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TUNGSTEN EXTRUSION DEVELOPMENT PROGRAM

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AF Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

MMP Project No. 7-793

(Prepared under Contract No. AF 33(600)-42395 by Albany Division, Wah Chang Corporation, Albany, Oregon. A. E. Riesen, C. T. Wang, and S. A. Worcester, authors)

FOREWORD

This final technical documentary report covers all work performed from 2 December 1960 to 27 June 1963 under Air Force Contract No. AF 33(600)-42395.

This contract with Wah Chang Corporation, Albany, Oregon, was initiated under Manufacturing Methods Project No. 7-793, "Tungsten Extrusion Program." The work was administered under the technical direction of Mr. T. S. Felker of the Metallurgical Processing Branch (MATB), Manufacturing Technology Division, AF Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The state-of-the-art survey was conducted by Battelle Memorial Institute under subcontract with Wah Chang Corporation. Personnel from Battelle Memorial Institute who contributed toward this survey were T. G. Byrer, F. F. Schmidt, D. J. Maykuth, A. M. Sabroff, and F. W. Boulger.

The extrusion work was conducted at Canton Drop Forge, Canton, Ohio, and Allegheny Ludlum Steel Corporation Research Center. This latter had a subcontract with Wah Chang Corporation. Mr. P. A. Santoli, Senior Research Metallurgist, was engineer in charge. Others who contributed to the work at Allegheny Ludlum Steel Corporation were E. G. Flynn, R. D. Eckel, F. L. Muscatell, J. H. Rice, J. Morgan, H. M. Johnson, D. Klingensmith, and P. Borneman.

Mr. A. E. Riesen of Wah Chang Corporation was the engineer in charge. This report was prepared by C. T. Wang and reviewed by S. A. Worcester.

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, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components. This program encompasses the following technical areas:

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

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

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ABSTRACT

Procedures were developed for preparation of tungsten-3 percent molybdenum extrusion billets by arc casting and by pressing and sintering. Round extrusions were made to evaluate die lubrication and die coatings in temperatures ranging from 3200°F to 4000°F at reduction ratios as high as 17:1. Efforts to obtain wrought extrusion billets by extruding large cast ingots at 2300°F and 2.6:1 were not successful because longitudinal cracking developed in the extrusion.

Efforts to meet program target dimensional and surface requirements with arc cast tungsten-3 percent molybdenum were unsuccessful. However, extruded tungsten "T" sections up to 138 inches long having surface finishes better than 100 RMS and dimensional run-out within .010 inch were successfully produced from pressed and sintered starting material.

The extrusion conditions necessary to achieve the program target dimensions resulted in a hot-worked microstructure which has a high ductile-brittle transition temperature and relatively low strength. Because of the undesirable microstructure achieved and the lack of requirement for tungsten extrusions of the target configuration, the program was terminated at the end of the Phase III effort.

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This final technical documentary report has been reviewed and is approved.

Melvin E. Fields

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

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I. INTRODUCTION

The recent development of the space and aircraft industry calls for structural materials which are serviceable in the temperature range of 3000°F to 4000°F. Among all refractory metals, tungsten and tungsten alloys are believed to have the highest potential for this application, due to the high melting point of tungsten. The objective of this project was to develop techniques by which tungsten and tungsten alloys could be extruded into a target section with the following configuration and property requirements:

1. Maximum "T" section circumscribed within a 2-inch diameter circle.
2. Minimum length of 10 feet.
3. Width of flange equal to twice the depth of section.
4. Thickness of flange and stem of 0.250 inch ±0.010 inch.
5. Surface finish of 150 RMS minimum.
6. Target mechanical property of 0.2 percent creep deformation at 3750°F after 100 hours under stress of 20,000 pounds per square inch (psi).

The program to develop a "T" extrusion process was divided into five phases:

Phase I. State-of-the-Art Survey

The evaluation of the current state-of-the-art of tungsten extrusion and the recommendation of the materials to be used for the program.

Phase II. Billet Process Development

The establishment of tungsten billet production processes to achieve satisfactory uniformity of billets.

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Phase III. Development of the Extrusion Operation

The extrusion of tungsten billets to establish process parameters.

Phase IV. Verification of Process Uniformity and Development of Post-Extrusion Operation

The verification and optimization of the process developed under Phase III and the establishment of post-extrusion conditioning.

Phase V. Pilot Production of the Target Section

Minimum pilot production sufficient to demonstrate the reliability of the billet process and the extrusion produced.

The state-of-the-art survey was conducted by Battelle Memorial Institute under the direction of Wah Chang Corporation. In conducting the survey, use was made of a questionnaire, plant visits, and extensive research of the literature and the Defense Metals Information Center.

A resume of physical and mechanical property data and present industrial capabilities for ingot production and extrusion practice was presented. It was reported that conventional extrusion experience on tungsten and its alloys had been limited primarily to round bar at reduction ratios of less than 10:1. The major problem areas which should be overcome before a successful tungsten "T" extrusion could be obtained were the limitations in die materials, lubrication, and billet heating capability.

On the basis of the findings of the survey, the following recommendations were made:

1. That unalloyed tungsten be selected as the base material for Phase II.

2. That consumable-electrode arc melting, alone or in conjunction with electron beam melting, be used to prepare ingots from which the extrusion billets are to be prepared.

3. That the usefulness of grain refining additions, preferably 2 percent molybdenum, be considered as part of the Phase II evaluation.

As a result of the melting evaluation program carried out in Phase II, tungsten-3 percent molybdenum was selected as the best alloy to achieve cast grain refinement while maintaining the high melting point of tungsten.

After attempts to achieve the extrusion target requirements with arc cast billets were unsuccessful, fine-grained sintered billets were used to achieve the program target requirements. The high temperature required to accomplish the extrusion resulted in a completely hot-worked structure with accompanying low strength and ductility. Lack of requirement for high tolerance tungsten extrusions in Air Force systems made continuation of the program into the production stage unnecessary. Therefore, work was terminated at the end of the Phase III effort.

II. SUMMARY AND CONCLUSIONS

A. Billet Process Development

Parameters for consumable electrode arc melting of tungsten-3 percent molybdenum and unalloyed tungsten have been established. Twenty-two 4.5- to 5.0-inch diameter ingots weighing up to 170 pounds were produced, thirteen of which were cast using mechanically joined sintered bars as electrode. Direct current (DC) straight polarity was utilized at a power above 7,500 amperes and 30 volts, under a vacuum generally less than 100 microns. Magnetic stirring coils were successfully used to control arc stability and prevent excessive grain growth. Chemical analyses showed low interstitial content with oxygen and carbon being well below 100 and 50 parts per million, respectively.

Pressed and sintered billets of tungsten-3 percent molybdenum and unalloyed tungsten 5 inches in diameter by 11 inches in length were also produced. They were sintered seven hours at 4350°F under hydrogen atmosphere. A density of 90 percent theoretical was achieved.

B. Solid Round Extrusion

In an attempt to produce wrought extrusion billets, two 6.55-inch diameter billets were extruded at 2300°F at an extrusion ratio of 2.6:1. Although the extrusions were successfully accomplished and precautions were taken to prevent post-extrusion cracking, longitudinal cracks running the entire length of the extrusions prevented use of the material as extrusion billet stock. Since higher temperatures could not be attained using existing extrusion facilities, attempts to obtain wrought billets were discontinued.

A series of round extrusions was accomplished to make a preliminary evaluation of die materials and lubrication. Extrusions were successfully made in the temperature range between 3200°F and 4000°F at reduction ratios of approximately 17:1. These extrusions demonstrated the feasibility of achieving the required extrusion ratios within the limitations of available tooling and billet heating equipment.

C. "T"-Shaped Extrusions

Full length "T"-shaped extrusions were made within target requirements from sintered unalloyed tungsten billets at 3720°F with a reduction ratio of 19:1. High liner pressures up to 222 kilograms per square inch (ksi) at an initial stem speed of 100 inches per minute were required to accomplish these extrusions.

Extruded "T" shapes of arc cast tungsten-3 percent molybdenum exhibited laps and folds perhaps related to billet cracking during entry into the die orifice.

To evaluate the effect of fine grain size, a series of extrusions were made using pressed and sintered tungsten-3 percent molybdenum billets. The folds and tears characteristic of the arc cast extrusion were minimized when the fine-grained powder metallurgy product was used. Since microstructural examination revealed evidence of inhomogeneity in the sintered tungsten-3 percent molybdenum alloy, a series of unalloyed tungsten extrusion billets was sintered. No substantial difference was noted in the maximum resistance to deformation of tungsten-3 percent molybdenum or the unalloyed tungsten. However, the minimum resistance to deformation was higher for sintered tungsten-3 percent molybdenum than for arc cast tungsten-3 percent molybdenum or unalloyed sintered tungsten.

