case, valid because neither of the forgings received post forging thermal treatment); 2) very little difference in longitudinal and transverse microstructures representing the same forging and location in either case; 3) variation in microstructures of the press forgings from one location to the other; 4) uniformity in microstructures of the hammer forgings from one location to the other.

The above indications were reinforced by review of microstructures from the other locations evaluated within the "T3" forgings and the web locations of the "check" forgings, numbers AL-T1, AL-T5, LA-T1, and LA-T5. The microstructures of hammer forged Ti 6Al-4V in Figures 158 and 159 were observed to be representative of all locations evaluated within forging numbers LA-T1, LA-T3, and LA-T5 except for an approximately 0.10 to 0.015 inch thick layer of surface metal. Microstructures of the press

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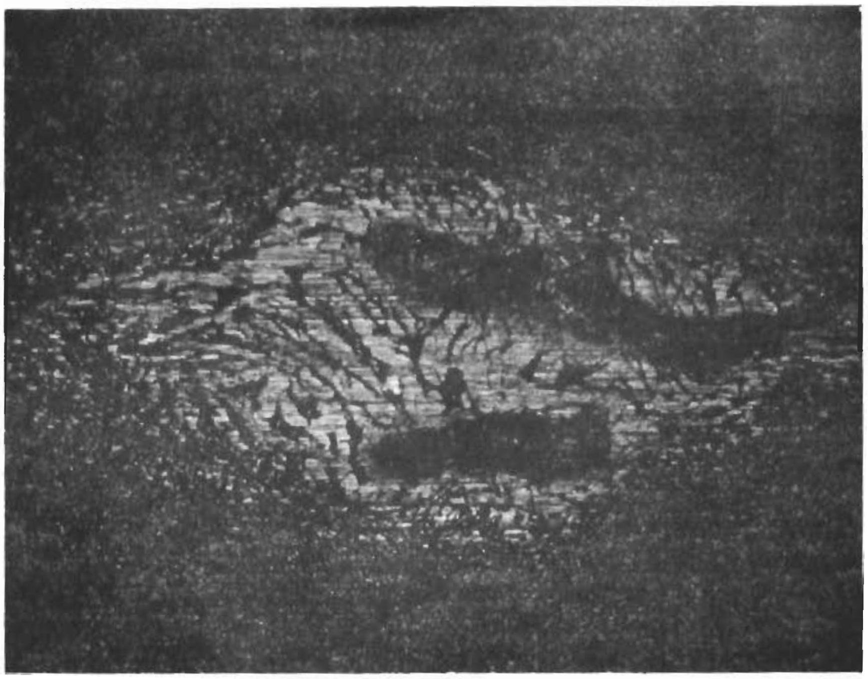
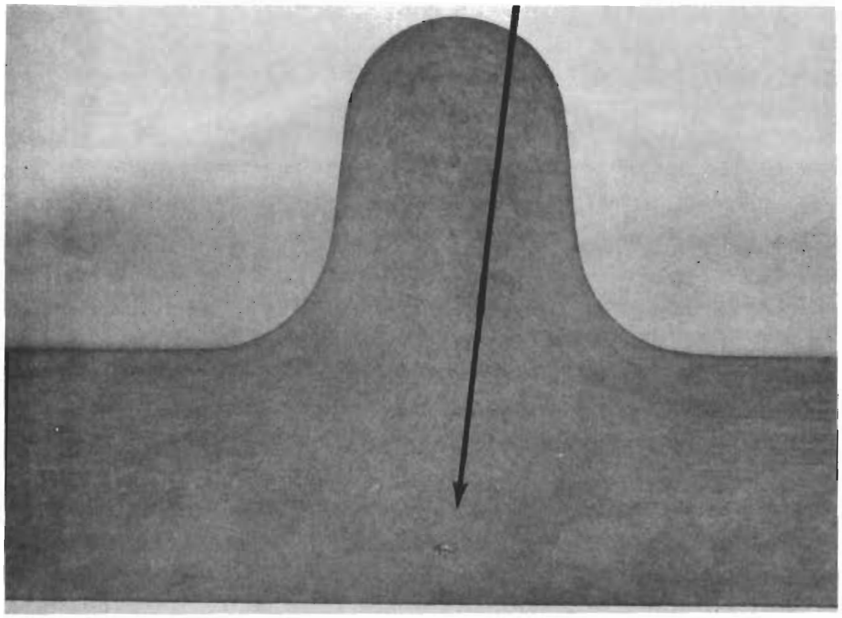


50X
LA-T1



1 3/4X

Figure 155. Inclusion in Ti 6Al-4V Bulkhead Forging Produced with the 125,000 MKG Counterblow Hammer. Location Corresponds to Section B-B, Point 32 in Figure 149.

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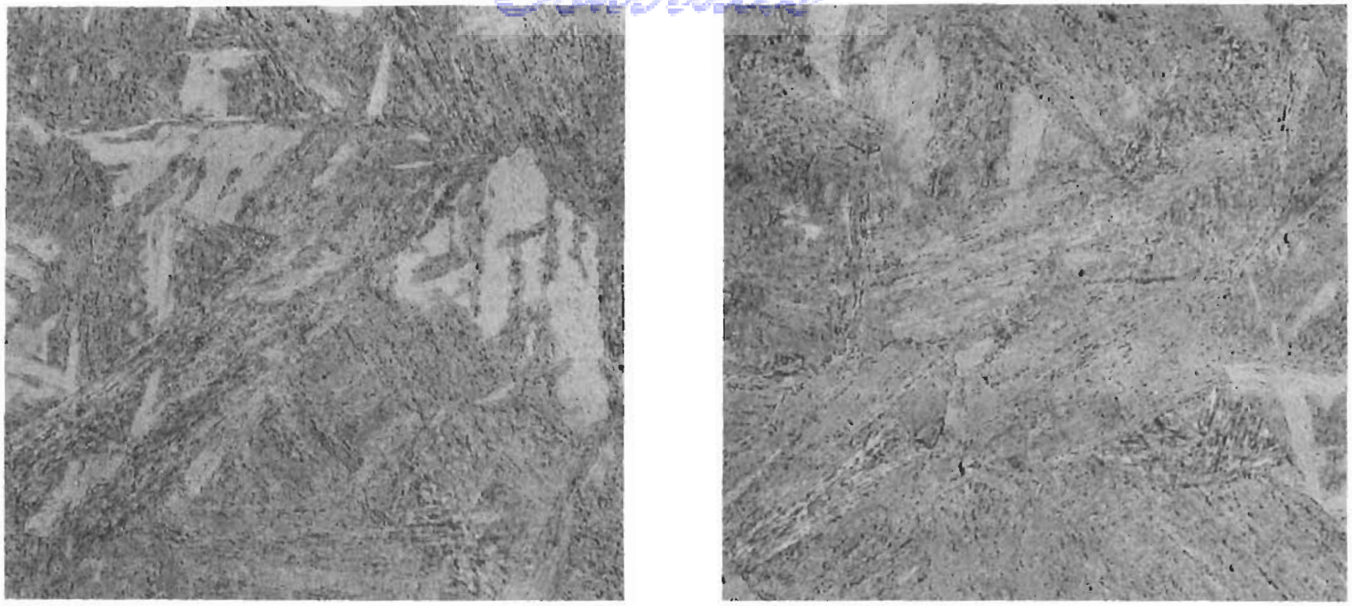
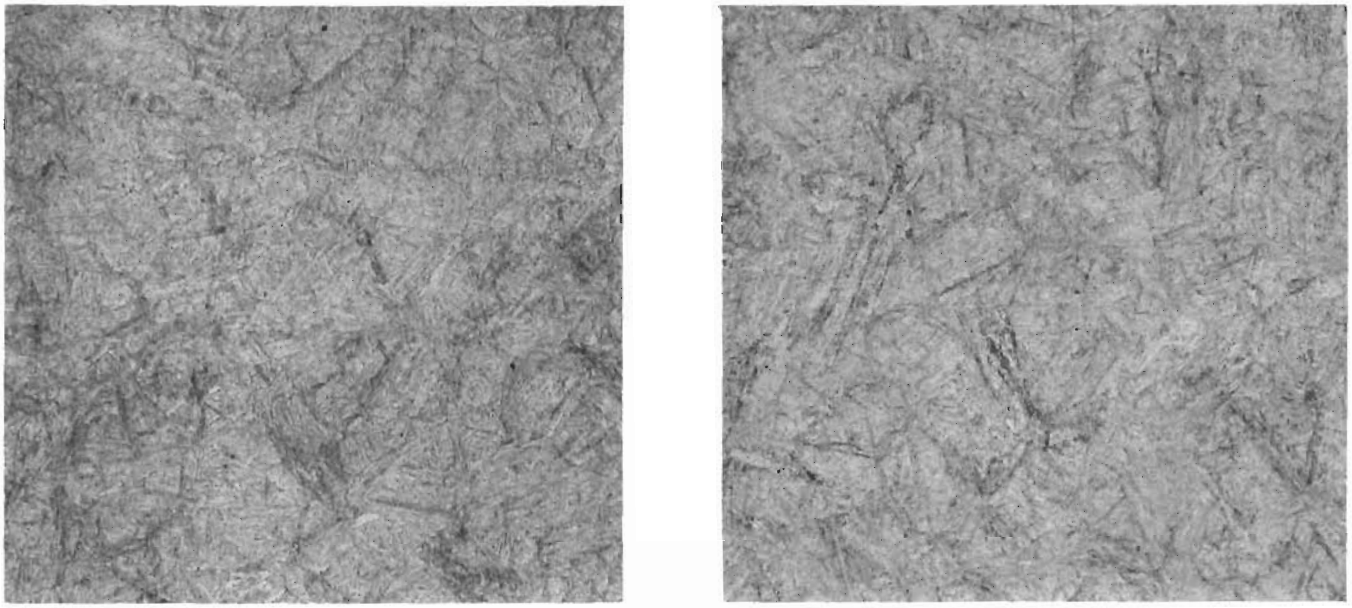


Longitudinal

Transverse

(a) 50,000 Ton Hydraulic Press, Rc 36, Forging No. AL-S2



Longitudinal

Transverse

(b) 125,000 MKG Counterblow Hammer, Rc 36, Forging No. LA-S2

Figure 156. Microstructures of Mid-Thickness Web Material from D6ac Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section A-A, Point 11 in Figure 149. Shown after One Hour, 1200°F Stress Relief (press) and As-Forged (hammer). All 100X. Representative Hardness Levels Indicated.

