FOREWORD

This Final Technical Documentary Report covers all work performed under Contract AF 33(657)-8791 from 20 June 1962 to 12 May 1964. The manuscript was released by the authors on 27 July 1964 for publication as an RTD Technical Documentary Report.

This contract with Thompson Ramo Wooldridge Inc. was initiated under Manufacturing Technology Project 7-930. The program was accomplished under the technical direction of Mr. L. C. Polley of the Metallurgical Processing Branch (MATB), Manufacturing Technology Division, AF Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

R. W. Redlinger of the Materials Processing Department, TRW Electromechanical Division of Thompson Ramo Wooldridge was the engineer in charge. A. S. Nemy, Manager, Materials Processing Department, and C. R. Cook, Senior Development Metallurgist, were responsible for program management at TRW. Other contributers to this program were J. A. Timura and J. D. Bitzer.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, economical production of USAF materials and components. The program encompasses the following technical areas:

Metallurgy	- Rolling, Forging, Extruding, Casting, Fiber, Powder.
Chemical	- Propellant, Coating, Ceramic, Graphite, Nonmetallics.
Electronic	- Solid State, Materials and Special Techniques, Thermionics.
Fabrication	- Forming, Material Removal, Joining, Components.

Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

ABSTRACT

PRECISION FORGING PROGRAM FOR TURBINE WHEELS AND GEARS

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The radial extrusion process has been developed and demonstrated to be feasible as a method for precision forging gears and turbine wheels with integral blades. A state-of-the-art survey indicated a need for an improved forming process to rapidly and economically fabricate the high temperature metals and superalloys into advanced aircraft and aerospace components. The development program initiated to fulfill these objectives included a single station screening phase to develop the process components and a full scale effort to fabricate and evaluate turbine wheels and gears. Results of the screening tests used to evaluate expendable materials for forging die inserts showed a high density alumina product to be most promising. Precision cast steel inserts performed satisfactorily as permanent type inserts. The success of using individual die inserts in a precision forging operation depended on a unique hydraulic closure mechanism which adapted the forging tooling in an 8000-ton mechanical press. The developed process was used to produce high quality turbine wheels with integral blades from several superalloys. Precision tolerances, excellent surface finish, and minimum stock removal were obtained by forging the material into individual die cavities having zero draft on the sides. The process was verified by the satisfactory metallurgical and mechanical properties obtained from the forgings produced during a prototype production run.

This Technical Documentary Report has been reviewed and is approved.

FOR THE DIRECTOR

Melvin E. Fields

MELVIN E. FIELDS, Col., USAF
Chief, Manufacturing Technology Division
AF Materials Laboratory

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I INTRODUCTION

This final report summarizes the contributions to the technology for precision forging turbine wheels and gears which were developed by the Materials Processing Department, Thompson Ramo Wooldridge Inc., under Contract AF 33(657)-8791. The program was initiated on 20 June 1962 and successfully completed on 12 May 1964.

Present and advanced aerospace vehicle systems require high strength, reliable turbine wheels and gears of a variety of sizes and configurations. The increasing complexity and decreasing size of turbine wheels significantly contribute to the increasing cost of manufacture. As the service temperatures increase, the more difficult-to-work alloys also must be used. The large number of applications for small integral bladed turbine wheels for auxiliary power supply units and for fuel pumping and metering systems warranted the development of a new process for forming such wheels.

The current method of producing small precision gears and turbine wheels with integral blades is to machine the components from wrought or cast metals or alloys. As the size of the gear or wheel decreases and the use of the difficult-to-work superalloys increases, the machining time and problems rapidly multiply. In addition, tool breakage and maintenance costs are extremely high for machining these superalloys in continuous production operations. For these reasons, the Research and Technology Division initiated this program with the Materials Processing Department of Thompson Ramo Wooldridge to develop a new precision forming process.

The primary objective of the program was the development of a new process for rapidly and economically forming high-strength, difficult-to-work superalloys into precision gears and turbine wheels with integral blades. To accomplish this aim, the program was divided into four phases, consistent with the state-of-the-art pertaining to the superalloys, forging, and turbine wheel industries. The objective of each phase is summarized below:

Phase I - State-of-the-Art Survey

Evaluation of the current precision forming processes, available superalloys, and turbine wheel requirements in order to satisfactorily plan the program required to advance the state-of-the-art. This was completed and reported in the First Interim Progress Report on 20 August 1962.

Phase II - Process Development

Development of a forming process and techniques for producing precision formed parts utilizing high-strength metals or superalloys, including design, building and/or modification of tooling and equipment. This was completed and reported in the Second through Fifth Interim Reports, the latter dated 13 October 1963.

Phase III - Process Refinement

Refinement of the process by precision forming high-strength materials into gears and turbine wheels with integral blades; establishment of process parameters by the analysis of processing variables; evaluation of processing controls and test procedures. This was completed and reported in the Sixth Interim Report on 15 February 1964.

Phase IV - Prototype Production

Demonstration of reliability of the developed process and the formed product by the minimum production of precision formed parts from specified metals. This was completed and reported in the Seventh Interim Report on 12 May 1964.

II SUMMARY

The objective of developing an improved process for rapidly and economically forming high strength, difficult-to-work superalloy into precision gears and turbine wheels with integral blades (Contract AF 33(657)-8791) was achieved.

A state-of-the-art survey of the metal-working industry's capability to precision form the difficult-to-work metals and superalloys into precision parts was conducted. The results obtained from a literature review, questionnaires, and personal contact with various organizations indicated a need for improved performance and reduced costs.

The development program initiated to fulfill the requirements was based on the radial extrusion process. Although the initial feasibility of the process had been established, a thorough study and selection of process components and evaluation of process reliability were required. The program was divided into two sections — a single station screening program to develop process components, and full scale fabrication and evaluation of turbine wheels and gears.

Planning, design and manufacture of forge tooling to develop and evaluate the process, and development of satisfactory die inserts were major requirements in the program. Process components and variables were evaluated using single station tooling which simulated a section of the turbine wheel or gear. Full scale forge tooling, designed to produce complete gears or turbine wheels, required relatively few replacement parts to adapt to either configuration. The flexibility was provided, in part, by replaceable die inserts which contained the turbine wheel blade or gear tooth configuration.

Two approaches were taken to develop forging die inserts — expendable materials and permanent types. The potentially useful types of expendable materials included ceramics, plastics, cermets, powder metallurgy parts and castings. A special grade of high density alumina with several metal oxide additions was found to be most promising. Satisfactory performance depended on adequate support by the tooling to gain the benefit of the material's high compressive strength.

Permanent type inserts, produced by precision casting and grinding AISI 6150 steel, were capable of being reused several times. Statistical evaluation of dimensional data obtained on as-cast inserts indicated a possibility of using precision cast inserts with minimum grinding after heat treatment.

A unique method of adapting the forge tooling and securing the die inserts in place was provided by a hydraulic secondary closure mechanism. Successful operation of the closure in an 8000-ton mechanical press provided the necessary pressure to maintain a compressive pre-stress on the inserts during forging. The performance of the closure significantly influenced the behavior of the alumina die inserts by maintaining the compressive load for the duration of the actual forging.

The precision forging process produced high quality turbine wheels and gears with continuous grain flow patterns and improved dimensional and surface quality. Dimensional evaluation of the forged turbine wheels indicated a blade profile deviation less than 0.002 in. and maximum blade displacement (from true position) of 0.015 in. Similarly, the gear tooth profile was within 0.004 in. and tooth spacing within 0.003 in. The dimensional reproducibility, minimum surface contamination, and desirable surface finish significantly contributed to reducing the machining time. Approximately 20% reduction in total production costs may be possible by the radial extrusion process.

The process capability was reflected in the satisfactory performance of the precision forged products under simulated service conditions. One basic requirement for turbine wheel acceptance is ability to withstand the effects of overspeed spin tests. Acceptance test requirements for the turbine wheel used in this program included overspeed spin testing at 66,000 rpm for two minutes.

Four gears were evaluated in a transmission test stand by Bell Helicopter Company. These gears were run for 500 hours under simulated full load conditions to evaluate wear patterns and fatigue characteristics. The evaluation indicated that the forged gears were equally serviceable with standard production pinion gears.

III STATE-OF-THE-ART

The state-of-the-art pertaining to the metal forming industry's capability to precision form the difficult-to-work metals and superalloys into precision parts was determined. Three approaches were actively pursued: (1) a detailed literature search; (2) questionnaires to high temperature metal producers, forgers, users, and research groups, and (3) selected visits to organizations known to be actively engaged in these areas. More than seventy organizations were contacted in the survey.

The survey analysis was divided into three categories: Metal processing techniques, turbine wheel and gear applications, and high temperature material evaluation. The results indicated that current and future reliability requirements for turbine wheels with integral blades and gears required the development of improved forming techniques to fabricate the high temperature alloys. Most of the information regarding precision forging of integral bladed turbine wheels pertained to radial in-flow type wheels where the blades extend along the radii of the wheels rather than around the circumference. Since limited information was available for axial flow turbine wheels, it appeared that the greatest development effort was required in this area.

A. Metal Forming Processes

The metal processing category of the state-of-the-art survey disclosed a variety of turbine wheel contours and sizes, as illustrated in Figure 1. Likewise, many different materials, shown in Table I, were reported as being used or tested to satisfy service requirements such as temperature, speed, environment, and function. In contrast, the methods for manufacturing turbine wheels were few.

1. Forging

a) Production Techniques

Production forging techniques for turbine wheels provide a disc or "pancake", which is subsequently machined to produce the turbine wheel and blade configurations. A typical pancake forging and machined turbine wheel for an auxiliary power unit are shown in Figure 2. The schematic drawing of a forged blank and the finished wheel outline shown in Figure 3 illustrates the amount of metal to be removed by subsequent machining. Although forgings provide the desirable metal flow lines shown in Figure 4, subsequent machining can destroy the benefits. Figure 5 illustrates an end-grain condition (flow lines terminating at the surface as a result of machining the forged disc in the hub and blade areas) which can cause points of initiation for a fatigue failure. The only solution for eliminating the eng-grain condition is to precision forge the finished part configuration so that minimum machining is necessary in the critical areas.

Gear manufacturing methods have been limited to powder metallurgy techniques, casting, machining wrought bar, or machining forged discs. Application requirements that can tolerate either the powder metallurgy or cast products

ILLUSTRATION OF VARIOUS CONTOURS AND SIZES OF TURBINE WHEELS AND IMPELLERS
(Courtesy of The Garrett Corporation - AiResearch Manufacturing Division)

FIGURE 1

TABLE I

ALLOYS FOR TURBINE WHEEL APPLICATIONS

Iron-Base Alloys

A-286 (AMS 5737)
W-545
16-25-6
19-9DL (AMS 5722)
Inconel 901

Nickel-Base Alloys

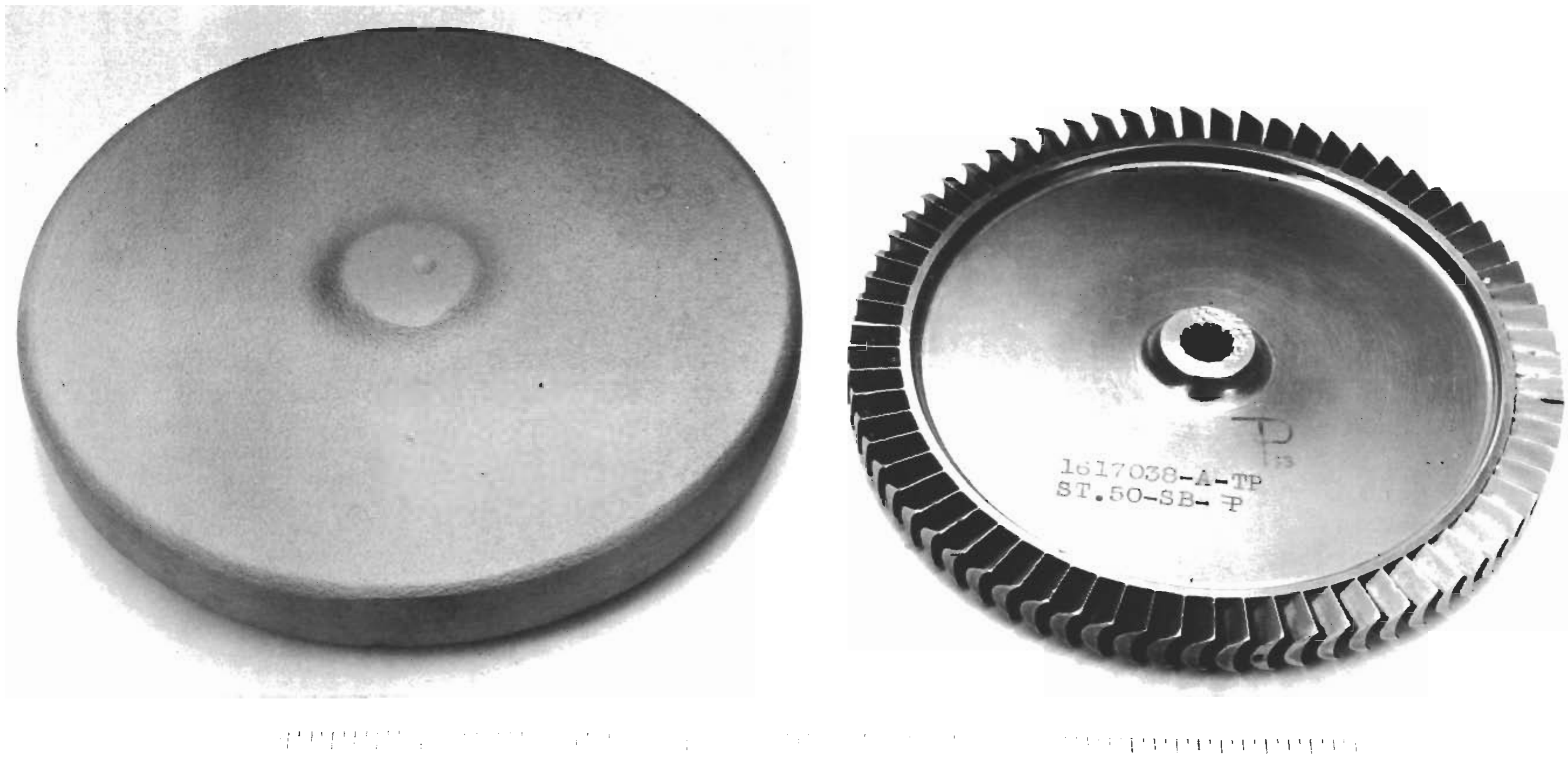
Waspaloy
Udimet 500
Udimet 700
Inconel X (AMS 5667, 5668)
Inco 713C
Inconel 700
Rene' 41 (AMS 5712)
IN-100
SM-200
GMR-235
D-979

Cobalt-Base Alloys

Haynes Stellite 21
Haynes Stellite 31 (AMS 5382B)
S-816

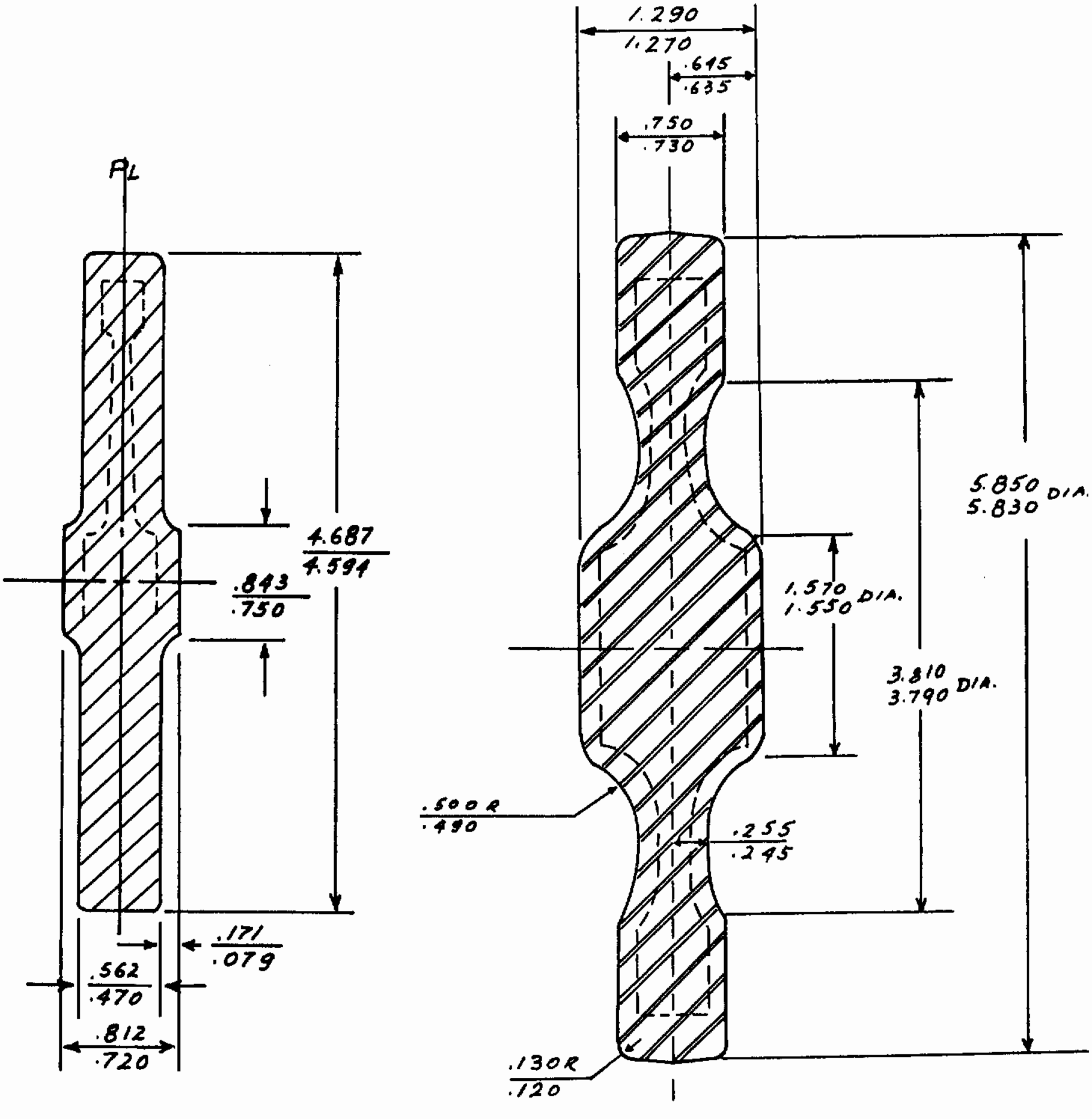
Other Alloys

Ti-6Al-4V, C120AV (AMS 4928)
Mo-1/2Ti
Mo-TZM



TYPICAL FORGING AND FINISH MACHINED TURBINE WHEEL WITH INTEGRAL BLADES FOR THE TERRIER AUXILIARY POWER UNIT

FIGURE 2



TYPICAL FORGING SKETCHES FOR SMALL TURBINE WHEELS
SHOWING FINISHED PART OUTLINES

FIGURE 3

MACRO ETCHED CROSS-SECTION OF SMALL TURBINE WHEEL FORGING SHOWING METAL FLOW

FIGURE 4

MACRO ETCHED CROSS-SECTION OF FINISHED MACHINED TURBINE WHEEL SHOWING METAL FLOW

FIGURE 5

normally involve low service speeds and as such would not be included in this program. However, gears that are normally machined and through-hardened are possible, although unlikely, applications which might be considered for precision forged gears. Therefore, it appeared that high speed gear requirements were more directly applicable to the precision forging program.

Depending on size and application, the gear blank would require either forgings or bar stock. A gear having an integral shaft, which has been machined from a forged blank, is shown in Figure 6. The rough machined gear in Figure 7 is made from rolled bar. Gears are machined by one or more of a variety of techniques such as hobbing, milling, shaving, or broaching to form the teeth within .005 in. of finish form. They are then heat treated and carburized or nitrided. Many sources then finish grind to tolerances of less than 0.001 in. (in some instances to 0.0001 in.).

Although no specific forging information could be established from the sources surveyed, the precision forging of gears apparently has been evaluated in several plants. An earlier program at TRW involved a capability study for precision forging a bevel gear, Figure 8. It was determined that both titanium and SAE 4620 steel could be forged into the bevel gear configuration within .002 in. tolerance. The gears were forged in tool steel dies which presented an unfavorable cost factor, but the initial capability of precision forging gears on a mechanical press had been demonstrated.

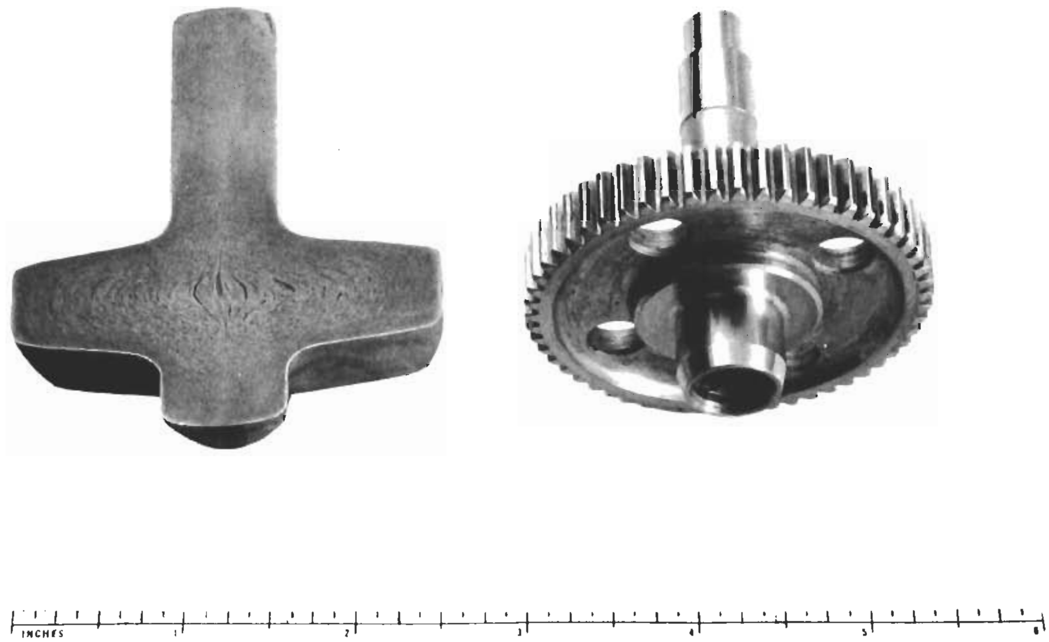
b) Development Techniques

Several other techniques were reported as potential methods for manufacturing turbine wheels, but these methods were not considered production processes.

Ford-SIFCO Process - A process had been reported in 1958 for the attachment of individual blades to the turbine wheel disc by upset forging the disc material around the roots of rigidly held blades[1]. The blades were positioned around the circumference of the wheel by casting a low-melting alloy ring over them as illustrated in Figure 9. Although a number of programs were conducted with potential users, this survey indicated that no production capability had been developed.

Curtiss-Wright Program - In another Air Force sponsored program, the radial extrusion method demonstrated capabilities for precision forging large (18-1/2 in. diameter) steel (AMS 6342) and titanium (AMS 4928) turbine wheel discs[2]. This program was directed toward precision forming the disc only; it did not include forming the integral blades. The web of the steel compressor disc was held to within ±.009 in. using a mechanical press. The developed technique required only 29.6% excess metal volume as compared to 230% used in conventional forgings.

TRW Radial Extrusion - A program at TRW demonstrated the initial feasibility of radial extrusion as a technique for precision forming turbine wheels with integral blades. In this process, machined preforms were forged in

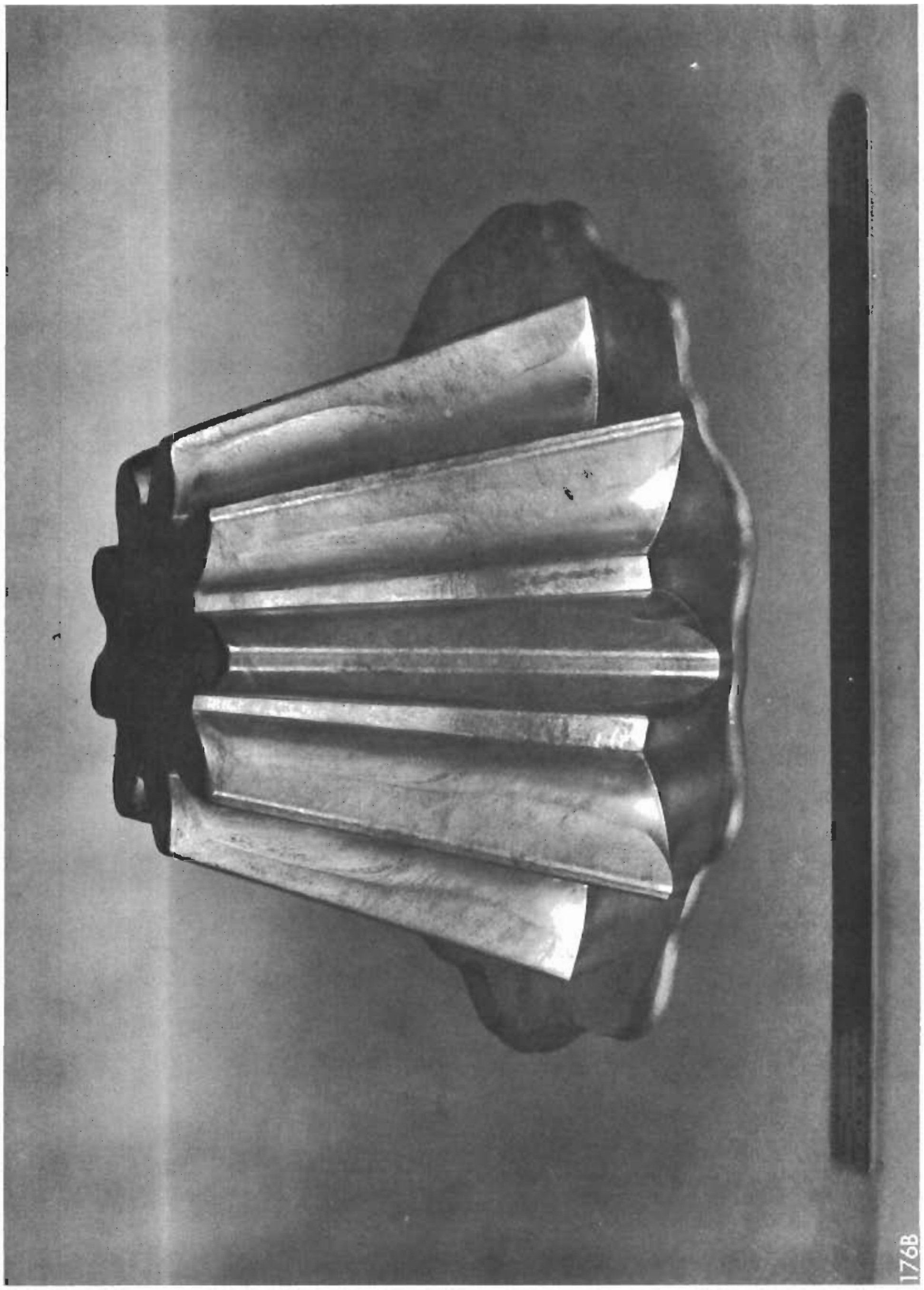


PRECISION GEAR FOR AUXILIARY POWER UNIT AND MACRO ETCHED CROSS-SECTION OF TYPICAL FORGING FROM WHICH GEARS ARE MACHINED

FIGURE 6

ROUGH MACHINED SPUR GEAR FOR HELICOPTER
POWER TRANSMISSION
(Courtesy of Bell Helicopter Company)

FIGURE 7



TITANIUM ALLOY GEAR FORGING PRODUCED BY TRW

FIGURE 8

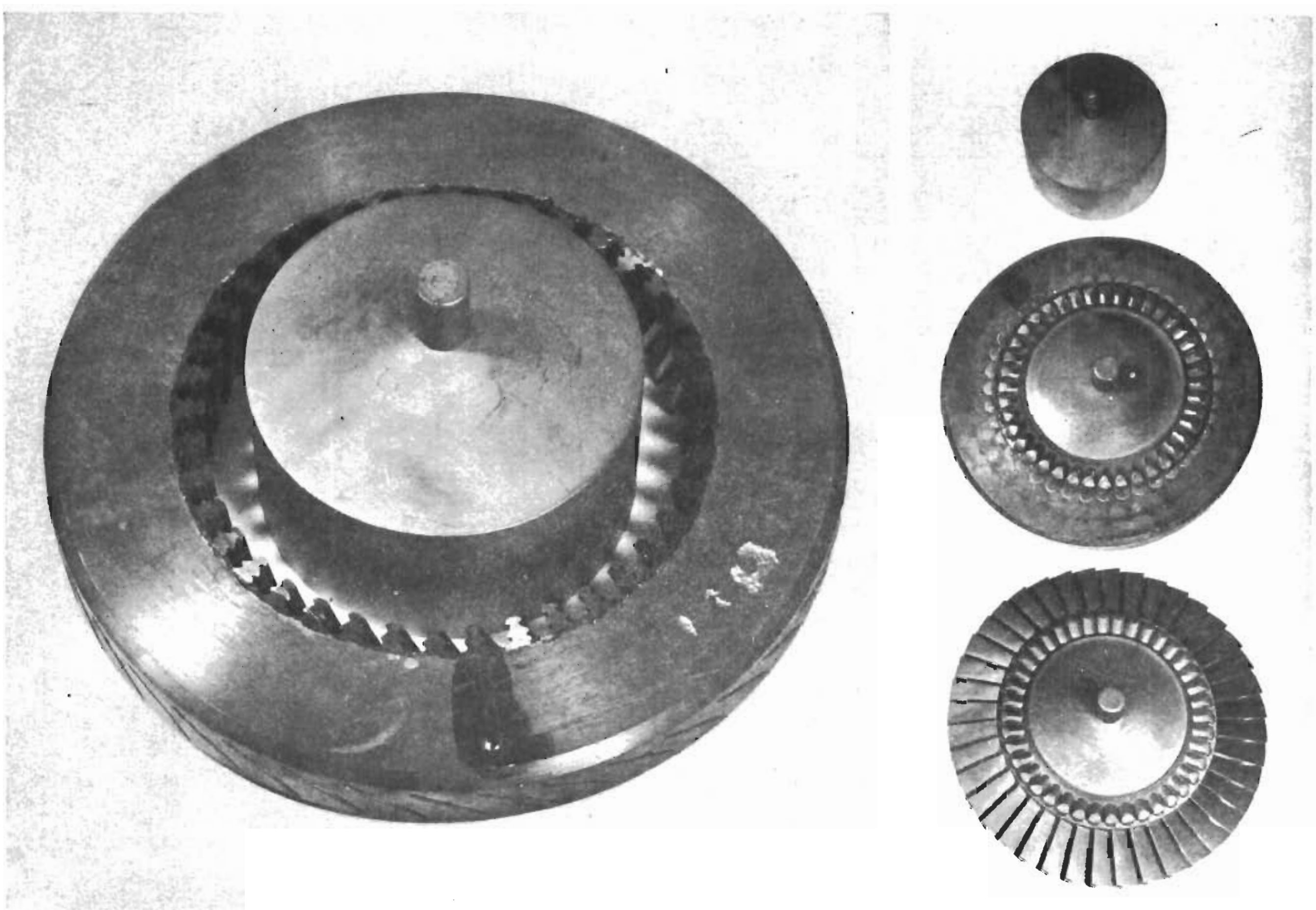


ILLUSTRATION OF FORD MOTOR CO. - STEEL IMPROVEMENT & FORGE CO. TURBINE WHEEL PROCESS. Left, blades in position in kirksite ring with billet in center. Right, billet, composite forging, and turbine wheel and blades after removal of kirksite ring.

FIGURE 9

special tooling(Figure 10) to radially extrude metal into blade shaped cavities. Process capability was first achieved by forging the aluminum and titanium alloy turbine wheels shown in Figure 11.

The program defined the basic problem areas of the radial extrusion process, such as: (1) the development of a suitable expendable die insert; (2) determining maximum blade lengths and minimum edge thickness; (3) establishing achievable tolerance levels; and (4) appraisal of cost factors.

2. Machining

a) Conventional

Until recently turbine wheels have been machined by conventional turning, broaching, and milling operations. The complexity of airfoil shapes, close spacing between blades, and exacting tolerances resulted in time-consuming expensive milling operations. As a result, special machines, such as that shown in Figure 12, were developed to produce the blade sections. Since the extremely small end-mills have limited strength and cutting surfaces, metal removal rates were slow, even for the easiest machining alloys. With alloys which readily work harden the problems are compounded by tool breakage and wear. One company reported that a minimum of 40 hours was required to machine the integral blades on a Waspaloy disc. It was estimated that this time could be reduced 75% if the wheel was precision forged with a .030 in. envelope.