Arc cast tungsten-3 percent molybdenum exhibited greater resistance to recrystallization than sintered tungsten-3 percent molybdenum or sintered tungsten. The grain size of the extruded unalloyed tungsten was slightly larger than the sintered tungsten-3 percent molybdenum. None of the extrusions examined had the wrought microstructure desirable in a tungsten product for structural use. The extrusion temperatures necessary to accomplish the target dimensions were too high to allow retention of a wrought structure.

One of the most significant contributions to the successful extrusion of tungsten "T" shapes was the development of a high quality die coating. An undercoating of nichrome about 0.002 to 0.003 inch thick and a final coating of about 0.040 inch thick of stabilized zirconia were applied by the oxyacetylene flame spray process with solid rod feed.

Another factor which contributed to successful extrusion of tungsten at high ratios was the development of an extrusion tooling arrangement capable of withstanding extrusion pressures in excess of 200 ksi.

III. BILLET PREPARATION

A. Arc Melting Practice

1. Starting Material

Both unalloyed tungsten and tungsten-3 percent molybdenum starting materials were utilized as a check on the grain refining effect of the molybdenum addition on tungsten. The starting materials chosen were C-10 tungsten powder with an average particle size of 3.5 to 5.5 microns and molybdenum powder with an average particle size of approximately 1.5 microns. Typical analysis of C-10 as compared to C-5 and C-40 tungsten powder is given in Table 1. The materials were weighed and fed into a rotating blender to obtain a homogeneous mechanical mixture.

Two methods of pressing were used, i.e., isostatic and mechanical. In the case of the isostatic pressing, the blended powders were sifted into a rubber sock surrounded by a perforated aluminum can. While the powder was being added, the entire container was vibrated to allow a maximum fill density of the material before starting compaction. After the sock was filled, the top of the rubber sock was sealed with a rubber stopper and evacuated through a rubber tube. The tube was then sealed with a clamp and the entire assembly loaded into a hydrostatic press where a water-soluble oil-water mixture was utilized to apply a pressure of 40,000 psi. After attaining the desired pressure, the pressure was released, the compact removed, and the rubber sock stripped from the compact. A view of the 16-inch compacting facility is shown in Figure 1.

Square bars were pressed to approximately 3/4 inch by 3/4 inch by up to 30 inches in length by mechanical compacting. The material was blended in the same fashion as before and fed into an open-top die. Pressures of up to 50 tons per square inch were applied to the bar. The as-pressed bar had sufficient green strength to allow subsequent handling.

2. Sintering

Because of the increased cross-sectional area obtainable by isostatic compaction as opposed to mechanical compaction, different sintering methods were utilized.

The mechanically pressed square bars were direct-resistance sintered in a hydrogen atmosphere at 4170°F for a minimum of two hours. The isostatic pressed bars were sintered by several techniques which included indirect-resistance hydrogen sintering, electron beam vacuum sintering, and electron beam drip melting operations. During indirect-resistance sintering, the pressed bars were introduced slowly into a hydrogen furnace at 2000°F. The tungsten bars were placed on molybdenum slabs and covered with a molybdenum sheet to prevent surface contamination which may occur within the furnace. The bars were exposed to a hydrogen atmosphere for one hour at 2200°F, raised to 2900°F over a period of seven hours, and held between 2900°F and 3000°F for a minimum of twelve hours. After the completion of this cycle, the bars were slowly removed from the hot zone of the furnace and allowed to cool under a hydrogen atmosphere at the water-cooled entry port of the furnace. After sintering, densities up to 87 percent were obtained on bars with a 2-inch diameter. The as-sintered bars were then sandblasted to remove any oxide discoloration which formed on the surface during cooling.

For vacuum sintering in the electron beam furnace, it was necessary to presinter the green bars in order to increase their strength whereby they could be hung in the furnace for sintering. Several bars were presintered in hydrogen at temperatures up to 2500°F for six hours. Some degree of purification was obtained, as shown in Table 2. The presintered bars were then sintered in the electron beam furnace. The bars were fed vertically at a constant rate of 4 inches per hour through a hot zone at least 3/4 inch wide. At this feed rate, the bars were subjected to sintering temperature for a period of about fifteen minutes. Due to the very high surface temperature attained, a surface glaze was formed which effectively restricted complete purification of the bars. The density obtained was not sufficient to allow successful welding into the final arc melting electrode configuration. In many instances due to the difficulty of maintaining a uniform circumferential heat zone, melting at random positions on the rod resulted in considerable warpage of the rod. These warped electrodes were unsuitable for arc melting.

In order to fully assess the purification potentials of electron beam vacuum sintering, several hydrogen presintered bars were hung in the electron beam furnace and the power was increased sufficiently to drip melt the material at the rate of about 4 inches per hour. The resulting material consisted of irregular globules of tungsten metal. Excellent purification was obtained by this technique as may be seen by the data of Table 3. However, the drip melted product could not be consolidated into a satisfactory arc melting electrode. A schematic diagram of the electron beam, drip melting setup is shown in Figure 2.

3. Melting

a. Arc Furnace

The melting control room is shown in Figure 3a, and the furnace is seen in Figure 3b. This furnace has the capability of producing ingots of from 2-7/8 inches to 8 inches in diameter. It may be noted that the furnace has a bottom-tap ground which produces a symmetrical magnetic field, reducing the possibility of sidewall burnthrough. A stirring coil on the furnace allows reversal of the molten pool to minimize collar buildup during melting of the ingot. In addition, the stirring coil functions as an effective deterrent to large grain growth during melting of the ingots. The furnace is water cooled under a pressure of 120 psi and is equipped with periscope observation ports which project the electrode-pool image onto the ground glass screen in the front of the control room to allow visual observation of the pool geometry, arc stability, and electrode centering.

The stinger can accomodate an electrode up to 90 inches in length and of any diameter which is compatible with the crucible size to be used on that specific melt. Thirty thousand amperes of DC power are available at 40 volts in this furnace. However, on sintered 2-inch diameter electrodes, the maximum power which was required was on the order of 7,500 amperes at 35 volts.

b. Electrode Preparation

To prepare electrodes suitable for melting, the sintered bars must be joined by welding or mechanical means. A density of 92 percent was found to be the minimum density necessary for welding on sintered tungsten. It was extremely difficult to avoid cracking as the weld areas cooled behind the hot zone. Therefore, mechanically joining by threading appeared to be more suitable in joining the material for proper current conduction to obtain the desired ingot size. Each end of the sintered bar was drilled and tapped. A nipple was then made up of similar material with suitable threads to connect the sintered bars. The faces of each of the sintered bars to be joined were machined parallel so that a flat, uniform surface contact was obtained at the interface. A sketch of a mechanically joined electrode may be seen in Figure 4. The tungsten electrode was then joined through a tantalum coupling device which had two male threads, one to fasten directly into the top of the electrode and the other to the stinger head. This arrangement allowed a gradual temperature buildup from the stinger to the tungsten electrode and minimized the thermal gradient caused by water cooling of the stinger head. Excellent success was obtained with tungsten electrodes using mechanically joined sintered material with a density of about 85 percent.

c. Melting Parameters

A major effort in this investigation was the study of arc melt variables which include:

1. Hydrogen versus vacuum sintered electrode stock.

2. Sintered electrode density.

3. Melting rates.

4. The use of stirring coils.

5. Electrode polarity.

6. Any other parameters which may prove to be effective.

Wah Chang Corporation's experience supported previous reports by Noesen (Reference 1) and Foyle (Reference 2) that the diameter of the electrode should not exceed half the diameter of the crucible mold, or in the case of larger crucible sizes, there must be a minimum of 1 inch clearance on each side of the crucible to prevent arcing to the crucible wall. To further control the arc during melting, it was found to be desirable to have a cylindrical electrode rather than clustered square bars. This minimized point arc discharge from the electrode and reduced the possibility of crucible burnthrough.

It was found that very little difference in the final ingot was obtained whether starting with hydrogen sintered or vacuum sintered material. However, the vacuum sintered material was limited in cross-sectional area to about 1 square inch due to power limitations on the vacuum sintering vessels; whereas, indirect-resistance sintering in a hydrogen atmosphere furnace easily accommodated electrodes up to 4 inches in diameter.

In the melting of the sintered and mechanically joined electrodes, it was found that material which had sufficient strength to be threaded and joined and did not have a density of above 90 percent was the most satisfactory. The lower density material made better electrode stock because of the increased electrical resistance during melting. This increased resistance caused the electrode to be significantly preheated. In many cases the electrode was white-hot, which distributed the electrical current more uniformly, maintaining a more uniform arc during the actual melting of the electrode. A density of approximately 85 percent of theoretical was used for melting most of the ingots in this program.