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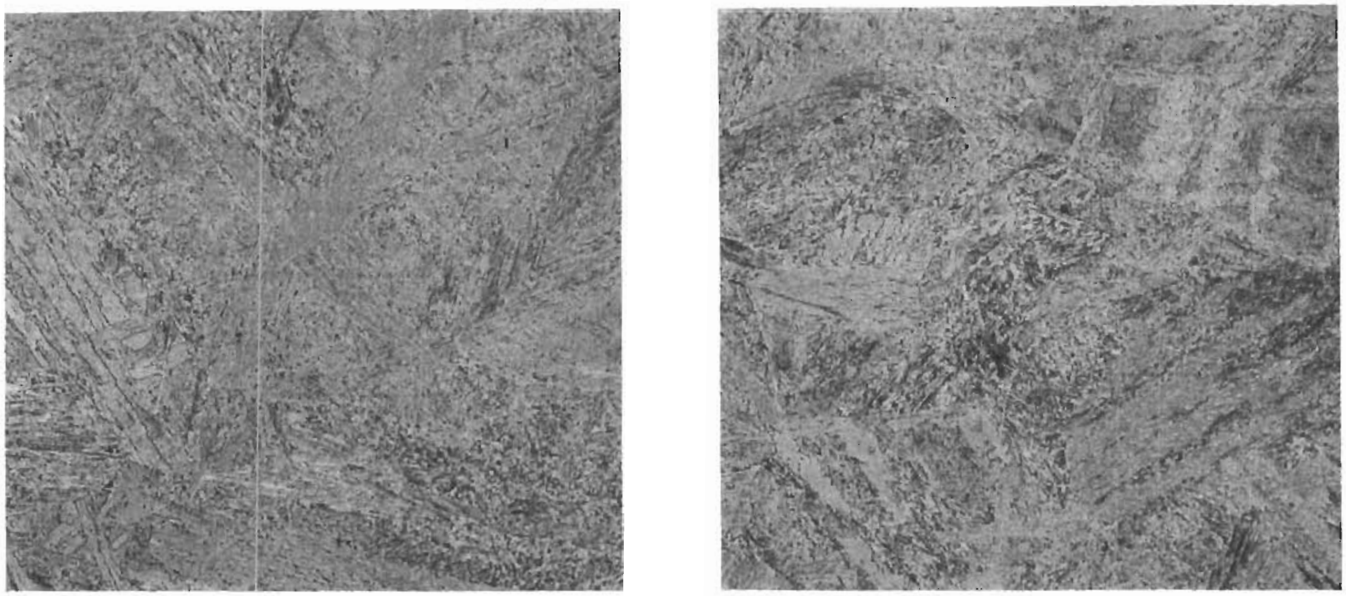
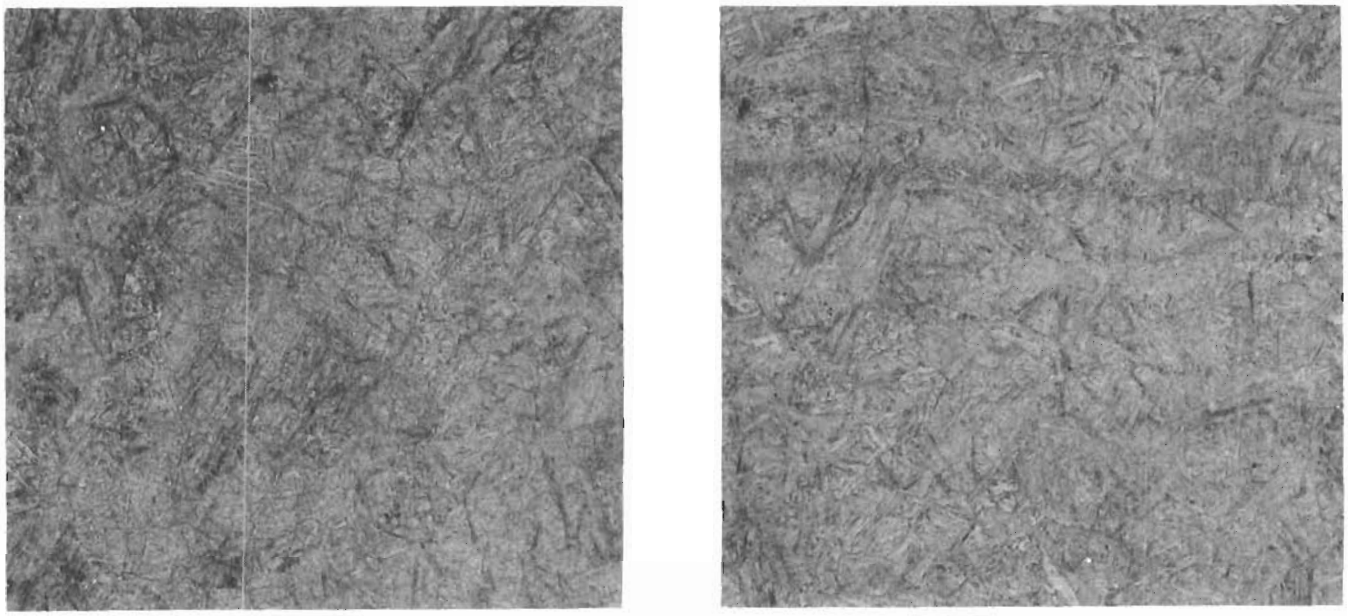


Longitudinal

Transverse

(a) 50,000 Ton Hydraulic Press, Forging No. AL-S2



Longitudinal

Transverse

(b) 125,000 MKG Counterblow Hammer, Forging No. LA-S2

Figure 157. Microstructures of Mid-Thickness Rib Material from D6ac Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section A-A, Point 20 in Figure 149. Shown after One Hour, 1200°F Stress Relief (press) and As-Forged (hammer). All 100X.

1453 C

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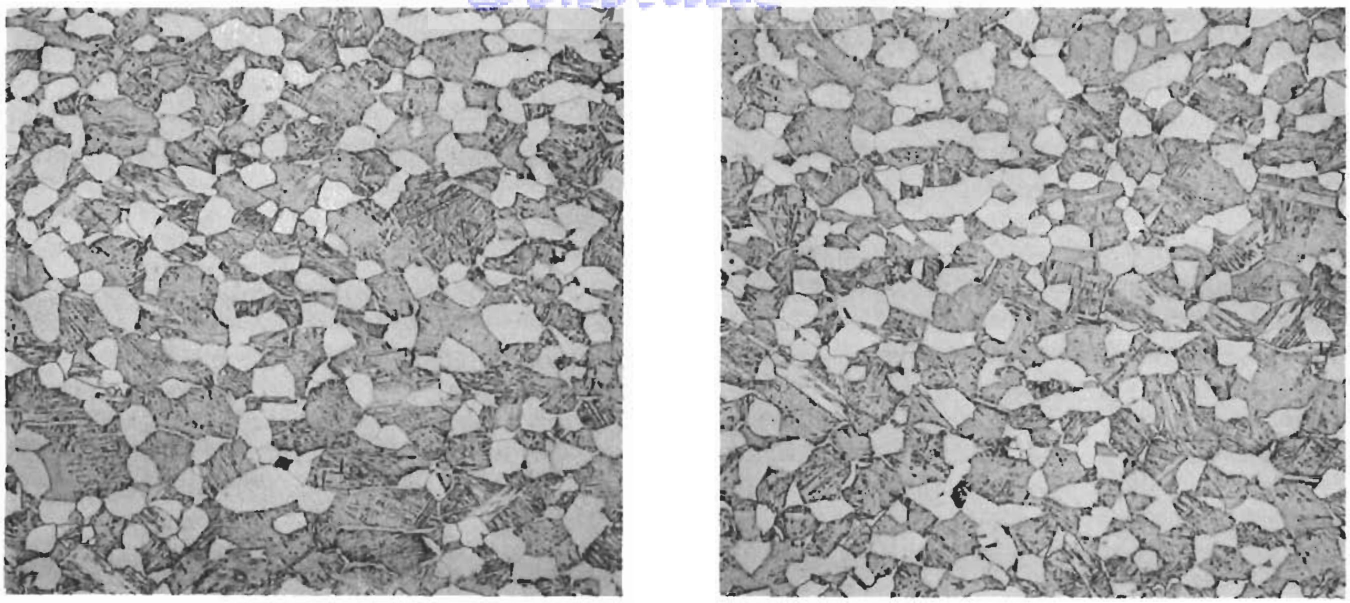

Longitudinal Transverse

(a) 50,000 Ton Hydraulic Press, Rc 36, Forging No. AL-T3

Longitudinal Transverse

(b) 125,000 MKG Counterblow Hammer, Rc 34, Forging No. LA-T3

Figure 158. Microstructures of Mid-Thickness Web Material from Ti 6Al-4V Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section A-A, Point 11 in Figure 149. Shown in As-Forged Condition. All 250X. Representative Hardness Levels Indicated.

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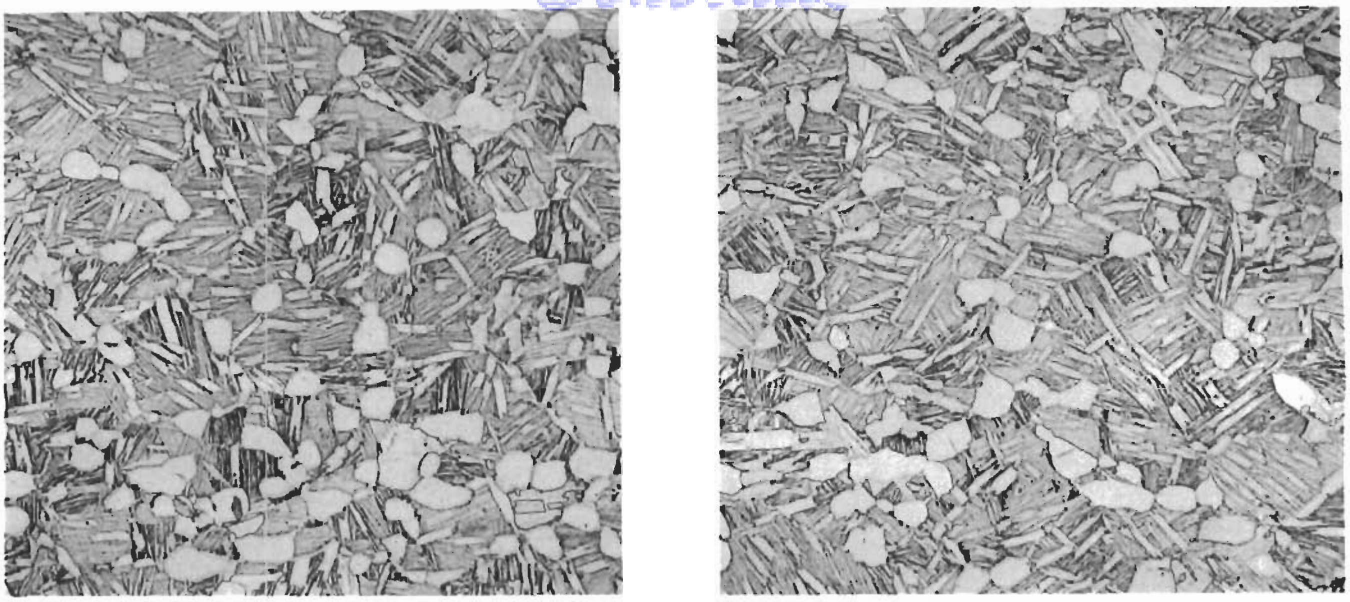
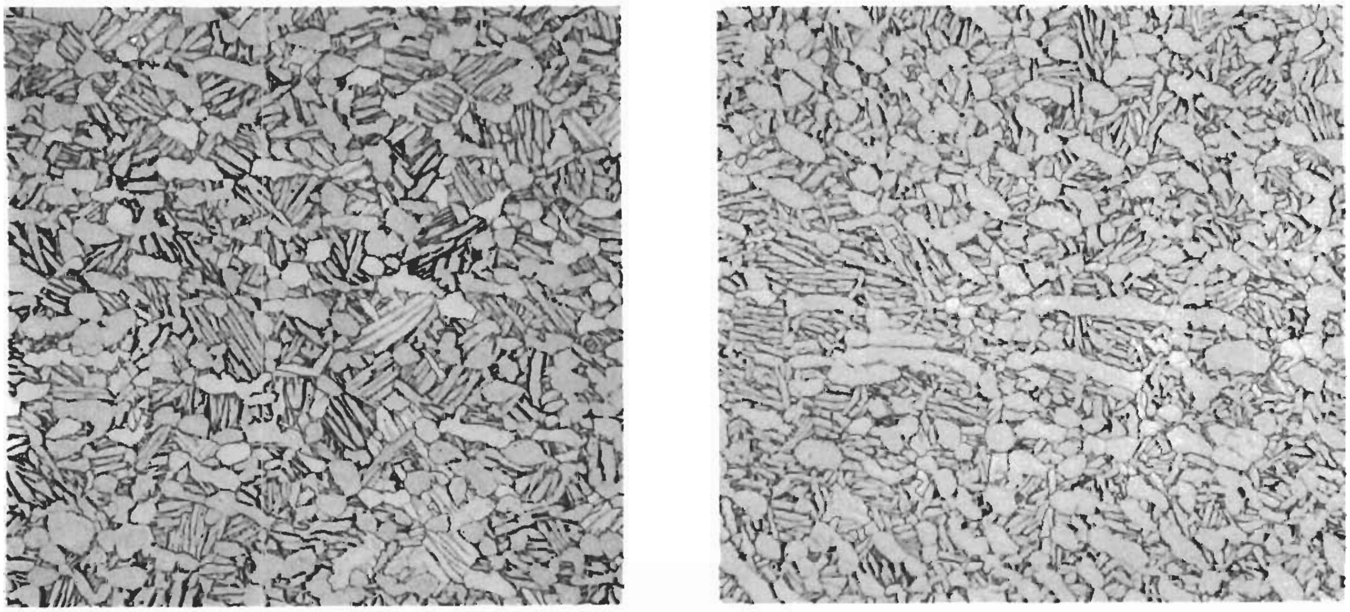


Longitudinal

Transverse

(a) 50,000 Ton Hydraulic Press, Forging No. AL-T3



Longitudinal

Transverse

(b) 125,000 MKG Counterblow Hammer, Forging No. LA-T3

Figure 159. Microstructures of Mid-Thickness Rib Material from Ti 6Al-4V Bulkhead Forgings Produced with the Two Large Machines. Location Corresponds to Section A-A, Point 20 in Figure 149. Shown in As-Forged Condition. All 250X.