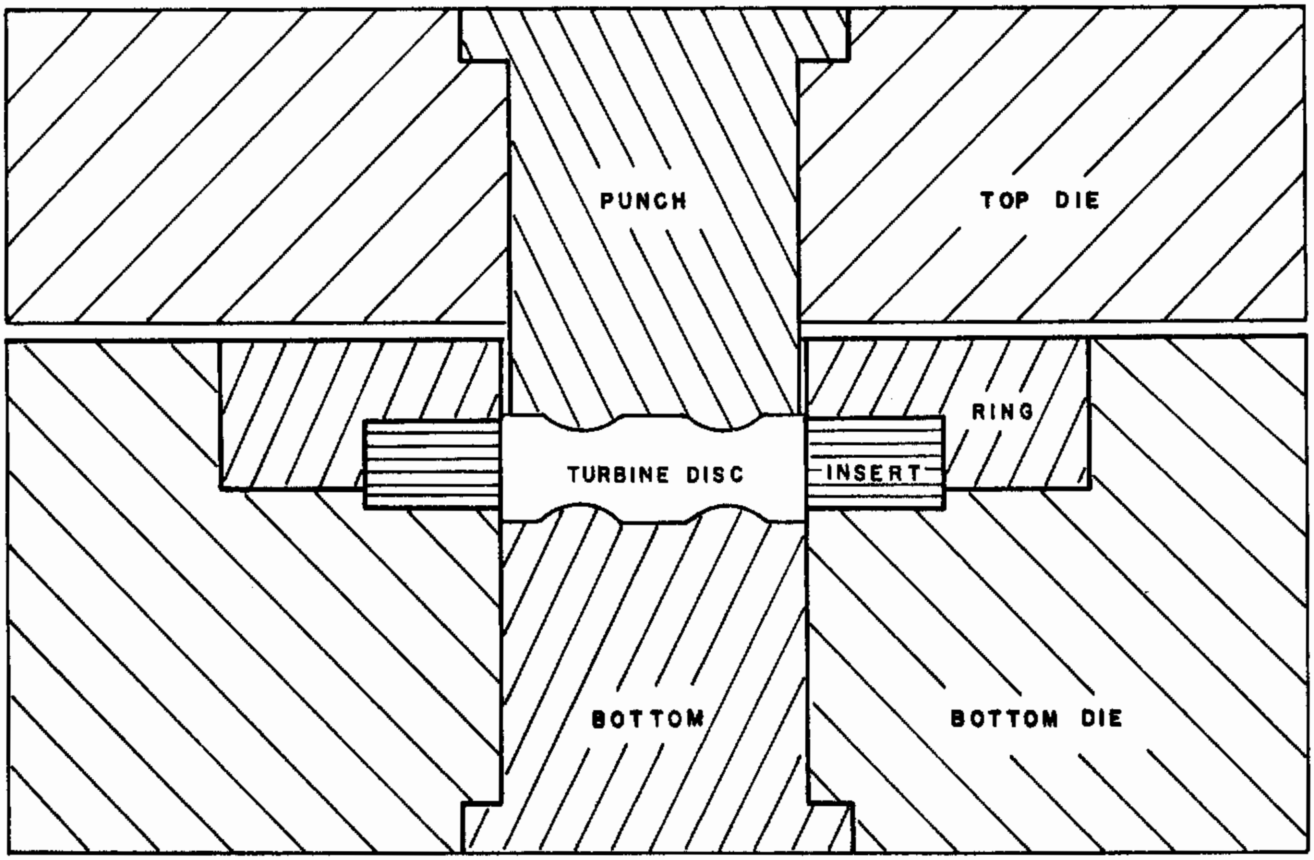
b) Electrolytic

In recent years, electrochemical (ECM) and electrical discharge machining (EDM) techniques have been developed. Both processes have been used to manufacture turbine wheels. The major advantage of these electrical energy machining methods is that material hardness or work hardening characteristics have no influence on metal removal rates[3]. The dimensional tolerances of both the ECM and EDM processes are dependent upon the precision of the cathode, positioning fixtures and control of the electrode movement, of which less than .005 in. tolerances are attainable. Surface finishes of 10 rms can be obtained by the ECM process, however, a pebbly finish between 5 and 50 rms is characteristic of the EDM process.

Although these processes resolve some of the problems associated with conventional machining, the end-grain effects caused by cutting the metal flow lines still prevails.

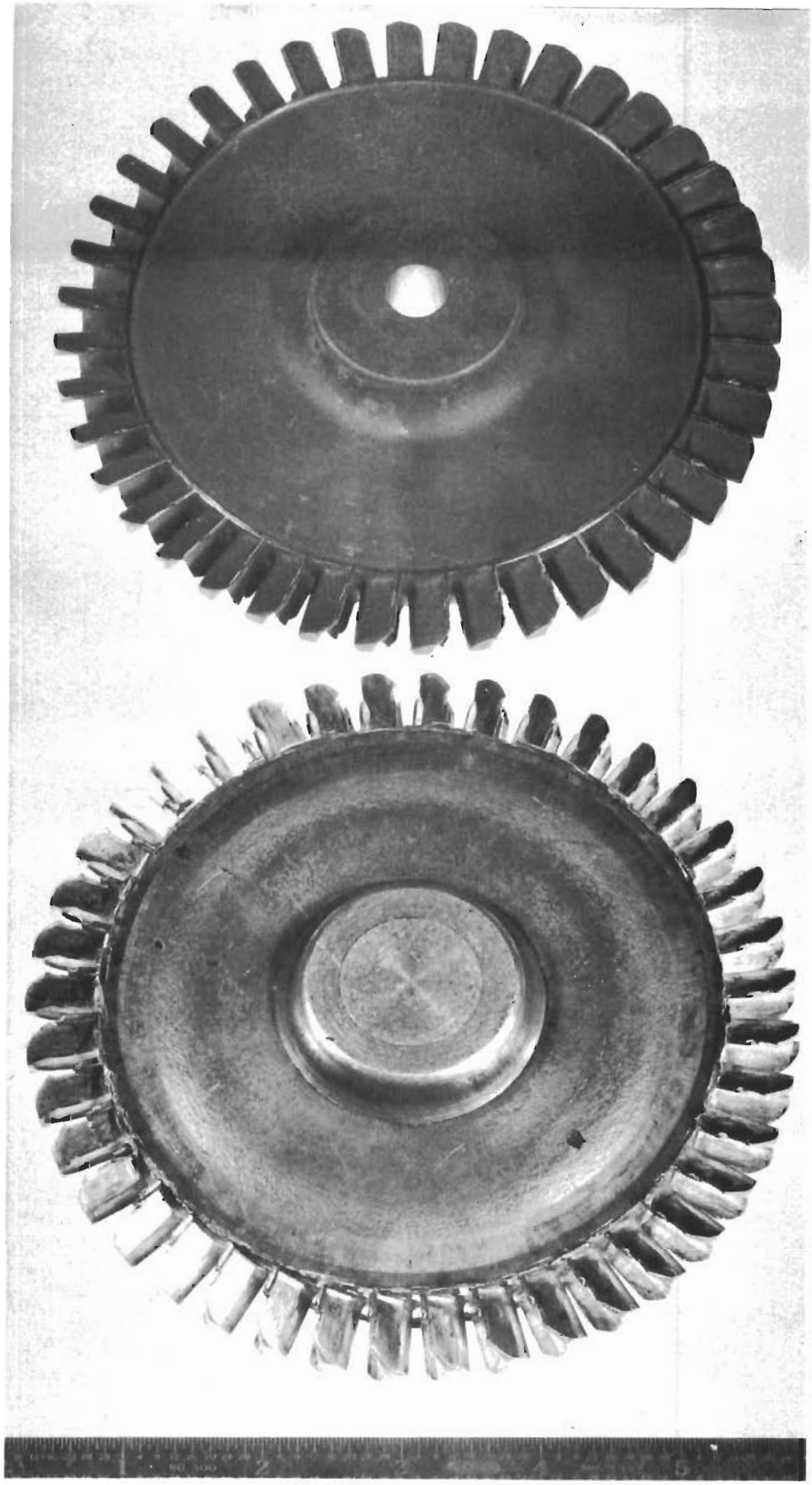
3. Casting

Castings have been used extensively in certain turbine wheel applications where the tolerances are less exacting. Tolerances of ±.010 in. are difficult to hold on wheels of six-inch diameter so some machining or grinding is usually required to finish the cast wheels. The advantage of castings, as compared to wrought products, are the higher stress-rupture properties at elevated temperatures, but the ductility is somewhat lower.



SCHEMATIC ILLUSTRATION OF TOOLING ARRANGEMENT FOR RADIAL EXTRUSION OF TURBINE WHEELS WITH INTEGRAL BLADES

FIGURE 10

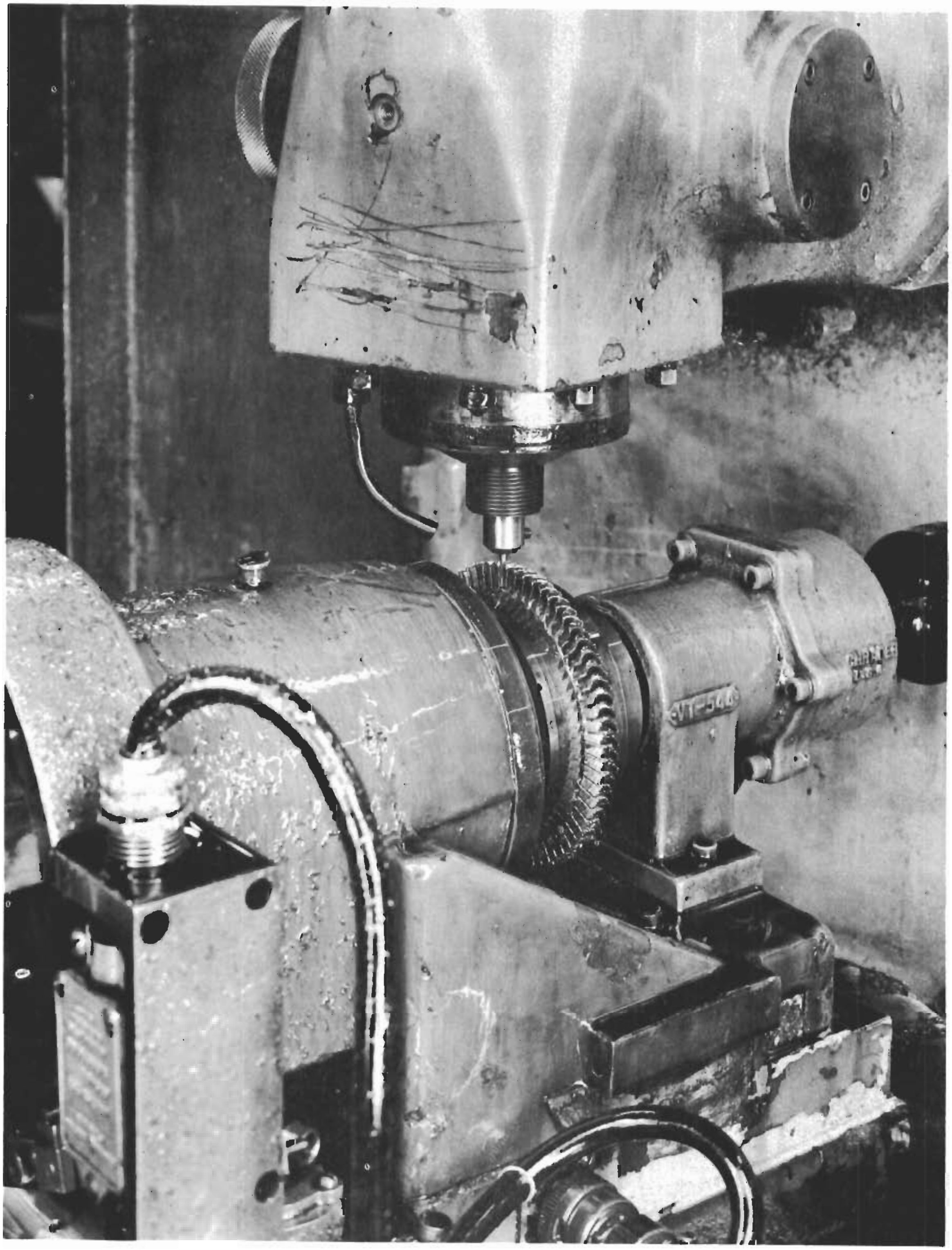


(a)

(b)

TRW RADIALLY EXTRUDED TURBINE WHEEL WITH INTEGRAL BLADES FOR BOEING WATER PUMP. (a) FROM C130 AM TITANIUM ALLOY; (b) SET-UP PIECE USING ALUMINUM ALLOY

FIGURE 11



AUTOMATIC MACHINING SET-UP FOR TURBINE WHEEL WITH INTEGRAL BLADES

FIGURE 12

B. Process Applications

The state-of-the-art survey showed a significant interest for precision formed turbine wheels and gears which offer an improvement in reliability over present forming processes. The interest was broadly divided over such areas of application as auxiliary power units, turbopumps, and small engine propulsion systems.

Various turbine applications require short time but very high performance output, while others must function over extended periods under extreme environmental conditions. The difficult-to-work superalloys are capable of meeting the present high temperature applications, however, the temperature requirements are anticipated by the designers to continue on an upward trend.

The major application of small turbine wheels is in auxiliary power units (APU) and aircraft starters. Although the operating time for these systems is relatively short (minutes or seconds), temperatures increase beyond what is thought to be the normal temperature limitations for the materials under the stresses encountered. However, the short-burst type of operation permits their use at these higher than conventional temperatures. Present auxiliary power units operate in the 1500° to 1900°F range, although service temperature requirements as high as 2500°F are expected.

C. Material Evaluation

The materials used in this program were selected primarily on the basis of properties and fabricability. It was essential that the materials to be considered meet the strength and oxidation requirements of the 1200° to 1700°F service temperature range, yet be amenable to the severe fabrication procedure of a radial extrusion operation. Cost, while of importance, can be compared to the conventional fabrication processes for the same material.

Conventional ferrous alloys, such as hot-work die steels or low alloy steels, do not retain sufficient strength and oxidation resistance to be usable beyond 1200°F. However, there is a group of heavily alloyed iron-base materials generally high in nickel and chromium, which retain their strength and corrosion resistance up to 1500°F. A few of the more common alloys are A-286, W-545, 19-9DL, and Unitemp 212. The compositions of the more prominent alloys are shown in Table II. Essentially these materials are extensions of the austenitic stainless steels, and most of these materials are workable with the proper control of process parameters.

The advantage of these iron-base alloys is their relatively low cost. However, their principal disadvantage is the reduction in creep strength beyond 1400° to 1500°F.

The most significant developments in high temperature technology for the 1500° to 1900°F range have been achieved with nickel-base alloys. Usable creep and oxidation resistance have been attained for this temperature range with these alloys. Most of the nickel-base superalloys are essentially modifications

TABLE II

Nominal Compositions of Alloys

Alloy Name	C	Mn	Si	Cr	Ni	Co	Mo	W	B	Ti	Al	Fe	Others
16-25-6	.08	-	-	16.0	25.0	-	6.0	-	-	-	-	Bal.	.15N
19-9DL	.32	1.1	.55	19	9	-	1.4	1.4	-	.22	-	Bal.	.50 Cu max. .50Cb + Ta
A-286	.05	1.4	-	15.0	26.0	-	1.25	-	.003	2.0	.20	Bal.	.3V
N-155	.15	1.5	.50	21.0	20.0	20	3.0	2.5	-	-	-	Bal.	1.0Cb
W-545	.08	1.3	.30	13.0	26.0	-	1.5	-	.05	2.7	-	Bal.	
Inco 901	.10	1.5	.40	12.5	42.5	1	6.0	-	.015	3.0	-	Bal.	
Unitemp 212	.08	.25	.25	16.0	25.0	-	-	-	-	4.0	.35	Bal.	.05Zr - .50Cb
D-979	.05	.50*	-	15.0	Bal.	-	4.0	4.0	.01	3.0	1.0	27.0	
M-252	.10	1.0*	.70*	19	Bal.	10	10	-	-	2.5	.75	Low	
GMR-235	.15	-	-	15.5	Bal.	-	5.3	-	.06	2.0	3.0	10	
SM-200	.15	-	-	9.0	Bal.	10.0	-	12.0	-	2.0	5.3	-	1.0Cb
TRW-1800	.09	-	-	13.0	Bal.	-	-	9.0	.03	0.6	6.0	Low	1.5Cb
IN-100	.17	-*	-*	9.5	Bal.	15.0	3.0	-	.015	5.0	5.5	Low	1V
INCO-700	.15	2.0*	1.0*	15.0	Bal.	29.0	3.1	-	-	2.0	3.0	4.0	
INCO-713C	.12	-	-	13.0	Bal.	-	4.5	-	.012	0.6	6.0	-	
Astroloy	.06	-	-	15.0	Bal.	15	5.25	-	.03	3.5	4.4	-	
Inconel X	.08	1.0*	.5*	15.5	Bal.	-	-	-	-	3.4	.7	7	1.0Cb
Nimonic 115	.15	-	-	15.0	Bal.	15.0	3.8	-	.015	4.0	5.0	Low	
Rene' 41	.09	-	-	19.0	Bal.	11	10	-	.005	3.1	1.5	-	
Udimet 500	.15	.75*	.75*	18	Bal.	17	4	-	.01	3.0	3.0	Low	
Udimet 700	.15	-	-	15	Bal.	18.5	5.0	-	.03	3.5	4.3	Low	
Waspaloy	.10	1.0*	.75*	19	Bal.	13.5	4.3	-	.007	3.0	1.25	Low	
H-151	.45	-	-	20.0	-	Bal.	-	12.5	-	-	-	-	
S-816	.40	1.2*	-	20.0	20.0	Bal.	4	4.0	-	-	-	3.0	4Cb
SM-302	.85	-	.3	21.5	-	Bal.	-	10.0	.005	-	-	.8	9.0Ta
WI-52	.45	.5*	.50*	21	1.0	Bal.	-	11	-	-	-	.60	1.8Cb + Ta
Stellite 21	.25	-	-	27.0	2.8	Bal.	5.5	-	.007	-	-	2 max.	
Stellite 31	.50	-	-	25.5	10.5	Bal.	-	7.5	-	-	-	2 max.	

* Maximum

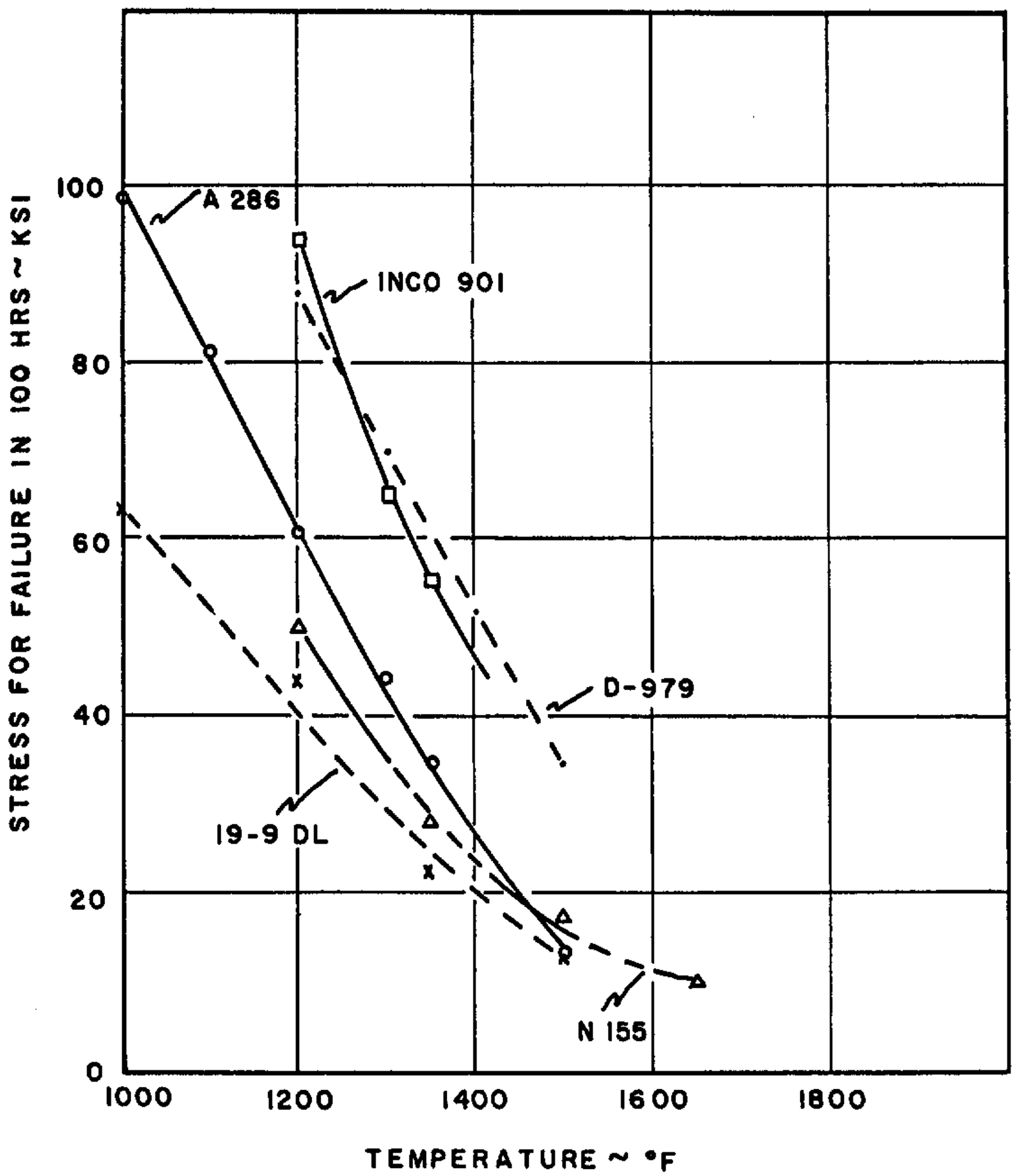
of the original Nimonic 75 composition (80Ni-20Cr) with additional alloying elements. The formation of an inert intermetallic compound, gamma-prime, is the primary reason for the nickel-base superalloy high temperature strength. Gamma-prime is formed with aluminum and titanium additions. Most nickel-base superalloys require vacuum melting to improve fabricability and provide optimum uniform properties. Stress-rupture properties of several nickel- and iron-base alloys are shown in Figure 13 and 14.

Increased use of nickel-base superalloys has presented the forging industry with serious problems. The necessity for avoiding temperature and working combinations which result in exaggerated grain growth, incipient melting, or undesirable mechanical properties establish the fabrication limits of these materials.

Temperatures to which the metals can be heated for forging are determined by the incipient melting temperature as an upper limit and strain hardening capacity indicating the lower limit. Thus, the acceptable forging temperature range is narrowed by 60° to 175°F for some of the nickel-base alloys.

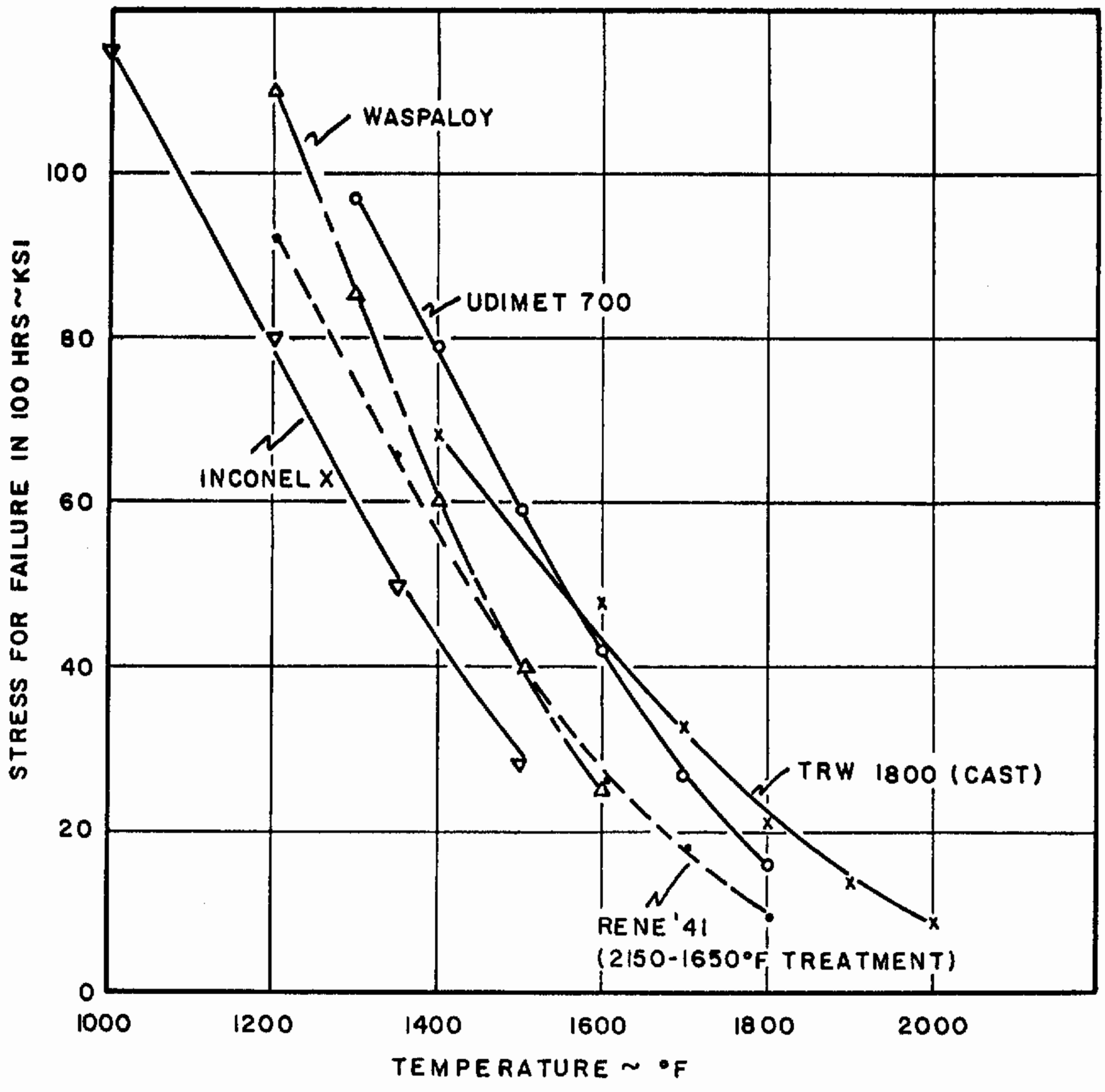
The amount of reduction and the working temperatures, particularly in the final working operations, greatly affect the mechanical properties. Therefore, these factors presented particular problems in the development of the radial extrusion process.

Cobalt-base alloys also have been used as a high temperature material. However, the development of these alloy systems has been less prominent because no intermetallic compound, analogous to the gamma-prime phase, has been developed. Most cobalt-base materials are only solid-solution strengthened and carbide hardened, of which very few are fabricable. The most advanced cobalt-base alloys, such as WI-52, SM 302, and H-151 are strictly cast alloys. However, Haynes 25 and S-816 are fabricable and have been used in a number of applications, particularly in the presence of corrosive media.



STRESS - RUPTURE PROPERTIES OF SOME IRON - AND NICKEL-BASE ALLOYS

FIGURE 13



STRESS - RUPTURE PROPERTIES OF SEVERAL NICKEL - BASE ALLOYS

FIGURE 14

IV EXPERIMENTAL PROCEDURES

Development of the forming process and techniques for producing turbine wheels and gears involved a thorough study and selection of process components. The planning, design, and manufacture of tooling used to evaluate and demonstrate the radial extrusion process, and the development of satisfactory expendable die inserts were major requirements in the program. Having developed suitable process components, evaluation of tooling performance and process reliability were required. Accordingly, the program was divided into two sections. First, a single station screening program was designed to develop tool concepts, process parameters, and potential die insert materials. And second, a full scale forging program evolved as an extension of the single station forging trials to fabricate full size turbine wheels with integral blades and gears.

A. Tooling

An initial requirement established by earlier work on the radial extrusion process was a need for the design of reliable forge tooling. The close tolerances demanded for gear and turbine wheel products and the support required for expendable die insert materials made necessary exceptionally rigid tooling. This basic requirement was considered in designing the initial evaluation tooling and the full scale development tooling.

1. Single Station

A tooling design incorporating a die and insert configuration simulating a section or single station of the turbine wheel or gear was established. This design offered the advantages of economy and adaptability to several types of forging presses. Yet it approximated the flow characteristics of full size wheels or gears. Basically, the tooling consisted of a die cavity, insert hold-down mechanism, and a punch. An exploded view of the components comprising the single station tooling is shown in Figure 15. The function of these components is described as follows:

a) A die containing a cavity for the inserts and forging slug is secured by a clamp ring.

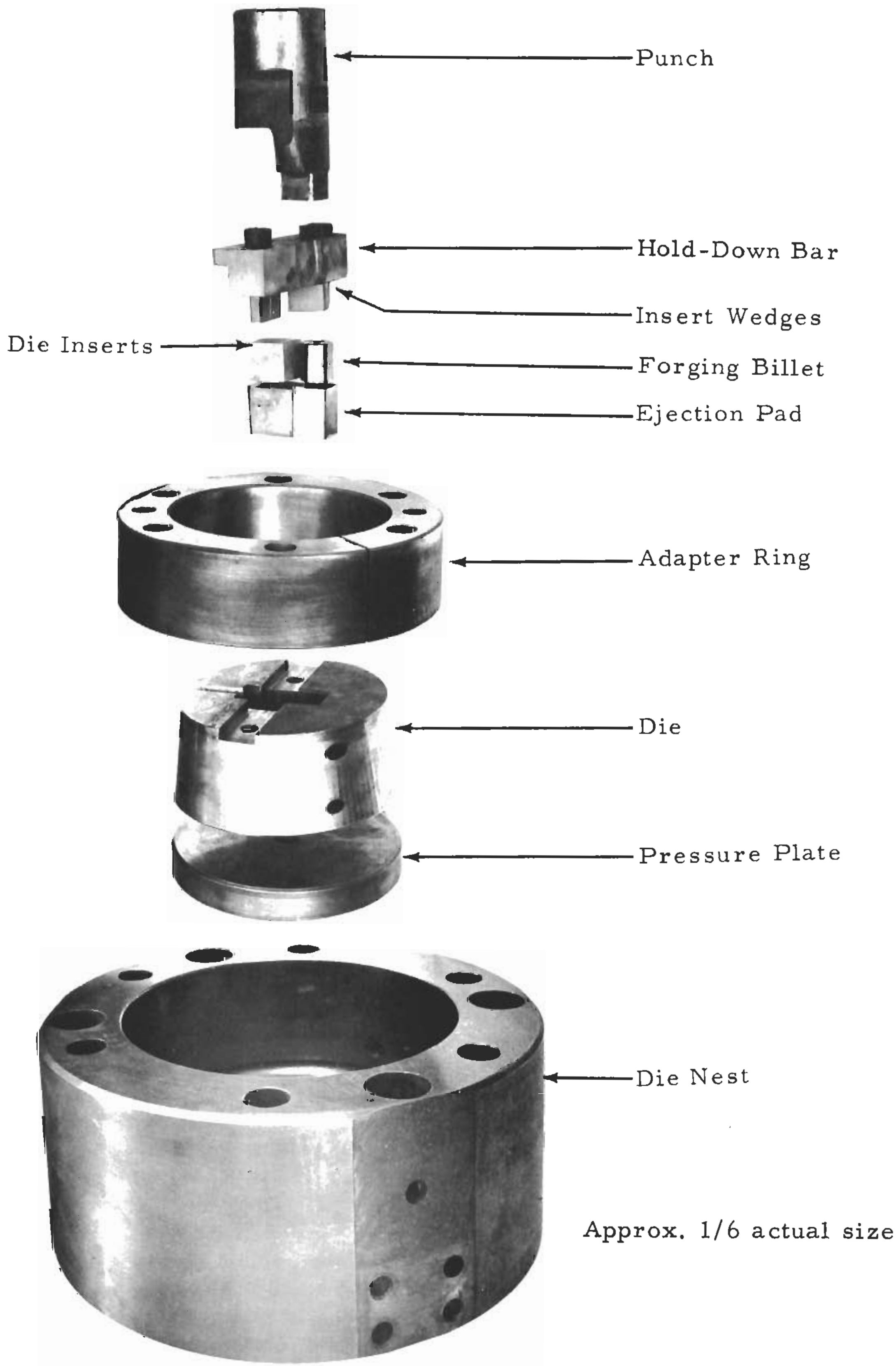
b) A die pad supports the inserts and forge slug, and serves as an ejection pad.

c) Wedges apply lateral pressure to the die inserts.

d) A hold-down bar bolted to the die applies a vertical pressure and holds the wedges in place.

e) A punch affixed to the ram is activated by the forge press.

f) A pneumatic ejection cylinder (not shown) is mounted below the die fixture and serves to eject the die pad, inserts, and forged slug after the metal has been extruded.



MODIFIED SINGLE STATION TOOLING UTILIZED FOR PROCESS COMPONENT DEVELOPMENT WITH THE MECHANICAL PRESS AND DYNAPAK.

FIGURE 15

As a result of the simplicity of working parts, this tooling was adaptable to a small mechanical press and a high velocity metalworking machine (Dynapak).

An important feature of the single station tooling design was the simplicity of the die insert. Instead of the complex blade or tooth configuration, the inserts were essentially cubes having a wedge form in one surface as shown in Figure 16. This simple form served several purposes:

a) The wedge-shaped cavity provided extreme limits of blade thickness,

b) the simple shape expedited procurement, and

c) the reduced cost allowed a variety of materials to be evaluated.