Direct current power with straight polarity was used for melting all of the ingots used in this program with the exception of the 8-3/4-inch diameter ingot purchased from Climax Molybdenum Company.

The stirring coils were used on continuous, intermittent, or full reversing operations as ingot collar buildup and arc stability dictated. For best arc stability and minimum collar buildup, it was found that reversing the coil at the rate of 12 times per minute produced the best results, although the sidewall condition was slightly inferior in ingots melted with a reversing coil.

Some purification of electrode stock during the melting can occur. The extent depends on the vacuum in the melt chamber at the top of the mold and the melt rate.

Melting data for all ingots obtained for this program are summarized in Table 4. In Heats 2 and 3, vacuum pressure rose to 1,000 microns near the end of the melting run, which was believed to be not due to the outgassing of the melt material but due to the outgassing of the furnace induced by excessive heating of the body of the furnace. After Melt 3, modifications to provide additional cooling water to the furnace shell and crucible walls were employed. Also, a larger capacity pump was installed to maintain the desired vacuum of 100 microns maximum during melting.

Among all seven initial heats, only two gave high yield ingots without electrode failure or other difficulties. They were: (1) Heat 4, in which case direct-resistance sintered bars with 94 percent density welded into electrodes were used; and (2) Heat 6, in which case indirect-resistance sintered bars with 83 percent density mechanically joined were used as the electrode.

In most cases the welded electrodes fractured causing interruption of the melt. Therefore, for all ingots which were prepared for extrusions through this program, indirect-resistance sintered bars, mechanically joined, were used as electrode stock.

The power required to melt the electrode was quite uniform regardless of the density of the starting material. The only variation in power which was attributable to the electrode was directly coupled with the cross-sectional area of the electrode. An electrode which was made by welding six 1/2 inch by 1/2 inch sintered bars required 6,500 amperes and 36 volts to obtain a melting rate of 2.4 pounds per minute; when the cross-section of the electrode was increased to an eight-bar cluster, the power was increased to 7,500 amperes and 33 volts, although the melting rate was approximately halved.

4. Ingot Evaluation

Among the first seven ingots melted, one ingot was lost through electrode rupture and crucible burnthrough, two sound ingots were extruded at an 11:1 reduction ratio to generate preliminary extrusion parameters, and the remaining four ingots were destructively evaluated. Their physical parameter data are given in Table 5, and the chemical analysis of the four ingots plus the analysis of Ingot 5-3770 which was fractured during handling are shown in Table 6.

Comparing the hardness traverse data of Table 5, it may be seen that the sidewall is predominantly softer than the center.

Base material cropoff to obtain sound ingot varied from 1-3/8 inches to 2-3/8 inches. This variance was a function of the rapidity with which the operator increased the power during start-up operations. If the electrode was allowed to play an arc over the base for at least three minutes, a very sound base with minimum loss was generally obtained. However, there was an ever-present danger of arcing through the base and sustaining crucible burnthrough. Therefore, it was found that nominally 2 inches of base was cropped to obtain a sound ingot.

The depth of shrink pipe obtained varied from 1 inch to none. During melting operations on production ingots, it was possible to produce several ingots with no shrink pipes. This was accomplished by a five-minute simmer operation at about half power while reversing the stirring coil every thirty seconds.

It may be seen from Table 6 that the chemistry of the evaluation ingots was extremely consistent, considering the variety of starting electrode materials utilized. It appears that single arc melting of tungsten supplies excellent purification so long as the melt rate is maintained low enough and high speed pumps are utilized.

B. Powder Metallurgy Techniques

The starting materials for powder metallurgy billets of tungsten-3 percent molybdenum were C-8 or C-10 tungsten powder and those for unalloyed tungsten billets were mixtures of C-8 and C-40 tungsten powder. The chemical analyses of the mentioned C-8, C-10, and C-40 powder used in this program are shown in Table 7.

After the proper percentage of powders were weighed and blended, they were sifted into a rubber sock and pressed isostatically at a pressure of 40,000 psi. The procedure was the same as that mentioned in the previous section for preparation of sintered bars for electrode.

The green compact was indirect-resistance sintered under a hydrogen atmosphere. The sintering furnace was heated from room temperature to 2750°F within one-half hour, held for one hour, and then raised to and held at 4350°F for seven hours. A sintered billet about 4 inches in diameter by 5 to 9 inches long with a minimum density of 90 percent of theoretical was generally obtained. The sintered billets were then machined to size for extrusion (see Tables 13 and 14).

IV. EXTRUSION OF SOLID ROUNDS

A. Extrusion of Large Ingots to Obtain Wrought Billets

Round sections were extruded in the preliminary stages of the program for two reasons: (1) to attempt to obtain wrought tungsten extrusion billets for subsequent extrusion at high ratios, and (2) to determine extrusion constants and study lubrication and die materials at ratios and temperatures necessary for the production of the "T"-shaped extrusions required in the program.

Two tungsten-3 percent molybdenum billets prepared by Climax Molybdenum Company were extruded with steel cans at Canton Drop Forge. These billets were obtained from a single ingot, 8-3/4 inches in diameter weighing approximately 549 pounds. The starting material for this ingot was 97 percent tungsten powder and 3 percent molybdenum machine chips which were blended before compacting into electrode. Table 8 gives starting material analysis as well as ingot chemistry for the Climax material.

The melting electrode was continuously formed within the melting chamber and sintered immediately prior to melting. The electrode was formed into a hexagonal cross-section measuring 2-1/2 inches across the flats.

The carbon-deoxidized ingot was melted into an 8-3/4-inch crucible at a rate greater than 10 pounds per minute. Alternating current was utilized to accomplish the rapid melt rate. Stirring coils were not used. Information as to power required and melt chamber vacuum during consolidation was not made available.

Each half of the ingot was then remachined to 6.55 ±0.020-inch diameter by 9 inches in length. The machined billets were then forwarded to Canton Drop Forge in Canton, Ohio. At Canton the billets were ultrasonically inspected, both diametrically and axially, by the contact method using a 1-inch diameter 5 megacycle quartz transducer. The test block utilized was 403 stainless, and the transducer was set to give a 1/4-inch node from a 3/32-inch diameter flat-bottom hole in the 403 stainless test block. No indications were discerned in either of the two billets.

After ultrasonic inspection, the billets were canned in mild steel to 8-inch nominal diameter. This produced a 3/4-inch wall of mild steel on the radius of the tungsten billets. A 1-inch thick cap was welded on each end of each billet. The billets were evacuated during canning to insure a tight fit between the mild steel and the tungsten billets.

Prior to extrusion, the ingots were heated in a salt bath to 2300°F and soaked one hour at temperature, after which they were extruded top first at a 2.6:1 reduction ratio through a round die at a ram travel rate of 5.9 inches per second. The pressure required ranged from 44.7 to 48 tons per square inch. These pressures were about half that normally required for uncanned tungsten billets.

After the first billet was pushed, it was observed that the first 6 inches of the billet had been stripped of steel during extrusion. On the second extrusion, an additional 1-inch thick steel plate preheated to 1400°F was inserted in front of the billet to prevent peeling of the steel can. Even so, the first 3 inches of the extrusion were completely stripped of steel.

After extrusion, the billets were immediately transferred to the salt bath which was maintained at 2300°F for two hours and then allowed to cool slowly to 1700°F and soaked one hour at 1700°F. After the thermal soak, the ingots were removed from the salt bath and buried in Sil-O-Cel for an additional 24 hours to insure slow cooling in an attempt to prevent cracking in the extrusions. When the extrusion billets were cool enough to handle, the steel cans were mechanically stripped from the billet; and the stripped ingots were then shipped to Wah Chang Corporation for machining and inspection.

Figures 5 and 6 show one of the two billets with a view of the stripped can as well as the nose and tail section of the billet. The sidewall is quite good, in spite of the fact that one billet did undergo slight alloying near the tail of the extrusion. Some nose bursting, approximately 3 inches long, was observed. However, it did not appear to propagate through the extrusion. Visual observation of the tail section indicated that the net extrusion reduction of approximately 2.8:1 undergone by these billets was not sufficient to work the structure throughout. A knob was observed near the center of the tail of the extrusion.

Comparing the center ingot slice grain structure and the bottom ingot slice (Figures 7 and 8), it may be seen that the geometry of the knob observed in the extrusion tail seems to correlate very well with the grain structure and geometry of the original ingot. This correlation would not be possible if the reduction ratio had been sufficient to thoroughly work the structure. It appears that the billet sidewalls received considerable work, but the fine-grained center was not significantly altered.