1455 C

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forgings, however, varied in concentration of primary alpha and in prior beta grain size to the degree shown at the left in Figure 160. Comparison of these microstructural features suggests, as did the macrostructural evidence, that the hammer forgings were produced under more uniform temperature conditions during deformation.

The surface layer noted during metallographic evaluation of the hammer forgings is shown at the lower right of Figure 160 and is apparently an "alpha case" or a combination of a thinner "alpha case" layer at the surface and higher concentrations of primary alpha directly beneath the embrittled layer due to deformation of near-surface material at a temperature lower in the alpha-beta field. The hammer forgings received no surface conditioning other than blasting prior to delivery to TRW. The press forgings, however, were chemically conditioned by acid etching to remove an approximately 0.010 inch thick layer of surface metal. It can be noted from the photomicrograph in the upper right in Figure 160 that this procedure resulted in press forging surfaces with no evidence of "alpha case".

C. Mechanical Properties

As with the testing program employed with the intermediate size forgings, evaluation of mechanical properties of the large bulkhead forgings was conducted in a selective manner for purposes of comparing equipment capabilities. A total of 70 specimens were tested to provide comparisons of tensile, notch tensile, notch impact, and fracture toughness properties of heat treated D6ac and Ti 6Al-4V materials from the 50,000 ton hydraulic press and the 125,000 MKG counterblow hammer. The locations from which these were removed from the forgings are illustrated in Figure 161. The first of each series of two D6ac forgings (numbers AL-S1 and LA-S1), and the third of each series of five Ti 6Al-4V forgings (AL-T3 and LA-T3) were employed as the "majority of tests" forgings. The forgings used to check reproducibility of properties within each series were the second D6ac forging from each machine (AL-S2 and LA-S2), and the first and fifth of the two titanium alloy series (AL-T1, AL-T5, LA-T1 and LA-T5). Samples were removed from locations 3 (smooth tensile), 8 (notch tensile), 9 (fracture toughness), and 12 (notch impact) from the "check" forgings.

The same precautions discussed for the intermediate size forging test program were employed with the specimen samples from the bulkhead forgings to insure that section size effects and possible heat treat procedure variations could not influence the test results. All samples were machined to three common sizes prior to heat treatment. Those scheduled for tensile or notch tensile testing were turned to a diameter of 0.562 ±0.005 inch; those scheduled for heat treat response or for notch impact tests were milled to a 0.456 ±0.005 inch square cross section; and those scheduled for fracture roughness determinations were milled to a 1.062 by 0.562 ±0.005 inch rectangular cross section. This provided a 1/32 inch envelope of excess stock over the eventually threaded ends of the cylindrical gage specimens employed for tensile and notch tensile testing, over the 0.394 inch square cross section of the Charpy V-notch specimens employed for notch impact testing, and over the 1.000 by 0.500 inch rectangular cross section of the fracture toughness specimens.

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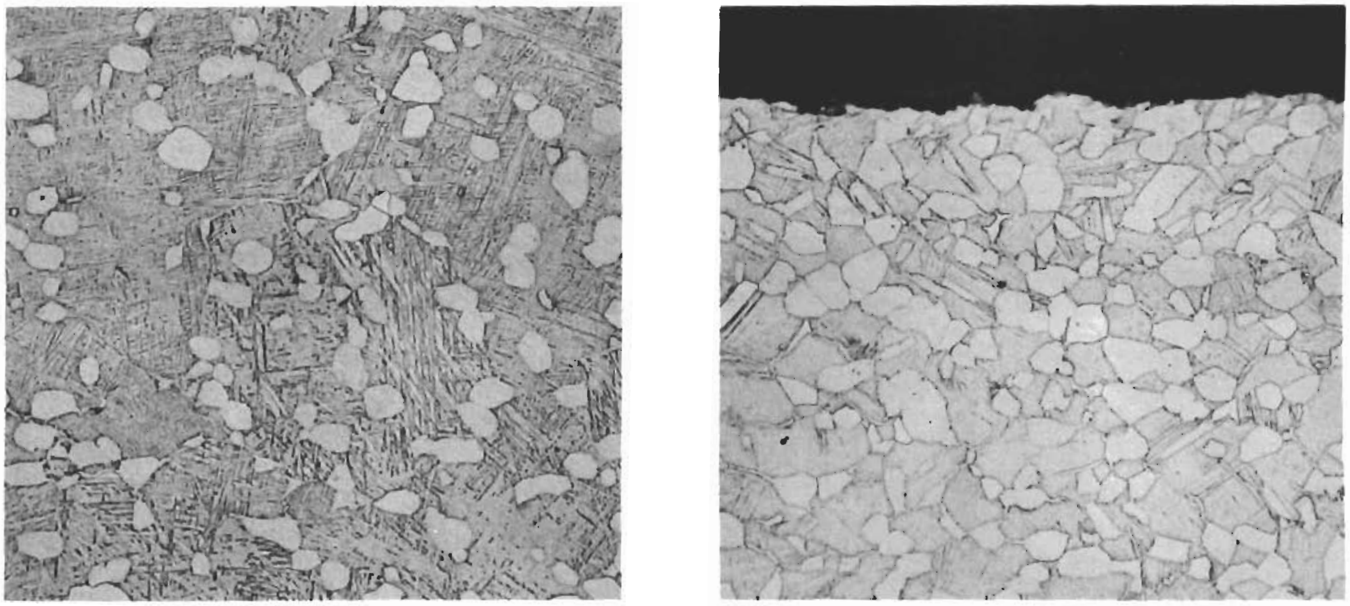
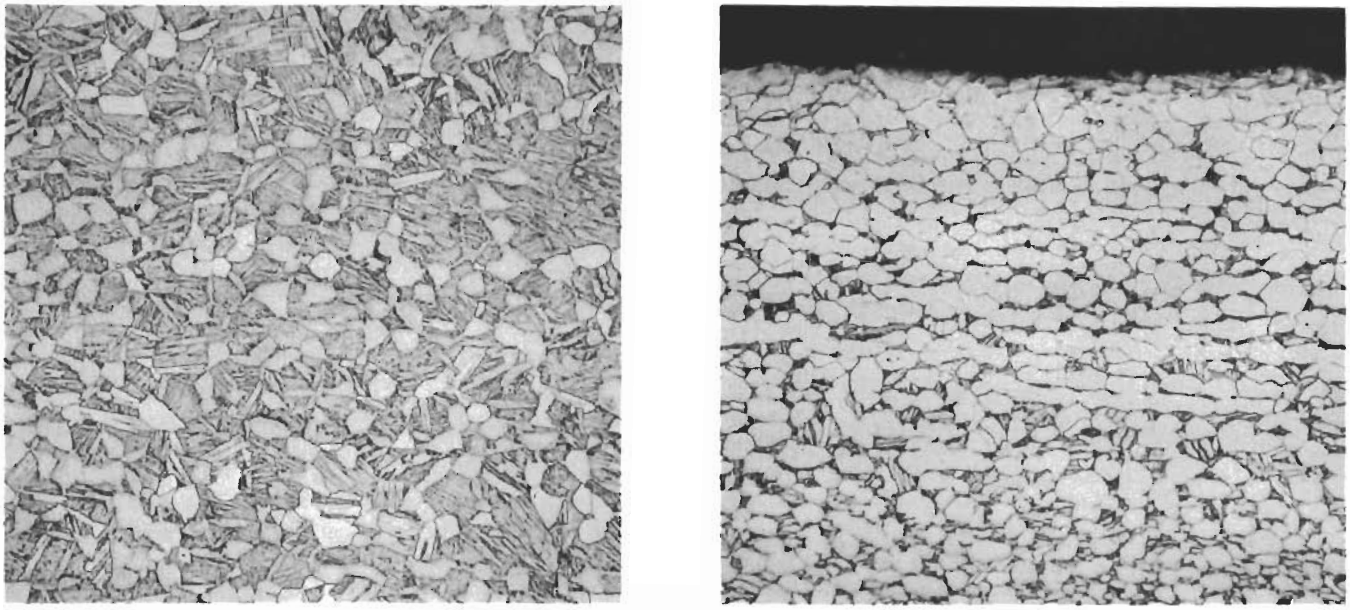


Press, Forging No. Al-T3
Longitudinal, Mid-Thickness Web
Section A-A, Point 2

Press, Forging No. AL-T3
Transverse, Web Surface
Section A-A, Point 11



Press, Forging No. AL-T5
Longitudinal, Mid-Thickness Web
Section A-A, Point 11

Hammer, Forging No. LA-T3
Transverse, Web Surface
Section A-A, Point 11

Figure 160. Selected Microstructural Features of Ti 6Al-4V Bulkhead Forgings Produced with the 50,000 Ton Hydraulic Press and the 125,000 MKG Counterblow Hammer. Photomicrographs at Left Compare Coarse Grained Material in Figure 153(a) with Finer Grained Material from Web of Different Press Forging. Those on Right Compare Surface Material Microstructures - See Text. Section and Point Designations Correspond to Locations Identified in Figure 149. Shown in As-Forged Condition. All 250X.