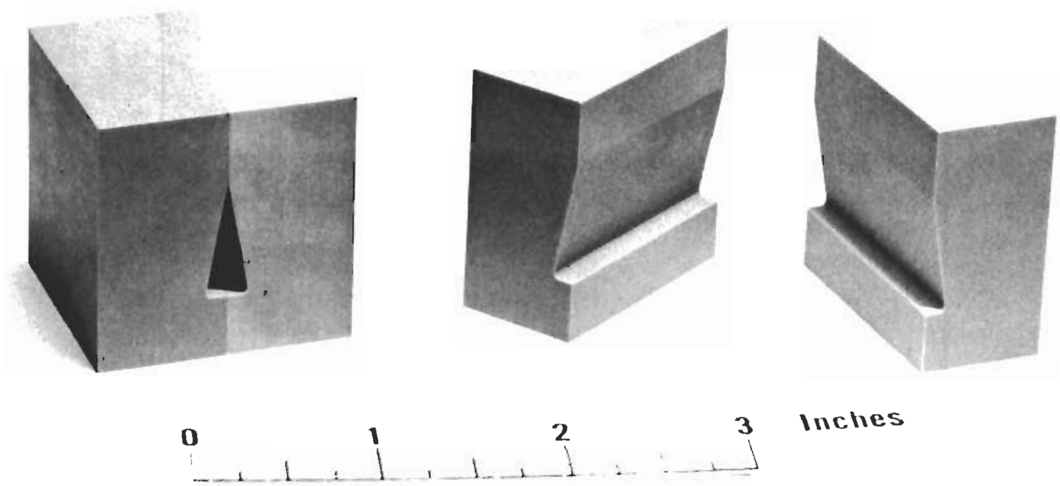
Performance of the inserts were greatly dependent on satisfactory support by the wedges and hold-down bar.

2. Full Scale

The basic tooling for full scale radial extrusion was designed to be adaptable to either gear or turbine wheel forging. This flexibility was attained by removable die inserts for the particular part and replacement of insert adapter rings, punches, and dies. A primary difference in the design of the single station and full scale tooling was the method of securing the inserts in place. Instead of the clamp bar bolted to the single station die, the full scale tooling used a hydraulic hold-down device termed a secondary closure mechanism.

The actual forge tooling components for the turbine wheel are shown in Figure 17. The insert adapter ring shown in the photograph contains an access slot with a removable plug to facilitate loading the last insert in the ring. Figure 18 illustrates the loading slot with the last insert ready to be positioned in the assembled ring. The individual placement of the inserts in the adapter ring relies upon the strict dimensional control of the inserts to provide the proper fit in the assembled ring. Since several thousandths clearance is required to allow the insertion of the final insert, it is not possible to create a pre-stress on the inserts. Thus, an alternate method of assembling the inserts by shrinking a ring around them (Figure 19) provided a pre-stress on the inserts and allowed for easier handling. Development of the shrink ring method was accomplished by an interference fit (0.010 inch) between the ring and assembled inserts. Assembly of the component parts was facilitated by heating the steel ring to 700°F, causing it to expand in excess of the insert diameter. The heated ring was positioned around the inserts then air cooled, allowing the ring to contract against a 2° angle on the matching surfaces.

Conversion of the basic tooling to accomodate the gear tooling required the replacement parts shown in Figure 20. The insert adapter shown in

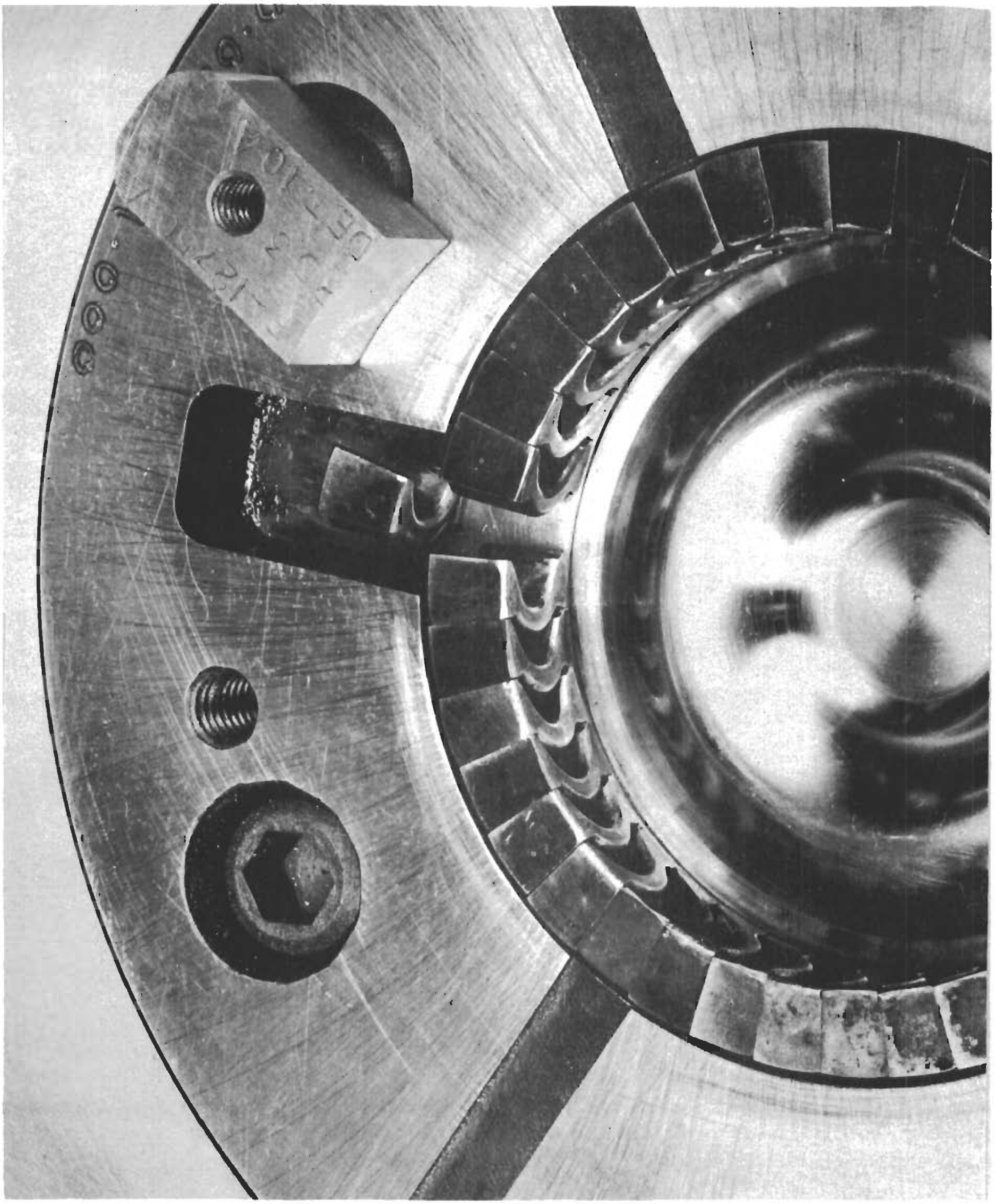


SINGLE STATION DIE INSERTS

FIGURE 16

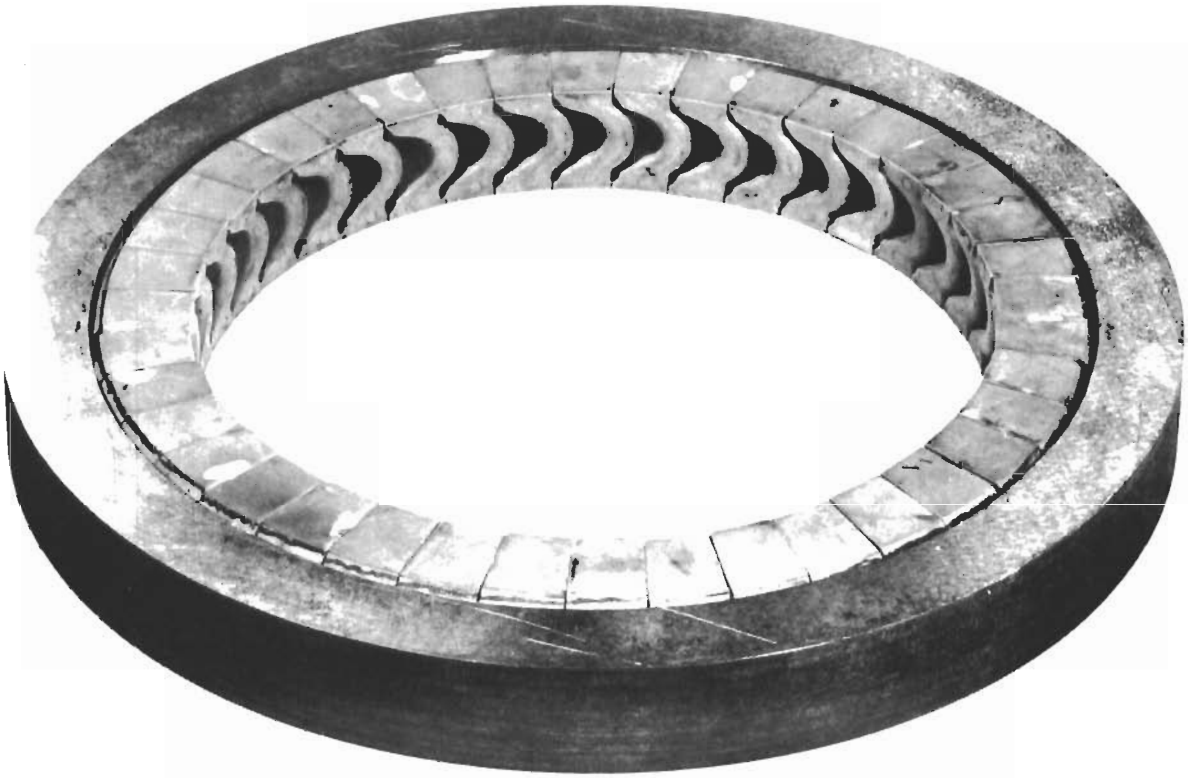
FORGE TOOLING FOR RADIAL EXTRUSION OF TURBINE WHEELS. COMPONENTS ILLUSTRATED ARE: (a) DIE ASSEMBLY WITH INSERT ADAPTER RING AND BASE PLATE (LEFT), (b) PUNCH AND PUNCH HOLDER (LOWER RIGHT), AND (c) CLOSURE RING (UPPER RIGHT). (REDUCED APPROXIMATELY 80% FOR REPRODUCTION)

FIGURE 17



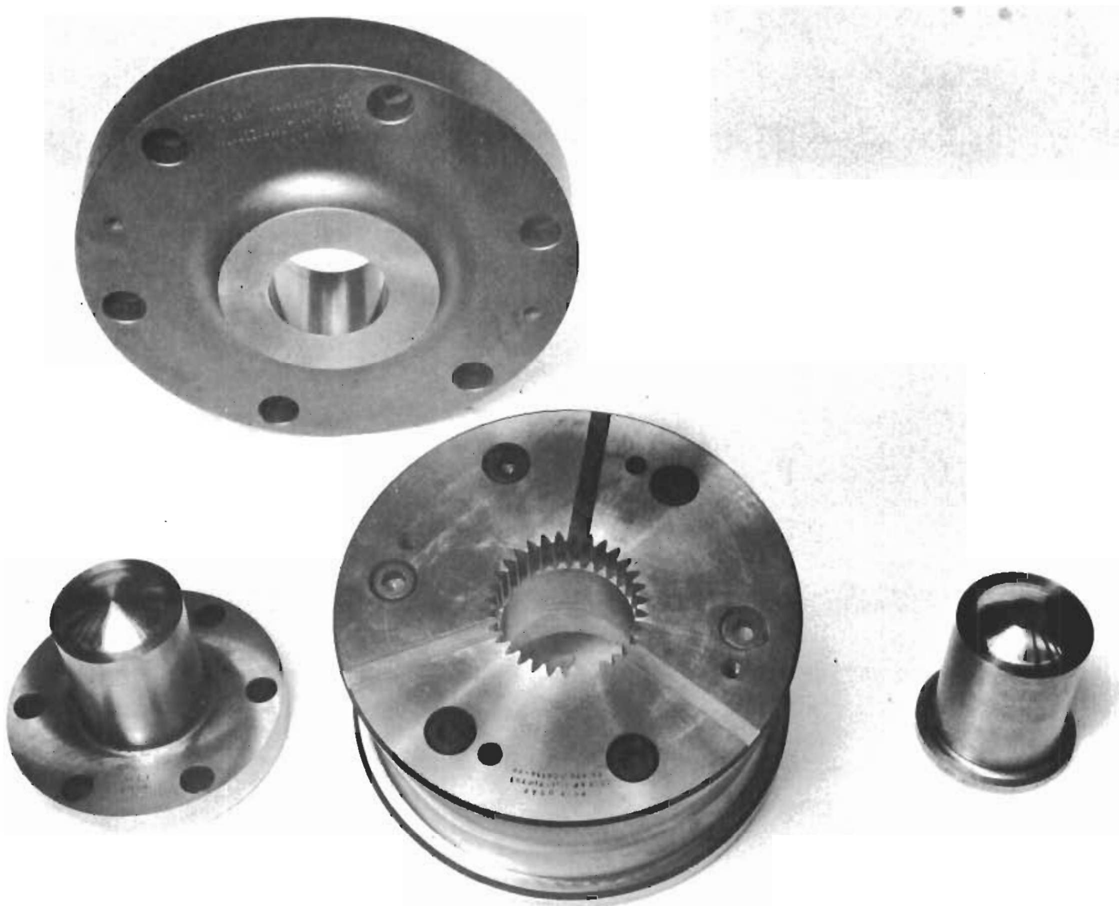
ASSEMBLY OF TURBINE WHEEL DIE INSERTS IN ADAPTER RING ILLUSTRATING LOADING SLOT REQUIRED TO INSERT LAST PIECE IN RING. (APPROXIMATELY FULL SIZE.)

FIGURE 18



INDIVIDUAL DIE INSERTS SECURED IN POSITION BY STEEL RING. INTERFERENCE FIT BETWEEN THE RING AND INSERT DIAMETERS CREATES A PRESTRESS ON THE INSERTS PRIOR TO FORGING.

FIGURE 19



FORGE TOOLING REPLACEMENT COMPONENTS REQUIRED FOR RADIAL EXTRUSION OF GEARS. ILLUSTRATED ARE: (a) CLOSURE RING (TOP), (b) PUNCH (LOWER LEFT), (c) DIE ASSEMBLY WITH INTEGRAL DIE ADAPTER (CENTER), AND (d) DIE PEDESTAL (LOWER RIGHT). (REDUCED APPROXIMATELY 80% FOR REPRODUCTION.)

FIGURE 20

Figure 21 illustrates the integral die with the gear teeth cavities, having zero draft on the sides, machined directly in the adapter. It was possible to use this approach for the gear since the straight sides on the teeth allowed the forged part to be ejected from the die. The alternate approach to forging gear teeth using individual die inserts was effected by replacing the integral die with an insert adapter that accomodated the individual inserts secured in a shrink-ring (Figure 22).

B. Inserts

Two primary approaches were taken to develop forging die inserts:

1. Expendable inserts, which were precise and serviceable, yet inexpensive enough to be used only once; and

2. Permanent inserts capable of being reused sufficiently to justify their high initial cost.

The major effort in the earlier part of the program was placed on expendable materials. But later developments showed a feasibility of using permanent type inserts for the complete airfoil shapes.

1. Expendable Type

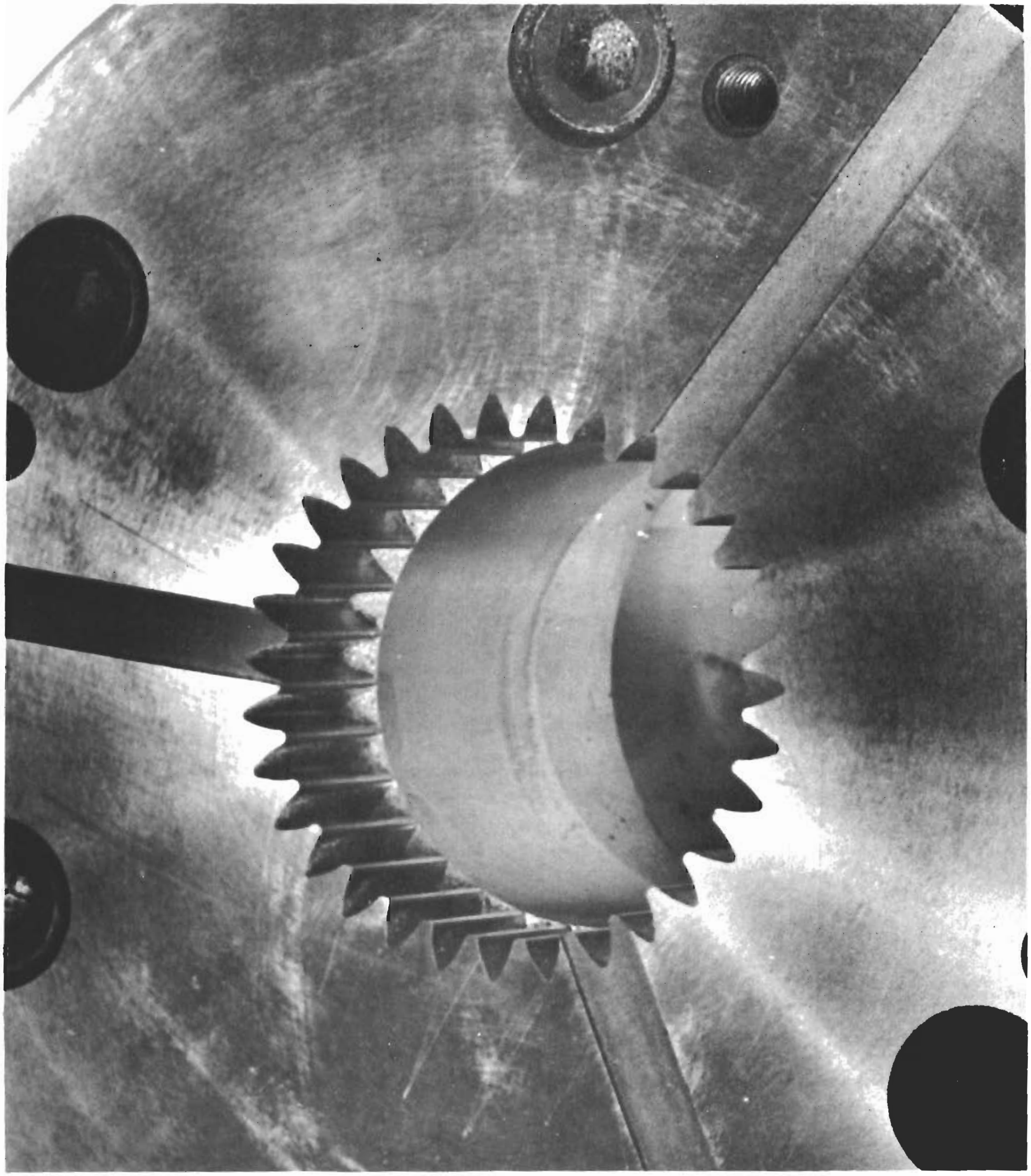
The potentially useful types of expendable materials considered for forging die inserts included ceramics, plastics, cermets, powder metallurgy parts, and castings. Procurement inquiries were submitted to more than twenty-five suppliers of precision products associated with the above materials. In addition to the dimensional requirements, the anticipated forging pressures and temperatures were given. The response indicated that suppliers interested in attempting to fabricate expendable die inserts in accordance with the predicted requirements were extremely limited. The majority of suppliers indicated that it would be impossible to adhere to the strict dimensional tolerances with either pressed and sintered, molded, or cast parts. Similarly, material suppliers were uncertain whether their products would satisfy the forging conditions.

a) Cermets

Cermet development arose from a demand for materials serviceable at temperatures above 2000°F. Cermets contain both metal and ceramic phases that retain adequate mechanical strength at high temperatures, and provide resistance to thermal shock, oxidation, abrasion, and erosion.

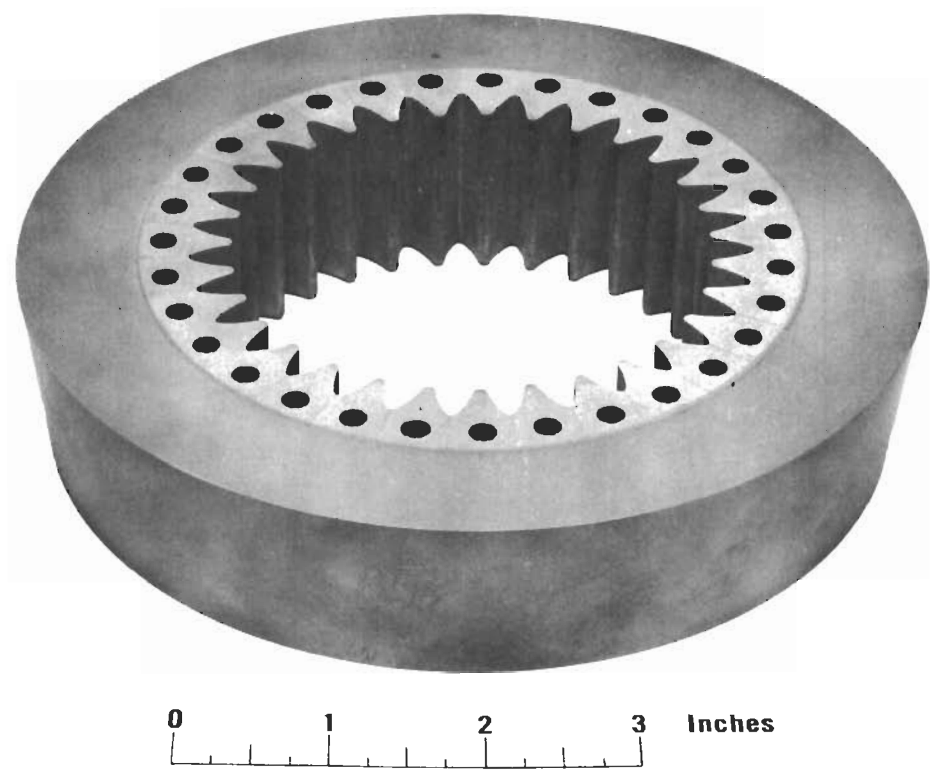
The inherent high temperature features of cermets indicated they might be suitable for radial extrusion die inserts. Property data for three types of cermets are shown in Table III.

Although cermet products appeared to satisfy the mechanical and thermal shock properties required for the radial extrusion process, their



FORGING DIE WITH INTEGRAL DIE CAVITIES FOR RADIAL EXTRUSION OF PINION GEARS.
(APPROXIMATELY FULL SIZE)

FIGURE 21



DIE INSERTS ASSEMBLED IN SHRINK RING FOR RADIAL EXTRUSION OF GEARS.

FIGURE 22

TABLE III

TYPICAL PROPERTIES OF CERMETS[4]

	Chromium-Alumina (LT-1)	Molybdenum-Chromium Alumina (LT-1B)	Tungsten-Chromium Alumina (LT-2)
Density, lb/in^3	0.21	0.22	0.33
Coeff. Therm. Exp., in/in/°F	4.7×10^{-6} (a)	5.2×10^{-6} (b)	-
Thermal Conductivity, $BTU/hr/ft^2/°F/in$	348 (c)	-	-
Specific Heat BTU/lb/°F	0.16	0.14	-
Hardness Rc	37	45-55	55
Compressive Strength, psi	110,000	240,000	-

(a) at 32 - 1832°F
(b) at 68 - 1472°F
(c) at 500°F

high initial cost and inability to be economically fabricated prohibited further investigation as die insert materials. Because cermets are a new development, a reduction in material cost and improvements in fabrication technology may warrant a more thorough investigation of this material as an expendable die insert material in the future.

Inquiries concerning types of cermet materials, such as the metal carbides and metal nitrides, resulted in costs which did not justify further investigation.

b) Plastics

A program was established to determine the properties of commercially available plastics and to select those offering the most promise of being able to withstand forging temperatures and pressures for several seconds. The effort consisted of a material survey, tool design and manufacture, process development, and prototype production.

Three fiber-reinforced plastic materials were selected for initial processing. The strengths of these glass-phenolic and glass-epoxy materials shown in Table IV are considerably lower than the minimum anticipated compressive strength required for forging. Consideration of using these low compressive strength materials was based on the short duration of both high temperature and compressive load.

The process and techniques for producing the precision formed inserts was developed for each of the selected materials. Molding characteristics, including pressure-temperature dependence and shrinkage, were established to determine the dimensional limitation of the as-molded parts. The initial process feasibility study indicated a dimensional compatibility with the insert requirements.

Compressive strength and hardness of representative samples of inserts fabricated from each material lot was taken. These data were typical of the material properties specified by the manufacturers, except the glass-phenolic exhibited slightly lower strength.

c) Powder Metallurgy Products

In addition to the non-metallic materials, powder metallurgy products also were evaluated. Three commercial grades of iron powders were pressed and sintered to provide insert blanks. The process data indicated a maximum sintered density of 90% which was improved to 94% by coining. The compressive strength, as reported by the suppliers, was 23,000 to 48,000 psi. It is possible to increase the strength of the powder compacts by the addition of carbon and subsequent heat treatment, but the increase is not significant.

d) Ceramics

Of the materials selected for evaluation, a high density alumina product offered the greatest potential as an expendable insert. In addition to

TABLE IV

STRENGTH VALUES FOR SOME FIBER REINFORCED PLASTIC MATERIALS

Material No.	Manufacturer	Type	Compressive Str. psi	Resistance to Impact Izod, Ft. lb/in of Notch
FM 8130	Fiberite	Glass-Phenolic	34,000	18
16771-1	Durez	Glass-Phenolic	16,500	15
X7008	U.S. Polymeric	Glass-Epoxy	25,000	23

alumina, other metal oxides such as magnesia and zirconia were considered as candidate materials. Because the material selected must have high compressive strength, impact, thermal shock and wear resistance, a high density alumina was selected for further evaluation. This choice also was supported by the past experience with the radial extrusion process at TRW. This work indicated that a high alumina (95-97%) product, with small amounts of silica, magnesia, and chromic oxide performed satisfactorily under certain conditions. Although these dense alumina inserts exhibited the capability of withstanding the forging conditions, removal of the insert from the forged turbine wheel was extremely difficult.

2. Permanent Types

The category of permanent inserts included those materials capable of being reused several times. The application of permanent die inserts for radial extrusion initially was directed toward simple spur gears and axial flow turbine wheels having straight blades with positive draft angles.

As a means of comparing the test results of expendable insert materials, tool steel (AISI H-21) and low alloy steel (AISI 4340) single station die inserts were used. Later in the full scale forging development precision cast inserts were produced from AISI 6150 steel.

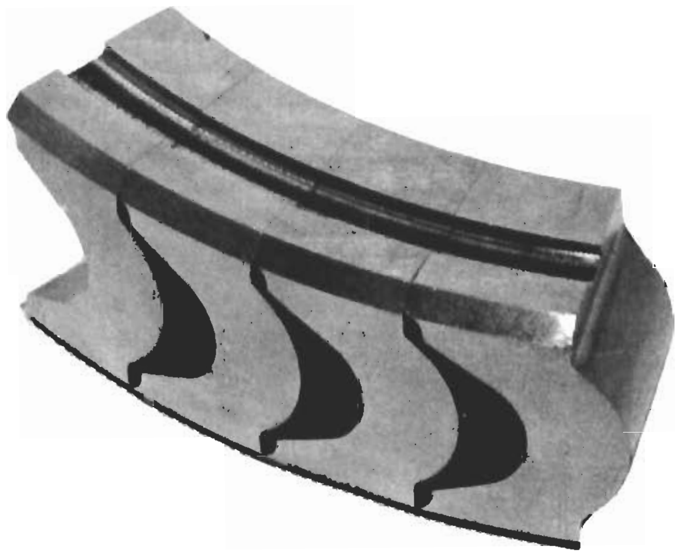
3. Fabrication

On the basis of the single station test results, full scale inserts for the turbine wheel and gear were fabricated from a special grade of high density alumina and H-21 tool steel. The turbine wheel inserts where provided with a recessed slot, as shown in Figure 23, to facilitate removal from the forged wheel.

One of the problems with alumina turbine wheel inserts was maintaining the precision required to provide intimate contact between mating surfaces of adjacent inserts. Precision grinding of the contacting surfaces was required to insure proper fit. Intimate contact between inserts and proper support of the remaining surfaces are imperative to the success of using this high compressive strength, brittle material.

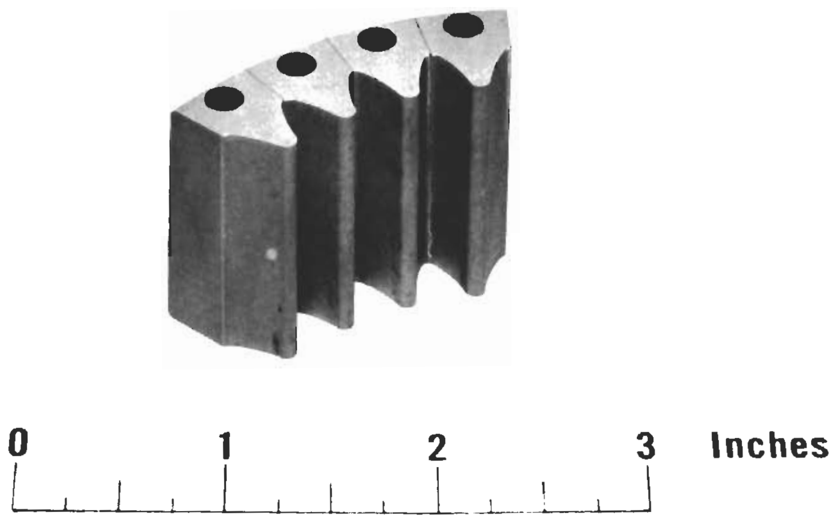
Individual die inserts for the gear tooling (Figure 24) were fabricated from alumina then used in a shrink ring assembly described previously. The problem associated with the fit between turbine wheel inserts was not present in the gear inserts because of better dimensional control.

As a result of the high initial cost of fabricating full scale turbine wheel inserts by machining and precision grinding H-21 tool steel, precision casting was investigated. The initial feasibility study with inserts precision cast from AISI 6150 steel indicated the process was economically desirable. Also, the required dimensional tolerances could be attained by finish grinding the critical dimensions.



TOOL STEEL (H-21) DIE INSERTS FOR RADIAL EXTRUSION OF TURBINE WHEELS. THE RECESSED SLOT IS PROVIDED IN THE TOP AND BOTTOM SURFACES TO FACILITATE AN INSERT REMOVAL FIXTURE. THESE PIECES ALSO CONTAIN THE 2° TAPER ON THE OD SURFACE. (APPROXIMATELY 2X)

FIGURE 23



INDIVIDUAL DIE INSERTS FABRICATED FROM HIGH DENSITY ALUMINA FOR GEAR FORGING STUDIES. THE TOOTH CONTOUR IS THE AS-FIRED SURFACE, WHEREAS THE FLAT SURFACES HAVE BEEN GROUND TO PRECISION TOLERANCES.

FIGURE 24

Although the casting supplier would not guarantee dimensional tolerances better than .005 in., inspection data for thirty random samples of the as-cast inserts was made to evaluate the process capability. Inspection of the blade contour of the inserts was made by means of an optical comparator chart. All of the pieces inspected were within ±.002 in. of the absolute form and the variation between pieces was within 0.001 in. A qualitative inspection of the mating surfaces revealed high dimensional uniformity; therefore, additional inspection was performed to determine the possibility of using cast inserts without finish grinding. Dimensional data of the as-cast inserts before and after heat treatment were obtained at the locations indicated in Figure 25. The data shown in Table V and VI were statistically analyzed to determine the probability factor and confidence levels of the dimensional reproducibility for large quantities. A summary of the statistical analysis, shown in Table VII, indicated a possibility that inserts could be used in the as-cast condition.