During billet cleanup, the extrusions were machined in one section to a diameter of 3.725 inches in an attempt to obtain four wrought extrusion billets from each large extrusion. However, as the rough tungsten-iron interface was machined off, four longitudinal hairline cracks appeared which ran the full length of each extrusion. The cracks were located at about 90-degree increments around the circumference of each billet. Machining down to a diameter of 3.500 inches failed to clean up either of the two extrusions. Further attempts to obtain wrought 3.725-inch diameter extrusion billets were abandoned after an evaluation of industrial capabilities at that time.

B. Extrusion of Rounds at High Ratios

1. Extrusion Press

The extrusions with glass coating were performed at Allegheny Ludlum Steel Corporation on a Lake Erie production press of a modified Schloemann design with an air-water accumulator system rated at 3,150 psi. The press could deliver 1,778 tons to the stem, with 1,500 tons coming from the main cylinder (950 square inch cross-sectional area) and 278 tons from the mandrel cylinder (176 square inch cross-sectional area). However, modification of the press increased the total tonnage to 2,200 tons. The mandrel cylinder permitted the movement of mandrels independent of the main ram. The press also had a container-shifting hydraulic system which permitted the container to be opened from the die assembly, thereby allowing a hot saw to cut extruded product at the exit end of the container. Die assemblies were loaded into a hydraulically operated die arm which moved perpendicular to, and on an axis parallel to, the direction of extrusion. The arm was located between the container and the front plate of the press. This feature permitted rapid changing of dies between pushes. Closing speeds of up to 2,000 inches per minute, one of the fastest closing speeds available for this type of press, were possible.

By appropriate valving, the press was converted to a stepped maximum tonnage press which would permit the limitation of tonnage to prevent breakage of tools when extruding small slugs.

A more detailed description of a Schloemann press is given by Pearson and Parkins (Reference 3).

2. Billet Material

Extrusion billets with 110-degree conical or 1-inch radius nose geometry were machined from 5-inch diameter arc cast tungsten-3 percent molybdenum ingots and were assigned code numbers as listed in Table 9. Chemical analyses for each extrusion billet are also given in Table 9.

All billets were examined ultrasonically without any indication of defects beyond rejection limits. A typical as-received extrusion billet is shown in Figure 9, and the dimensional sketch of the 110-degree conical billet is shown in Figure 10.

3. Billet Heating

Heating of billets to at least 4000°F for extrusion was accomplished with a vertical induction coil, capable of heating billets of 3-3/4 inches diameter by 16 inches long. Power for the coil was provided by one or two 100 kilowatt Multiductors, taking three-phase power at 60 cycles and delivering single-phase power at 180 cycles. The output could be varied continuously and under load between 25 and 200 kilowatts by means of simple controls. The top of the coil was capped to keep heat losses down and to permit the use of inert gases during heating for control of billet surface conditions. The temperature of the billets up to 2900°F was measured by a platinum, platinum plus 13 percent rhodium thermocouple in contact with the bottom-center of the billet. Above 2900°F, the temperature was measured by an optical pyrometer.

After Extrusion 7 was made, a platinum plus 6 percent rhodium, platinum plus 30 percent rhodium thermocouple replaced the platinum, platinum plus 15 percent rhodium thermocouple to measure temperatures up to 3300°F at the bottom-center of the billet. The billet temperature was also measured by a Land radiation pyrometer sighting at the side, through a port midway between top and bottom. Since the minimum temperature of the billet was at the bottom-center, the temperature as indicated by the thermocouple was used for extrusion purposes. A typical heat-up curve for a 4.5-inch long extrusion billet is shown in Figure 11.

4. Billet Handling

For Extrusions 1 through 7, when billets had reached the extrusion temperature, they were carried to the press manually after being placed in a graphite heat shield pre-heated to 2000°F. From Extrusion 8 on, however, the billet was pushed from the pedestal to a molybdenum rod skid-frame. The billet slid down the skid-frame onto the "glass" table. The billet rolled over the "glass" table and down into a "V"-trough from which a mechanically operated arm pushed it into the liner. These operations were easily accomplished within thirty seconds after unloading from the induction coil to press close.

5. Die and Spacer Design

The die design was an internal type with 130-degree or 90-degree entry angle, in accordance with the sketch shown in Figure 12. Die material used was Super DBL, a high-speed tool steel of the M-36 type.

The following heat treatment was used to produce a hardness range of 52 to 74 Rockwell C:

1. Preheat in salt at 1500°F.

2. Heat at 2175°F in salt for three minutes at temperature.

3. Quench in salt at 1050°F until at temperature.

4. Air cool.

5. Double draw at 1170°F for two hours.

The extrusion of tungsten-3 percent molybdenum was expected to require high liner pressures in the order of 200,000 psi. In order to reduce elastic deflection of the die surface beneath any insulation coating, a more preferable surface hardness was thought to be 58 to 60 Rockwell C. An investigation was conducted to determine a suitable heat treatment to obtain this hardness range.

A piece of Super DBL, approximately one-half the size of a die blank from the same heat as above, was heat treated in accordance with the following procedure:

1. Preheat in salt at 1550°F for approximately ten minutes.

2. Heat at 2175°F for seven minutes.

3. Quench in salt at 1050°F until at temperature.

4. Air cool. Rockwell C hardness: 62.0.

5. Single draw at 1100°F for two hours. Rockwell C hardness: 57.7. Shephard grain size: 7.

Since the hardness before tempering was low and the grain size was rather large, another similar piece was heat treated as follows:

1. Preheat in salt at 1550°F for fifteen minutes.

2. Heat at 2175°F for fifteen minutes.

3. Quench in salt at 1050°F until at temperature.

4. Air cool. Rockwell C hardness: 64 to 65. Shephard grain size: 8 to 9.

5. Single draw at 1150°F for two hours. Rockwell C hardness: 59.

Grain size after this heat treatment was quite suitable.

A microscopic examination of various Super DBL samples after heat treatment was made to determine decarburization at the surface. It was found that the extent of decarburization was less than 0.001 inch, which could be removed by polishing. The initial practice of leaving 0.015 inch for machining after heat treatment was discontinued, and all dies were machined to size before heat treatment.

Spacers were made for the dies shown in Figure 13. Spacer material used was Potomac M of the H-13 type having the following analysis:

C	Mn	P	S	Si	Cr	Mo	W	V
0.40	0.21	0.016	0.013	1.10	5.35	1.24	0.11	1.00

The following heat treatment was used to obtain a hardness range of 50 to 52 Rockwell C:

1. Preheat in salt at 1500°F.

2. Heat at 1825°F in salt for fifteen minutes.

3. Air cool.

4. Double draw at 1050°F for two hours.

6. Die Coating

For all extrusions a special coating was applied to the face and orifice of the die to avoid "wash" of die material through loss of strength from high heat input from billet material during extrusion. Stabilized zirconia was applied to the dies by the Linde Company using a plasma arc spraying process. An initial flash coating of nichrome 0.002 to 0.003 inch was applied before applying approximately 0.030 inch of zirconia. The zirconia coating was then honed to proper dimensions and finish. The coated die is shown in Figure 14.

A study was made to establish the relationship between surface hardness and roughness as prepared by several different coating sources. RMS surface measurements on flat test panels were found as follows:

	Surface Hardness (Rc)	Coating Source		Average RMS
Super DBL	53.5	A	Alumina grit 16-24 mesh 100 psi	131
Super DBL	56.5	A	Alumina grit 16-24 mesh 100 psi	129
Super DBL	60.5	A	Steel grit	105
Potomac A	51.5	A	Steel grit	225
Potomac M	51.0	B	Steel grit SAE G16 + G25 mesh 90 psi	600
Potomac M	51.0	C	Alumina grit 90 psi	150

These data indicate that there is a direct relationship between surface roughness and hardness. In addition, considerably more roughness can be achieved by the use of steel grit rather than alumina grit on an equivalent surface hardness.

In order to strengthen the die surface and add support to the coating, nitriding after roughening with steel grit was done by the "Nitrocycle" process. Examination of small specimens treated with the dies indicated a core hardness of about 900 DPN microhardness (200 gram load) or Rockwell C 61.5 with a case hardness of about 1,100 DPN. The nitriding cycle was 64 hours at 1000°F with a 5-gram concentration of ammonia.

Die design and coating data are shown in Table 10.

7. Lubrication

Proprietary compositions of lubricants as provided under license agreements are designated by code numbers.

a. Billet Lubrication

Billets for extrusion were coated according to one of the following two techniques:

(1) Spray Precoating

Billets were heated to about 400°F and then spray coated with glass to a total thickness of 0.030 inch by siphon-feed gun.

The glass in powder form of -325 mesh was mixed with other ingredients as follows: (a) Glass, 56.5 percent; (b) Methocel, 0.25 percent; (c) Bentonite, 0.25 percent; (d) Ball Clay, 3 percent; (3) Distilled Water, 40 percent. Proprietary composition of the glass used for each extrusion is indicated in Table 11.