1456 C

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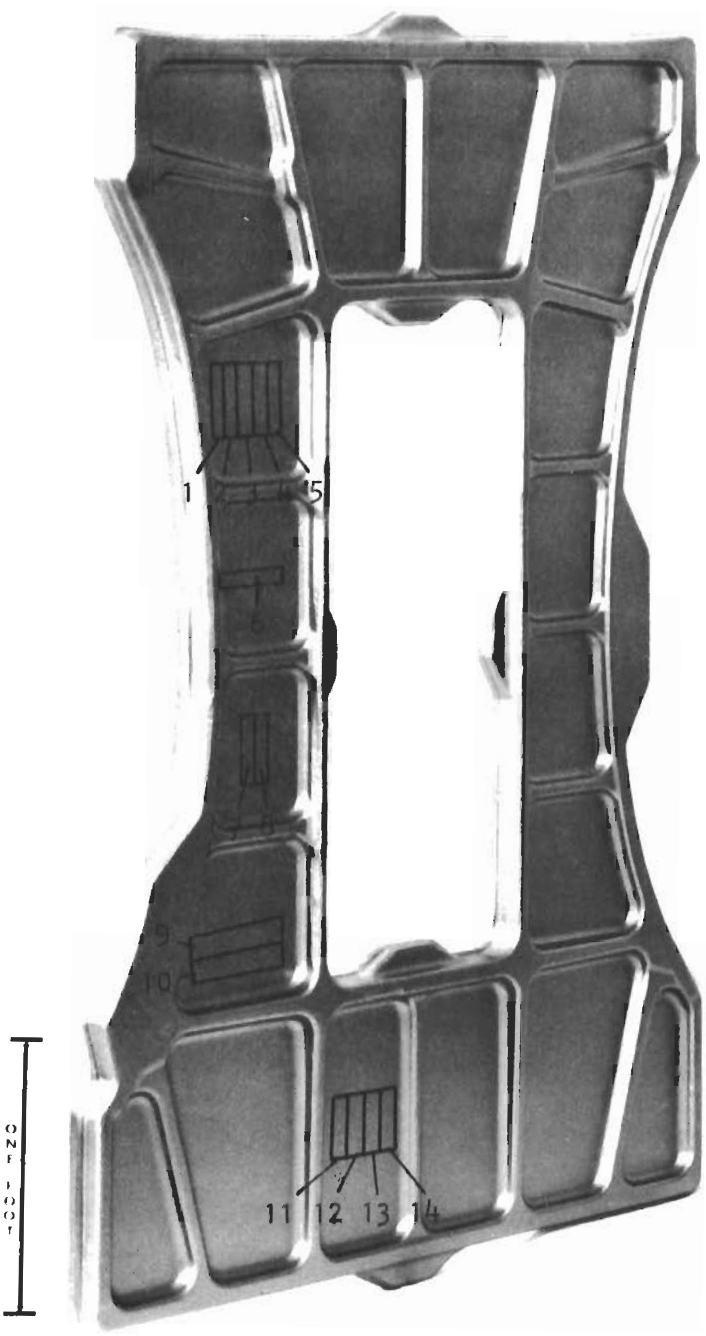

D6ac AND Ti 6Al-4V

1,2,3 = ROOM TEMPERATURE SMOOTH TENSILE, LONGITUDINAL

4 = ELEVATED TEMPERATURE SMOOTH TENSILE

5 = SPARE SMOOTH TENSILE

6 = ROOM TEMPERATURE SMOOTH TENSILE, TRANSVERSE

7 = HEAT TREAT RESPONSE

8 = ROOM TEMPERATURE NOTCH TENSILE

9,10 = ROOM TEMPERATURE FRACTURE TOUGHNESS

11,12,13 = ROOM TEMPERATURE NOTCH IMPACT

14 = SPARE NOTCH IMPACT

Figure 161. Locations from which Heat Treat Response and Mechanical Test Specimens were Taken from Bulkhead Forgings.

1457 C

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Prior to heat treatment, the milled surfaces of the location number 7 samples scheduled for heat treat response studies were lightly surface ground to provide a more uniform surface condition. Each of these samples were then tested five times for "as-received" hardness. The averaged results of these tests have been given in Figure 156 (D6ac) and Figure 158 (Ti 6Al-4V).

Heat treatment of samples from the bulkhead forgings was only conducted once for each material; i.e., all D6ac samples were heat treated together and all Ti 6Al-4V samples were heat treated together. The potential effects of any minor variation in heat treat practices on the comparisons were avoided in this manner. Heat treat response characteristics and mechanical properties of the samples are discussed separately below.

1. Heat Treat Response Characteristics

a) Procedures

The two heat treatments involving samples from bulkhead forgings were conducted as follows:

D6ac: austenitized by heating to 1625°F ±10° in a salt bath, holding for 1 hour and quenching in oil;

stress relieved by heating to 400°F ±10°, holding for 1 hour and cooling in air;

tempered by heating to 1000°F ±15°, holding for 4 hours and cooling in air.

Ti 6Al-4V: solution heat treated by heating to 1750°F ±25° in a protective atmosphere, holding for 1 hour, and quenching in agitated water;

aged by heating to 1000°F ±15°, holding for 4 hours, and cooling in air.

These procedures were identical to those employed for heat treatment of the smaller samples of the same materials from the fin rib forgings. With one exception, this resulted in agreement with the procedures given in the AMS specifications to which the bulkhead starting materials were procured, Tables 21 and 23. No AMS specification covers "heat treatable" Ti 6Al-4V plate. Thus, the samples from the hammer forgings which resulted from AMS 4911B (annealed) plate stock were heat treated in accordance with the AMS 4967A (heat treatable) bar specification representing the starting stock used for the press forgings.

The heat treated samples scheduled for evaluation of heat treat response characteristics, Figure 161, were surface ground to a 0.394 inch square cross section, were tested for hardness, and were sectioned to provide samples for metallographic evaluation. The hardness tester employed is a Wilson Rockwell Model 3JR unit, and five values for each sample were

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obtained in conformance with ASTM E18. The metallographic samples were prepared for evaluation of heat treated microstructures longitudinal and transverse to the major axis of the sample. This corresponded to the same orientations relative to the major axis of the forging, Figure 161. Etchants were the same as those described for the "as-received" metallographic samples, and photomicrographs were taken at 500X for the D6ac samples and at 250X for the Ti 6Al-4V samples.

b) Results

The microstructures obtained from the heat treated D6ac samples proved to be very similar regardless of orientation or whether they were press or hammer forged. This can be seen in Figure 162, which shows four similar examples of fine grained tempered martensite. The higher hardness exhibited by the hammer forged material is indicative of higher strength levels, as will be subsequently noted, and possibly reflects the higher vanadium content of this material (see Tables 21 and 23). Both D6ac materials met the specification minimum hardness of Rc 47 after the prescribed heat treatment.

Microstructures of the heat treated Ti 6Al-4V samples from the press and hammer forgings are shown in Figure 163. These can be observed to be considerably different as a function of machine origin; consisting of 15 to 20 percent and 40 to 45 percent primary alpha, respectively, for the press forged and hammer forged materials. Although the heat treated samples from the press forging proved to be harder as can be noted in the figure, both of the samples yielded average hardness values in conformance with the AMS 4967A requirement of a maximum hardness of Rc 43.

2. Mechanical Testing

a) Procedures

The heat treated mechanical test specimens from the bulkhead forgings were ground to their finish dimensions. Smooth tensile specimens had 0.252 inch diameter by 1.250 inch long gages which, with their radii, were form ground to a surface finish of 32 microinches or better. Notch tensile specimens were identical to the smooth tensile specimens except that, after grinding, a 60 degree included angle notch was turned into the gage at mid-length until a 0.177 root diameter was obtained. The notch root radius was 0.0015 ±0.0005 inch. The standard Charpy V-notch specimens were surface ground to their 0.394 inch square cross section, after which the required (ASTM E23) 45 degree included angle notch with a root radius of 0.010 ±0.001 inch was form ground such that specimen thickness at the root of the notch was 0.315 inch.

Completion of the fracture toughness specimens in accordance with ASTM E399 required several post heat treatment procedures. First, the specimens were surface ground to the 1.000 by 0.500 inch cross section (the ends of the 4-1/2 inch long specimens did not require finishing). A "crack starter slot" was then machined at mid-length of each specimen using EDM techniques and the specimens were fatigue precracked to the depth required by the E399 design. Finally, knife edges were attached to accommodate the displacement gage prescribed for the test.

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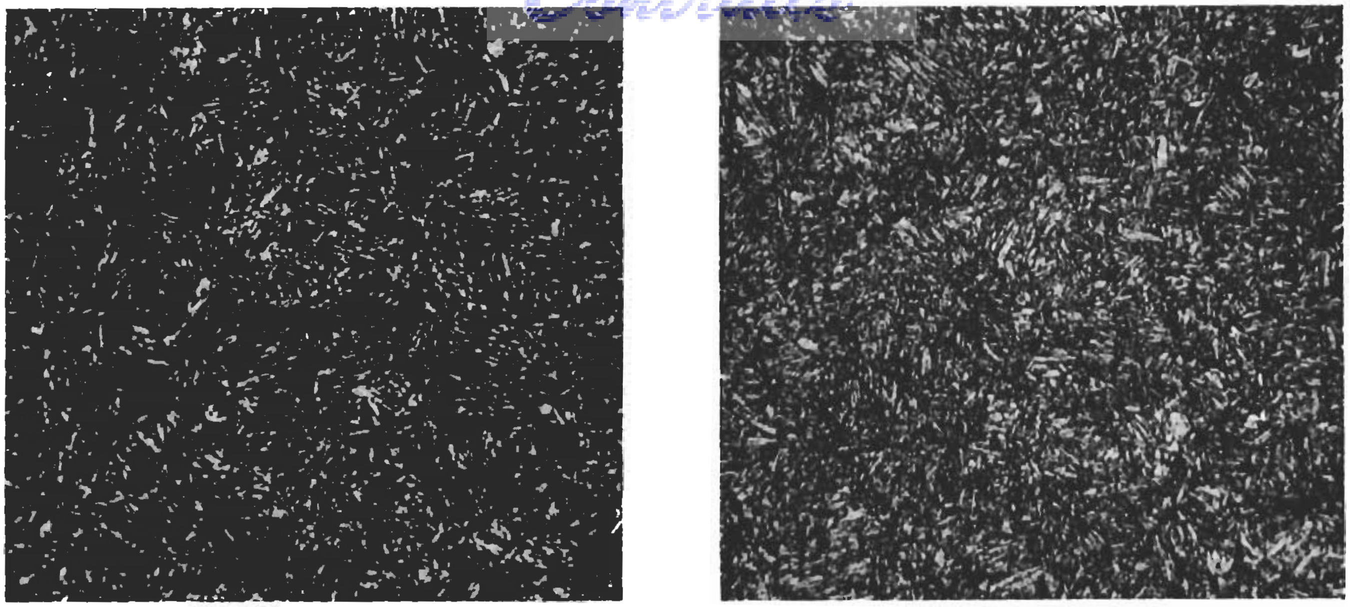
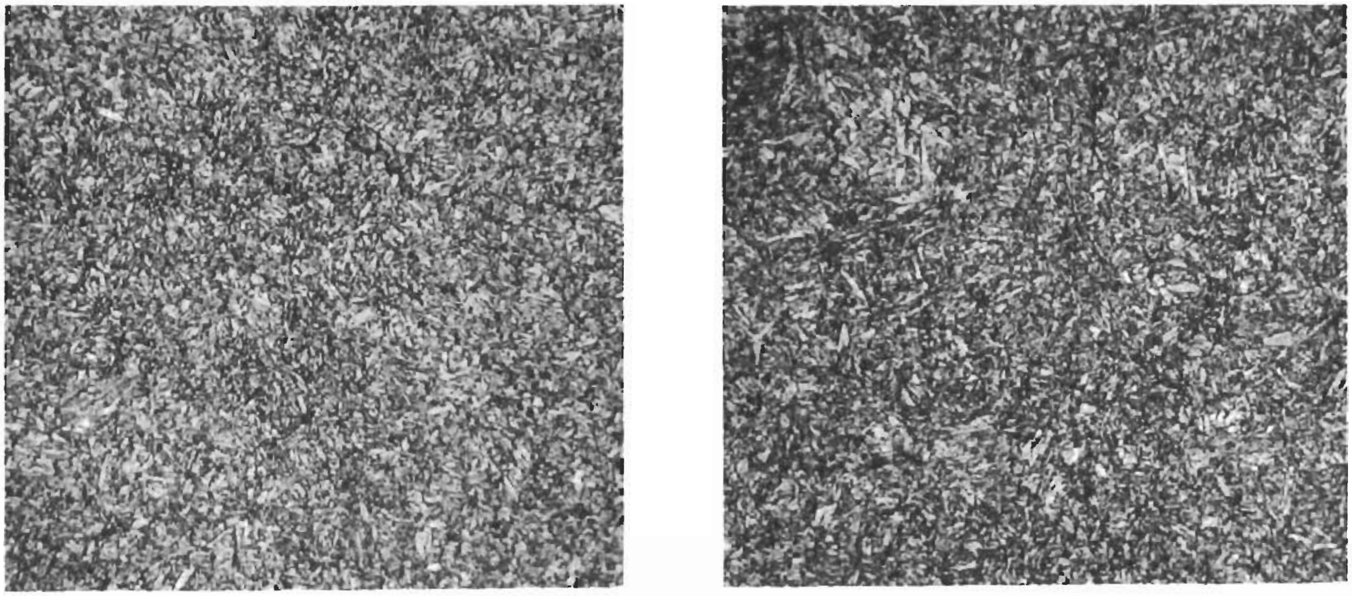


Longitudinal

Transverse

(a) 50,000 Ton Hydraulic Press, Rc 47, Forging No. A1-S2



Longitudinal

Transverse

(b) 125,000 MKG Counterblow Hammer, Rc 49, Forging No. LA-S2

Figure 162. Microstructures of Mid-Thickness Web Material from D6ac Bulkhead Forgings Produced with the Two Large Machines. See Figure 161 for Specific Web Location. Shown in Heat Treated Condition - See Text. All 500X. Representative Hardness Levels Indicated.