C. Equipment

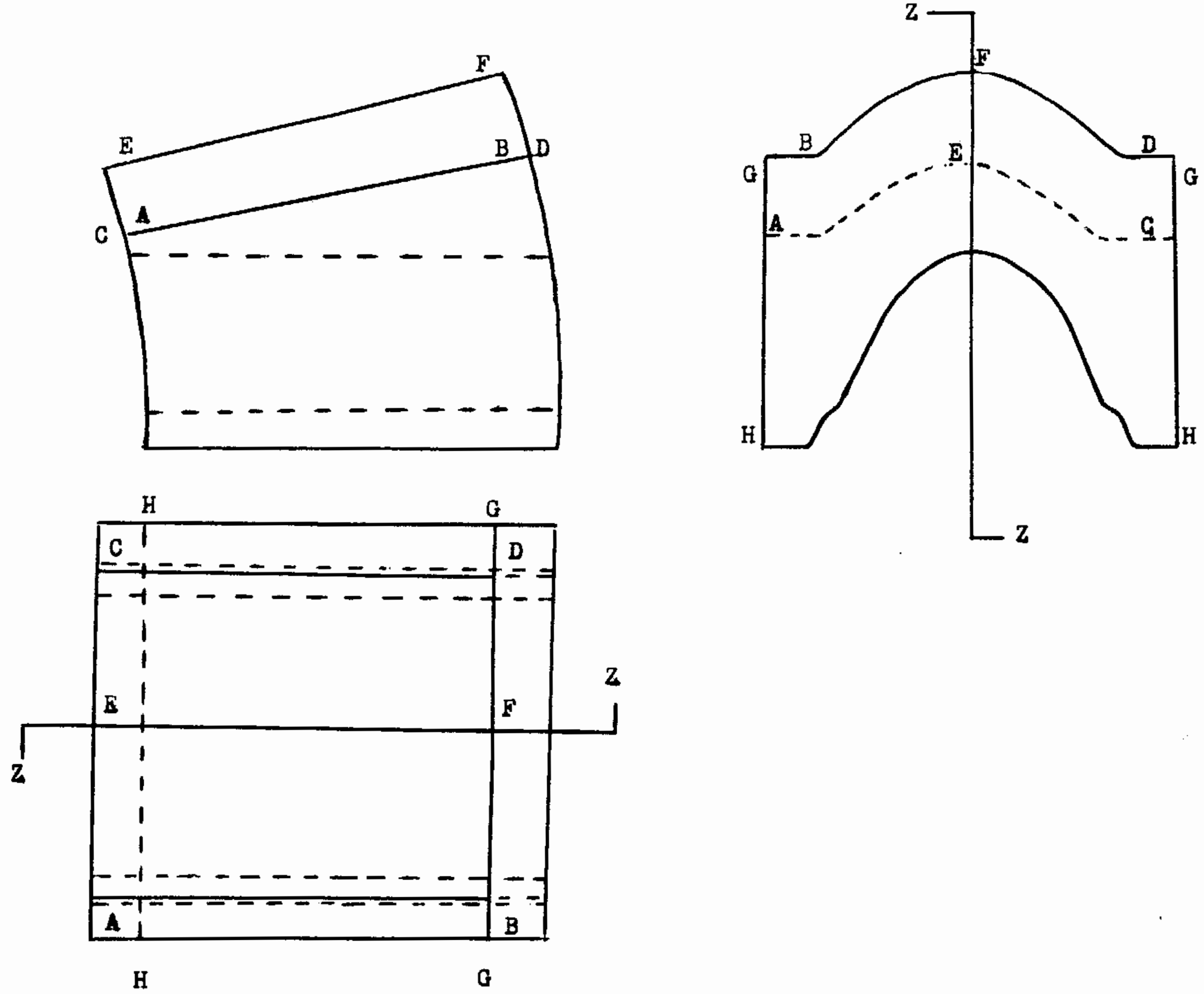
1. Forging Machines

Earlier development work at TRW on the radial extrusion process was accomplished using a 2500-ton mechanical forging press. Although this work defined several problem areas in the radial extrusion process, considerable preliminary development was necessary to establish process variables. The initial process development studies of the recent program were conducted using a Dynapak. Since the single station tooling was adaptable to the Dynapak or a mechanical press, similar tests were performed to provide comparative data for the two machines. Investigation of the effects of forging deformation rate on the material behavior was possible because of the significant difference in ram velocities of the two machines. The ram velocity of the mechanical press was approximately 20 in./sec., while the Dynapak produced 200-400 in./sec. (for the energy levels used in this program). Within the limits of these tests, no outstanding difference in forging response could be observed between the Dynapak and a mechanical press.

Although the single station forging trials were accomplished with small mechanical presses, full scale forging of turbine wheels and gears was performed on the 8000-ton mechanical press shown in Figure 26. The forging capacity of this press was considerably greater than the loads necessary to deform the turbine wheels and gears, but the hold-down mechanism for the inserts required the increased capacity to function properly.

2. Secondary Closure Mechanism

This unique closure mechanism illustrated in Figure 27 was designed expressly for operation in the 8000-ton mechanical press to apply a secondary pressure during forging. The principle on which the unit was based evolved from preliminary design studies of mechanical and hydraulic closure systems. It involves a closed hydraulic system that uses pressure obtained from the movement of the press ram. The downward movement of the ram causes a down-



SCHEMATIC DRAWING OF TURBINE WHEEL INSERT ILLUSTRATING SURFACES
INSPECTED FOR DIMENSIONAL EVALUATION

FIGURE 25

TABLE V

DIMENSIONAL SURVEY FROM A RANDOM SAMPLE OF CAST STEEL DIE INSERTS BEFORE HEAT TREATMENT

Piece No.	A	B	C	D	E	F	G	H
1	.0	+ .006	- .003	+ .004	.0	+ .006	.764	.765
2	+ .001	+ .005	- .002	+ .003	- .001	+ .003	.770	.767
3	.0	+ .006	- .003	+ .003	- .002	+ .003	.767	.767
4	.0	+ .005	- .001	+ .003	.0	+ .005	.765	.767
5	.0	+ .004	- .002	+ .003	+ .001	+ .008	.764	.766
6	.0	+ .005	- .001	+ .004	+ .003	+ .007	.766	.766
7	- .001	+ .004	- .002	+ .003	+ .002	+ .003	.764	.766
8	.0	+ .004	- .002	+ .003	+ .001	+ .005	.768	.768
9	.0	+ .004	- .003	+ .004	- .001	+ .005	.768	.770
10	- .001	+ .004	- .002	+ .003	+ .001	+ .004	.765	.765
11	- .001	+ .005	- .003	+ .003	.0	+ .002	.763	.767
12	+ .002	+ .006	.0	+ .004	+ .001	+ .004	.765	.769
13	+ .002	+ .008	- .001	+ .004	- .001	+ .005	.770	.773
14	- .001	+ .005	- .002	+ .004	- .001	+ .003	.765	.766
15	- .001	+ .005	- .002	+ .003	- .002	+ .002	.767	.766
16	.0	+ .005	- .002	+ .003	- .002	+ .002	.766	.772
17	.0	+ .006	- .003	+ .003	- .002	+ .003	.769	.770
18	- .001	+ .005	- .002	+ .005	+ .001	+ .004	.766	.765
19	.0	+ .007	- .002	+ .003	- .001	+ .002	.763	.767
20	.0	+ .004	- .003	+ .003	- .002	+ .002	.767	.769
21	+ .001	+ .004	- .001	+ .003	+ .001	+ .002	.765	.770
22	.0	+ .005	- .002	+ .005	- .003	+ .005	.770	.769
23	.0	+ .004	- .002	+ .003	- .001	+ .004	.765	.769
24	- .001	+ .004	- .002	+ .003	.0	+ .004	.766	.767
25	+ .001	+ .005	- .001	+ .005	- .001	+ .004	.767	.766
26	+ .001	+ .007	- .002	+ .005	- .001	+ .003	.766	.771
27	.0	+ .004	- .001	+ .005	+ .001	+ .004	.763	.765
28	+ .001	+ .006	- .001	+ .004	.0	+ .004	.770	.769
29	.0	+ .005	- .002	+ .003	.0	+ .002	.764	.769
30	.0	+ .004	- .001	+ .003	+ .001	+ .004	.765	.767

Note: Columns A through F are deviations from reference point (See Figure 25)

TABLE VI

DIMENSIONAL SURVEY FROM A RANDOM SAMPLE OF CAST STEEL DIE INSERTS AFTER HEAT TREATMENT

Piece No.	A	B	C	D	E	F	G	H
1	.0	+ .005	- .002	+ .007	.0	+ .008	.765	.765
2	+ .003	+ .007	.0	+ .005	- .002	+ .004	.770	.773
3	+ .002	+ .007	.0	+ .005	- .002	+ .005	.768	.769
4	+ .002	+ .007	.0	+ .004	+ .001	+ .006	.768	.768
5	+ .002	+ .006	.0	+ .005	+ .002	+ .006	.767	.767
6	+ .003	+ .007	+ .001	+ .006	+ .003	+ .007	.766	.769
7	+ .002	+ .006	.0	+ .004	+ .002	+ .004	.764	.767
8	+ .002	+ .006	.0	+ .005	+ .001	+ .005	.769	.770
9	+ .002	+ .006	.0	+ .005	- .002	+ .006	.768	.772
10	+ .001	+ .006	- .001	+ .005	+ .002	+ .006	.767	.764
11	.0	+ .005	- .001	+ .003	.0	+ .003	.764	.768
12	+ .004	+ .007	+ .002	+ .006	+ .001	+ .007	.767	.766
13	+ .004	+ .009	+ .001	+ .006	.0	+ .007	.771	.775
14	.0	+ .006	- .001	+ .004	.0	+ .005	.767	.768
15	+ .001	+ .005	+ .001	+ .004	- .001	+ .004	.768	.769
16	+ .001	+ .006	- .001	+ .005	- .002	+ .003	.768	.775
17	+ .002	+ .007	+ .001	+ .006	- .001	+ .005	.771	.772
18	+ .001	+ .006	.0	+ .006	+ .001	+ .005	.765	.767
19	+ .001	+ .006	+ .001	+ .005	+ .001	+ .005	.766	.767
20	+ .001	+ .005	- .003	+ .003	- .002	+ .003	.770	.773
21	+ .003	+ .006	.0	+ .005	+ .001	+ .004	.766	.772
22	+ .002	+ .008	.0	+ .007	.0	+ .006	.772	.770
23	+ .002	+ .005	.0	+ .004	.0	+ .005	.767	.770
24	.0	+ .005	.0	+ .005	+ .001	+ .006	.766	.768
25	+ .002	+ .006	+ .001	+ .007	+ .001	+ .005	.769	.772
26	+ .003	+ .007	.0	+ .005	- .001	+ .003	.768	.772
27	+ .002	+ .006	+ .001	+ .006	+ .002	+ .007	.765	.766
28	+ .003	+ .006	+ .001	+ .006	+ .001	+ .006	.772	.771
29	+ .002	+ .007	- .001	+ .004	+ .001	+ .004	.766	.770
30	+ .002	+ .005	+ .001	+ .005	+ .002	+ .005	.767	.769

Note: Columns A through F are deviations from reference point (See Figure 25)

TABLE VII

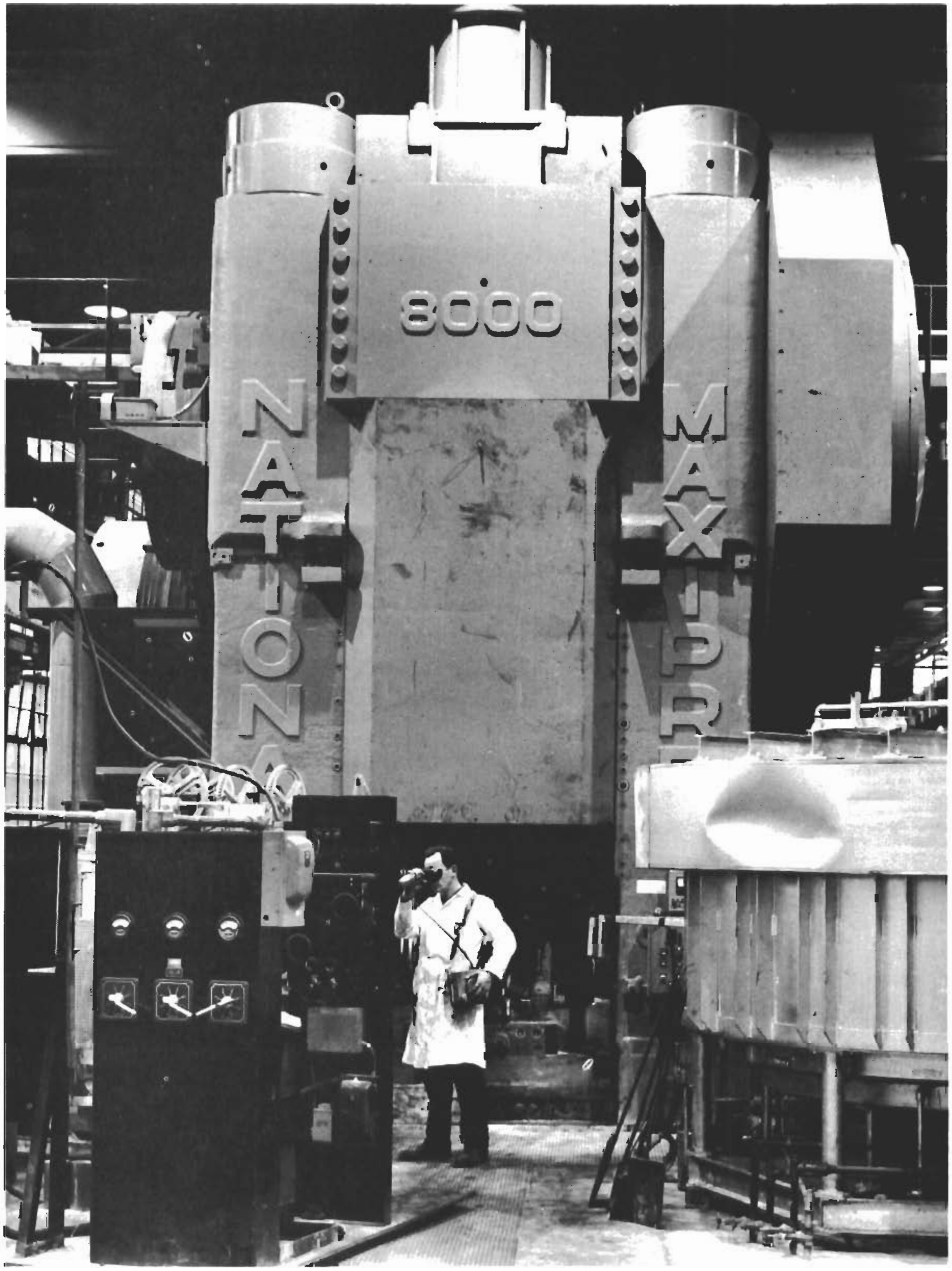
CALCULATED TOLERANCE LIMITS ON TURBINE WHEEL INSERTS

Y	P	Dimension A	Dimension B	Dimension C	Dimension D
		Limits (L) on:			
0.90	0.90	(-.00161, +.00174)	(+.00287, +.00719)	(-.00344, -.00030)	(+.00200, +.00513)
	0.95	(-.00193, +.00206)	(+.00246, +.00761)	(-.00374, +.00001)	(+.00170, +.00543)
	0.99	(-.00256, +.00269)	(+.00165, +.00841)	(0.00433, +.00059)	(+.00111, +.00602)
0.95	0.90	(-.00170, +.00184)	(+.00275, +.00731)	(-.00353, -.00021)	(+.00191, +.00522)
	0.95	(-.00204, +.00218)	(+.00232, +.00775)	(-.00385, +.00011)	(+.00159, +.00554)
	0.99	(-.00271, +.00284)	(+.00146, +.00860)	(-.00447, +.00073)	(+.00097, +.00616)
0.99	0.90	(-.00191, +.00204)	(+.00249, +.00758)	(-.00372, -.00002)	(+.00172, +.00541)
	0.95	(-.00226, +.00242)	(+.00200, +.00806)	(-.00407, +.00034)	(+.00137, +.00577)
	0.99	(-.00302, +.00316)	(+.00105, +.00901)	(-.00476, +.00103)	(+.00068, +.00646)

Y	P	Dimension E	Dimension F	Dimension G	Dimension H
		Limits (L) on:			
0.90	0.90	(-.00308, +.00254)	(+.00073, +.00687)	(.76174, .77046)	(.76343, .77211)
	0.95	(-.00362, +.00308)	(+.00014, +.00746)	(.76090. .77130)	(.76259, .77294)
	0.99	(-.00467, +.00413)	(-.00101, +.00861)	(.75927, .77293)	(.76097, .77456)
0.95	0.90	(-.00324, +.00270)	(+.00055, +.00705)	(.76149, .77071)	(.76318, .77236)
	0.95	(-.00381, +.00327)	(-.00007, +.00767)	(.76061, .77159)	(.76230, .77323)
	0.99	(-.00492, +.00438)	(-.00129, +.00889)	(.75888, .77332)	(.76058, .77495)
0.99	0.90	(-.00358, +.00304)	(+.00018, +.00742)	(.76096, .77124)	(.76265, .77288)
	0.95	(-.00421, +.00368)	(-.00051, +.00811)	(.75998, .77222)	(.76168, .77386)
	0.99	(-.00545, +.00491)	(-.00187, +.00947)	(.75806, .77414)	(.75976, .77577)

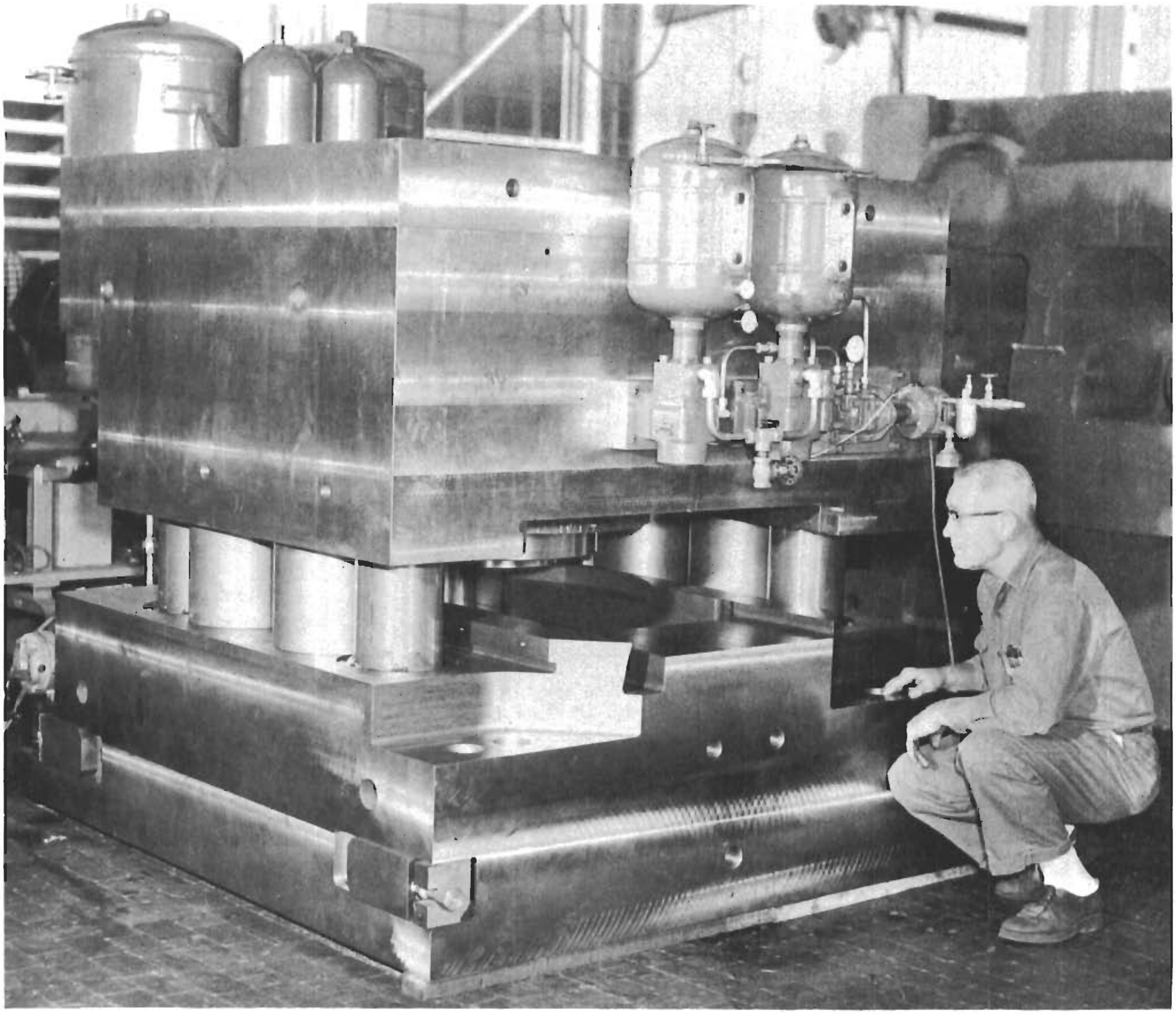
(Y) Percent confidence that (P) percent of dimensions (A-H) will be within the limites (L).

Refer to Figure 25 for dimension locations.



FRONT VIEW OF THE 8000 TON MECHANICAL FORGE PRESS USED FOR FULL-SCALE FORGING OF TURBINE WHEELS AND GEARS

FIGURE 26



FRONT VIEW OF SECONDARY CLOSURE MECHANISM SHOWING RAM RETURN HYDRAULIC SYSTEM (FRONT) WITH OIL ACCUMULATOR AND NITROGEN TANKS (REAR). (COURTESY OF NATIONAL MACHINERY COMPANY)

FIGURE 27

ward movement of the closure slide simultaneously with, but slightly ahead of, the ram until the closure ring contacts the die inserts contained in the insert adapter. A constant pressure is created on the inserts by the closure ring as the ram continues its downward movement and reaches the bottom of the cycle. Pressure is attained by metering the oil from the closure through a series of orifices and returning the oil to reservoirs. At the completion of the press stroke, the closure system retracts from the die with the punch allowing the forged component to be ejected from the die. A schematic illustration of the secondary closure mechanism and tooling arrangement is shown in Figure 28.

The pressure exerted by the hydraulic system on the closure slide imparts a load on the closure ring, calculated to be approximately 600 tons. The actual magnitude and duration of the load created by the action of the press was determined by a test ring (Figure 29), positioned between the lower die assembly and the closure adapter. Strain gages mounted on the inside and outside diameters of the test ring were used to measure the elastic strain induced in the ring during the closure cycle. The load on the ring and the duration of applied load were determined from strain-time plots recorded on a variable speed strain recorder. The load as a function of time and displacement with respect to the ram position was then determined.

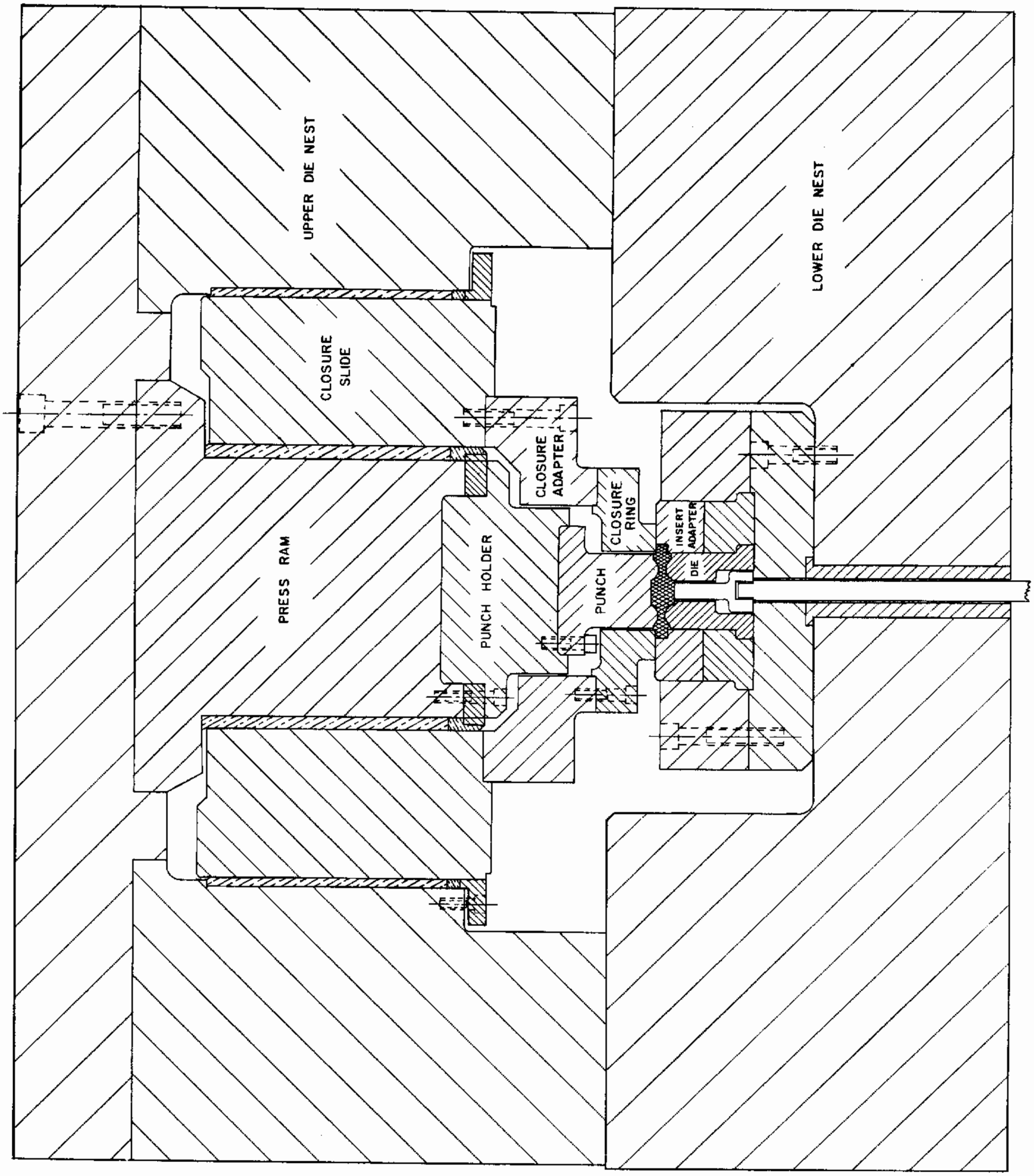
A series of tests with closure travel variations between 2 and 6 inches indicated the load to be unaffected by closure travel distance. The load applied on the test ring was greater than 600 tons and was maintained during the full travel of the closure. A typical trace of the load as a function of press cycle time is shown in Figure 30. This trace, obtained with the variable speed strain recorder also reveals the total load applied by the press as the ram passes through the bottom of the stroke. These patterns illustrate that the closure load is maintained during the complete forging cycle then released as the ram begins its upward movement.

D. Forging Parameters

In addition to the evaluation of potential expendable insert materials, the single station forging was used to evaluate the forging parameters; lubrication, heating, and protective coatings. The various forging parameters evaluated are listed in Table VIII.

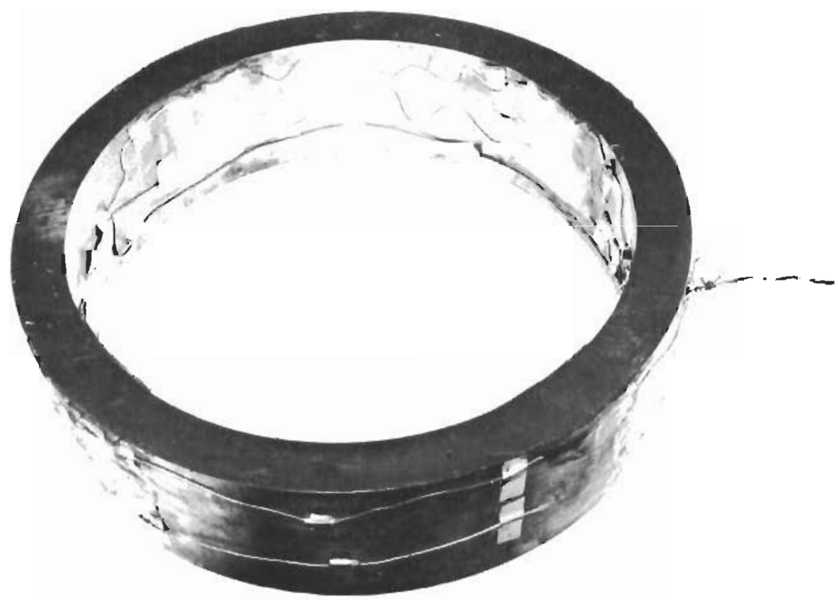
1. Heating

The materials used in the single station and full scale forging were classified as readily-forgeable and difficult-to-forge alloys. Those alloys which were considered as being readily-forgeable were AISI 9310 and Nitralloy, which are gear materials. Since the gear forging was not considered as difficult as the turbine wheel forging, forging temperatures were not evaluated for these materials. A-286 and Waspaloy have a limited forging temperature range; therefore, all forging was conducted toward the upper limit of the forging range.



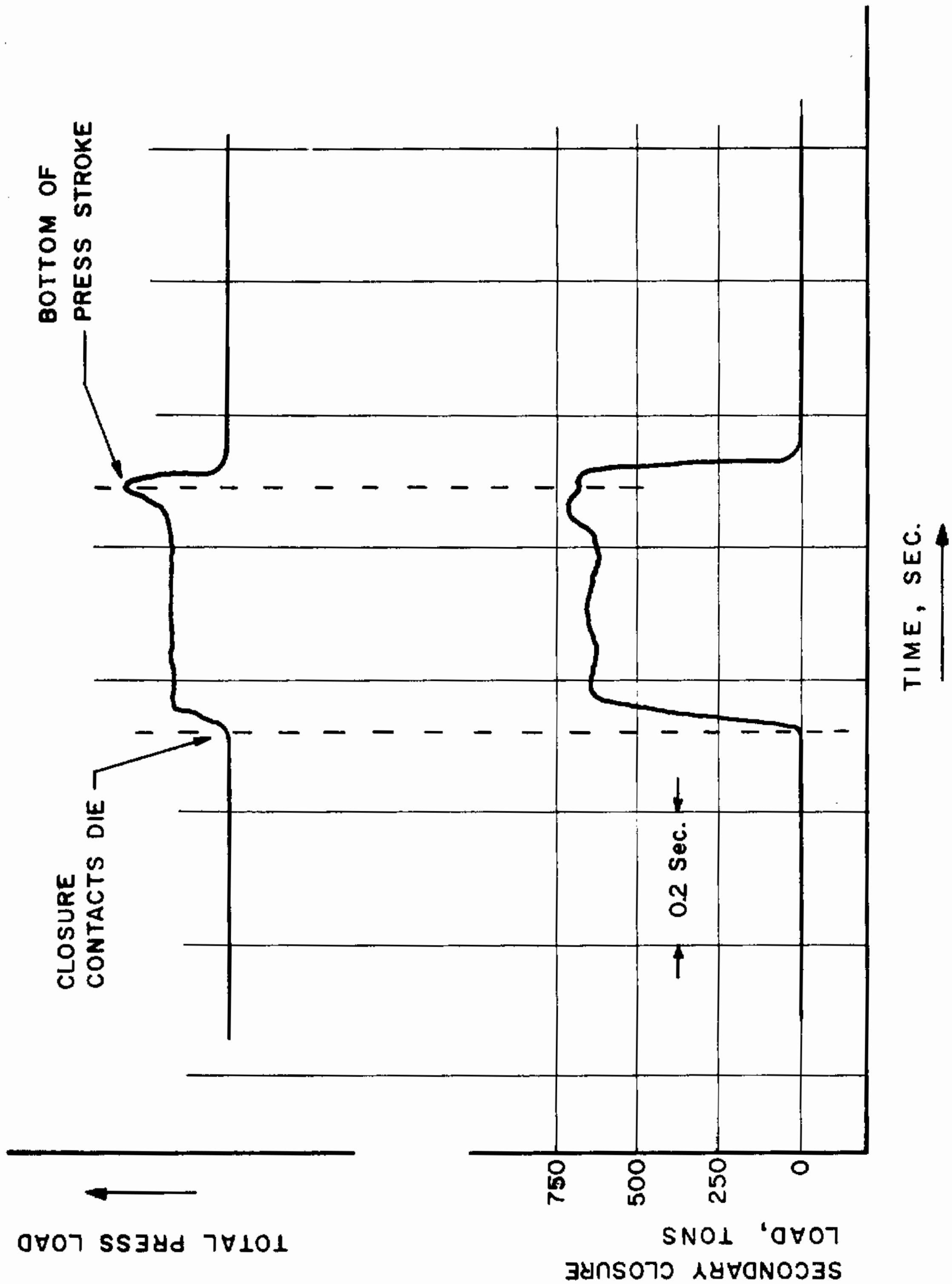
SCHEMATIC ILLUSTRATION OF SECONDARY CLOSURE MECHANISM AND TOOLING ARRANGEMENT FOR RADIAL EXTRUSION OF TURBINE WHEELS AND GEARS

FIGURE 28



TEST RING USED TO EVALUATE THE SECONDARY CLOSURE MECHANISM. STRAIN GAGES ATTACHED TO THE INSIDE AND OUTSIDE DIAMETERS WERE CONNECTED TO A VARIABLE SPEED STRAIN RECORDER TO DETERMINE THE APPLIED LOAD AND DURATION.

FIGURE 29



TYPICAL TEST TRACE OF SECONDARY CLOSURE LOAD SHOWING A DURATION EXCEEDING THE TIME OF MAXIMUM PRESS LOADING

FIGURE 30

TABLE VIII

SINGLE STATION FORGING TESTS CONDUCTED ON MECHANICAL PRESS

Piece No.	Material	Coating	Lubrication	Inserts	Forge Temp.
1	AISI 9310	Nickel	F14C3	Steel	1900° F
2	"	"	"	"	"
3	"	"	"	Alumina	"
4	"	Copper	T-lube	Steel	"
5	"	"	"	Alumina	"
6	"	"	F14C3	Steel	"
7	"	None	"	Alumina(H)	"
8	"	"	"	Steel	"
9	"	"	"	"	"
10	"	"	Delto 45	"	"
11	"	"	"	Alumina	"
A 1	A 286	Nickel	F14C3	Steel	2000° F
A 2	"	Ceramic	"	"	"
A 3	"	"	"	Alumina	"
A 4	"	"	T-lube	Steel	"
A 5	"	"	"	Alumina	"
A 6	"	"	Delto 45	Steel	"
A 7	"	"	"	Alumina	"
N 1	Nitralloy	Nickel	F14C3	Powder A1M A2M	1900° F
N 2	"	"	"	" 4,5	"
N 3	"	"	"	" A-1,A-2	"
N 4	"	Copper	"	" B-1,B-2	"
W 3	Waspaloy	Ceramic	F14C3	Steel	2050° F
W 4	"	"	Delto 45	Alumina (H)	"

TABLE VIII (continued)

Piece No.	Material	Coating	Lubrication	Inserts	Forge Temp.
W 5	Waspaloy	Ceramic	Delto 45	Steel	2050° F
W 6	"	Nickel	F14C3	"	"
W 7	"	"	"	"	"
W 8	"	"	"	"	"
W 9	"	"	"	Alumina	"
W10	"	"	T-lube	Steel	"
W11	"	"	"	"	"

(H) Inserts in horizontal plane.

Heating of all pieces was done in an electric furnace controlled within ±25%. The heating time was established to provide a 5-minute soak at temperature. For the full scale forgings a temperature measurement was taken on each piece with an optical pyrometer before forging.