(2) Pickup by Rolling

Glass in powder form of -325 mesh was placed on the "glass" table for pickup by rolling after heatup to the extrusion temperature. For this purpose, glass of composition Code AL-11-45 was used.

b. Die Lubrication

A glass pad was placed between the billet and the die.

For Extrusions 1 and 2, the glass pad was approximately 1/2 inch thick with a hole in the center of approximately 1 inch diameter. These pads were made by pressing a mixture of -20 mesh glass powder and corn starch followed by baking until hard.

For the remaining extrusions, the pads were glass fibers impregnated with glass powder of -325 mesh. The die glasses as designated by code numbers are listed in Table 11.

c. Liner Lubrication

Fisk's 604 was used for lubrication of the liner for Extrusions 1 and 2. For Extrusions 3 through 7, a special preparation of WS_2 from the Alpha-Molykote Corporation was applied, while Molykote G, which contains MoS_2, oil, and lithium grease, supplied by the same corporation, was used for Extrusion 9.

8. Extrusion Data

The extrusion data for solid rounds of arc cast tungsten-3 percent molybdenum alloy are summarized in Table 11. The typical extrusion is shown in Figure 15. As-extruded surface conditions are shown in Figure 16.

Two extrusion billets (AF-3694 and W6) were heated to about 4000°F, but were dropped during discharge from the induction coil. These were not extruded.

The extrusion data show that Billet W2 was extruded at a lower liner pressure than that of Billet W1. Both were extruded at the same temperature, while the former was conducted at a higher reduction ratio. There is no apparent reason for this anomaly. It was observed, however, that more glass remained on Billet W2 after heating to temperature, probably as the result of shorter heating time.

The lower limit of billet heating temperature for the extrusion of arc cast material appeared to be about 3000°F, from which Billet W7 blocked the press at a reduction ratio of about 15:1.

Extrusion 8 was cancelled for several reasons. The reduction ratio of 11.8:1 planned for this extrusion was too low to be of any interest at this point in the program, since higher reduction ratio extrusions had been accomplished. Furthermore, the use of alumina grit for blasting the die surface had shown a low surface roughness, which was believed to be related to low bond strength and subsequent die wash.

Extrusion 9 was the first attempt to extrude at about 17:1 from 3200°F billet temperature. This extrusion was initiated at 195 ksi liner pressure on about 88 percent of capacity, but was not completed due to separation of the container from the die holder. The extrusion and die performance could not be evaluated.

Since Extrusion 9 indicated that the reduction ratio of about 17:1 could be accomplished from 3200°F billet temperature, Extrusion 10 was canceled. Furthermore, the extrusion of molybdenum-base alloy TZM on a concurrent program indicated that satisfactory die performance can be achieved with an oxyacetylene spray coating of zirconia and Potomac M at Rockwell C 48 to 50. Special surface preparation prior to coating is now believed unnecessary and only roughing by steel grit blasting to at least 500 RMS is required for good bond strength.

9. Extrusion Evaluation

A summary of evaluation results pertaining to the metallurgical properties of solid round extrusions at the front, middle, and back locations are shown in Figure 17. The transverse slices were obtained by using an Allison Abrasive cut-off wheel designated C-90-K-RA operating at approximately 7,400 surface feet per minute. Preparation for macrostructural examination was made by grinding with a 60H grade alumina wheel in a stream of oil coolant followed by a 120 grit belt with water coolant. The macrostructures were revealed by etching in Aqua Regia (75 percent HNO_3 + 25 percent HCl).

Each macrostructure examined under binoculars was good without any evidence of macroporosity or cracks. A typical coarse-grained, fibered structure was found for Extrusion 1 while a fine-grained structure was found for Extrusion 2. The occurrence of coarse or fine macrostructure evidently was more related to reduction ratio than to billet temperature as used in this program.

Transverse microstructures from the center location in the middle of Extrusions 1, 2, 3, 4, and 5 are given in Figure 18. Microstructures were revealed by electropolishing and electroetching in a solution of 1-1/2 percent sodium hydroxide.

No extrusion exhibited a fully worked structure. Some wrought grains were observed in Extrusion 2, although complete recrystallization was expected due to the high temperature and ratio involved. Most microstructures, regardless of extrusion conditions, exhibited no excess grain growth. The maximum grain size of ASTM 3 was experienced in Extrusion 2. The ASTM grain size range of 5 to 8 characterized most of the recrystallized areas. The general presence of recrystallization in the microstructure indicates that the extrusion conditions were unsuitable to induce strain hardening.

Rockwell C hardness surveys of the front, middle, and back transverse slices from as cast tungsten-3 percent molybdenum solid round extrusions are given in Table 12. Most extrusions exhibited a non-uniform degree of hardness from front to back except Extrusion 2.

Die appearance after extrusion of solid rounds of tungsten-3 percent molybdenum alloy is shown in Figure 19. The variation of extrusion diameter versus extrusion length is shown in Figures 20 and 21.

Good die performance was found for Extrusions 2 and 4. There was little variation in extrusion diameter along the extrusion length. Loss of coating did occur on Die DW1, especially on the entry surface. Dies DW2, DW3, and DW6-5 washed and exhibited spalling of the coating. The poor results with Die DW2 were related undoubtedly to the abrasive action of the pedestal support block stuck to the nose of the billet.

Very little change was noted in the O.D. dimensions of the dies indicating that useful hardness and strength was achieved at hardness of Rockwell C 52 to 54.

V. EXTRUSION OF "T" SHAPES

A. Billet Material

Billets as listed in Table 13 were machined from 5-inch diameter arc cast ingots of tungsten-3 percent molybdenum alloy. Billets of tungsten-3 percent molybdenum and unalloyed tungsten which were prepared by powder metallurgy techniques are listed in Tables 14 and 15, respectively. Chemical analyses, size, weight, and density are also given in these tables.

All billets were examined ultrasonically. Indications of discontinuities were found in billets with code numbers SW17 and SW18.

B. Extrusion Equipment, Tooling, and Procedure

1. Extrusion Equipment, Billet Heating and Handling

The extrusion press and billet heating and handling equipment was the same as that described for solid round extrusions.

2. Die and Spacer Design

Extrusions 11 through 13 were planned primarily to evaluate die materials and coating. Die design for this purpose was an external type with a modified flat face, as shown in Figure 22. The supporting spacer allowed 1/16 inch clearance per side in relation to the exit-relief dimensions of the die.

The second group of five extrusions, Extrusions 14 through 18, was primarily planned to determine the most suitable die glass composition. The die design for this purpose was an external type with a variable included angle, as shown in Figure 23. Internal dimensions are specified to allow for the deposition of 0.030 inch of stabilized zirconia per surface. The spacer, with the die shown in Figure 24, had no clearance in relation to the exit-relief dimensions of the die.

Other dies used for "T"-shaped extrusions were designed according to the drawings in Figures 25 through 36. Nichrome and zirconia were used as die coating by one of two techniques: (1) plasma arc spraying, or (2) oxyacetylene flame spraying an undercoating of nichrome about 0.002 to 0.003 inch thick, followed by a final coating of stabilized zirconia approximately 0.040 inch thick.

All die design data are listed in Table 16.

3. Lubrication

Proprietary compositions of lubricants as provided under license agreements are designated by code numbers.

a. Billet Lubrication

Glass of composition Code AL-30-45, in the form of -325 mesh powder, was placed on the "glass" table in a layer no more than 1/32 inch thick. After the billet was heated to extrusion temperature, it was rolled in the glass layer prior to extrusion.

b. Die Lubrication

For each extrusion, a glass pad 4 inches in diameter by 1 inch thick was placed between the billet and the die. For Extrusions 11 through 18, the pad composed of glass fibers was 4 inches O.D. by 1-1/2 inches I.D. by 1/2 inch thick. Composition code numbers for each pad are given with other extrusion data in Table 17.

c. Liner Lubrication

Molykote G was used for lubrication of the liner. This was applied by swabbing the liner I.D. with a cloth saturated with the lubricant. Molykote G contains MoS_2, oil, and lithium grease.

C. Extrusion Data and Evaluation

Extrusion data for all arc cast tungsten-3 percent molybdenum billets are shown in Table 17. Those of pressed and sintered tungsten-3 percent molybdenum and unalloyed tungsten are shown in Table 18.

1. Physical Characteristics

a. First Group of Arc Cast Tungsten-3 Percent Molybdenum Billets

The first group of arc cast tungsten-3 percent molybdenum extrusions, Extrusions 11 through 13, was planned primarily to evaluate die materials and coatings. A typical extrusion is shown in Figure 37. Die appearance after extrusion is shown in Figure 38.