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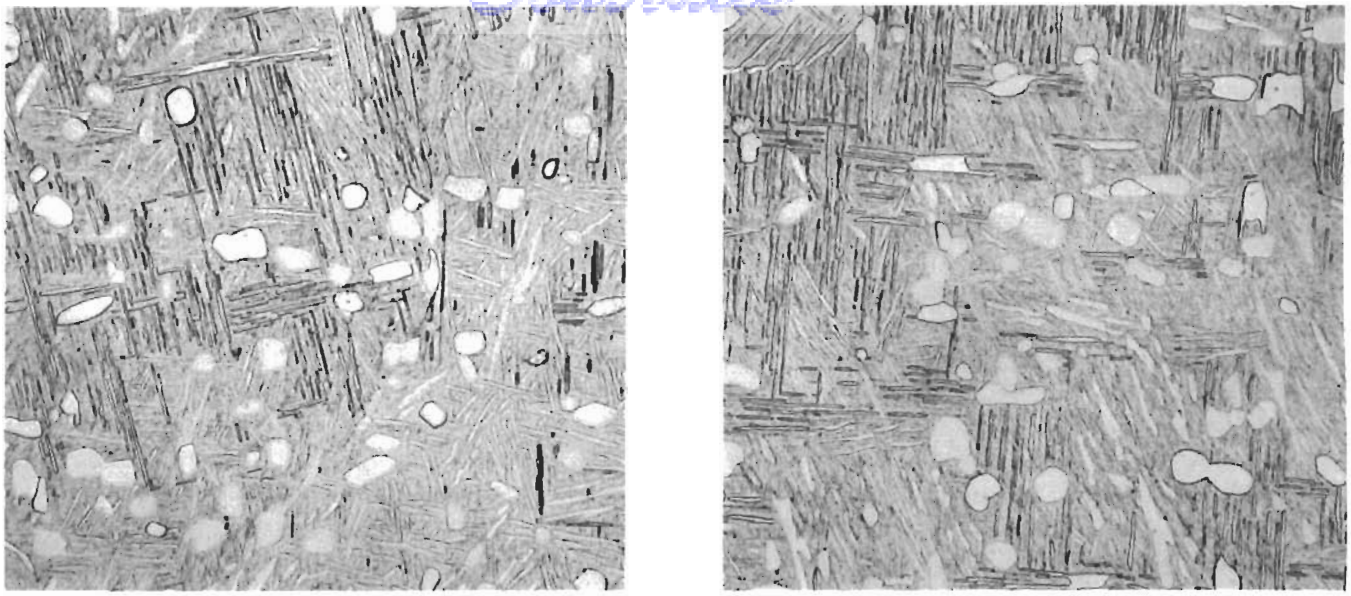
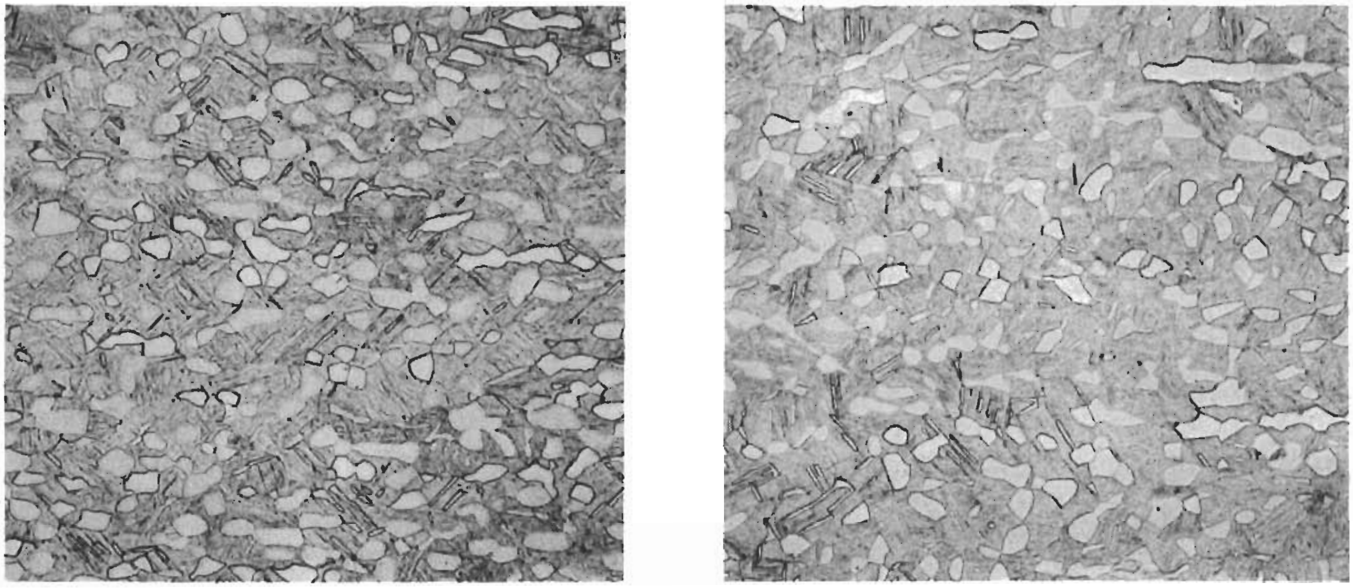


Longitudinal

Transverse

(a) 50,000 Ton Hydraulic Press, Rc 43, Forging No. AL-T3



Longitudinal

Transverse

(b) 125,000 MKG Counterblow Hammer, Rc 41, Forging No. LA-T3

Figure 163. Microstructures of Mid-Thickness Web Material from Ti 6Al-4V Bulkhead Forgings Produced with the Two Large Machines. See Figure 161 for Specific Web Location. Shown in Heat Treated Condition - See Text. All 250X. Representative Hardness Levels Indicated.

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As with the smaller specimens from the fin rib forgings, mechanical testing of the specimens from the bulkhead forgings was conducted in accordance with ASTM procedures; i.e., E8 for room temperature tensile tests, E21 for elevated temperature tensile tests, E23 for room temperature notch impact tests, and E399 for room temperature fracture toughness tests. Smooth tensile specimens at room and elevated temperatures were tested with a Baldwin Southwark Emery Model 120-T-E-304 tensile tester, and the 0.2 percent offset yield strengths were obtained with a 1 inch LVDT extensometer. A constant cross head travel of 0.020 inch per minute from application of load until failure was used in all cases. Notch tensile specimens were tested in an identical manner except, of course, without the extensometer. Notch impact specimens were tested with the same, previously described Sonntag Charpy impact tester used with the subsize Charpy specimens from the fin rib forgings. Fracture toughness tests were conducted with a special fixture in the Baldwin Southwark Emery tensile tester.

b) Results

Room temperature smooth tensile results for the D6ac specimens are listed in Table 28. Although all values exceeded specification minimums, it can be noted that the specimens of the hammer forged material provided higher strengths and lower ductility values. This reflects the previously discussed higher hardness values obtained from the counterblow hammer forged D6ac samples, Figure 162. The consistency of the values representing different locations and orientations within one forging as well as between both forgings within each series is apparent.

The Ti 6Al-4V smooth tensile specimens from the bulkhead forgings also exceeded specification minimums for room temperature properties in all instances as can be noted in Table 29. In view of the microstructural variation (Figure 163), however, the general similarity of the values from the press forged and the hammer forged bulkheads is surprising. The data suggests slight superiority of the hammer forged material in terms of room temperature strength, particularly yield strength; and slightly superior ductility of the press forged material only as measured by reduction of area. Also, it can be observed that the specimens from the hammer forgings provided somewhat more consistent strength values.

Elevated temperature tensile properties of D6ac and Ti 6Al-4V bulkhead forgings produced by both machines are given in Table 30. For the D6ac material, the order of superiority remained the same as at room temperature; i.e., the hammer forged material was stronger and less ductile. This order was reversed, however, with the Ti 6Al-4V materials. The slightly stronger hammer forged material at room temperature, Table 29, proved to have less strength and less ductility at 750°F upon comparison of values from the "location number 4" samples, Table 30. Duplicate tests were then conducted with the "spare" specimens from "location number 5" (see Figure 161), and the results confirmed the difference. This effect is probably related to the microstructural differences between the press and hammer forged materials, Figure 163, and to the slight variations in starting chemistries, Tables 21 and 23.

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TABLE 28

Room Temperature Smooth Tensile Properties (a) of D6ac Bulkhead Forgings (b)

Machine	Forging Number	Specimen Location (c)	Ultimate Strength (psi)	Yield Strength (d) (psi)	Elong. (%)	Reduct. of Area (%)
Hyd. Press	AL-S1	1	230,800	207,700	11.9	45.7
	"	2	230,800	207,200	12.9	44.5
	"	3	230,400	206,600	13.6	45.1
		Ave.	230,700	207,200	12.8	45.1
	AL-S2	3	230,400	207,300	12.8	49.0
	AL-S1	6	229,600	207,000	14.9	49.6
C-b. Hammer	LA-S1	1	234,400	213,800	11.7	38.3
	"	2	235,700	214,400	11.4	40.9
	"	3	235,700	214,400	12.5	44.5
		Ave.	235,300	214,200	11.9	41.2
	LA-S2	3	234,200	212,600	11.6	38.9
	LA-S1	6	235,900	212,700	11.1	41.5
AMS (b)	Spec.	Min.	224,000	195,000	7.0	30.0

(a) - Specimen design and test procedures in accordance with ASTM E8. Specimen gage diameter 0.252 inch.

(b) - Heat treated in accordance with AMS 6431A and 6438A. Minimum tensile properties in specifications after such heat treatment are listed above.

(c) - See Figure 161.

(d) - 0.2% Offset.

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TABLE 29

Room Temperature Smooth Tensile Properties (a) of Ti 6Al-4V Bulkhead Forgings (b)

Machine	Forging Number	Specimen Location (c)	Ultimate Strength (psi)	Yield Strength (d) (psi)	Elong. (%)	Reduct. of Area (%)
Hyd. Press	AL-T3	1	173,500	161,300	12.5	35.0
	"	2	175,800	163,400	9.9	30.8
	"	3	169,500	157,400	11.2	30.4
		Ave.	172,900	160,700	11.2	32.1
	AL-T1	3	176,200	164,700	13.0	35.6
	AL-T5	3	168,000	155,200	10.5	26.8
	AL-T3	6	172,400	159,200	9.5	27.5
C-b. Hammer	LA-T3	1	173,500	163,900	10.4	25.1
	"	2	173,800	164,400	11.3	30.2
	"	3	173,600	164,400	12.1	28.2
		Ave.	173,600	164,200	11.3	27.8
	LA-T1	3	170,100	160,700	13.0	37.5
	LA-T5	3	175,200	165,200	12.1	36.0
	LA-T3	6	175,600	169,000	9.9	27.5
AMS (b)	Spec.	Min.	165,000	155,000	8.0	20.0

(a) - Specimen design and test procedures in accordance with ASTM E8. Specimen gage diameter 0.252 inch.