2. Lubrication and Coating

Lubrication evaluation for the closed-die forging was restricted to non-volatile aqueous graphite lubricants because of the gases evolved from oil suspensions, greases, and other volatile or combustible products. These gases could, if trapped in the closed-die cavities, restrict metal flow and result in an incomplete fill of the forged product. As listed in Table VIII, three commercial graphite lubricants were evaluated. Seven lubricants were evaluated originally, however, four were eliminated due to inferior metal movement as determined by upset tests.

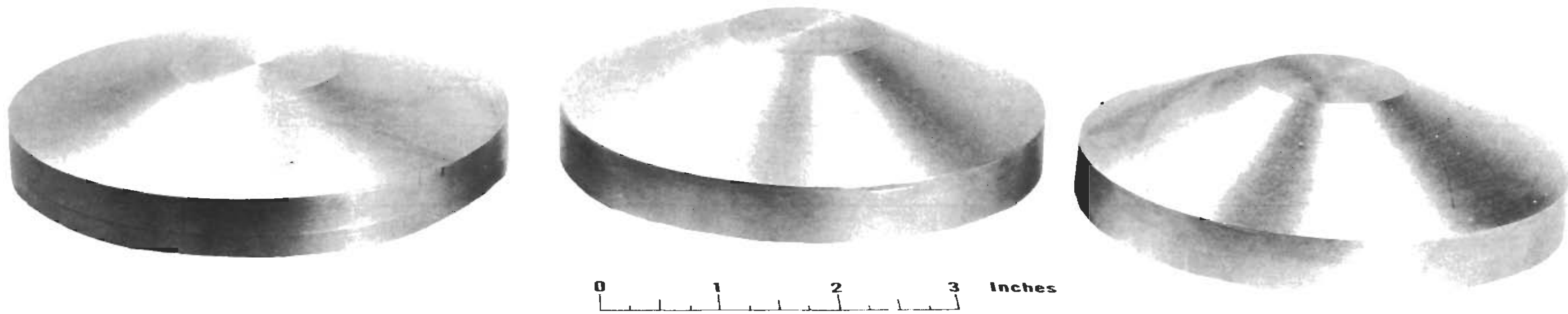
Evaluation of the three remaining lubricants showed no apparent difference in metal movement or surface quality. Therefore, all full scale forging was conducted with a commercially available aqueous graphite lubricant ("T" lube).

Since considerable stock is removed after most forging operations, the as-forged surface quality is not a major consideration. But the radial extrusion process requires little or no metal removal after forging. Therefore, scale and surface contamination normally considered minor becomes a major consideration. Thus, three coatings were evaluated for surface protection; copper and nickel plating and metal oxides.

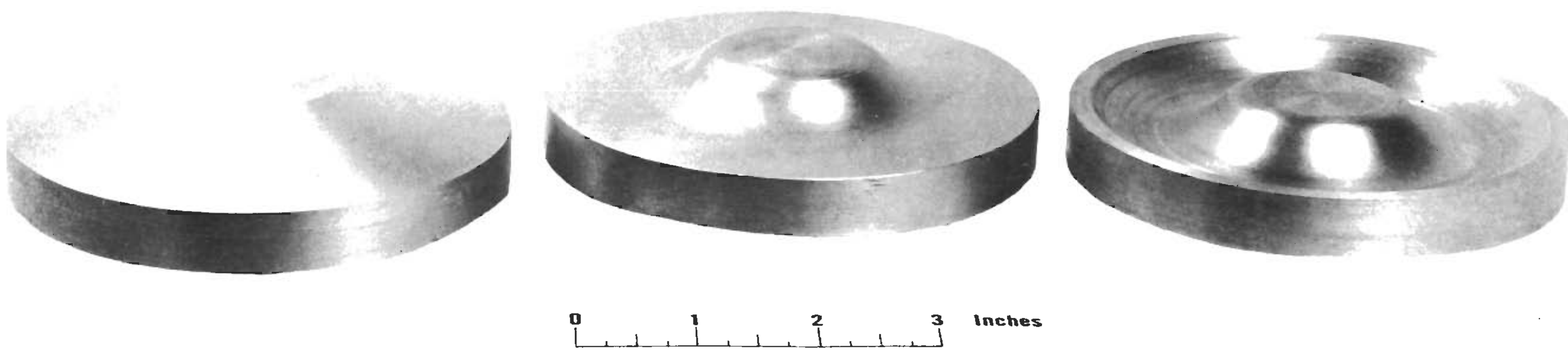
3. Preforms

Precision closed-die forging requires tooling, forging parameters and preparatory operations to be designed and controlled to produce accuracy and reproducibility within thousandths of an inch. In addition, controlled metal flow is necessary to obtain the maximum attainable increase in strength in the highly stressed areas. Thus, three turbine wheel and three gear preform configurations (Figure 31 and 32 respectively) were designed. Because of the necessary close volume control, each preform was machined to a calculated weight and controlled to within .05 pounds.

The bottom surfaces of both gear and turbine wheel preforms B and C contain a contour similar to that of the die pad, thereby providing positive location of the preform in the die cavity. The difference in volume required to provide these contours was compensated by angular differences on the top surfaces.



a) Top Surface

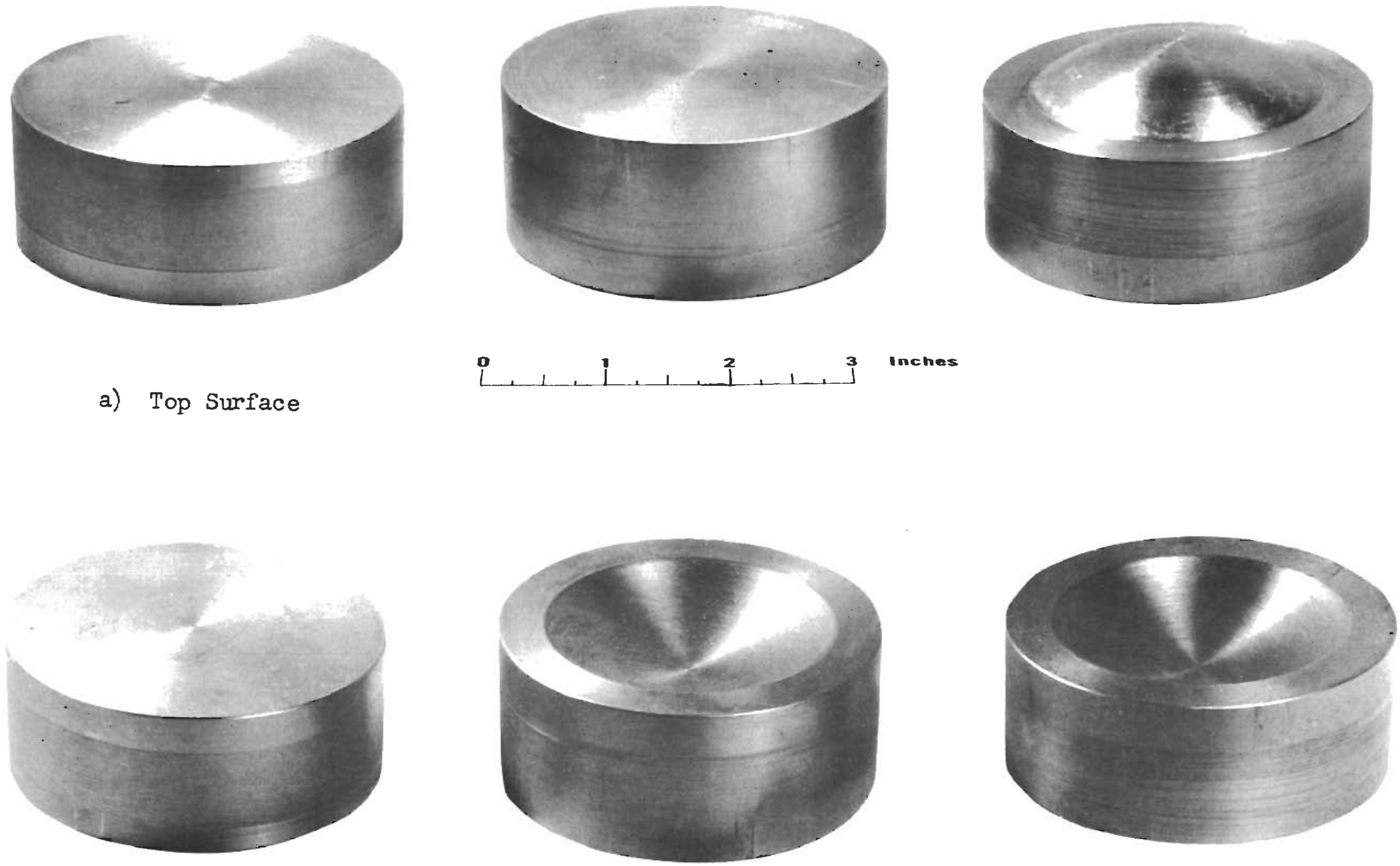


b) Bottom Surface

A B C

TURBINE WHEEL FORGING PREFORM CONFIGURATIONS EVALUATED FOR THE RADIAL EXTRUSION PROCESS. EACH CONFIGURATION CONTAINS 12.5 IN^3

FIGURE 31



a) Top Surface

A B C

b) Bottom Surface

GEAR FORGING PREFORM CONFIGURATIONS EVALUATED BY THE RADIAL EXTRUSION PROCESS. EACH CONFIGURATION CONTAINS 12.1 IN^3

FIGURE 32

V. EXPERIMENTAL RESULTS

A. Single Station Evaluation

The objectives of the single station forging trials were to evaluate the forging parameters that could be applied to the full scale forging and to screen potential die insert materials.

1. Tooling Design

The original single station tool design included a spring-loaded pressure plate to hold the inserts in position. In addition the sides of the die insert adapter were designed with straight walls. The initial forging trials demonstrated that these two factors were not adequate. The spring-loaded pressure plate did not provide adequate support to the inserts, and the straight side walls would not allow for easy removal of the inserts and forged piece. Thus, the single station tooling was redesigned as previously illustrated in Figure 15. The success of the modified single station design provided a basis for the full scale design. Since the die insert wedges provided adequate support for the single station inserts, the concept was used in the full scale shrink ring insert assembly design where the 8° matching angle of the shrink ring and die adapter was similar to the relief angles provided on the single station die pad and adapter die.

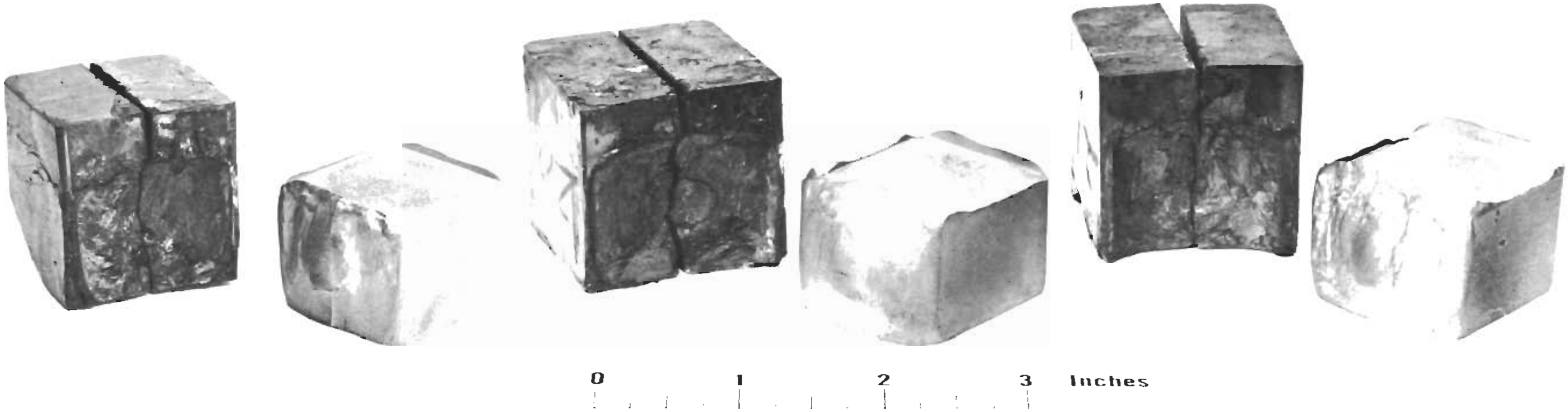
2. Inserts

Of primary importance to the development of the radial extrusion process was the development of either expendable or permanent die inserts. The insert material had to be capable of: (1) withstanding the forging pressures, (2) being formed into complex shapes, and (3) manufactured economically in large quantities. Thus cermets, ceramics, plastics and powder metallurgy products were evaluated as expendable products.

Three commercial fiber reinforced plastic materials were fabricated into inserts. Forging results with AISI 403 stainless steel billets caused all three materials to upset and deform. The wedge-shaped die cavity became closed as a result of the upsetting as illustrated in Figure 33. Additional billets were forged after heating to 2000°F, but again the forging pressure exceeded the compressive strength of the plastic material.

Preferred fiber orientation and other strengthening mechanisms are known to increase the strength of fiber reinforced plastic materials, but the increase would not be of sufficient magnitude to satisfy the forging requirements. Therefore, further investigation of reinforced plastics were not warranted.

Iron powder compacts with compressive strengths similar to the plastic products (23-48,000 psi) were evaluated. The forging response with pressed and sintered iron powder inserts paralleled that of the plastic materials. The inserts upset into the wedge-shaped cavity, thereby pre-



a) Glass - Phenolic
Fiberite FM8130

b) Glass - Epoxy
U.A. Polymeric X7008

c) Glass - Phenolic
Durez 16771-1

SINGLE STATION TEST RESULTS OBTAINED WITH EXPENDABLE DIE INSERTS FABRICATED FROM COMMERCIAL PLASTIC MATERIALS. FORGINGS WERE MADE WITH STAINLESS STEEL (AISI 403) BILLETS HEATED TO 1800°F.

FIGURE 33

venting the billet from extruding into the cavity. Again some strengthening mechanisms are available, but the increase would not be adequate.

During the early development stages of the radial extrusion process at TRW a high density alumina was evaluated. Although complete success was not achieved at that time, the results were promising enough to include alumina as a potential die insert material in this program. Thus, approximately twenty sets of single station inserts were fabricated.

The first piece forged in alumina was AISI 403 stainless steel which was successful as illustrated in Figure 34. Post forging examination of the inserts revealed no evidence of insert failure during the forging cycle. The spalled surface on the lower insert occurred during removal of the inserts and forged billet from the die adapter.

On a substantial number of additional tests with alumina inserts, the results ranged from complete success, no breakage and only slight cracking as illustrated in Figure 35, to complete failure, total breakdown and embedding of the insert material into the forging as illustrated in Figure 36. This wide range of results was attributed to insufficient support on the inserts, which was caused by:

1. Lack of hold-down pressure on the two wedges and hold-down bar, and

2. lack of contact on the complete surface of the inserts by the two wedges.

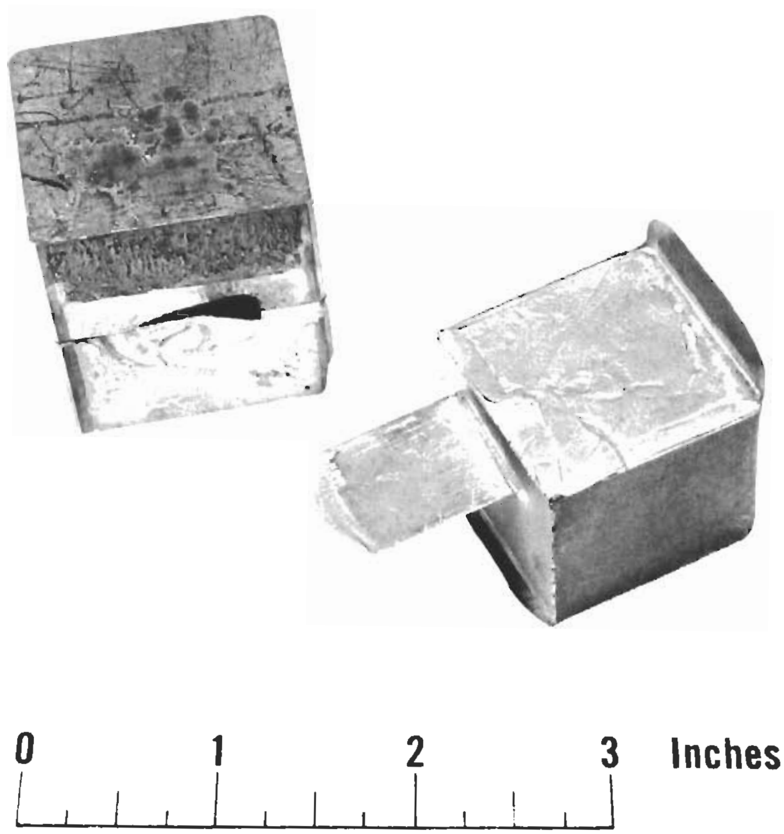
Evaluation of the forging quality obtained with alumina inserts as compared to AISI 4340 steel inserts showed the flat surfaces of the extruded wedge to be comparable, but the thin edge of the wedge was improved with the alumina inserts. This improved condition with alumina inserts could be attributed to the different lubricating effect between steel and alumina and/or the insulating properties of alumina.

Finish grinding of the steel inserts produces microgrooves, which are parallel to the flow of the metal as illustrated in Figure 37. As a result, the lubricant, which is not mechanically bonded to the surface of the die, is wiped away as the metal flows across the die surface. The alumina inserts, also shown in Figure 37, contain micropits rather than grooves. The pits, in contrast to the grooves, tend to retain the lubricant; therefore, a continuous film of lubricant between the forged metal and the die surface is maintained. In addition to the effect of lubrication, the insulating properties of alumina would permit greater heat retention in the forged part. Thus, the forged metal would retain the greater ductility and reduced strength at the higher temperature thereby contributing to an improved thin edge.

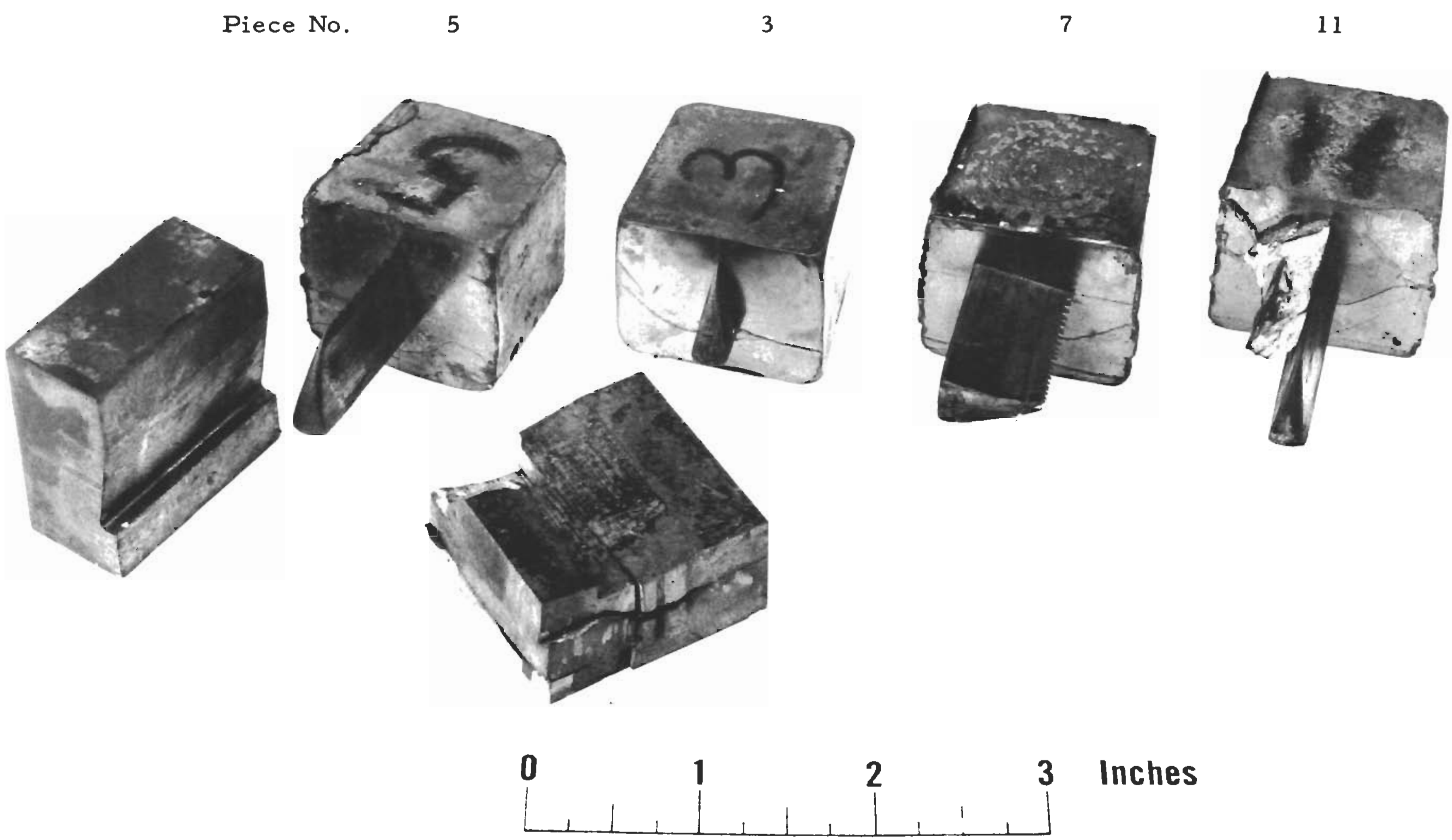
3. Coating

Materials used during the single station forging trials were coated with either a metal-oxide or a .002 in. plating of nickel or copper. Copper

FIGURE 34



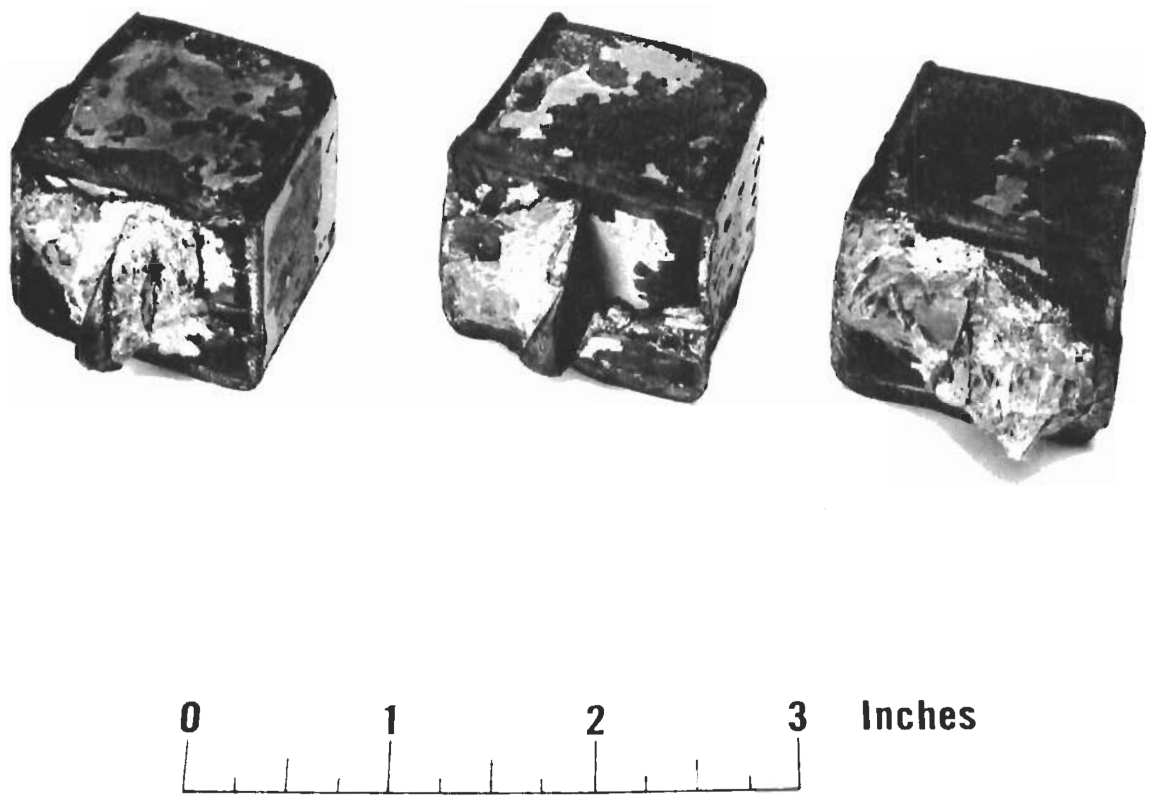
SINGLE STATION FORGING PRODUCED FROM AISI 403 STEEL BILLET EXTRUDED INTO ALUMINA INSERTS



AISI 9310 STEEL FORGINGS PRODUCED ON A MECHANICAL PRESS TO EVALUATE ALUMINA INSERTS. PIECE 7 ILLUSTRATES THE RESULT OF HORIZONTAL DIE CAVITY ORIENTATION.

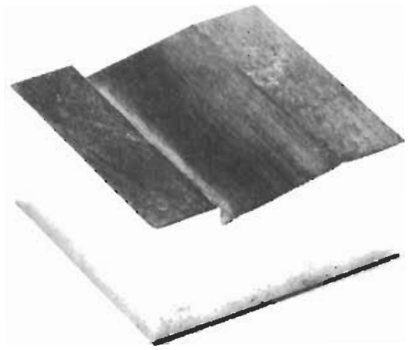
FIGURE 35

Piece No. A-5 A-7 A-3

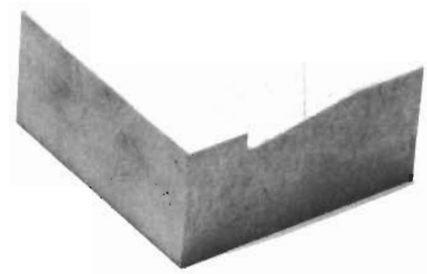


A-286 FORGINGS PRODUCED ON A MECHANICAL PRESS WITH ALUMINA DIE INSERTS. THE INSERT FRACTURE WAS INDEPENDENT OF THE THREE DIE LUBRICANTS USED FOR THESE PIECES.

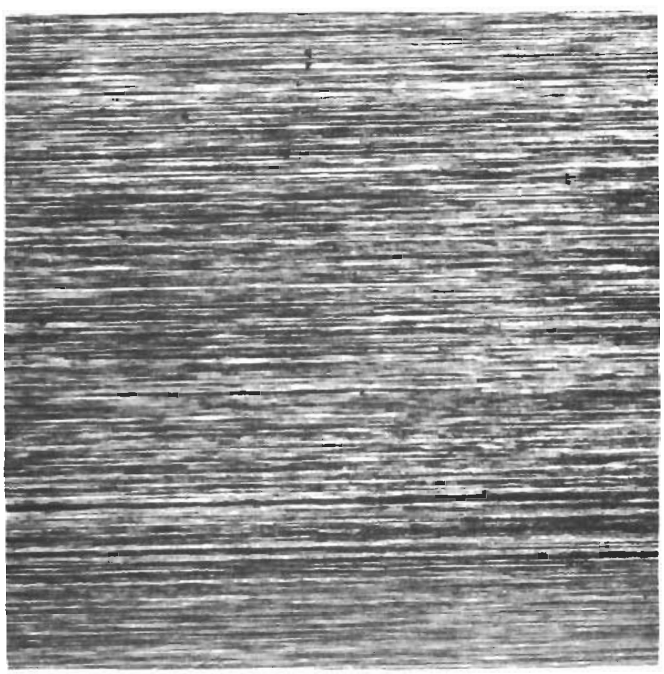
FIGURE 36



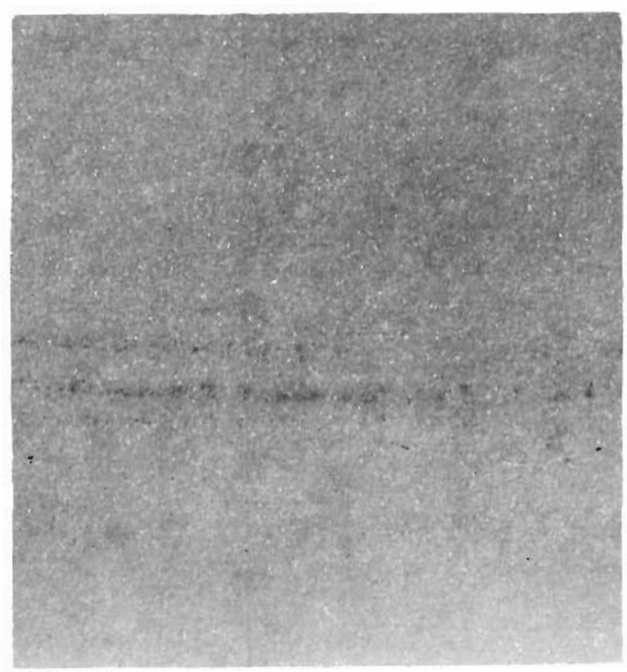
Steel Insert (1X)



Alumina Insert (1X)



Steel (10X)



Alumina (10X)

STEEL AND ALUMINA INSERTS ILLUSTRATING MICROGROOVED (STEEL) AND MICROPITTED (ALUMINA) SURFACES CONTRIBUTING TO THE DIFFERENCES IN FORGING RESPONSE.

FIGURE 37

plating was evaluated on AISI 9310 and Nitralloy. Metallographic examination of as-forged pieces showed negligible decarburization, as illustrated in Figure 38.

Nickel plating was evaluated on AISI 9310, Nitralloy, A-286, and Waspaloy. Metallographic examination of the as-forged pieces showed excellent protection, as illustrated in Figure 39. No apparent surface contamination occurred on Waspaloy and a maximum of .0005 in. contaminated surface resulted on A-286. For AISI 9310 nickel offered protection equivalent to copper, but on Nitralloy, nickel was not adequate.

A metal-oxide coating was evaluated on A-286 and Waspaloy. Post-forging metallographic examination indicated no detectable surface oxide on either the Waspaloy or A-286. Because of ease in application, the metal-oxide was selected for the full scale turbine wheel forging of A-286, Waspaloy, and René 41.

All of the pieces used in the coating evaluation were sand blasted and evaluated for surface quality. None of the coatings exhibited any detrimental effects on surface quality when compared to forgings of the same material without coating.

B. Full Scale Forging

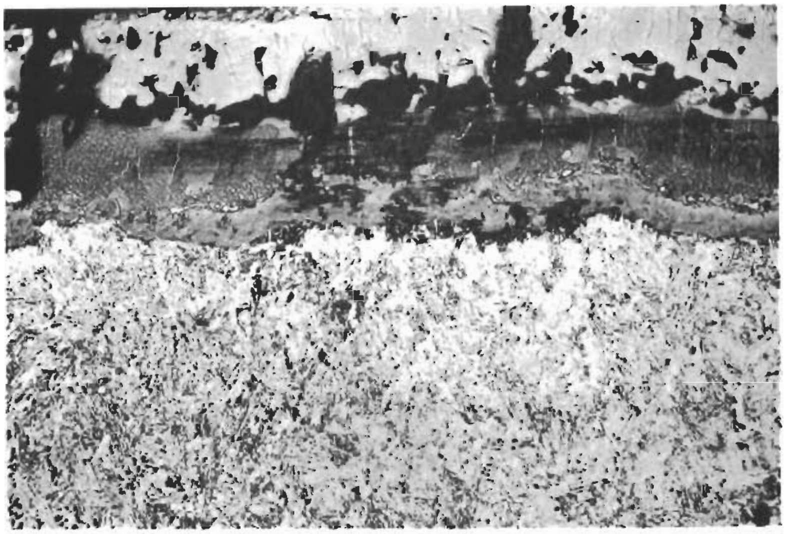
The full scale forging consisted of precision forging gears and turbine wheels with integral blades. Forging was conducted on an 8000-ton mechanical press using the previously discussed secondary closure mechanism. The turbine wheel selected as being typical of the high performance products needed by industry was the axial flow impulse type turbine wheel illustrated in Figure 40. Design parameters for this turbine wheel are shown in Table IX. The gear selected was a high speed, high precision helicopter transmission gear shown previously in Figure 7, with nominal dimensions of 3.75 inch diameter, 1-5/16 inch tooth length and 31 teeth.

The initial full scale forging was to establish optimum metal flow by macroexaminations of forgings produced from three preform configurations. Early attempts to illustrate the flow condition were not completely successful. Therefore, composite preforms, Figure 41, were fabricated and forged. The photomacrographs in Figures 42 and 43 illustrate the transverse and longitudinal metal flow. The continuous flow into the highly stressed areas of the gear tooth and turbine blade clearly illustrate the desirable metal flow obtainable only by precision forging. Also, precision forging minimizes the amount of metal removal after forging, thereby eliminating undesirable end-grain effects normally produced by machining an oversize forging. Thus the performance and reliability factor of the highly stressed components can be improved.