Die materials ALX-6 and ALX, used for Extrusions 12 and 13, respectively, are cast cobalt-base alloys that are not affected by heat treatment. After plasma arc spraying with nichrome and zirconia, each die was given a special diffusion heat treatment to enhance bond strength. Severe die wash and loss of orifice resulted in poor surface quality and dimensional run-out during extrusion using Die DW13 at the high hardness level of Rockwell C 59. No cracking occurred in Die DW12 at the hardness of Rockwell C 42.

No further work was done with extrusion dies prepared with cobalt-base alloys and diffusion treated coatings.

b. Second Group of Arc Cast Tungsten-3 Percent Molybdenum Billets

The second group of arc cast extrusions, Extrusions 14 through 18, was planned primarily to determine the most suitable die glass composition. Typical extrusions are shown in Figure 42. Extrusion dimensions versus extrusion length for Extrusions 14, 16, and 17 are shown in Figures 43, 44, and 45.

Die glass for this group of extrusions were varied from "hard" to "soft" as each extrusion was made. All other variables were maintained as constant as possible, except that the billet temperature for Extrusions 17 and 18 was raised to 3200°F to avoid the partial press block encountered with Extrusions 14, 15, and 16. Raising the billet heating temperature to 3200°F allowed extrusion of the entire billet.

Extrusions 14 and 15 were characterized by the appearance of striations and glass rub-in. Glass rub-in resulted in cross-tears which were prevalent on the corners of Extrusion 14 (Figure 39), but more prevalent on the flat surfaces of Extrusion 15 (Figure 40). Fair dimensional run-out for Extrusion 14 was found, as shown in Figure 43. Extrusion dimensions on Extrusion 15 could not be measured.

With a lower softening point die glass, Extrusions 16 and 17 resulted in better extrusions, less glass rub-in, and good dimensional run-out (Figures 44 and 45). Extrusion 18 was poor as a result of severe die wash and heavy die pickup.

In general, the die glass used for Extrusion 17 was considered more favorable than those tried for the other extrusions of cast tungsten-3 percent molybdenum alloy.

c. Third Group of Arc Cast Tungsten-3 Percent Molybdenum Billets

In the third group of arc cast extrusions several die designs were used for the extrusions, primarily to evaluate their influence on liner pressure. The flat-face die design B-0486 (Figure 29) used for Extrusion 23 resulted in the highest liner pressure, and only a partial extrusion was made. The other die designs employed consisted of basic conical die entry angles of about 120 to 130 degrees and a variety of entry radii to the land, which was a constant 1/4 inch wide. There was no strong influence upon liner pressure regardless of die design. Unfortunately, Extrusion 43, involving the lesser conical die entry angle of 114 degrees, was not completed.

Maximum liner pressure for each extrusion was in excess of 200 ksi. This pressure did not decrease appreciably during extrusion, indicating a low billet friction along the liner wall. High minimum liner pressures, even at billet temperatures of 3700°F, are believed more strongly related to the resistance to deformation of the material and die friction. The average resistance to deformation associated with maximum liner pressure for these extrusions is about 72 ksi.

After billets were extruded, the surfaces were cleaned by blasting with fine alumina grit. For each completed extrusion, the surface finish was then determined by a profilometer employing a diamond stylus at a tracing speed of 0.3 inches per second. Results of these measurements are given in Table 19. RMS readings were taken as an average of high peaks only. Extrusion dimensional plots are shown in Figures 46 through 49.

Typical as-extruded surface quality of completed "T"-shaped extrusions of Group 3 arc cast tungsten-3 percent molybdenum billets are shown in Figures 50 and 51. In general, the extrusions were characterized by the appearance of longitudinal striations. Glass rub-in and cross-tears were not observed, indicating suitable lubrication practice and speed during extrusion. Extrusions 36 and 44 revealed a good, smooth surface finish for nearly the entire extrusion length. Measurements as low as 60 RMS were found in some portions of these areas. However, these same extrusions were not acceptable due to gross defects in some areas. Straight, sharp longitudinal striations are considered the result of local die coating failures. Folds or laps, as shown in Figure 50 for Extrusion 36 (top view of the nose surface), are believed related to billet cracking during entry to the die orifice. Cross-sectional views of the macro-etched discard from Extrusion 14 illustrate this cracking during entry into the die. Apparently these cracks then fold over and string out on the extrusion surface forming defects such as those shown in Figure 50.

An improvement in dimensional run-out coincided with improved surface quality, as indicated by comparison of Figures 48 and 49 and Figures 50 and 51.

d. Pressed and Sintered Tungsten-3 Percent Molybdenum Billets

In crder to evaluate the effect of decreasing billet grain size on the surface quality of the extrusions, a series of tungsten-3 percent molybdenum billets prepared by pressing and sintering were evaluated. It was anticipated that the finer grain size obtained on the sintered product would reduce surface cracking during extrusion.

The extrusions were difficult to complete, even from the high billet temperature of 3650°F. Liner pressures in excess of 200 ksi were required to overcome an apparent high resistance to deformation of the material. Most billets extruded at lower temperatures resulted in blocking or partial blocking of the press. However, Extrusion 35 extruded at 3650°F was completed without blocking the press. Good surface and dimensional characteristics were found for the entire 106 inches of extrusion length (Figure 55). The extrusion data for this extrusion indicated an upset liner pressure of 216 ksi, and a run liner pressure of 212 ksi. This decrease in liner pressure during extrusion corresponds to a billet coefficient of friction of approximately 0.002. High liner pressure, therefore, was required to overcome an inherent high resistance to deformation of the material and die friction.

A wide variation in die design was used for the extrusions. There was no strong influence of die design upon liner pressure. The most successful extrusion, Extrusion 35, was made with die design B-0508 (Figure 32), involving a conical die entry angle of about 100 degrees, which affords a more gradual rate of reduction in the material.

Typical as-extruded surface quality of completed "T"-shaped extrusions of pressed and sintered tungsten-3 percent molybdenum billets are shown in Figures 53 through 55.

Surface quality, as shown in Table 19 for Extrusions 33 and 35, was well below 150 RMS, the program goal. Some corner tears were found that were perhaps related to extrusion speed or unbalanced flow of material through the die cavity.

The variation in extrusion dimensions with extrusion length is shown in Figures 56 through 60. An improvement in dimensional run-out coincided with improved surface quality, as indicated for Extrusions 33 and 35 (Figures 54 and 55), with less than 0.010 inch dimensional run-out.

e. Pressed and Sintered Unalloyed Tungsten Billets

Typical as-extruded surface quality of completed "T"-shaped extrusions of pressed and sintered unalloyed tungsten billets are shown in Figures 61 through 64. Full-length "T"-shaped extrusions, up to 138 inches long, were made. A billet heating temperature of 3720°F was used for extrusion at a reduction ratio of 19:1. Maximum liner pressures were in the range of 196 to 222 ksi, which is equivalent to a resistance to deformation of 66.6 to 75.5 ksi.

Full-length extrusions were completed within a total time of thirty seconds. Dwell time in the back of the liner prior to stem pickup appeared critical and was up to ten seconds.

Die design B-0542 (Figure 35), with a basic included 120-degree angle of entry, was used for Extrusion 40, which exhibited excellent characteristics.

Surface quality below 150 RMS was found for Extrusions 40 and 41 (Table 18). Blisters, observed on the bottom-middle and back surfaces of Extrusion 41 (Figure 64) are believed related to sonic indications from the original billet.

The variation of extrusion dimensions versus extrusion length is shown in Figures 65 through 67. Excellent dimensional run-out, within 0.010 inch, was found for Extrusions 40 and 41. Some dimensions appeared to vary only 0.002 inch for the entire extrusion length, indicating very adequate die support and die coating performance.

2. Metallurgical Evaluation

For arc cast tungsten-3 percent molybdenum, typical transverse microstructures from the center location in the front, middle, and back of Extrusions 23 and 24 are shown in Figures 68 and 69.

An almost completely worked structure was observed in Extrusion 23, regardless of location. The transverse microstructures of Extrusion 24, shown in Figure 69, revealed considerably more recrystallization. The same billet heating temperature of 3200°F and reduction ratio of about 18:1 were used for both extrusions. In addition, the conditions of billet size, extrusion time, and lubrication practices were also similar. It should be noted, however, that Extrusion 23 was not completed, resulting in a 1-inch long discard in the liner. Extrusion 24 was completed by full ram travel, with only a small portion of the billet left in the die entry bell. This difference in extrusion response was probably more related to die design, which was flat-face (Figure 29) for Extrusion 23 and conical (Figure 27) for Extrusion 24. It is also possible that the difference in extrusion response and microstructure of the extrusions may be related to the original billet condition, which could vary depending upon the position in the ingot.