(b) - Heat treated in accordance with AMS 4967A. Minimum tensile properties in specification after such heat treatment are listed above.

(c) - See Figure 161.

(d) - 0.2% Offset.

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TABLE 30

Elevated Temperature Smooth Tensile Properties(a) of Bulkhead Forgings

Material(b)	Machine	Forging Number	Specimen Location(c)	Test Temp. (°F)	Ultimate Strength (psi)	Yield Strength(d) (psi)	Elong. (%)	Reduct. of Area (%)
D6ac	Hyd. Press	AL-S1	4	600	204,700	164,600	16.7	68.2
"	C-b. Hammer	LA-S1	4	"	210,600	171,400	13.4	49.7
Ti 6Al-4V	Hyd. Press	AL-T3	4	750	125,100	99,500	13.8	63.4
	"	AL-T3	5	"	126,600	102,500	15.5	56.3
"	C-b. Hammer	LA-T3	4	"	120,400	97,700	10.9	53.0
	"	LA-T3	5	"	120,100	95,400	13.0	59.2

(a) - Specimen design and test procedures in accordance with ASTM E8 and E21, respectively. Specimen gage diameter 0.252 inch.

(b) - Heat treated in accordance with AMS 6431A and 6438A for D6ac, and AMS 4967A for Ti 6Al-4V.

(c) - See Figure 161.

(d) - 0.2% Offset.

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Results of testing for room temperature toughness characteristics of the press and hammer forged D6ac and Ti 6Al-4V materials are presented in Table 31 (notch tensile), Table 32 (notch impact), and Table 33 (fracture toughness). For the D6ac material, the results from the three types of tests confirmed the expected relationship that the less strong, more ductile press forged material (Table 28) was tougher. Anticipated differences in room temperature toughness characteristics of the Ti 6Al-4V material based on the observed variation in microstructures, hardness levels, and room temperature reduction in area values (Figure 163 and Table 29), however, were not realized. The notch tensile, notch impact, and fracture toughness values of Ti 6Al-4V specimens from press and hammer forgings can be observed to be similar to a degree which certainly does not suggest superiority of either of the two types of forging practice in terms of imparting improved room temperature toughness to the alloy in the solution heat treated and aged condition.

Summary review of all of the mechanical property data in Tables 28 through 33 reveals no indication that either of the two large machines provided bulkhead forgings of the alloy steel or of the titanium alloy with significantly superior mechanical property levels that can be directly attributed to the machine characteristics. The moderate variations in hardness, strength, ductility, and toughness exhibited by the D6ac materials forged by the 50,000 ton hydraulic press and the 125,000 MKG counterblow hammer appear to be consistent with variations in heat treat response which would be expected to result from slight differences in chemistry among different heats of starting material. Upon comparison of the press and hammer forged Ti 6Al-4V materials, the mechanical property levels proved to be surprisingly comparable in consideration of the variations in microstructural characteristics after heat treatment.

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TABLE 31

Room Temperature Notch Tensile Properties (a) of Bulkhead Forgings

Material (b)	Machine	Forging Number	Specimen Location (c)	Ultimate Strength (psi)	Notch Strength Ratio (d)
D6ac	Hyd. Press	AL-S1	8	318,900	1.38
	"	AL-S2	"	313,200	1.36
"	C-b. Hammer	LA-S1	8	300,700	1.28
	"	LA-S2	"	321,800	1.37
Ti 6Al-4V	Hyd. Press	AL-T1	8	190,200	1.08
	"	AL-T3	"	202,400	1.19
	"	AL-T5	"	173,400	1.03
"	C-b. Hammer	LA-T1	8	166,900	0.98
	"	LA-T3	"	212,900	1.23
	"	LA-T5	"	179,300	1.02

(a) - Test procedures in accordance with ASTM E8. Specimen gage diameters 0.252 inch outside of notch and 0.177 inch at root of 60 degree included angle notch. Notch root radius 0.0015 ±0.0005 inch.

(b) - Heat treated in accordance with AMS 6431A and 6438A for D6ac and AMS 4967A for Ti 6Al-4V.

(c) - See Figure 161.

(d) - The ultimate strength value from the notch tensile specimen from location 8 divided by the ultimate strength value from the smooth tensile specimen from location 3 for the same forging (Table 28 for D6ac and Table 29 for Ti 6Al-4V).

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TABLE 32

Room Temperature Notch Impact Properties[a] of Bulkhead Forgings

Material[b]	Machine	Forging Number	Specimen Location[c]	Energy Absorbed (foot-pounds)
D6ac	Hyd. Press	AL-S1	11	22.5
	"	"	12	22.5
	"	"	13	22.0
			Ave.	22.3
	"	AL-S2	12	21.5
"	C-b. Hammer	LA-S1	11	16.0
	"	"	12	16.5
	"	"	13	15.5
			Ave.	16.0
	"	LA-S2	12	14.0
Ti 6Al-4V	Hyd. Press	AL-T3	11	9.0
	"	"	12	10.0
	"	"	13	10.0
			Ave.	9.7
	"	AL-T1	12	9.5
	"	AL-T5	12	9.0
"	C-b. Hammer	LA-T3	11	10.5
	"	"	12	10.0
	"	"	13	10.0
			Ave.	10.2
	"	LA-T1	12	10.0
	"	LA-T5	12	9.5

(a) - Specimen design (Charpy V-Notch) and test procedures in accordance with ASTM E23.

(b) - Heat treated in accordance with AMS-6431A and 6438A for D6ac and AMS 6967A for Ti 6Al-4V.

(c) - See Figure 161.

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TABLE 33

Room Temperature Fracture Toughness Properties(a) of Bulkhead Forgings

Material(b)	Machine	Forging Number	Specimen Location(c)	Fracture Toughness K_{IC} (Ksi $\sqrt{in.}$)
D6ac	Hyd. Press	AL-S1	9	89.7
	"	"	10	84.9
	"	AL-S2	9	84.5
"	C-b. Hammer	LA-S1	9	75.7
	"	"	10	78.1
	"	LA-S2	9	80.4
Ti 6Al-4V	Hyd. Press	AL-T3	9	40.9
	"	"	10	40.4
	"	AL-T1	9	39.9
	"	AL-T5	9	37.4
"	C-b. Hammer	LA-T3	9	39.8
	"	"	10	43.6
	"	LA-T1	9	41.5
	"	LA-T5	9	42.0

(a) - Specimen design (notched bend specimen loaded in three-point bending) and test procedures in accordance with ASTM E399-70T. Nominal specimen cross section 1.000 by 0.500 inch.

(b) - Heat treated in accordance with AMS 6431A and 6438A for D6ac and AMS 4967A for Ti 6Al-4V.

(c) - See Figure 161.

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VIII DISCUSSION

Report Sections IV through VII include description of specific forging processes and difficulties, and also include ratings of fin rib and bulkhead forgings according to separately identified precision, quality, and mechanical property factors. This section provides: 1) a more general discussion of program results regarding the influence of forging equipment on the precision, quality, and properties of structural forgings and on certain inverse relationships, or "trade-offs", which exist between precision and quality; 2) a discussion of die life factors under conditions requiring significant elastic response to achieve closure; and 3) a general review of the forging cost factors associated with the type of equipment employed.

A. Precision, Quality, and Properties

Mechanical property levels of heat treated materials sectioned from the forgings have been shown to be generally independent of the forging practice or the forging equipment employed except for suggestions of a slight-to-moderate influence in the titanium alloy and the nickel-base alloy as a result of microstructural differences related to the thermal environment experienced during deformation. In contrast to the behavior of the D6ac alloy steel during heat treatment, the Ti 6Al-4V and Inconel 718 materials retained some evidence of prior microstructure after their respective solution heat treatments. For the shapes, sizes, and materials forged in this program, the multiple-blow forging mode appears to offer a more uniform thermal environment during deformation under conditions which include use of conventional die steels heated to conventional die temperatures. This feature is probably most important in the case of the titanium alloy in view of its frequent employment in the forged and annealed condition for improved toughness; i.e., without benefit of the somewhat homogenized effect which solution heat treatment generally exercises on a variable microstructure.

"Precision" in forging has been defined separately as: 1) capability in accurately and reproducibly meeting a forging design target within prescribed dimensional tolerance limits; and 2) the degree of detail provided by the forging design relative to that of the finished component in terms of radii, draft angles, and thickness of the envelope of excess metal. The machines under study have been shown to have afforded approximately equivalent control of overall tolerance levels within their small forging production runs. The results from the fin rib forgings suggest that single-stroke (presses) and single-blow (HERF) equipment can afford superior forging-to-forging reproducibility in control of tolerances, but that this advantage may be offset by superior section-to-section accuracy afforded by multiple-blow equipment (hammers) due, presumably, to the influence of workpiece temperature uniformity in contributing to less variation in deflection of impression surfaces.

It should be noted that the six separate forging efforts represented in the program were all conducted using the commercial practice of preheating the dies in ovens or with gas torches prior to installation in their respective machines, and selectively torch heating as required after

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installation. This practice, although economical, typically results in considerable variation in die temperature (as can be inferred from the data in Tables 2, 4, 6, 8, 22, and 24) and is the cause of minor inconsistencies in shrinkage and more significant variations in the effectiveness of the die lubricant employed. For production of greater quantities of forgings than are currently characterized by needs for airframe structurals; thermocouple controlled, electrically heated die systems afford more consistent control of shrinkage and lubricant effectiveness. Such die systems are more compatible with presses than with impact energy machines because of the influence of inertial and impact forces on the life of the flexible conduits, wires, and resistance-type cartridge heaters usually used.

The precision-quality "trade-offs" experienced during the program all relate to forging precision in its "envelope" context. In general, more highly detailed structural forging designs representing small radii, small draft angles, and thin sections are more susceptible to development of variable flow profiles which frequently result in surface defects. Program results have illustrated how the flow profiles and defect types vary as a function of the deformation modes and deformation rates afforded rib-web structurals by the different types of equipment. Multiple-blow forging appears to promote more uniform flow profiles in thin sections and to be chiefly limited by occurrence of "lapping" defects in fillet radii and rib sidewalls as radii and draft angles decrease. Single-stroke and single-blow forging appear to be more generally characterized by variable flow profile effects ranging between the extremes of: 1) chill zones, surface tears, and inability to achieve target section thicknesses due to particularly slow deformation rates; and 2) severe "shear bands", "flow-through" defects, and defects apparently resulting from selective overheating caused by the combined influence of thin, detailed sections and particularly high deformation rates.