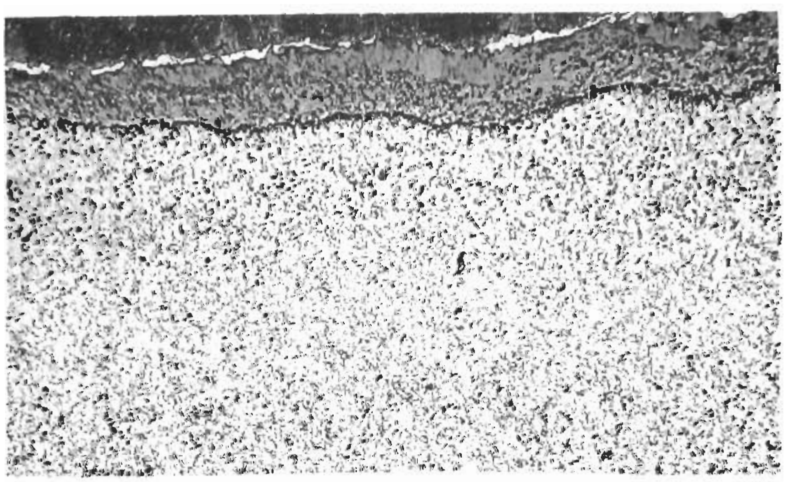
1. Turbine Wheel Development

The forging sequence for turbine wheels was established as follows:

a. heat preform (2050°F)



(b) Nitralloy

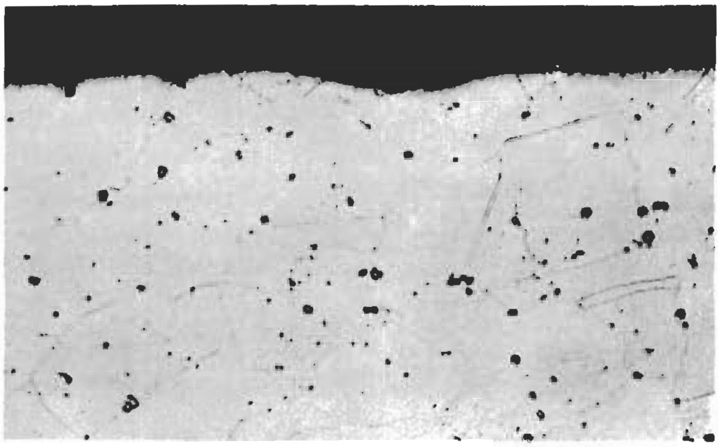


(c) AISI 9310

SUBSURFACE MICROSTRUCTURE AND REACTION ZONES OF COPPER PLATED NITRALLOY AND AISI 9310 FORGING SPECIMENS AFTER HEATING AT 1900°F FOR 15 MINUTES.

2% Nital Etch Mag. 250X

FIGURE 38



(a) Waspaloy - 2050°F, 15 Min. HCl - H_2CrO_4 Etch

(b) A-286 - 2000°F, 15 Min. Refractory Metal Etch

(c) Nitralloy - 1900°F, 15 Min. 2% Nital Etch

SUBSURFACE MICROSTRUCTURE OF NICKEL PLATED WASPALOY, A-286 AND NITRALLOY FORGING SPECIMENS AFTER HEATING AS INDICATED.

FIGURE 39

Mag. 250X

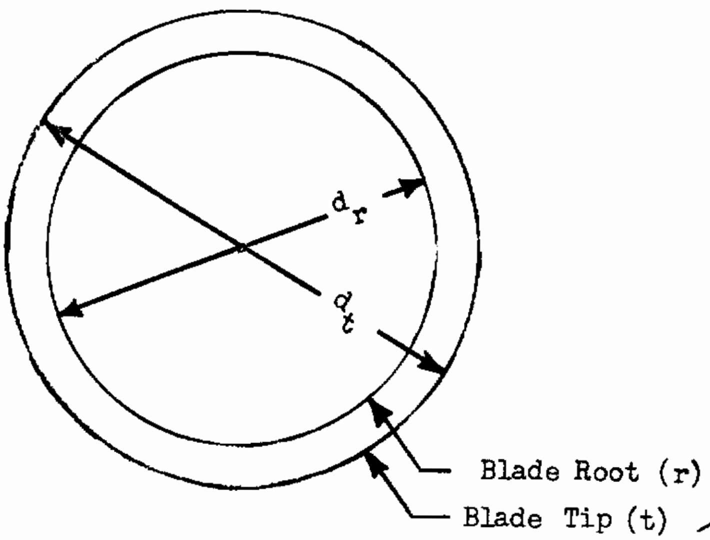
TYPICAL AXIAL FLOW, IMPULSE TYPE TURBINE WHEEL
IN THE FINISH MACHINED CONDITION

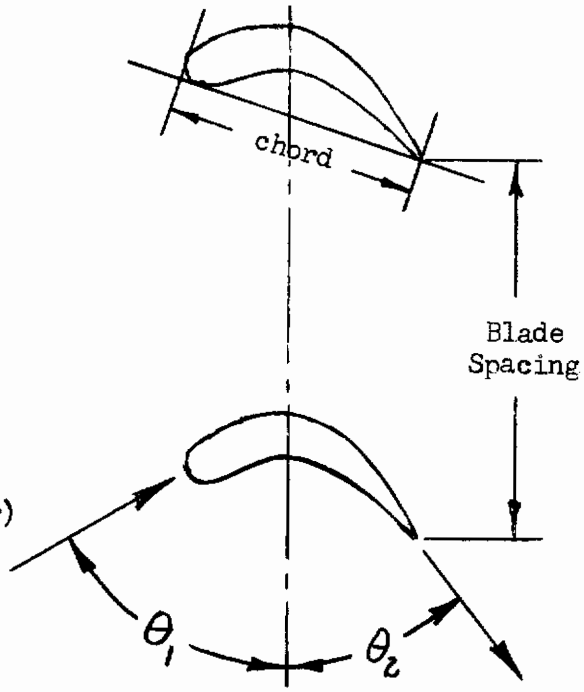
FIGURE 40

TABLE IX

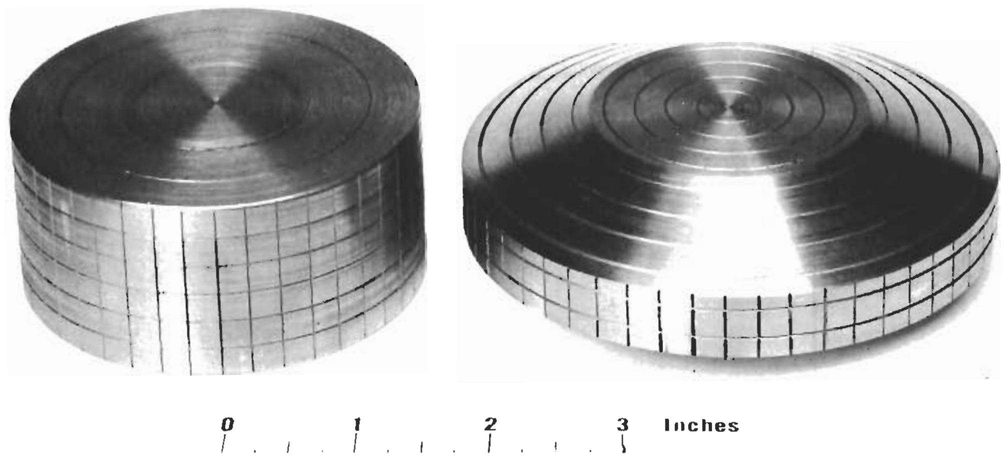
TURBINE WHEEL AND BLADE DESIGN PARAMETERS

Parameter	Definition	Forged Wheel
1	z = No. of blades	40
2	σ = Solidity = $\frac{\text{mean blade chord}}{\text{mean blade spacing}}$	1.21
3	A = Aspect ratio = $\frac{\text{blade height}}{\text{mean blade chord}}$	0.81
4	$\tau_{max.} = \frac{\text{max. blade thickness}}{\text{mean blade chord}}$	0.376
5	$\tau_{min.} = \frac{\text{min. blade thickness}}{\text{mean blade chord}}$	0.0544
6	R = reaction parameter = $\frac{\sin \theta_1}{\sin \theta_2} - 1$	0
7	C = Camber = $180° - (\theta_1 + \theta_2)$	120°
8	T = Twist = $\frac{(\theta_1 - \theta_2)_t - (\theta_1 - \theta_2)_r}{(d_t - d_r)}$ (deg/in)	0
9	d_t = Overall diameter (inches)	5.25
10	α = Blade cross sectional area ratio = $\frac{\text{area tip}}{\text{area root}}$	1
11	β = Hub-tip diameter ratio = $\frac{d_r}{d_t}$	0.855



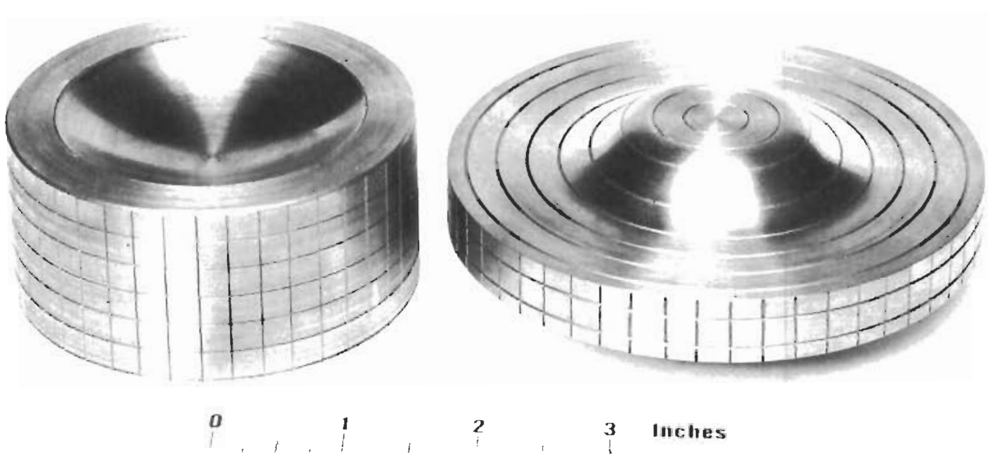


Top Surface



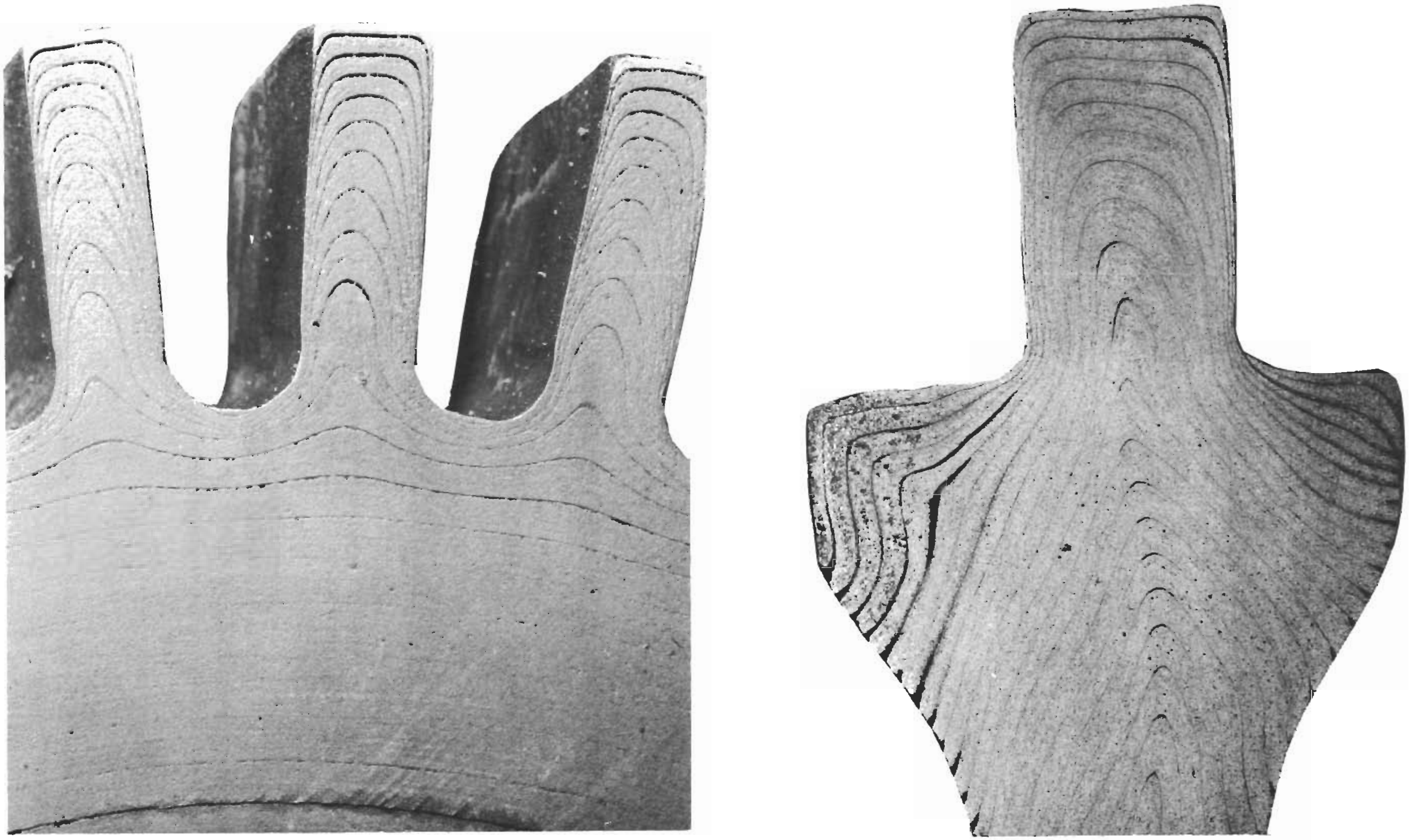
a) Gear b) Turbine Wheel

Bottom Surface



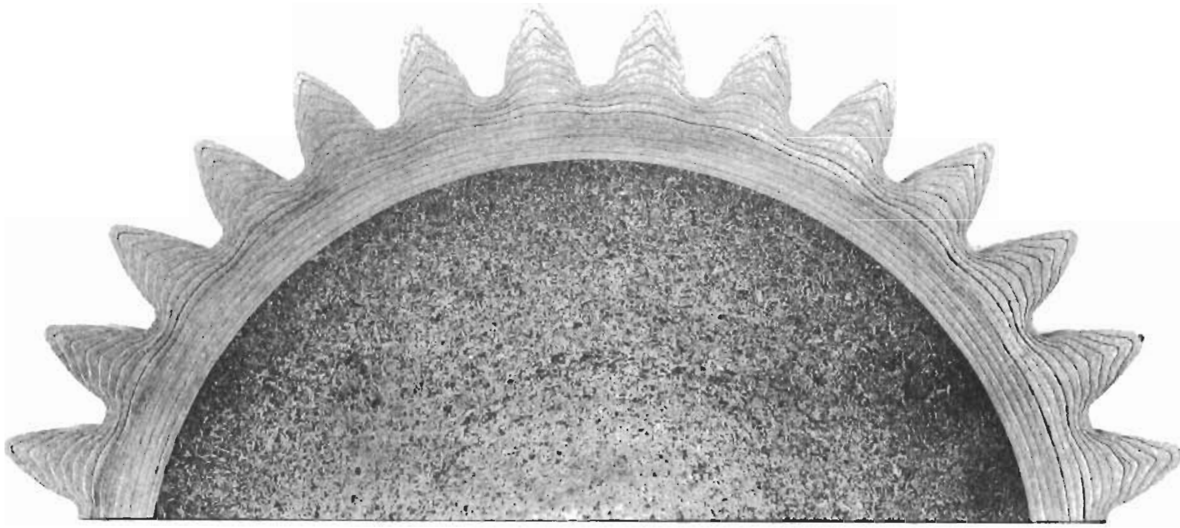
COMPOSITE, GRIDDED STEEL PREFORMS USED TO STUDY FLOW CHARACTERISTICS OF GEAR AND TURBINE WHEEL FORGING BY THE RADIAL EXTRUSION PROCESS.

FIGURE 41



PHOTOMACROGRAPHS OF COMPOSITE TURBINE WHEEL FORGING ILLUSTRATING THE CONTINUOUS METAL FLOW INTO THE BLADE AREA OBTAINABLE ONLY BY PRECISION FORGING. Mag. 5X

FIGURE 42



PHOTOMACROGRAPHS OF COMPOSITE GEAR FORGING ILLUSTRATING CONTINUOUS METAL FLOW INTO GEAR TEETH.

FIGURE 43

b. install inserts into shrink ring

c. load ring and inserts into die cavity and lubricate

d. forge

e. remove inserts

This sequence of operations was used to precision forge turbine wheels with alumina inserts. The initial full scale forging with alumina was successful as illustrated in Figure 44. However, in subsequent forging trials the inserts were broken to such an extent that they could not be removed from the forged blades. Many methods were attempted to remove the inserts including mechanical and thermal shock, and ultrasonic vibration. None of these methods were successful.

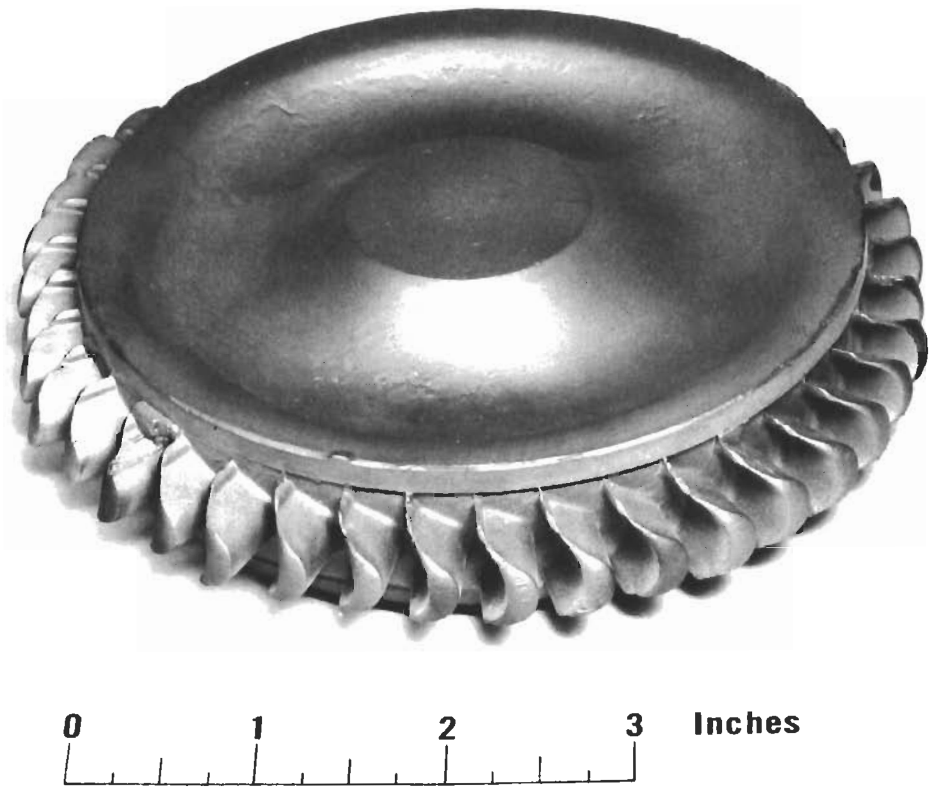
The causes of failures and difficulties in removing the alumina inserts from forged pieces were investigated. One condition revealed 0.012-0.015 in. separations at the inside edge of assembled inserts (Figure 45). This condition was caused by inconsistently grinding a 9° angle on mating surfaces of the inserts. Dimensional inspection of one set showed that the angle varied between 9° and 9°30'. Thus when a set of 40 inserts was assembled into a shrink ring the mating surfaces of two adjacent inserts were not in intimate contact. As determined from the single station forging tests, full support on all surfaces of the inserts was necessary to withstand the impact and compressive stress of the forging operation. Since this undesirable condition existed on almost all alumina inserts, precision ground AISI H-21 tool steel inserts were used.

To prevent surface annealing of the steel inserts during the time required to remove the inserts from the hot forging, an oil quench was included after the forging operation. As a result, it was possible to forge eleven pieces using one set of steel inserts. These included the A-286, Waspaloy, and René 41 turbine wheels shown in Figure 46. After eleven pieces, wear on the inserts began to detract from the surface and dimensional quality of the forged pieces.

As material forgeability decreased from mild steel to René 41, the lack of fill of the blade thin edge became more severe as shown in Figure 47. Therefore, the insert design was modified as shown in Figure 48 to increase the thin edge from 0.025 to 0.072 in.

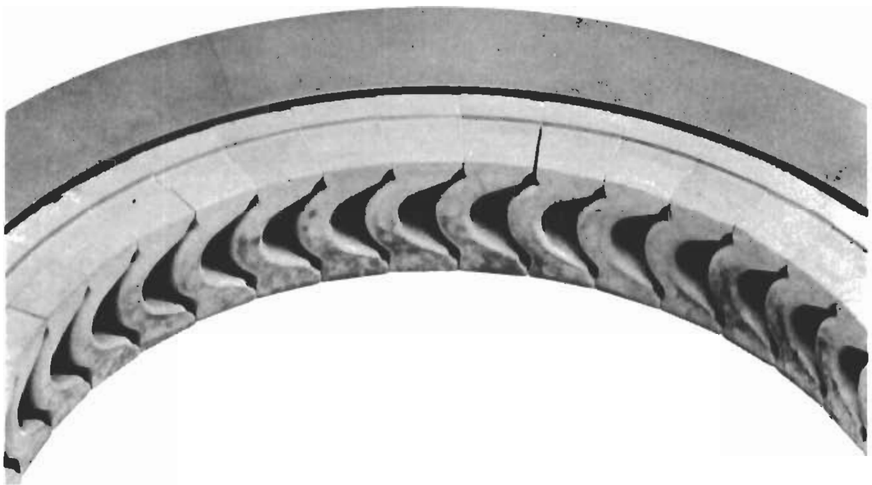
To evaluate the minimum thin edge thickness attainable for each material, eight steel inserts were modified to produce edge thicknesses of 0.040 and 0.050 in. Each of the alloys (A-286, Waspaloy, and René 41) were forged into the modified inserts with the following results:

a. A-286 did not tear at edge thicknesses greater than 0.040 in. (Figure 49).



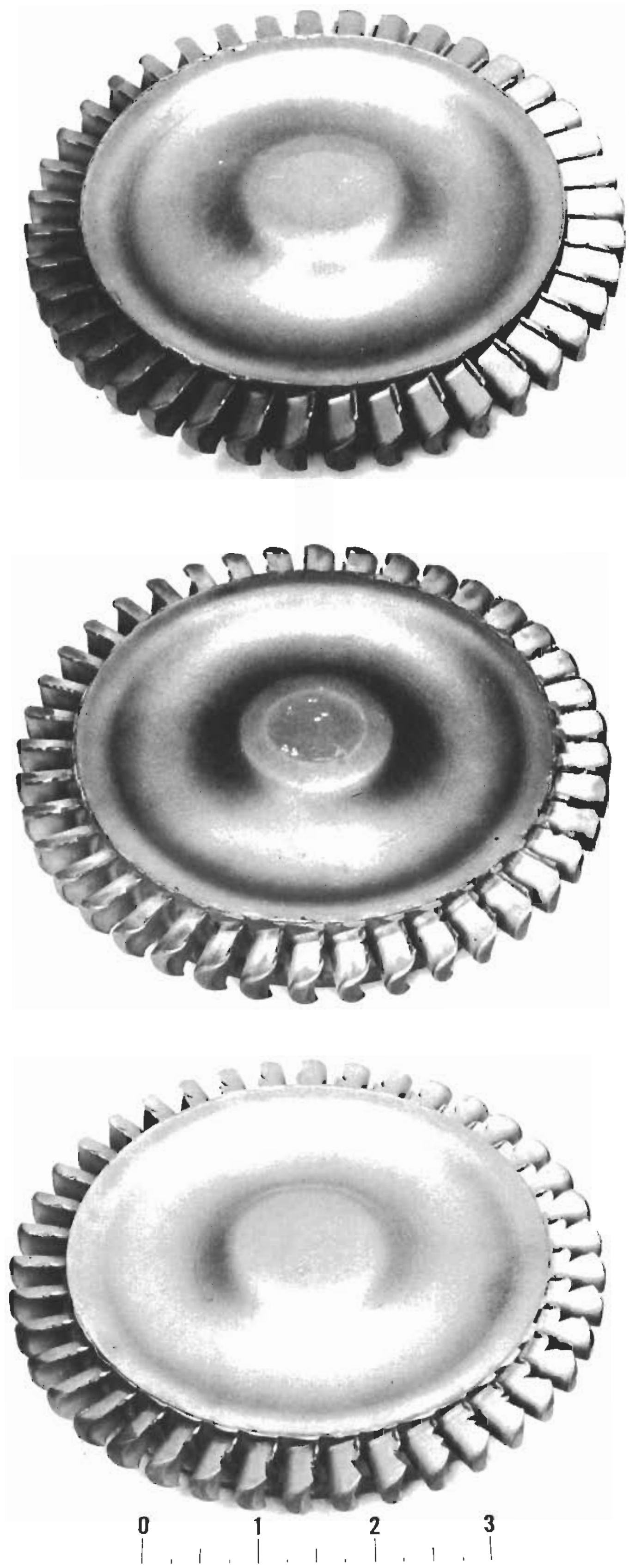
TURBINE WHEEL FORGING PRODUCED BY THE RADIAL EXTRUSION OF A 403 STAINLESS STEEL PREFORM IN ALUMINA DIE INSERTS.

FIGURE 44



TURBINE WHEEL CERAMIC INSERTS ASSEMBLED IN STEEL SHRINK RING ILLUSTRATING UNDESIRABLE GAP BETWEEN INSERTS. THIS CONDITION RESULTS IN PREMATURE FAILURE OF THE INSERTS DURING FORGING. (APPROXIMATELY FULL SIZE.)

FIGURE 45



a) A-286

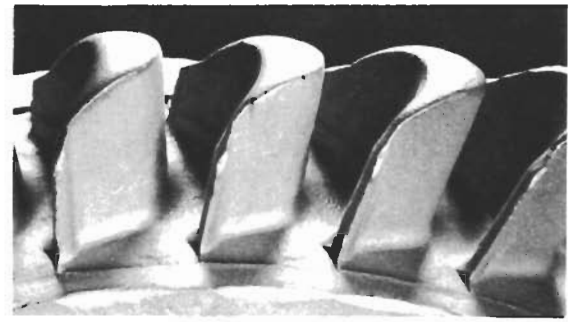
b) Waspaloy

c) René 41

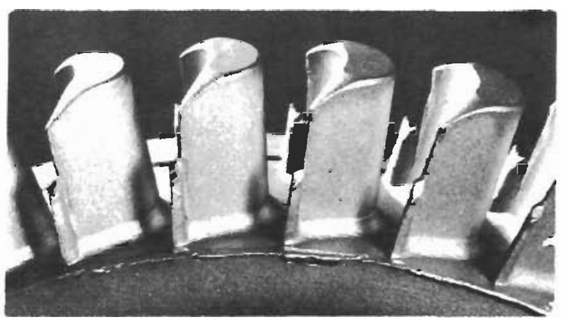
FIGURE 46

AXIAL FLOW, IMPULSE TYPE TURBINE WHEELS PRODUCED FROM VARIOUS ALLOYS BY THE RADIAL EXTRUSION PROCESS.

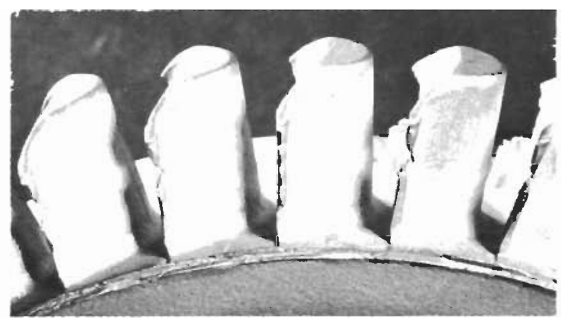
Mild Steel



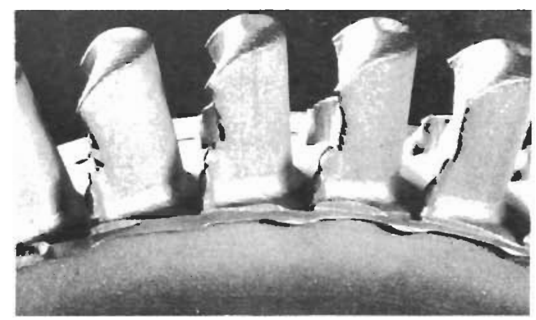
403 Stainless



A-286



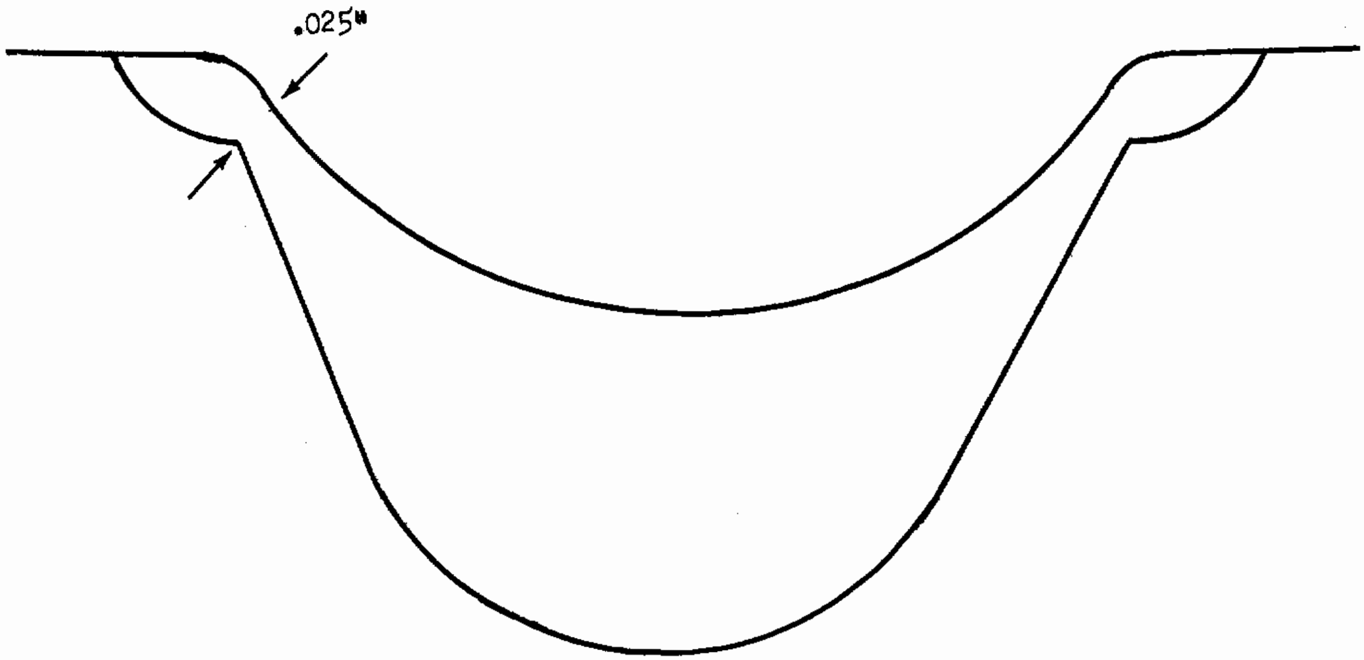
Waspaloy



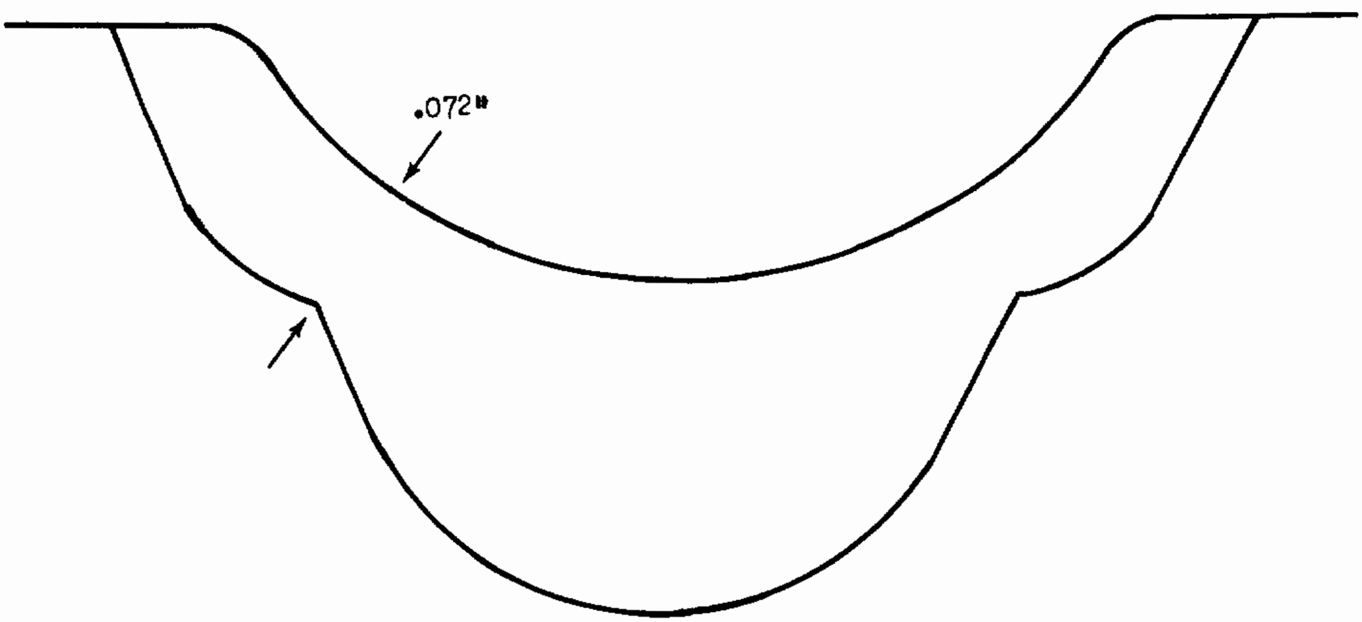
Rene' 41

AS-FORGED AND SAND BLASTED TURBINE WHEEL BLADES ILLUSTRATING THE SURFACE QUALITY OF VARIOUS MATERIALS RESULTING FROM THE MATERIALS BEING EXTRUDED INTO THIN SECTIONS.