In the group of pressed and sintered tungsten-3 percent molybdenum extrusions, typical transverse microstructures from the center location in the front, middle, and back of extrusions are shown in Figures 70 and 71.

The microstructures, in general, consisted of very fine recrystallized grains. Some difference was observed in the structures from front to back, with the center structure showing a slightly larger grain size and more complete recrystallization. This result is believed related to higher temperature maintained in the center of the billet during extrusion. It is expected that a billet temperature below 3000°F would be required to realize a fully wrought structure in the extrusion of the program "T" shape.

Representative of the group of pressed and sintered unalloyed tungsten extrusions, transverse microstructures from Extrusion 41 are shown in Figure 72. The microstructures, in general, consisted of recrystallized grains (ASTM grain size 5 to 8). Little difference was observed in the structures, the front structure showing a slightly larger grain size. This difference was believed related to a lower billet temperature as the result of a delay for the back portion of the billet to reach the die.

Figure 73 shows the longitudinal microstructures of representative extrusions of all three materials. Although the duplex structure of the arc cast tungsten-3 percent molybdenum extrusions was more desired than the hot-worked structure of the other two materials, the surface quality of the arc cast tungsten-3 percent molybdenum extrusions was inferior to that of the others. The grain size of the sintered unalloyed tungsten extrusions was coarser than that of the sintered tungsten-3 percent molybdenum extrusions. This was believed due to the fact that molybdenum is an effective grain-refinement element which also increases the recrystallization temperature. However, the sintered tungsten-3 percent molybdenum extrusions, Extrusions 22 and 35, showed bands which at high magnification revealed wrought structure. These bands probably were areas of high molybdenum concentration as a result of incomplete homogenization during sintering.

Hardness measurements in terms of Rockwell C for selected extrusions are given in Table 20. Each extrusion was given a stress relief heat treatment at 1800°F for forty-five minutes prior to evaluation of hardness characteristics. Hardness values were taken at ten different locations on each transverse section of a specimen; each specimen was taken at the front, middle, and back of the extrusion, respectively. The microhardness survey for selected extrusions in terms of Diamond Pyramid Hardness (DPH) were taken in the same method as above, except DPH values were taken at fourteen different locations instead of ten on each transverse section. They are shown in Table 21.

The average hardness values for pressed and sintered tungsten-3 percent molybdenum, ranging from Rockwell C 39.5 to 44.0, or DPH 383 to 406, were generally lower than that of arc cast tungsten-3 percent molybdenum, which ranged from Rockwell C 40.3 to 44.4, or DPH 385 to 441. This reflects the fact that the former material had a hot-worked microstructure, whereas the latter revealed a duplex microstructure. Pressed and sintered tungsten showed even lower hardness values (DPH 368 to 377), characteristic of recrystallized tungsten. In each extrusion, hardness values were generally lower in the center than on the ends; these also reflected the microstructures of the extrusion at different locations. Both arc cast and pressed and sintered tungsten-3 percent molybdenum showed a larger grain size at the middle than at either end of the extrusion.

3. Heat Treatment Studies and Mechanical Properties

Some heat treatment and mechanical property studies were conducted for one of the pressed and sintered tungsten-3 percent molybdenum extrusions.

Transverse sections from the back portion of Extrusion 35 were used to study changes in microstructure and hardness after heat treatment at 1800°F and 2400°F. The results of this study are given in Figure 74. Considerable grain growth occurred after one hour at 2400°F; accordingly, the DPH hardness of 416 (10 kilogram load) for this heat treatment indicated some drop from a hardness of 431 DPH for one hour heat treatment at 1800°F.

Extrusion 35 was also evaluated in terms of tensile and bend properties. The extrusion, prior to cutting into specimen blanks, was given a stress relief at 1800°F for forty-five minutes. Specimens for bend testing were obtained from the transverse direction only. All specimens were prepared by grinding with an alumina wheel (Norton 38A-46H) at a surface speed of 3,500 feet per minute. Each specimen was 0.090 inch thick by 1/2 inch wide and 2 inches long. The center of the specimens coincided with the center of the original "T"-shaped section. Dye check and visual examination at twenty magnifications were performed prior to testing.

Bend tests were made with a deflection speed of 5 inches per minute and plunger radius of 0.200 inch into a 90-degree die seat. This is, in effect, a 2.2T bend. The results of these tests are shown in Figure 75. The transverse transition temperature is higher than 1550°F, but lower than 1575°F.

Tensile specimens were prepared to dimensions shown in Figure 76. Each specimen was prepared by grinding under oil with an alumina wheel (Norton 32A-60L7VG) at surface speeds of 3,000 surface feet per minute. Specimens were also rotated during grinding at a speed of 300 revolutions per minute. Tensile test results are summarized in Table 22.

Room temperature tensile tests were conducted at the Allegheny Ludlum Research Center. No data were obtained at the lowest possible strain rate of 0.002 inch per inch per minute. Specimens failed during loading.

Elevated temperature tensile tests in vacuum were made at the Hyda Laboratories, Inc. Specimens were given a stress relief heat treatment of one hour at 2400°F in vacuum prior to preparation by grinding. No heat treatment was given prior to testing in vacuum. Tensile tests were made with a strain rate of 0.002 inch per inch per minute in the elastic range, and 0.02 inch per inch per minute in the plastic range.

It is evident from the high bend transition temperature and relatively low tensile properties obtained in the extruded product that the high extrusion temperatures dictated by the program goals were not compatible with attainment of good mechanical properties.