The correct balance between forging design detail and occurrence of defects is, of course, even more significantly influenced by the material being forged. It is important to note that the detail and thinness attempted with the CEFF machine resulted in ten sound D6ac forgings which, after heat treatment, provided a uniform microstructure and mechanical property levels equivalent to those of the less detailed D6ac forgings produced with the other machines. These same impression dies closing at rates of the same general order of magnitude, however, also produced Ti 6Al-4V and Inconel 718 fin rib forgings exhibiting classic examples of defects as a result of narrow bands of shearing deformation bordering apparent "dead metal" zones. Although possibly slightly influenced by the principles of "inertial metal flow", which suggest such shearing due to added difficulty of metal flowing at high rates to accommodate abrupt changes in direction, the fact that the higher density D6ac (in comparison to Ti 6Al-4V) forgings did not contain the defects disclaims this mechanism as a major cause. Instead, the defects in the Ti 6Al-4V and Inconel 718 forgings appear to be principally the result of much greater sensitivity of these materials to a variable thermal profile during deformation. In the case of the Ti 6Al-4V, the very significant reduction in flow stress with increasing temperature within the alpha-beta field is considered chiefly responsible; i.e., the degree of reduction in flow stress within an initially forming band of high rate shearing deformation tends to insure, in keeping with the principles

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of conservation of energy, that all ensuing deformation created by the blow will occur within the same band. This results in an added tendency for occurrence of "dead metal" zones and "flow-through" defects terminating in particularly narrow "shear bands", and can be alleviated by geometrically promoting more uniform flow patterns (increasing radii, draft angles, and section thicknesses), and/or by changing to a different deformation mode or rate such that the thermal profile is more uniform. For the Inconel 718 material, the same mechanism is considered responsible for initiation of the defects observed in the highly detailed fin rib forgings produced with the CEFF machine. The greater severity of the defects in the nickel-base alloy forgings is presumed to be due to the greater influence of grain boundary weakening and possible incipient melting within the "shear bands" in contrast to the lesser effect of reduced flow stress.

In reviewing the foregoing discussion regarding precision and quality levels afforded by the different machine types, several generalizations are apparent. First, the highly variable energy rates and incremental deformation characteristics provided by hammers are desirable from the standpoint of flexibility in producing high quality structural forgings in different shapes and sizes from different materials. This advantage only applies, however, in instances where reasonable draft angles, radii, tolerances, and envelopes of excess material can be accepted. Second, the overall closure rates afforded by the hydraulic presses employed, particularly the smaller (6000 ton) press, are too slow to be technically competitive with the other types of equipment evaluated in production of thin-section alloy steel, titanium alloy, and nickel-base alloy structural forgings unless consideration is given to higher temperature die systems and/or to other means of reducing workpiece heat losses. Third, although excessive chilling or adiabatic heating of workpieces did not occur due to a single ram action intermediate in rate between those of the hydraulic press and the CEFF machine, demonstration of the capabilities of the mechanical press in providing reproducible high quality forgings within very close tolerance limits was compromised by program goals involving a uniform envelope of excess metal and by use of sequential impressions and forging practices more applicable to multiple-blow hammer forging. These capabilities are associated with the ability to use ejectors and with the reproducible closure characteristics provided by mechanical presses but, for greatest effectiveness, they also require controlled die temperatures and modification of impressions to offset the effects of deflection; practices usually reserved for forgings required in considerable quantity. As a fourth generalization, the closure rates provided by the CEFF-type HERF machine are too rapid to permit production of thin, high quality rib and web structural shapes in "difficult-to-forge" materials to the degree of detail which the energy level (per unit die space) and control capabilities of the machine allow. In this instance it appears that precise, detailed, unsymmetrical forgings with abrupt shape transitions can be successfully produced of materials such as alloy steels but that, in forging of materials having responses increasingly sensitive to variations in temperature, shape difficulty factors must be accordingly reduced to provide more uniform microstructures and to avoid the occurrence of defects.

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B. Die Life Factors

A primary purpose of impression die forging is to machine a shape once which can be used to economically reproduce itself (as a mirror image) many times. High quality is also a generally recognized feature of impression die forgings, but achievement of high quality levels cannot be considered as the single chief purpose of the process. Impression dies are not machined with an objective of producing only one high quality forging. Reasonable die life is, therefore, a mandatory requirement.

It is difficult to establish the correct number of forgings associated with the definition of "reasonable" die life. This depends on many factors including the obvious one of the total number of forgings desired of the particular shape. For airframe structurals of the materials forged in this program, numbers from fifty to fifteen hundred probably fall within an appropriate range. The correct number also depends on the control of tolerances desired and the deterioration mechanism experienced. If tolerances are not critical, considerable die "wear" as a result of abrasion and/or of thermal effects from contact with hot workpieces may be acceptable, after which the dies can usually be renewed several times for continued use by remachining the impressions. If, however, the dies are also forged during the operation or if they fail by severe cracking after production of very few forgings, as occurred during program efforts to produce fin rib forgings with the hydraulic press and the CEFF machine, the number is no longer reasonable.

The numbers of forgings produced during this program were insufficient to allow definitive evaluation of die "wear" mechanisms as a function of the equipment employed. The failures experienced, however, were obviously the result of applied forces which exceeded the capabilities of the die materials. With presses, average unit force on die impression surfaces can be calculated from the projected area of the forging and the maximum press force applied. Provision is conventionally afforded for potential localized overloads within selected areas of the impression by allowing a safety factor based on experience with the shape, the material, and the closure characteristics of the press. Maximum applied force is a preset criterion with a hydraulic press and is becoming an accurately measured parameter with modern, correctly instrumented mechanical presses. No further explanation is necessary in addition to that provided in Section IV-B to understand the progressive die insert "lug" failures which occurred during forging of Inconel 718 with the 6000 ton hydraulic press. The maximum force applied to the insert surface was known and resulted in an average unit force in excess of 83 tons per square inch; i.e., a value which proved to allow an insufficient safety factor for higher localized forces which the "lugs" experienced during forging of the nickel-base alloy.

Maximum applied force represents an extremely transient condition which is very difficult to measure when using impact energy machines such as hammers or HERF machines. Attempts were not made to instrument the steam drop hammer, the CEFF machine, or the large counterblow hammer during the course of the program. As discussed in concluding paragraphs of Sections IV and VI of this report, die force values calculated for the CEFF machine and the counterblow hammer from known energy and deformation distance values,

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neglecting elastic responses, proved to be meaningless. The following discussion is therefore provided to explain, in general terms, the reasons for the different life behaviors of dies in these two opposed ram impact energy machines during the program.

The energy required to forge a shape is the product of the average force times the average distance through which it is applied; i.e., Energy = Force x Distance. This is, of course, true regardless of the type of equipment employed. The average distance is, in turn, the sum of the average distance through which the workpiece is deformed plus the average distance through which the dies and the die support members must elastically distort (deflect) in order to provide the force necessary for the deformation to occur; i.e., Distance = Deformation + Deflection. The average force and energy requirements to achieve the same shape, however, vary due to die design characteristics (for example, different degrees of flashline relief for excess metal), due to interfacial friction factors involving greater or lesser restraint of flow as a function of lubricant composition and application, and due to material flow stress dependency upon temperature (including the effects of die chilling and adiabatic heating) and strain rate. The flow stress factors are strongly influenced by the different die closure characteristics afforded by the different types of equipment.

The force and energy requirements in forging also are frequently not uniform from initiation to completion of deformation and, for the thin-section structural subjects of this program, necessarily result in high peak forces at full closure which are even more strongly influenced by die design factors, lubricant effectiveness, and material flow stress dependency upon the closure characteristics provided by the equipment. It is these peak forces which cause dies to fail in an unreasonably short time by immediate yielding or fracture (depending on die material composition and hardness level) or by a very low-cycle mechanical fatigue cracking mechanism.

Within the limits of the closure rates pertinent to the equipment studied, no data have been revealed from review of literature or from program results which would indicate an influence on average or on peak forces experienced by forging dies which should not be explained by the design, friction, and flow stress factors just mentioned. If all other factors were equivalent in each instance, it also appears that the same peak forces would be experienced by the dies regardless of whether completion of closure were accomplished as the result of the final action of a single blow (or stroke) or by the last of a series of incremental steps (multiple blow). It is therefore suggested that the yielding and low-cycle cracking failures which occurred in the AISI Type H-13 steel dies during finish forging of the Inconel 718 material with the CEFF machine were primarily a combined result of:

1. a highly detailed die design which, although very desirable from a "precision-envelope" point of view, served to excessively restrict flow;

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2. a workpiece material with an inherent very high resistance to flow, particularly after chilling during the interval between the first and second blow struck; and
3. an energy level per unit area of impression surface (plan area) which, in view of the restraint and resistance to deformation of the workpiece, required an elastic response of the die steel which exceeded its capabilities.

It is also suggested that lesser severity of the same three considerations was primarily responsible for lack of comparable failure of the large, lower strength Heppenstall "Hardtem C" dies employed in the counterblow hammer. In this case the less detailed die design having more conventional flashline geometry afforded less restraint to flow, the Ti 6Al-4V workpiece material offered less resistance to flow, and a much lower energy level (per blow) per unit plan area was available.

As an alternative to the "deformation distance" approach to die force comparisons in Section VI, it is interesting to note the comparative unit forces that the CEFF machine and the counterblow hammer dies would have experienced during the same operations as a function of the energy per unit plan area under theoretical conditions of completely rigid die support members and workpieces. Such conditions would, of course, subject the dies to more severe force environments than they could ever encounter in service. However, comparisons obtained in this manner reveal the importance of the relationship between forging plan area and the energy applied during "hard" blows when considerable die deflection can be expected. In the case involving the counterblow hammer operation, each blow of as much energy as 1,080,000 foot pounds could only provide an approximate average of 800 foot pounds per square inch over the 1350 square inch impression surface in striking the bulkhead forging. Each of the final 125,000 foot-pound blows used in forging of the 54 square inch Inconel 718 fin rib shapes with the CEFF machine, however, provided in excess of 2300 foot pounds per square inch. Since the compressive moduli of elasticity are approximately the same for both die materials, these values indicate that necessary energy dissipation requirements through elastic force-times-distance response of the dies alone would result in almost triple the compressive unit force on the smaller dies even if they were of comparable section thickness (height).

C. Costs

As inferred by previous discussion of "reasonable" die life, forging costs are highly influenced by the quantity of forgings produced. Any relationships developed among equipment types producing total quantities of five or ten forgings of each material would probably be invalid and might possibly be reversed if the subcontract work statements had specified five hundred or one thousand forgings of each material from each machine. Also, precision and quality levels attained have been shown to be considerably different as functions of the material being forged and the equipment performing the operation. For several reasons such as these, cost comparisons based on subcontract costs experienced during this program would only be applicable to the particular circumstances of the program and could be quite misleading. Examples of other factors which could not be controlled to common status during the program include the accounting

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practices employed by the forgers, equipment ownership (private versus government), equipment depreciation status, and corporation-employee agreements relative to necessary crew size during "short run" production of experimental forgings.

Several generalizations can be made which; properly qualified regarding shape, quantity, material, etc.; are valid in comparing major forging cost factors in terms of the equipment employed. These are reviewed separately below under equipment, tooling, and production cost categories.

1. Equipment Costs

It must be understood that costs to purchase and install new equipment will vary extensively depending on the particular performance features desired and on the difficulty in providing a proper foundation. In general, hammers sized to produce small to medium size forgings by multiple-blow operation are much less expensive to purchase than are presses correctly sized and powered to produce approximately equivalent forgings in single-stroke operation. Prices for appropriately sized HERF machines for single-blow forging of the same shapes are intermediate. Purchase savings are materially offset in the case of a steam drop hammer, however, due to considerably higher foundation costs which are necessary to provide proper support for the anvil. Also, steam remains an economical power source compared to electric motor driven hydraulic pumps or flywheels, but only if generating facilities are already available and the demand for steam is fairly constant and represents fairly high quantities. The equipment cost comparisons are being made without consideration of steam generating facilities.