FIGURE 47



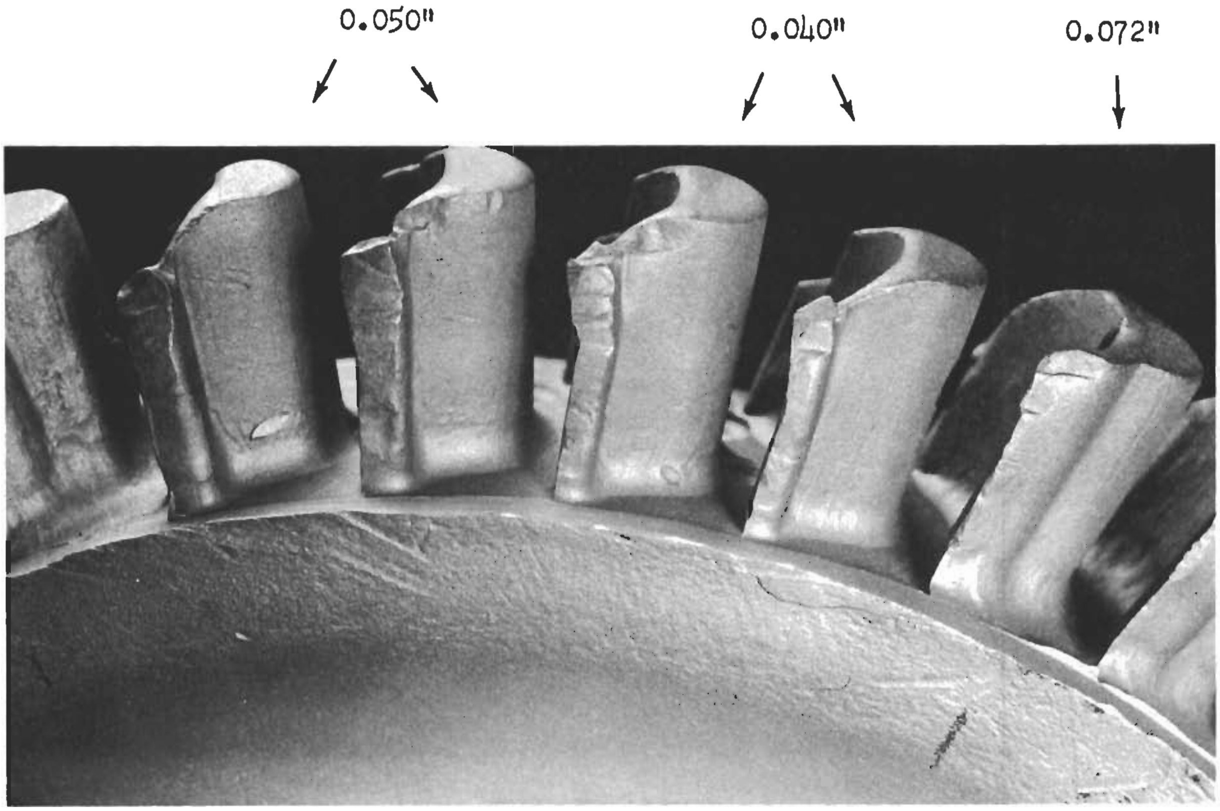
a) Original Design



b) Modified Design

SCHEMATIC ILLUSTRATION OF TURBINE WHEEL BLADE CROSS SECTION SHOWING THE MODIFIED EDGE THICKNESS DESIGNED TO ELIMINATE A TEARING CONDITION AT THE THIN EDGE

FIGURE 48



EFFECT OF VARIOUS BLADE EDGE THICKNESSES ON THE EXTRUSION FLOW CHARACTERISTICS OF A-286 FORMED AT 2050°F BY THE RADIAL EXTRUSION PROCESS. THE DEFORMED EDGES RESULTED DURING INSERT REMOVAL. (SEE FIGURE 48 FOR THICKNESS DETERMINATION.) Mag. 3X

FIGURE 49

b. Waspaloy showed some tearing at 0.040 in. and very little at 0.072 in. (Figure 50).

c. René 41 exhibited tearing at 0.072 in. and, as illustrated in Figure 51, showed a significant amount of resistance to deformation as the restriction became greater.

However, to achieve these results the time interval between removal of the piece from the heating furnace to the completion of the forge cycle must be held to a minimum.

The change in insert design was accompanied by a change in insert fabrication and material. As previously discussed, precision cast and machined inserts were manufactured to the new design. Approximately thirty turbine wheels were forged successfully with cast inserts of which twenty are shown in Figure 52.

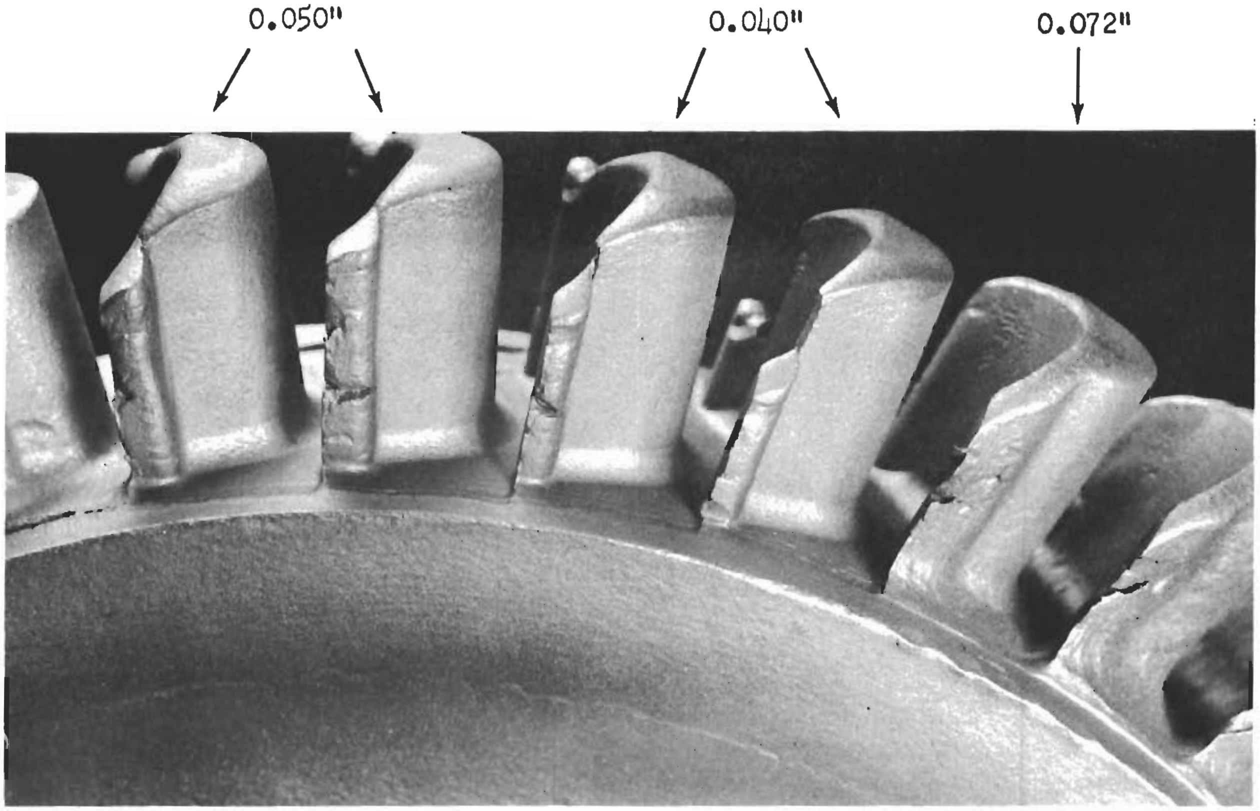
Since the blade profile of the cast inserts was not machined, as illustrated in Figure 53, the as-cast surface finish was important. Profilometer readings on ten as-cast and heat treated inserts showed the blade surfaces to be 100 rms or finer. Although the as-cast surface was not as fine as desired, the surface quality of the as-forged blades was affected to a larger degree by the insert wear rather than the initial surface quality of the inserts. Evidence of insert wear is reflected by the five pieces shown in Figure 54. These five pieces were forged using the same set of inserts to determine nominal insert life. The absolute insert life depends on surface quality requirements of a particular turbine wheel, since the surface quality of each succeeding piece progressively decreased.

2. Gear Development

After the gear preform configuration and volume were established, forging followed two successful routes: (1) the use of expendable ceramic inserts, and (2) the use of an integral-splined die. Although the integral-splined die was designed with zero draft, the initial pieces were forged with satisfactory fill on each tooth and were ejected from the die cavity without difficulty.

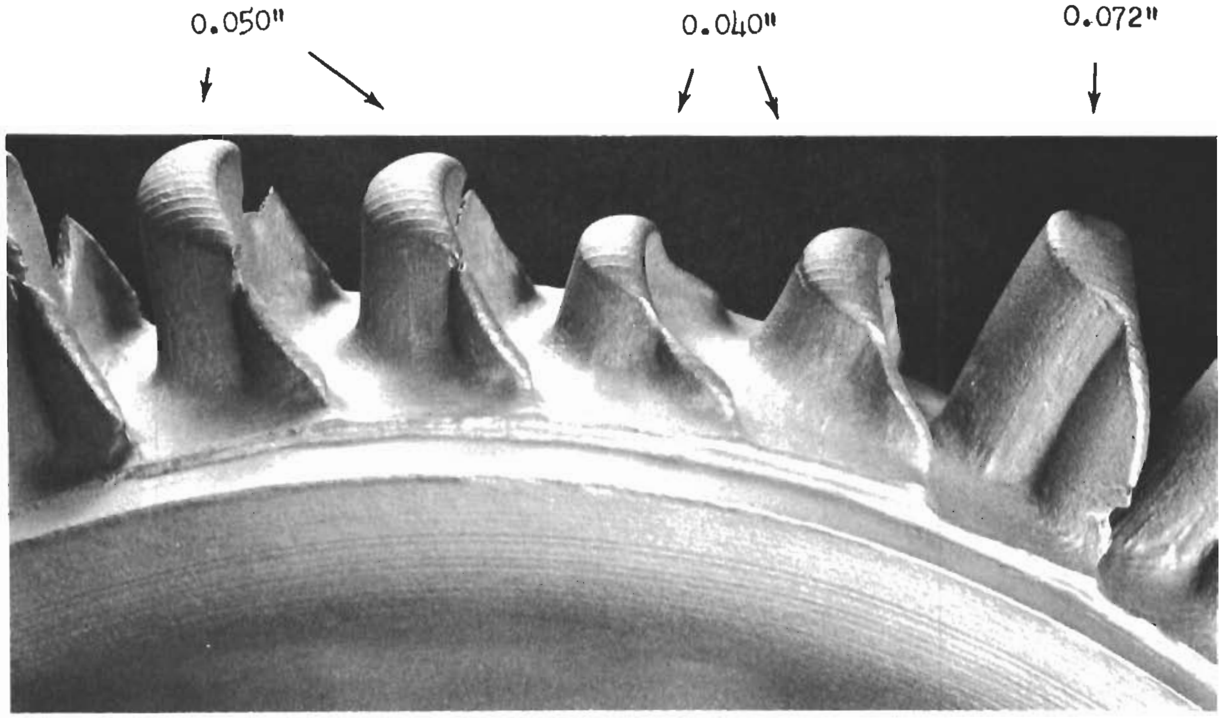
When a sufficient number of pieces were forged successfully to prove the feasibility of the integral die, an alternate adapter for individual inserts was used. Here again, the success achieved on the initial pieces showed that this method also was satisfactory. Approximately twenty pieces of AISI 9310 and an 18% nickel maraging material were forged in alumina inserts to prove the use of alumina as an expendable die insert material for gears.

To further determine the capabilities of this forging process, the temperature of the forging billet was decreased to 1500°F, and under some conditions, no lubricant was used. Visual examination of the pieces forged at the lower temperature and without lubricant showed no detrimental defects on surface quality or lack of fill on the as-forged gear.



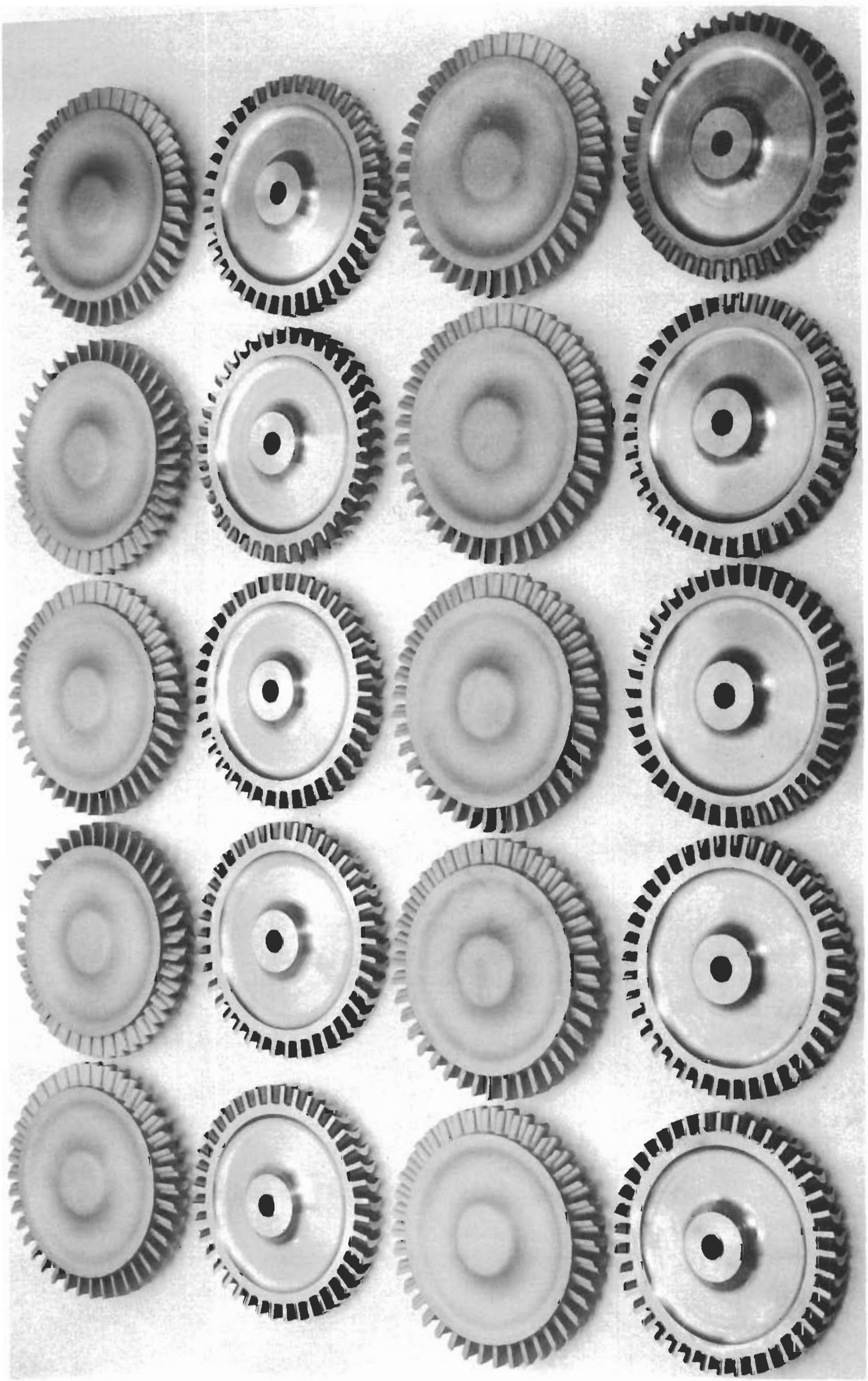
EFFECT OF BLADE EDGE THICKNESS ON THE EXTRUSION FLOW CHARACTERISTICS OF WASPALOY. THE BLADES WERE FORMED AT 2050°F BY THE RADIAL EXTRUSION PROCESS. THE TEARING CONDITION AT THE 0.050 IN. THICKNESS WOULD BE ELIMINATED BY FINISH MACHINING OPERATIONS. Mag. 3X

FIGURE 50



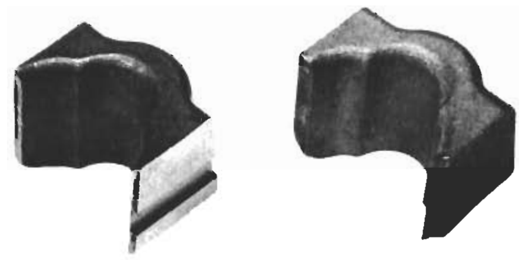
EFFECT OF BLADE EDGE THICKNESS ON THE EXTRUSION FLOW CHARACTERISTICS OF RENE 41 FORMED AT 2050°F BY THE RADIAL EXTRUSION PROCESS. THE TEARING CONDITION ENCOUNTERED AT THE 0.050 IN. THICKNESS IS NOT ACCEPTABLE. Mag. 3X

FIGURE 51



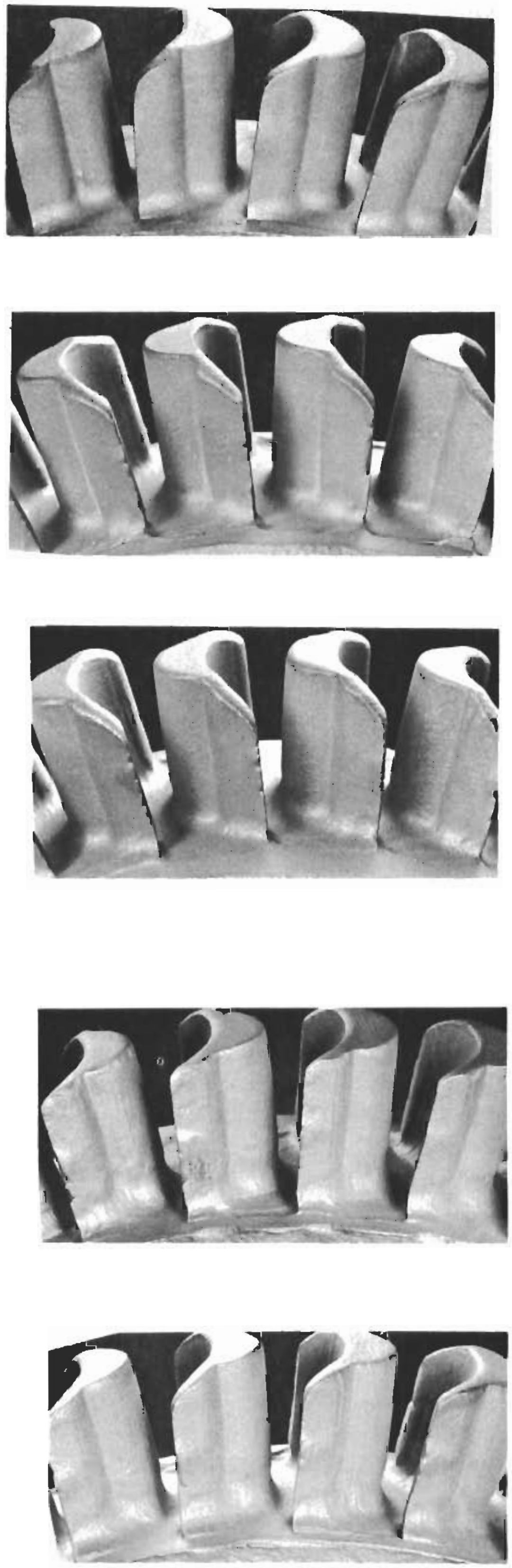
PRECISION FORGED TURBINE WHEELS WITH INTEGRAL BLADES PRODUCED AS PART OF A PROTOTYPE PRODUCTION RUN.

FIGURE 52



PRECISION CAST STEEL (AISI 6150) DIE INSERTS FOR TURBINE WHEEL FORMING BY THE RADIAL EXTRUSION PROCESS. FINISH MACHINING AND GRINDING STOCK WAS ALLOWED ON THE AS-CAST PARTS SINCE THE CASTING SUPPLIER WOULD NOT GUARANTEE DIMENSIONAL TOLERANCES CLOSER THAN $\pm$ .005 IN.

FIGURE 53



1

2

3

4

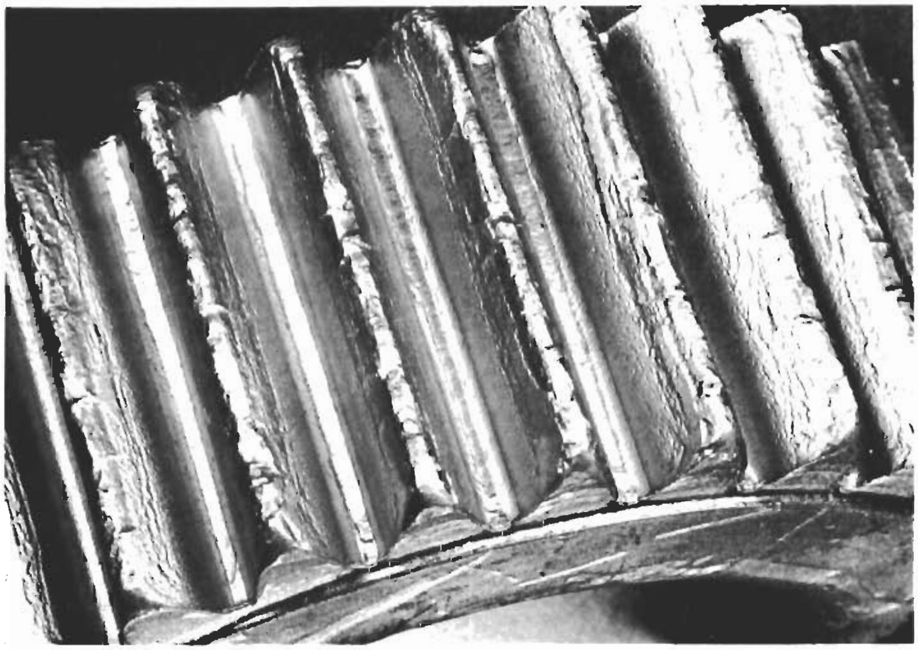
5

DETERMINATION OF CAST INSERT DIE LIFE BY REPEATED FORGING OF A-286 TURBINE WHEELS AT 2050°F INTO ONE SET OF INSERTS. EVIDENCE OF INSERT WEAR ON THE EXTRUDED BLADE SURFACE APPEARS AFTER THE FOURTH PIECE.

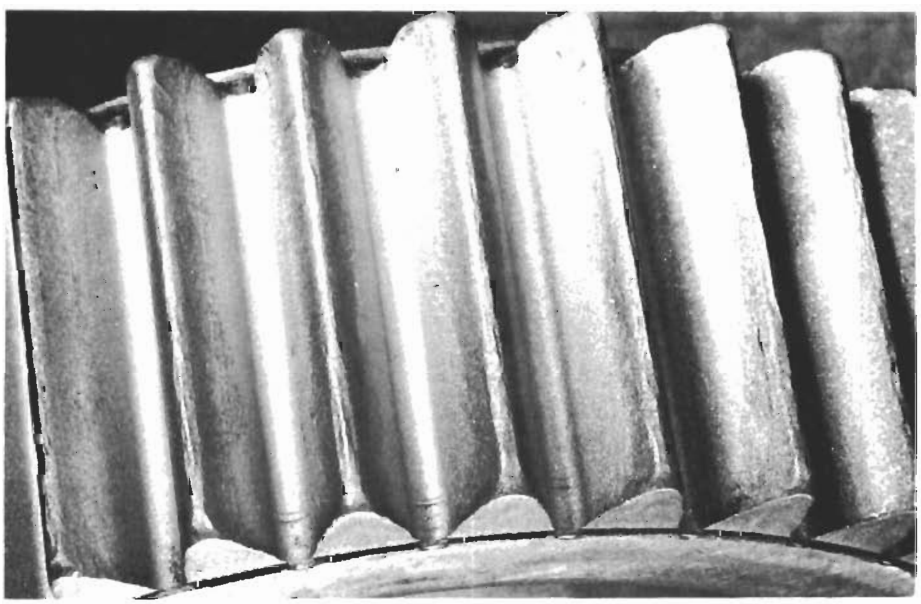
FIGURE 54

For protection against decarburization and scale, the initial pieces were plated with a 0.002 in. layer of nickel or copper. Preliminary metallographic examination of single station forgings showed that both platings offered adequate protection against decarburization. Therefore, these pieces were evaluated for surface quality only. Although both nickel and copper produced satisfactory quality forgings, copper was selected because of facilities and economics. However, subsequent evaluation of these pieces showed an undesirable surface on the as-forged parts. The surface quality representative of the initial and subsequent pieces is shown in Figure 55. Evaluation of the plating thickness before forging showed a 0.005 in. layer of plated copper rather than the desired .002 in. The excess copper extruded into the tip of the tooth die cavity and adversely affected surface quality and dimensional reproducibility. A sufficient number of quality pieces were forged to show that the irregular surface finish could be improved by maintaining proper control of plating thickness. The excessive plating did, however, show the need for adequate quality control in all stages to produce high quality forgings. The as-forged and finish machined gears illustrated in Figure 56 represent the attainable surface quality and proximity of the as-forged tooth profile to that of the finished gear.

During the final stages of development, approximately thirty-five pieces were forged as a part of a prototype production run. Because of limited furnace capacity, the pieces were forged in groups of five at 1.5 minute intervals. The time delay between pieces was provided to assure proper functioning of the secondary closure, eject the forged piece from the integral die and lubricate the die in preparation for the next forging cycle. No difficulties were encountered in forging either the AISI 9310 or the 18% nickel maraging steel.



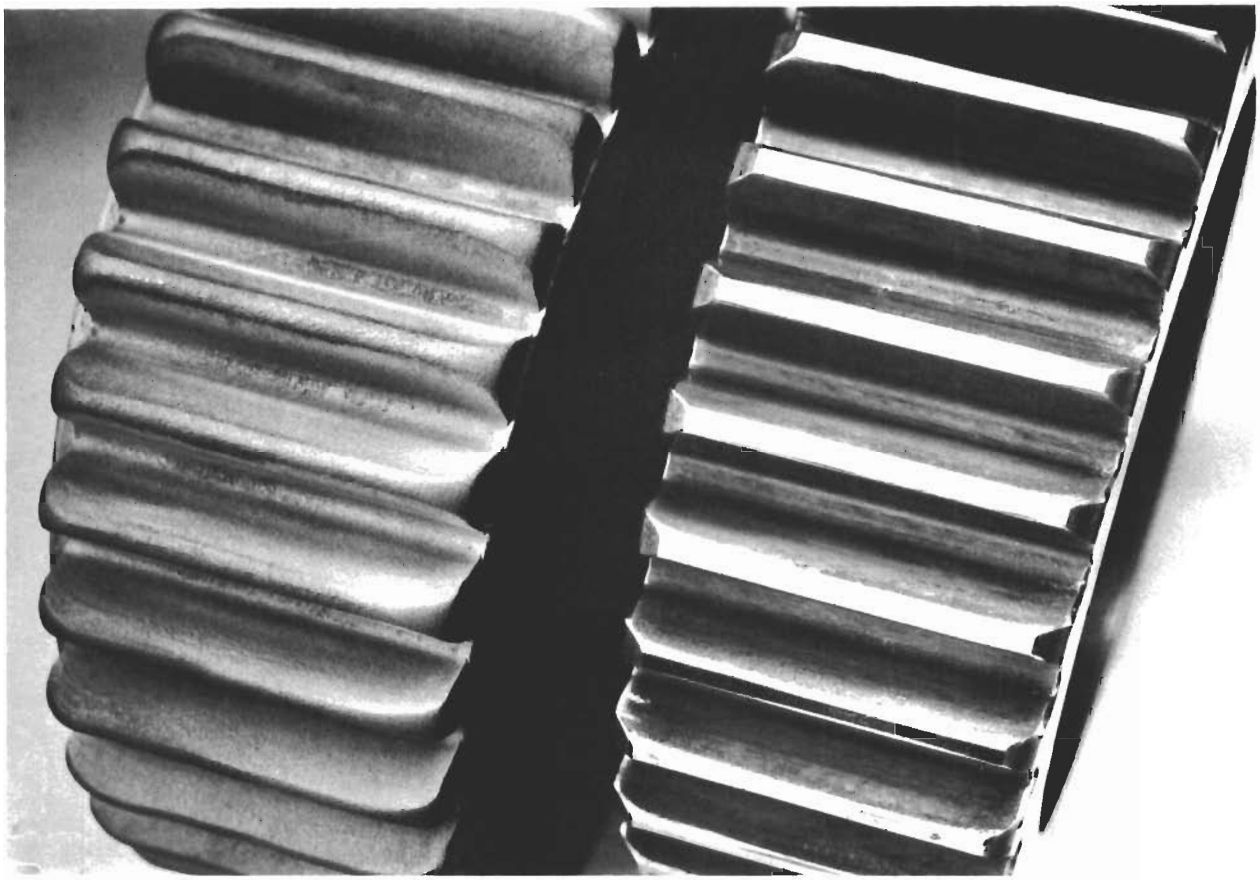
a) 0.005 in. or Greater



b) 0.002 in. or Less

EFFECT OF PREFORM COPPER PLATING THICKNESS ON THE SURFACE QUALITY OF AS-FORGED AND SAND BLASTED GEAR TEETH.

FIGURE 55



THE SMOOTH SURFACE FINISH (75 RMS) OF THE AS-FORGED GEARS PROVIDES THE PRECISION CONTOUR AND TOOTH SPACING FOR FINISH GRINDING TOLERANCES REQUIRED FOR HIGH SPEED, HIGHLY STRESSED GEAR APPLICATIONS.

FIGURE 56

VI PRODUCT EVALUATION

A. Turbine Wheel

1. Dimensional

Preliminary dimensional evaluation of the forged turbine wheels indicated that the blade profile deviation was less than 0.002 in. and a maximum blade displacement of 0.015 in. from true position. Ten turbine wheels (5 Waspaloy and 5 A-286) were inspected for blade spacing. These results were statistically analysed to determine realistic blade spacing tolerance limits. Representative blade spacing data for five of the wheels inspected are shown in Table X and the statistical evaluation of the data for all ten wheels inspected are shown in Table XI. From these results, it can be predicted with 99% confidence that 99% of the turbine wheels can be precision forged with blade spacing between ±0.026 in. and with 90% confidence that 90% of the blades will be within ±0.016 in. The dimensional quality of the blade spacing is dependent upon the insert quality; therefore, the blade spacing quality can be improved with an appropriate improvement in insert quality at an increase in insert cost.

2. Surface Quality

A visual examination was made on every forged part to detect any gross defects. Fluorescent penetrant inspection techniques were used to reveal any laps, cracks, folds, or other surface defects. The surface finish of the forged turbine blades were acceptable having a surface finish between 70 and 110 rms. The poorer surface finish resulted from insert wear which caused striations on the blade surface. However, no machining or repair work was required.

3. Metallographic

Both macro- and microexaminations were made on the forged turbine wheels of A-286 and Waspaloy. The surface area was examined for surface oxidation, however, as found in the single station coating evaluation, a maximum of .0005 in. was evident which was readily removed by a chemical etchant.

4. Mechanical Properties

Room temperature tensile and elevated stress-rupture properties of the forged turbine wheels were determined from specimens located as shown in Figure 57. The results in Table XII show a uniformity in radial and tangential properties, but only a slight improvement over the properties reported for the bar stock. This condition is attributed to the insignificant amount of work imparted to the hub area as a result of machining the preform directly from bar stock. It would be expected that the mechanical properties would be enhanced by forging the preform configuration rather than machining the bar stock.

TABLE X

TURBINE WHEEL BLADE SPACING DATA RECORDED AS DEVIATIONS FROM TRUE POSITION

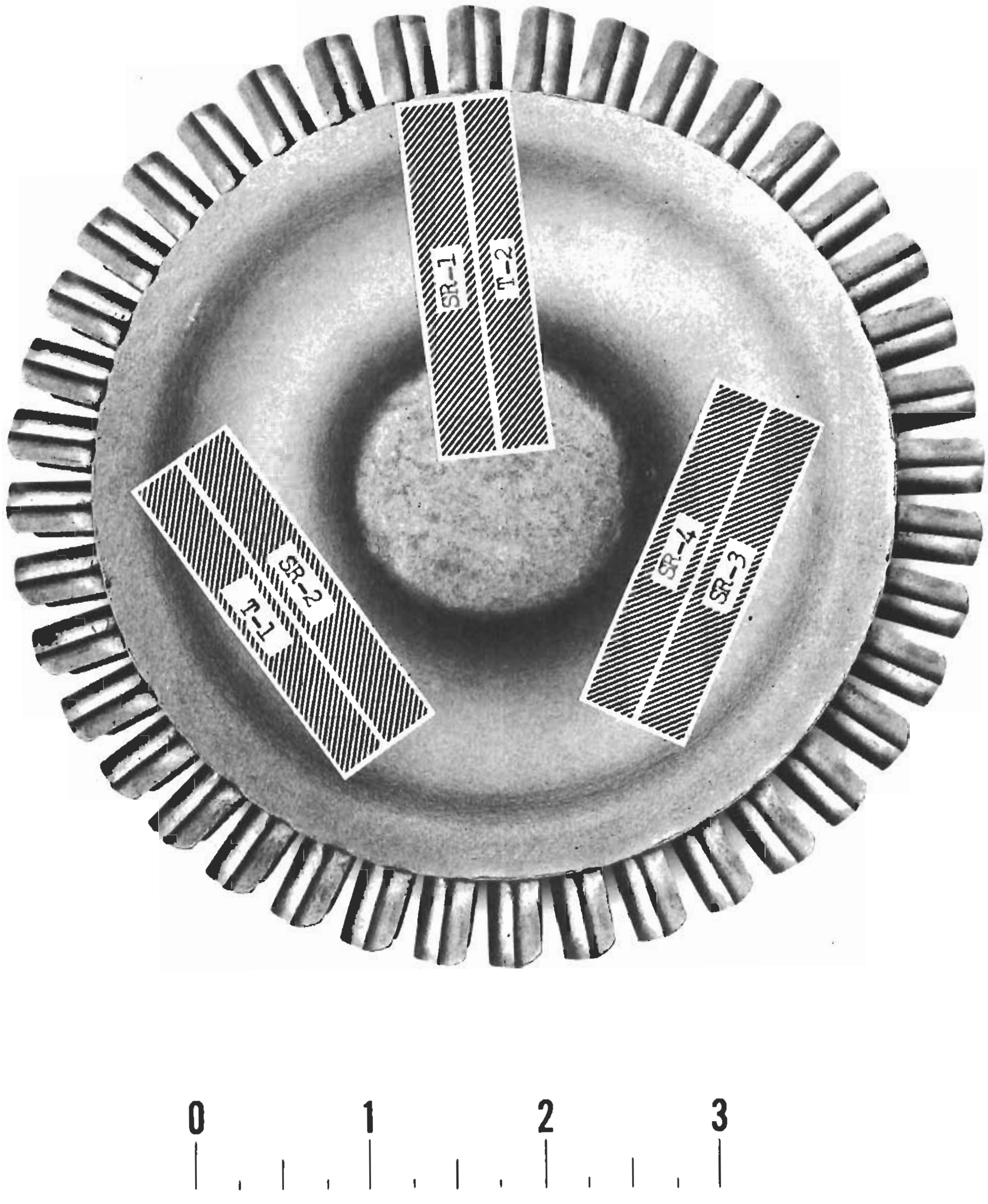
Turbine Wheel No:	2		3		4		6		10	
Blade No:	1-20	21-40	1-20	21-40	1-20	21-40	1-20	21-40	1-20	21-40
	-.002	+.007	-.004	+.004	+.004	-.001	+.001	0	-.003	+.003
	-.002	+.007	0	+.003	+.004	-.009	-.001	+.003	-.010	+.002
	-.004	+.007	0	+.004	-.001	-.001	0	+.004	-.005	-.003
	-.001	+.006	+.001	+.007	0	-.004	-.006	+.005	-.004	+.004
	-.002	+.003	+.001	+.005	+.003	+.005	-.002	+.006	-.010	+.001
	-.002	+.004	+.003	+.002	+.001	+.002	-.005	+.005	-.005	+.002
	-.004	+.003	+.001	+.002	0	+.001	-.003	+.001	+.005	-.005
	-.005	+.006	0	-.006	-.004	+.003	-.004	+.006	+.005	+.001
	-.002	0	-.003	-.006	-.005	+.006	-.005	+.002	+.002	0
	-.005	+.005	+.002	-.002	-.006	+.008	-.005	-.001	+.003	0
	-.003	+.003	+.001	-.001	-.007	+.005	-.006	0	+.002	-.008
	-.005	+.002	0	+.005	-.005	0	-.004	+.002	+.006	-.002
	-.005	+.005	+.002	0	0	-.002	-.003	-.002	+.002	-.007
	-.003	+.002	-.003	-.001	-.001	+.001	0	+.002	+.010	-.003
	-.004	0	+.001	0	0	0	0	-.003	+.002	-.001
	+.001	-.006	+.002	0	-.006	+.007	0	-.003	+.003	-.002
	-.002	-.003	+.005	-.001	-.003	+.005	-.001	-.001	0	+.001
	+.004	-.007	+.005	-.002	0	+.005	0	0	+.002	-.007
	+.005	-.007	+.005	-.001	-.005	+.006	+.003	+.002	+.005	-.010
	+.005	0	+.005	-.003	0	+.002	+.002	+.007	0	-.005
	High	+.007		+.007		+.008		+.007		+.010
	Low	-.007		-.006		-.009		-.006		-.010

TABLE XI

STATISTICAL ANALYSIS OF TURBINE WHEEL BLADE SPACING DEVIATION FROM TRUE POSITION (Based on Data from 10 Turbine Wheels)

Y	P	L	
90	90	-.01602 -	+.01630
90	95	-.01911	+.01939
90	99	-.02517	+.02145
95	90	-.01623	+.01651
95	95	-.01938	+.01966
95	99	-.02750	+.02878
99	90	-.01666	+.01694
99	95	-.01989	+.02017
99	99	-.02617	+.02645

(Y) Percent confidence that (P) percent of turbine wheel blade spacing will be within (L) tolerance limits.



LOCATION OF MECHANICAL TEST SPECIMENS USED TO EVALUATE TENSILE AND STRESS RUPTURE PROPERTIES OF A-286 AND WASPALOY TURBINE WHEELS.

FIGURE 57

TABLE XII

TENSILE AND STRESS RUPTURE TEST DATA FOR BILLET MATERIAL

Material Condition[1]	Spec. No. & Location (See Fig.57)	Ult.Str. psi	Yield Str. psi	Elong. %	R.A. %	Stress psi	Temp. °F	Hrs. to Rupture	Elong. %
Waspaloy									
Spec. Requirements (TRW-TAP-MS-528c)						47,500	1500	23.0	7.5
4 1/2 diam. billet material						47,500	1500	50.9	14.2
Forged Turbine Wheel	T-1-Tangential	179,300	118,600	14.6	13.0				
	T-2-Radial	180,500	119,600	15.1	13.0				
	SR-1-Radial					47,500	1500	39.0	13.3
	SR-2-Tangential					47,500	1500	63.0	16.3
	SR-3-Tangential					47,500	1500	37.7	20.1
	SR-4-Tangential					47,500	1500	43.0	23.2
A-286									
Spec. Requirements (AMS 5736)		130,000	85,000	15.0	18.0	65,000	1200	23.0	5.0
4 1/2 diam. billet material		163,400	111,700	27.0	46.6	65,000	1200	144.5	22.6
Forged Turbine Wheel	T-1-Tangential	160,800	116,600	18.6	18.7				
	T-2-Radial	158,700	111,500	24.9	32.7				
	SR-1-Radial					65,000	1200	216.5	23.3
	SR-2-Tangential					65,000	1200	235.6	23.6
	SR-3-Tangential					65,000	1200	218.2	34.5
	SR-4-Tangential					65,000	1200	230.8	26.8

(1) Specimens were obtained from billet material and forged turbine wheels after the following heat treatments:

A-286
1650°F, 2 hrs, oil quench
1325°F, 16 hrs, air cool

Waspaloy
1975°F, 4 hrs, air cool
1550°F, 24 hrs, air cool
1400°F, 16 hrs, air cool

A noticeable improvement in the stress-rupture life of the A-286 turbine wheels in comparison to the bar stock was shown. Also the test results for both materials were considerably above the minimum requirements of the appropriate AMS specifications. Although these tests were representative of the hub area in the turbine wheels, the results do not reflect the primary advantage of improved strength in the blade and root areas resulting from the continuous grain flow pattern. This advantage could be evaluated better by investigating the complex stress field in the root area by spin tests and advanced techniques in photomechanics of photoelasticity.

5. Service Testing

One of the basic requirements for the turbine wheel is to satisfactorily withstand the effects of overspeed spin tests. This test can be used effectively to evaluate stress distribution, failure pattern and burst initiation points. The spin test was preceded by balancing the turbine wheels within 0.03 oz. in. to minimize vibration and eccentric loading. Acceptance test requirements for the turbine wheel used in this program includes overspeed spin testing at 66,000 rpm for two minutes. Further analysis involving the evaluation of stress distribution and burst speed was not included in this program.

B. Gears

1. Dimensional

Dimensional evaluation of the forged gears included tooth spacing and diameter measurements over gage pins. Statistical analysis of the tooth spacing data shown in Table XIII for three gears indicated a .003 in variation within individual gear samples which was greater than the variation between samples. Therefore, it could be expected that the tooth spacing tolerance of ±.003 in. is characteristic of the precision forged gears.

Diameters over a .216 in. gage pin, shown in Table XIV, were recorded for ten random samples. Statistical analysis of these results, shown in Table XV, indicated that gears can be precision forged with 90% confidence that 90% of the gear diameters over gage pins will be within ±0.0075 in. of the nominal dimension.

The gears used for this dimensional survey represent two factors that would detract from the true quality of the precision forging process. First, the method of forging is not considered ideal for a true evaluation of the dimensional reproducibility. All of the pieces forged during this development program were forged under conditions where die temperatures, handling time and forging temperature were of secondary importance. Since all of these factors dictate dimensional reproducibility, a true evaluation of the process capabilities must include consideration of the aforementioned factors. Secondly, the poor surface quality of the as-forged and grit blasted gears influences the reproducibility of the dimensional analyses. Thus, under controlled production conditions the dimensional reproducibility should be better than indicated by the results of this evaluation.

TABLE XIII

GEAR TOOTH SPACING DEVIATION FROM TRUE POSITION (MILS)

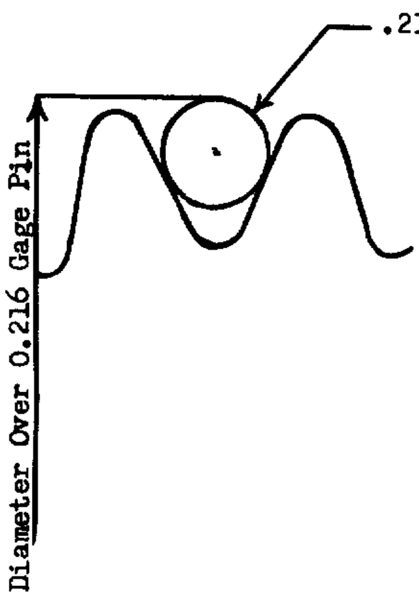
Tooth No.	Piece #39		Piece #21		Piece #60	
1	-1.2	0	1.3	2.0	-0.3	0.6
2	-1.0	-1.4	0	1.7	0.7	1.5
3	.2	-1.2	-0.4	0	-2.0	-1.2
4	.5	0.7	-0.5	1.7	-1.0	-0.7
5	-4.0	-3.5	-1.7	-0.7	-1.0	0
6	-2.0	-2.0	0	1.3	-1.0	0
7	-2.0	-0.7	0.8	1.4	0	0.3
8	-1.0	-2.0	1.5	-1.0	-2.5	-2.0
9	-1.0	-1.0	-2.7	-1.0	-2.0	-2.0
10	-2.0	-4.0	1.0	2.0	-4.7	-4.7
11	+0.5	-1.5	-0.3	1.7	0	0
12	-0.5	-2.5	0.7	2.5	-3.5	-3.0
13	-1.2	-3.0	-0.5	1.0	-2.5	-4.0
14	1.0	-1.5	2.5	3.5	-1.7	-2.0
15	-0.5	-3.0	1.0	1.3	-2.0	-2.5
16	-0.3	-1.5	3.0	4.0	-5.0	-4.5
17	-3.5	-4.0	1.0	1.5	-2.0	-5.0
18	-0.2	-0.7	-0.7	0.5	-1.2	-2.2
19	-0.8	-1.5	1.8	3.3	-2.0	-1.5
20	-0.5	-2.0	3.0	0.3	-2.0	-2.5
21	-1.0	-1.5	3.5	3.5	-2.7	-3.0
22	0	-0.8	2.5	2.5	-1.0	-1.0
23	1.5	1.5	3.2	2.7	-1.5	0
24	2.0	2.0	1.6	1.8	-0	1.0
25	1.5	1.0	1.5	1.6	1.0	2.0
26	0	1.0	1.3	1.8	0.5	2.0
27	2.0	3.5	3.0	3.7	-1.5	0.7
28	2.5	3.8	1.0	2.0	-2.5	0
29	2.5	4.0	3.5	4.5	2.0	2.5
30	0.8	2.0	1.8	2.3	0.5	1.0
31	0	1.5	0	2.5	0	1.6
Average	1.2	1.9	1.4	2.0	1.6	1.8

TABLE XIV

GEAR DIAMETER MEASUREMENTS OVER 0.216 IN. WIRES

Piece #1	d_1	d_2
21	3.9554	3.9559
22	3.9574	3.9552
28	3.9619	3.9605
29	3.9635	3.9597
38	3.9648	3.9614
39	3.9648	3.9606
52	3.9633	3.9641
53	3.9668	3.9592
59	3.9588	3.9594
60	3.9619	3.9617

d_1 and d_2 correspond to opposite ends of the same gear tooth.



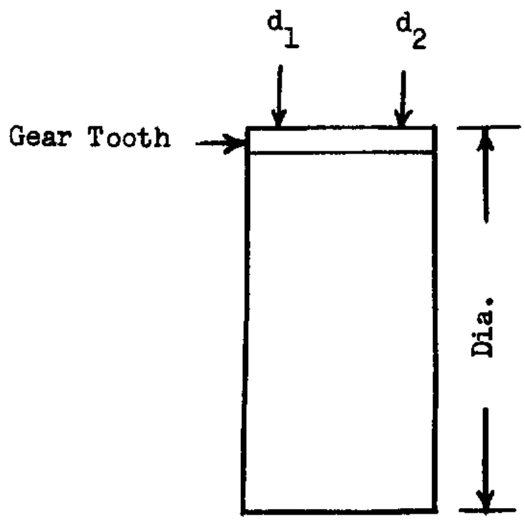


TABLE XV

STATISTICAL ANALYSIS OF GEAR DIAMETER MEASUREMENTS

Y	P	R (in.)	Tolerance ±
90	90	3.953 - 3.968	.0075
90	95	3.951 - 3.969	.009
90	99	3.949 - 3.972	.0115
95	90	3.952 - 3.969	.0085
95	95	3.950 - 3.970	.010
95	99	3.947 - 3.973	.013
99	90	3.950 - 3.971	.0105
99	95	3.948 - 3.973	.0125
99	99	3.944 - 3.977	.0165

(Y) percent confidence that (P) percent of gears will have diameters over .216 in. wires within (R) range.

2. Surface Quality

Visual examination of the forged gears did not reveal any gross defects which would detract from the quality of the as-forged gear, except the previously discussed undesirable surface condition. Since the undesirable surface condition was not considered representative of the process, surface finish measurements were taken on a piece forged with less than .002 in. copper plating. A surface finish of 60-75 rms was determined.

3. Metallographic

Since the precision forging allows a minimum).004 in.) stock removal after forging, decarburization must be minimized. Surface coating evaluation performed during the single station forging showed that copper or nickel plating offered protection from decarburization during forging operations. Additional evaluations were conducted on the as-forged gears. Typical as-forged and heat treated samples of both AISI 9310 and 18% nickel maraging steels are illustrated in Figures 58 and 59. A decarburized layer is not evident, but the microhardness data in Table XVI indicate a decarburized layer less than .0025 in., which is within the .004 in. envelope to be removed by subsequent finishing operations.

4. Service Testing

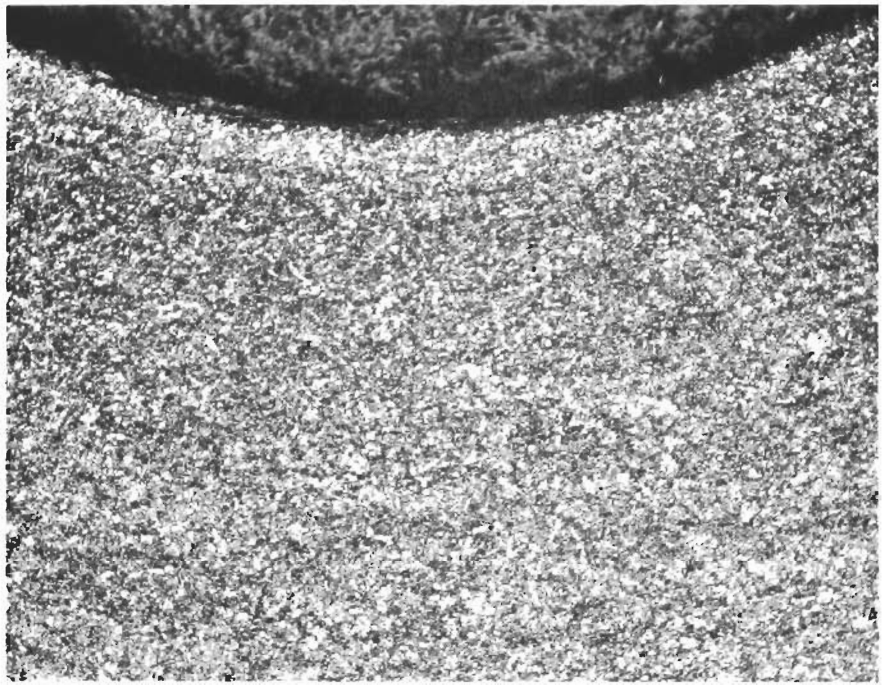
Four gears of satisfactory quality were heat treated and finish machined by Bell Helicopter Company then evaluated in a transmission test stand. These gears were run in conjunction with four standard production gears to compare tooth patterns and evaluate wear under full load conditions. Inspection of the gears after 500 hours revealed a crack in one gear which was attributed to grinding burns. Examination of other gears revealed similar burns. Therefore, the test was discontinued. Since the crack was not associated with the forging process, Bell Helicopter Company concluded that the forged gears were equally serviceable with their standard production pinion gears.

C. Finishing and Machining

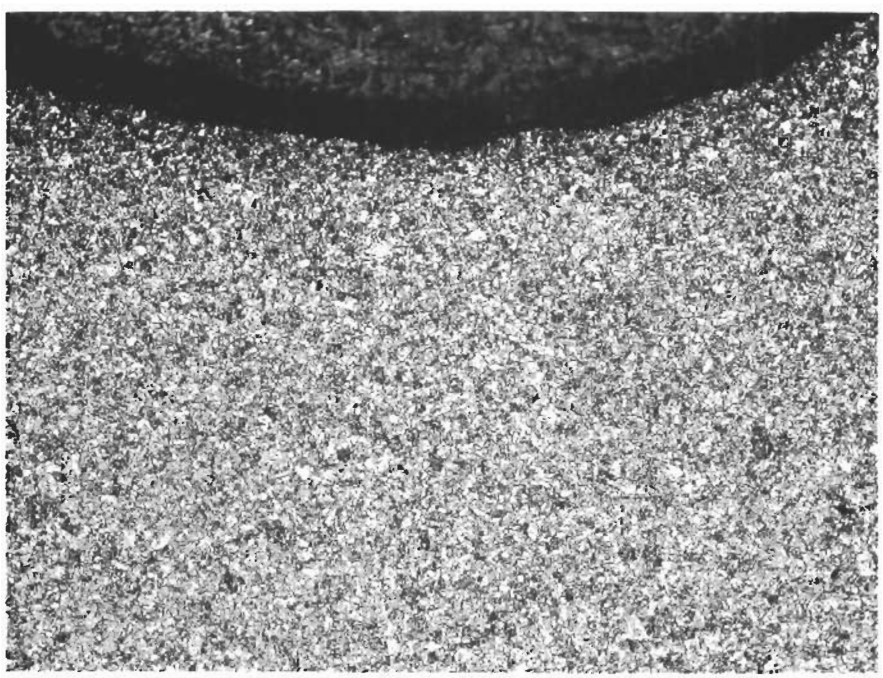
1. Turbine Wheels

The as-forged parts were sandblasted then deburred before heat treatment. A typical heat treatment cycle used for the Waspaloy turbine wheels included four hours at 1975°F, followed by 24 hours at 1550°F and 16 hours at 1400°F; each cycle succeeded by air cooling to room temperature.

The machining operations required to produce turbine wheels are significantly reduced by precision forging the blades as an integral part of the wheel. By precision forming the blade contour, the need for complex, time-consuming milling operations is eliminated. Although special machines have been developed to produce blade sections with automatic indexing and contour followers, the main problem associated with machining the high work-



Before Heat Treatment

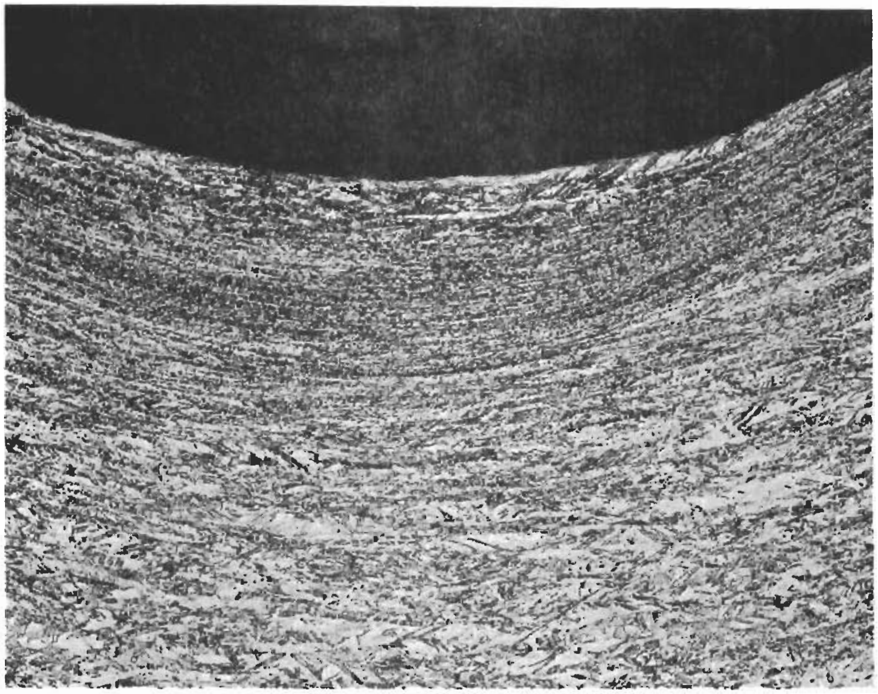


After Heat Treatment

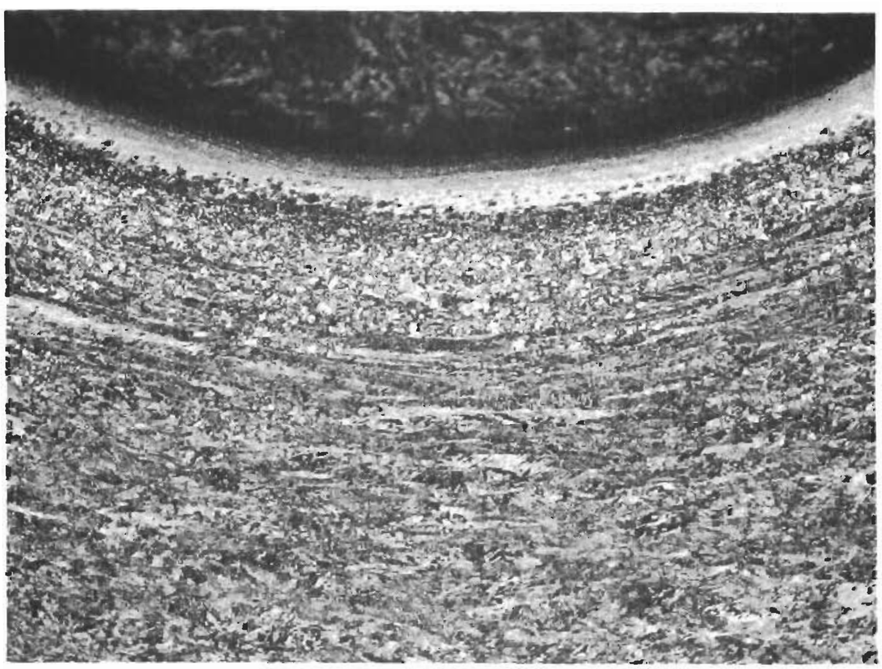
GEAR TOOTH ROOT RADIUS OF AISI 9310A STEEL BEFORE AND AFTER HEAT TREATMENT ILLUSTRATING THE FINE GRAIN SIZE IN THE FORGING.

100X

FIGURE 58



Before Heat Treatment



After Heat Treatment

GEAR TOOTH ROOT RADIUS OF 18% NICKEL MARAGING STEEL BEFORE AND AFTER HEAT TREATMENT. 100X

FIGURE 59

TABLE XVI

KNOOP MICROHARDNESS (100 GM LOAD) OF REPRESENTATIVE GEARS

Distance From Edge $\times 10^{-3}$ in.	Piece #6 DPH	Piece #17 DPH	Piece #18 DPH	Piece #20 DPH	Finished Gear DPH
.5	177	307	342	291	695
1.5	321	329	400	400	757
2.5	400	372	400	400	757
4.0	400	372	400	400	757
5.0	400	372	400	400	757
7.0	400	372	400	400	757
11.0	452	372	400	400	757
13.0	452	372	400	400	757
18.0	452	400	400	400	694
20.0	452	400	400	400	612
25.0					600
30.0					561
40.0					467
75.0					467
100.0					467

Ni plated pieces: #18 and #20

Cu plated pieces: #6 and #17

Finished gear as supplied by Bell Helicopter Co. in carburized condition.

hardening, nickel-base alloys is the very short cutter life. The precision forged turbine wheels required less total machining time than similar wheels produced from upset forged blanks.

An analysis of the particular machining operations required to produce a finished turbine wheel from the precision forged part illustrated the significance in minimizing material losses. Turbine wheels with integral blades machined entirely from upset forged blanks require 20 in.^{3} (5.7 lb. of A-286), while similar wheels precision forged with integral blades require an initial volume of only 12.5 in.^{3} (3.6 lb. of A-286). A comparison of the finish machined wheel produced from a precision forged part is shown in Figure 60.

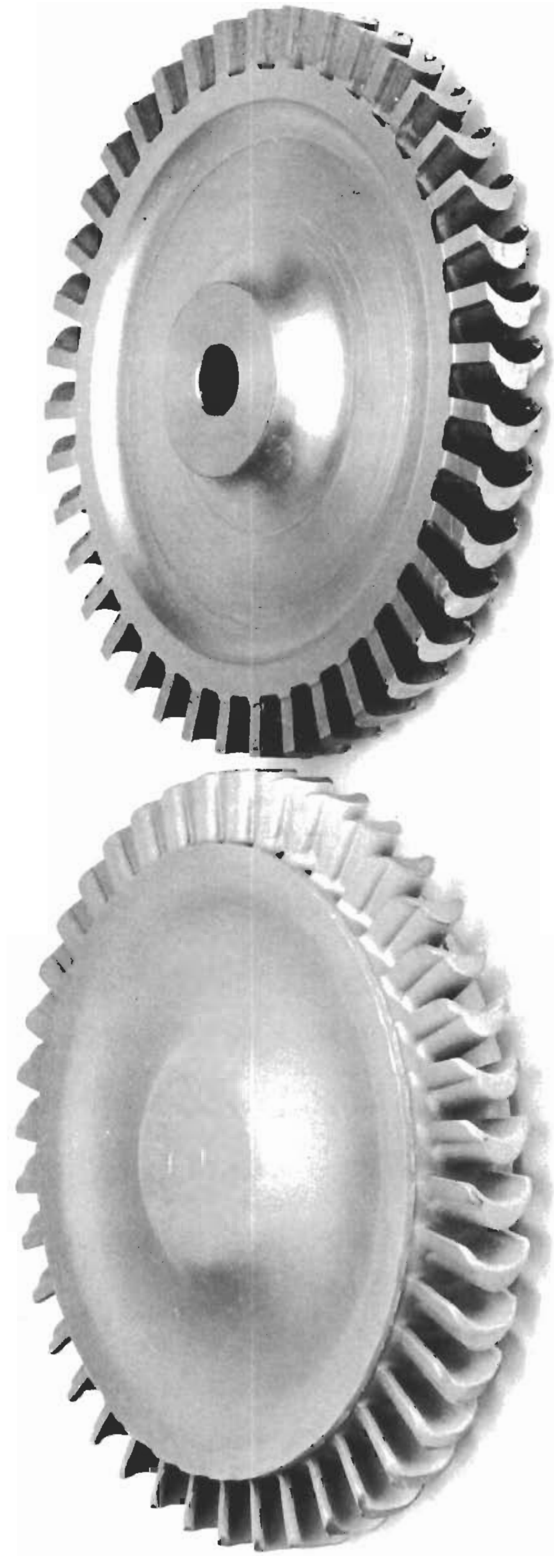
2. Gears

Similarly, the precision forged gears eliminate the need for hobbing or green grinding the tooth contour. Although other machining operations are required to produce a finished part, the amount of machining can be reduced by precision forging the hub contour within 0.040 in. of the final shape. By forging the gear teeth within 0.004 in. and the hub configuration within 0.040 in. of finished sizes, it is possible to eliminate most of the machining operations before carburizing. This would provide not only substantial reductions in machining time and material losses, but also improved quality of the gear as a result of controlled metal flow into the tooth and hub areas.

3. Cost Analysis

The initial effect of the radial extrusion process on product cost is evident from a comparison of raw material requirements. Since the radial extrusion process precision forms the material into the desired configuration, excess stock is not required for finish machining. The conventional method of machining turbine wheels with integral blades from upset forged blanks requires 37% more material than the same wheel produced by the radial extrusion process. This significant difference is realized by elimination of blade machining and by more precise forging of the wheel disc. Considering the current cost of high temperature turbine materials, the total product cost can be substantially reduced by the radial extrusion process.

The effect of die insert cost on the overall forging cost depends greatly on the performance of the inserts. Low alloy steel (AISI 6150) inserts produced by precision casting and finish grinding were approximately one-sixth the cost of tool steel (H-21) inserts produced entirely by machining from bar stock. However, the comparative life of the machined tool steel pieces was only slightly better than twice that of the low alloy cast inserts. Die inserts produced from high density alumina were approximately one-half the cost of the cast steel pieces, but the alumina inserts could not be reused. Considering the initial cost of the inserts and their apparent life as a reusable die, the precision cast parts appear to offer a greater economic advantage over the other materials and types. However, there is the possibility that ceramics still may offer an advantage if their life can be improved, particularly if the ceramics offer lower friction surfaces.



TURBINE WHEELS PRODUCED BY THE RADIAL EXTRUSION PROCESS ILLUSTRATING THE PROXIMITY OF THE AS-FORGED CONTOUR TO THE FINISHED PART.

FIGURE 60

The importance of the precision forging operation to the overall product cost is reflected in the reduced machining operations. By completely eliminating three milling operations including rough milling of the blade contour, and reducing the finish milling operations, the total machining time is significantly decreased.

Considering the thirty operations required to machine, test, and inspect the turbine wheels produced from the upset forged blanks, the total manufacturing cost can be reduced at least 10% by forging the turbine wheels with the radial extrusion process. The cumulative effects of process differences indicate the radial extrusion process offers a 10 to 20% net savings in the production of small turbine wheels with integral blades.

The basic technique for precision forging turbine wheels is readily adaptable to gear forming. The inherent features and cost savings provided by the radial extrusion process are applicable to both products. Material, manufacturing, and machining cost reductions can be effected by precision forging the individual teeth as an integral part of the gear. A reduction of one-third in the material utilization factor contributes significantly to the overall cost, not only in raw material costs but also in decreased machining time. It is difficult to apply a quantitative evaluation of manufacturing and machining operations to the total production costs of gears because of the extreme variance in specific requirements imposed by the gear consumers.

VII CONCLUSIONS

A state-of-the-art survey confirmed the need for developing an improved process to produce precision turbine wheels and gears. Both improved performance and reduced costs were cited as reasons for the industry's interest in such a process.

Present machining methods for producing turbine wheels with integral blades result in considerable waste of material, and the loss becomes greater as more expensive metals are required. The close spacing and tolerances for the blades also have made machining a costly process with the superalloys. In machining the blades and hubs, the metal flow lines are cut through which cause deleterious end-grain conditions.

Therefore, the radial extrusion process has been developed and demonstrated as an improved method for producing precision gears and turbine wheels with integral blades. The process development resulted in several significant conclusions regarding forging procedures, die materials, and product quality.

1. Precision forged products require accurately controlled preform configuration and volume to provide proper die fill and grain flow characteristics.

2. The feasibility of precision forging small turbine wheels with integral blades was accomplished by the development and successful operation of a unique secondary closure mechanism in an 8000-ton mechanical press.

3. Forging die insert materials capable of withstanding the conditions incurred in the radial extrusion process are extremely limited. Screening tests indicated that plastics, ceramics, and powder metallurgy products having compressive strength less than 100,000 psi were inadequate. Cermets appeared to satisfy the property requirements, but economics precluded their use.

4. A high density alumina product with several metal oxide additions offered the greatest potential as an expendable insert. Satisfactory performance of alumina inserts depended on adequate prestress during forging to obtain the benefit of the material's high compressive strength (300,000 psi). Removal of the alumina inserts from the forged part caused considerable difficulty. Mechanical, chemical, and thermal techniques were ineffective in removing the inserts from complex parts, thereby limiting their use to simple shapes with straight sides and positive draft angles.

5. Permanent type die inserts were capable of being reused several times. Precision cast steel (AISI 6150) inserts satisfied the dimensional requirements and were economically desirable.

6. The precision forging process produced high quality forgings with continuous grain flow patterns following the finished part contour. Dimensional reproducibility within ±0.003 in. of the finished contour, surface contamination less than .0025 in., and surface finish better than 75 rms contribute to approximately 20% reduction in machining time. As a result, significant material savings are realized.

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