Installed, a new 12,000 pound steam drop hammer should cost from \$175,000 to \$225,000. Costs for a new 4000 ton mechanical press having flywheel energy and clutch torque characteristics compatible with shapes such as the fin rib would be within a range from \$450,000 to \$550,000 by the time the machine was operational. Four thousand to 6000 ton hydraulic presses with overall closure rate characteristics competitive with those of mechanical presses are not catalogue items, but it is assumed that such a particularly highly powered hydraulic machine would cost at least as much as its motor-flywheel powered counterpart. The Model HE-55 CEFF machine is currently the only actively marketed pneumo-mechanical HERF machine in the correct size range for the comparison and, installed, might cost from approximately \$360,000 to \$500,000, depending on whether the standard or the heavier "55S" frame and guiding system were desired.

The above figures indicate that the type of equipment selected to produce intermediate size forgings could result in equipment cost variations as high as \$300,000 or more. This would affect forging costs to a degree obviously influenced by the forging quantities forecast for production throughout the depreciation lifetime of the machine. Other factors such as degree of precision desired, energy efficiency levels, maintenance requirements, necessary crew size, production rate capabilities, and depreciation schedules employed must, of course, also be considered.

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The large machines employed to produce the bulkhead forgings are "one-of-a-kind" items for which direct comparisons of acquisition or replacement values would not provide a valid indication of the relative effect of equipment costs on the costs of large forgings. From observation of the bulkhead forging dies installed in the counterblow hammer, Figures 140 and 141, it is apparent that the hammer was performing the operation for which it was generally intended; i.e., the dies appear to be short, but are not dwarfed by the 72 inch by 200 inch rectangular die space provided. Features of the press in Figure 122 include a rectangular die space measuring 144 inches by 312 inches, and eight pressing cylinders which can be deliberately unbalanced with "intensified" water to accommodate severely eccentric forging loads. These features accentuate the size and versatility characteristics of the press which are of such importance in forging of massive aluminum alloy spars and side frames(9). They doubtless also significantly influenced the cost of the press, however, and are not requirements in forging of shapes and sizes exemplified by the Figure 2 bulkhead.

If engineered for faster ram action and smaller die space, it is estimated that a new 50,000 ton hydraulic press and pumping system could be designed, manufactured, and installed for possibly the order of twice the cost of a duplicate 125,000 MKG counterblow hammer installation connected to existing steam generating facilities. Costs of either new machine would probably be quoted in fairly low millions of dollars and, within the bounds of any commercially realistic depreciation schedule and allowance for the "cost of money", would be expected to have considerable impact on costs of the forgings produced.

2. Tooling Costs

Tooling costs for impression die forging can be identified as those involving engineering, manufacture, and set-up of dies in the equipment. Costs for die try-out efforts and for necessary modification to achieve correct impression fill and sound forgings can also be considered as tooling expense items.

Results from this program do not suggest significant differences in tooling costs from the standpoint of engineering requirements of die design. Two subjects have been discussed in Section IV of this report, however, which can influence costs of manufacturing dies to produce a complex structural shape. First, comparisons of the performance of the steam drop hammer and the mechanical press have indicated that a skilled hammer operator can exercise greater control of metal flow within an impression and thereby potentially reduce the number of impressions required. Second, in comparison to those used with the other three machines, the dies prepared for forging of the fin rib shape with the CEFF machine were of such size as to incur considerably greater manufacturing expense in terms of both material and machining costs. Also, the finish die was prepared of a much more expensive material than was employed for any of the other dies used during the program, and its design was complicated by the yoke-type of ejector employed, Figures 74 and 75. To a large degree, however, these features merely reflect the much more difficult forging design attempted. If the CEFF machine were to produce fin rib forgings with suitably modified dies containing the

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approximate sequence of impressions designed for the hammer, it is probable that the costs to manufacture the dies would have been much closer to those experienced for the other efforts.

Tooling set-up time, as this contributes to costs, appeared to be similar for equivalently sized equipment except in the case of the mechanical press. The fixed stroke of a mechanical press necessitates additional attention to die set-up regarding closure in order to prevent potential damage to the dies and to the machine itself. This requires a procedure whereby the dies are initially installed with generous clearance, and correct closure is established through a small series of forging trials and progressive vertical adjustment of the lower die. In instances where small quantities of workpieces are to be forged through a sequence requiring several different sets of dies, set-up cost implications relative to the time and the number of extra workpieces required are obvious.

One of the larger cost items identified during preparation of fin rib forging tooling appeared to have been more closely associated with the general shape of the component than with the equipment. Costs to re-engineer and remachine impressions for intermediate shapes in order to obtain complete corner fill in the finish forging were significant in all four instances. Also, although modification of impression dies was not required, the difficulties in initially designing correct preforms that could be produced without cracking the Ti 6Al-4V alloy contributed materially to costs of bulkhead forgings from both of the large machines. Without an improved level of understanding of thermal effects and preferential metal flow patterns during forging of complex structural shapes, such difficulties can be expected to increase as a function of increased forging detail and thinness.

3. Production Costs

Of the many individual factors which contribute to direct production costs of impression die forgings, two are most significantly influenced by forging equipment. The first relates to the size of the crew necessary to perform the operation. The second involves the time necessary, per forging, to conduct the operation; i.e., it is associated with production rate. Crew size and crew time necessary per forging represent direct man-hour expenses. Indirect costs, or "burden", are charged at a fixed hourly rate for machine time or as a fixed surcharge on the direct man-hour rate or rates. Man-hour utilization and production rate factors do not, by themselves, influence total costs of forgings for aircraft structural use to the degree associated with high quantity forging items (as examples, piston engine connecting rods or turbine engine compressor blades). However, it is apparent that contributions of equipment and tooling in reducing man hours and machine hours charged to the operation will reduce production costs for any type of forging. Further, such reductions are quite important even for forgings ordered in low quantities when conditions include a very large depreciation value divided by the inevitably fixed number of hours.

The flexibility of operation which a steam drop hammer operator enjoys also requires his undivided attention. He therefore usually has an assistant to perform functions such as application of die lubricant and

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blowing of scale. Operation of the other intermediate size machines is such that die lubrication and scale blowing is not or cannot be effected during the operation anyway, thus the operator of a press or a HERF machine frequently performs all auxiliary tasks required to insure that the dies are clean and lubricated prior to the single stroke or blow. The steam drop hammer crew, therefore, can be considered to generally require at least one more man than the crews of the competing machines under production rate conditions which, for the low quantity requirements of the fin rib forgings, were observed to be generally similar. This has the effect of generally offsetting the lower burden rate and tooling costs which result from the lower installed cost and greater flexibility of the hammer.

It is presumed that the above relationships regarding crew size will continue to exist between variable-energy, multiple-blow machines and single-stroke or single-blow machines until a particular set of economic circumstances dictates that remote console operated, programmable power hammers should be scaled up in size. Currently available machines of this type are air, rather than steam, powered and are limited in energy capabilities to 66,000 foot pounds per blow(19).

A somewhat different set of rate-time conditions appears to provide the same offsetting influence between equipment costs and production costs for the large machines. Operators of machines of this size, regardless of type, require assistants to perform auxiliary functions, and high burden rates reflecting high depreciation values most significantly influence forging production costs. The installed cost of a large counterblow hammer has been indicated to be considerably less than that of a hydraulic press capable of producing similar forgings. From the description in Section VI regarding the multiple reheat and restrike efforts employed with the counterblow hammer, however, it is reasonable to assume that considerably more time was required than would be associated with the single stroke closures provided by the press. As a general, highly oversimplified example to illustrate the offsetting influence of the above, one half of the hours times an hourly rate which is twice as high equals the same cost.

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IX CONCLUSIONS AND RECOMMENDATIONS

This program has resulted in definition and comparison of the influence of forging equipment on the precision, quality, properties, and costs of representative unsymmetrical rib and web structural shapes produced of advanced aerospace materials; e.g., high strength alloy steels, alpha-beta titanium alloys, and nickel-base alloys. Major conclusions which are indicated from the results of this work regarding overall effectiveness of equipment in producing such forgings are given below. Pertinent recommendations which the results also suggest are included.

1. The highly variable energy rates and incremental deformation characteristics provided by hammers are most effective from the standpoint of flexibility in producing high quality, oversize structural forgings in different shapes and sizes of different materials. Further, hammers are known to be generally cost effective in this typically low to medium quantity forging application area. Hammer forging techniques can be considered to be closest to being developed to their optimum potential for this application, and significant further advances in precision and quality levels attained are not expected. Increasing consideration should be given to development of programmable blow sequence machines in larger sizes to improve forging-to-forging reproducibility and man-hour utilization.

2. Hydraulic presses are also known to be cost effective in this application, but the slow closures afforded by all but possibly a very few machines typically limit the section thinness and quality characteristics of high temperature forgings unless special consideration is given to more costly, higher temperature die systems and/or other means to reduce workpiece heat losses. A general need for higher ram speeds is indicated, particularly with the smaller machines. Also, hot die isothermal forging techniques, applicable only to hydraulic presses, afford an approach to attainment of high quality structurals of a significantly improved degree of detail regarding draft angles, radii, and section thinness. Continued consideration should be given to development of cost effective tooling systems to produce structurals by this method.

3. Mechanical presses are more limited in their potential application to forging of structurals. This is because of machine size limitations in comparison to counterblow hammers and hydraulic presses, and because the "fixed-by-design" fast acting closure characteristics of a particular machine cannot be varied to accommodate the deformation requirements of widely different shapes and materials. Also, if correctly sized and conventionally tooled for a low quantity requirement of structurals, a mechanical press is moderately less cost effective in comparison with a hammer or hydraulic press. If fairly common shapes and materials represent continuing high quantity forging requirements; precision, quality, and cost features

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associated with the reproducible closure rate, the reproducible stroke, and the high production rate capabilities of a mechanical press more than offset typically high machine and special tooling costs.

4. Pneumo-mechanical HERF machines are also more limited in potential application to forging of structurals. Machine sizes are most limited of the four equipment types studied, particularly in die space. Also, the closure rates provided by such machines are too rapid to permit production of high quality rib and web structurals in alpha-beta titanium and nickel-base alloys to the degree of thinness and detail which their energy levels and control capabilities allow. Although capable of producing high quality, highly detailed forgings in alloy steels, cost effectiveness in producing such advanced structural forgings in steels is questionable because of high costs of necessary dies and questionable die life. Cost effectiveness in forging of structurals of conventional section thinness and detail remains undefined.

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13. ABSTRACT

A program to compare equipment effectiveness in providing superior structural forgings of advanced aerospace materials has been completed. Comparisons of precision, quality, properties, and costs have been made from structural forgings produced to common shapes with different equipment. The program was divided into separate efforts involving intermediate size and large forgings.

An "H" section rib was used as a target component for intermediate size forgings of a high strength steel, a titanium alloy, and a nickel-base alloy. Subcontractors and equipment items were: Ladish Company, hammer and mechanical press; Cameron Iron Works, hydraulic press; and Precision Metal Products, CEFF machine. Forging quality features relative to defects and uniformity of macro- and microstructural characteristics were different. Program results demonstrated the importance of equipment closure mode and rate in maintaining a uniform, metallurgically correct workpiece temperature profile during deformation.

An "H" section fuselage bulkhead was the target shape for large forgings of the steel and the titanium alloy. The Ladish Company (125,000 MKG counterblow hammer) and Alcoa (50,000 ton hydraulic press) produced the forgings. Results of TRW evaluation indicated that control of tolerances was similar in both instances, but that the hammer forgings were lighter and thinner. The macro- and microstructural features of the hammer forgings were more uniform, but the degree of thinness and detail achieved by the hammer also resulted in the onset of a "lapping" tendency in the titanium alloy forgings.

In general, hammers and hydraulic presses are both cost effective in forging structurals to the variety of shapes, sizes, and materials in the quantity requirements typical of aerospace applications. Mechanical presses and HERF machines are limited in application to structurals because of limited variability in die closure characteristics.

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Forging Equipment						
Steam Drop Hammers						
Counterblow Forging Hammers						
Hydraulic Forging Presses						
Mechanical Forging Presses						
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