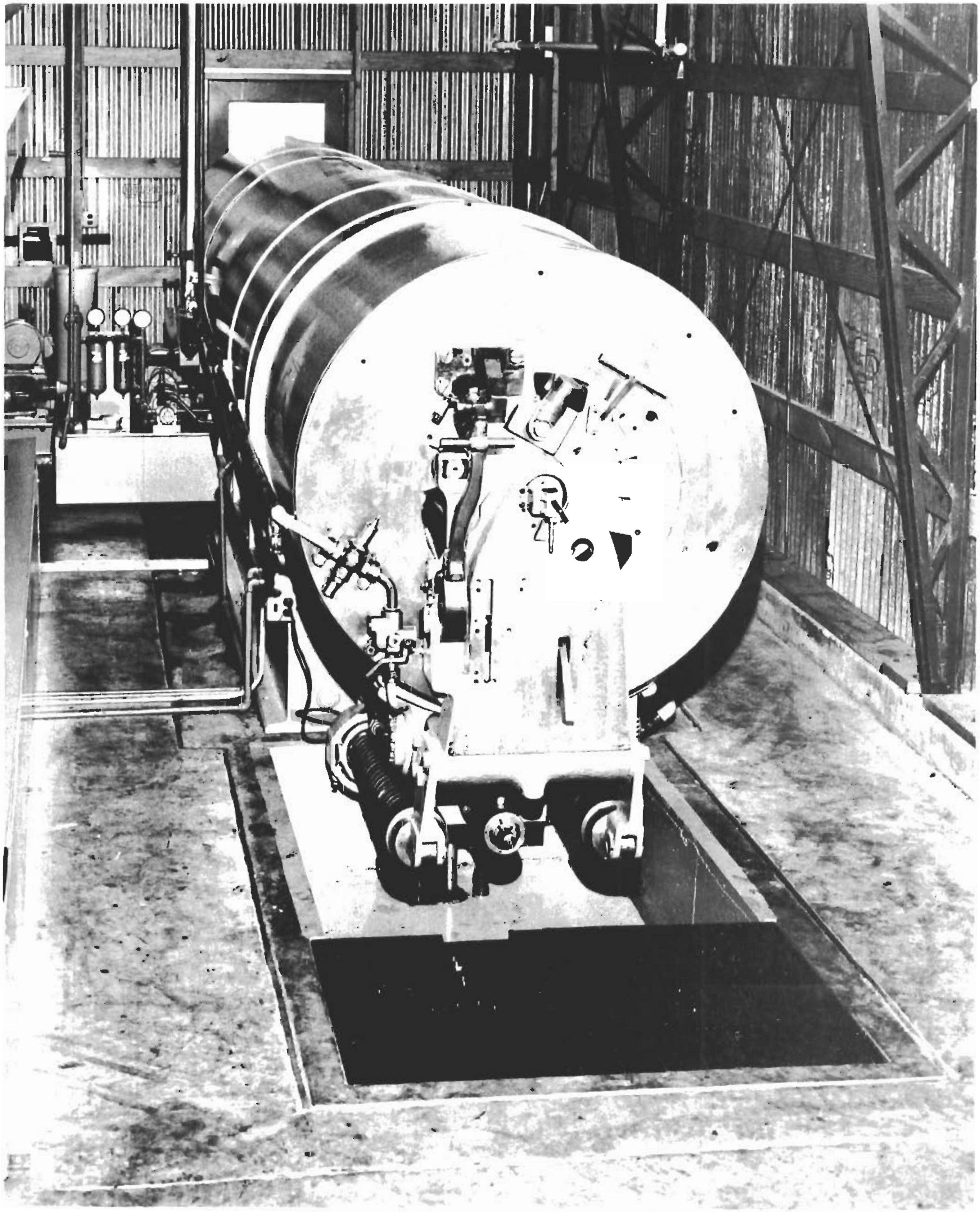


Figure 1. Sixteen-Inch Naval Gun for Isostatic Compacting at 40,000 psi

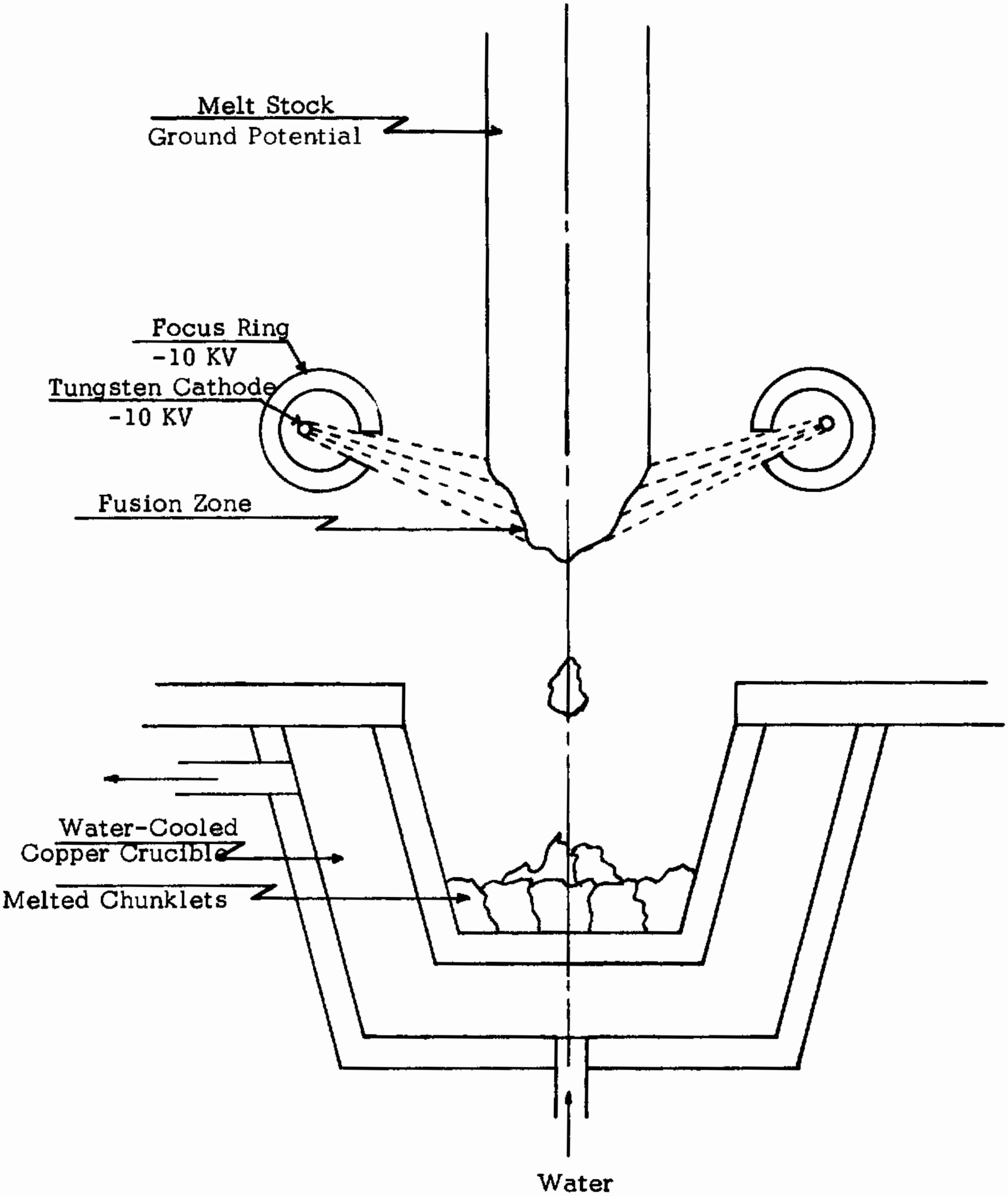
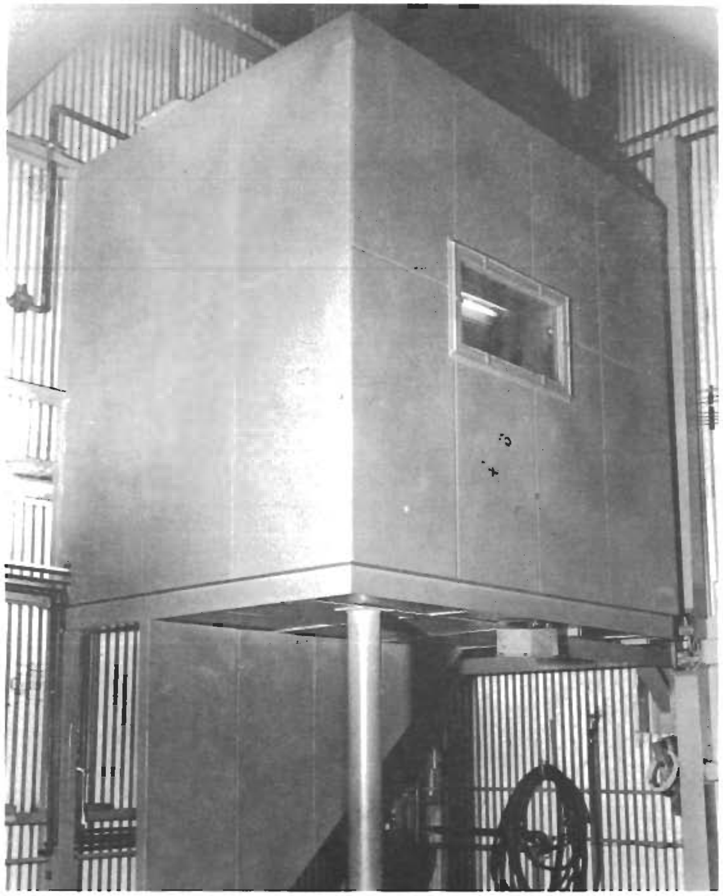
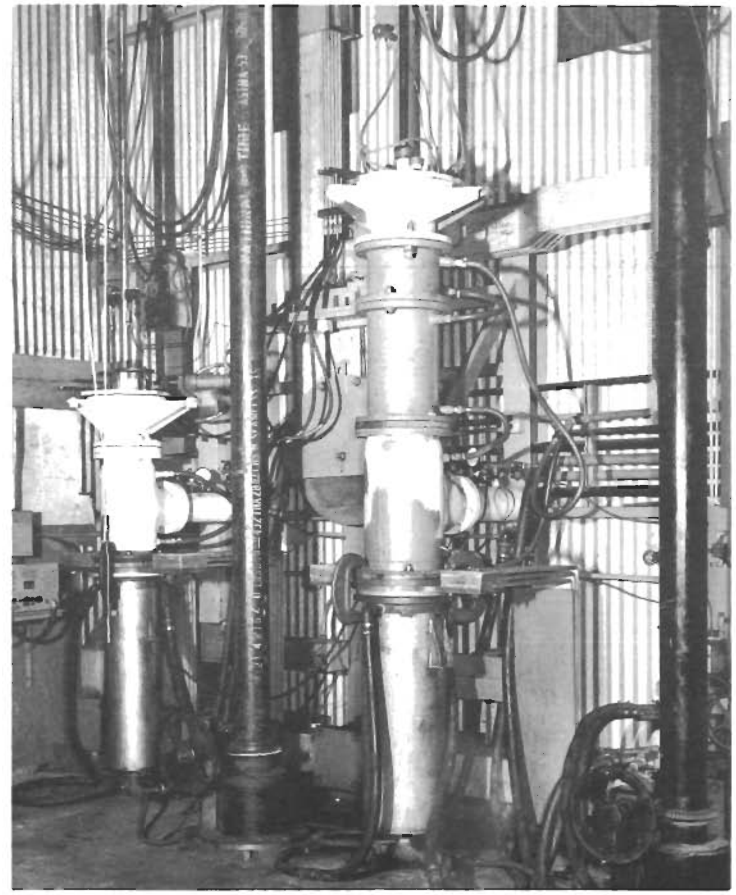


Figure 2. Schematic Diagram of Electron Beam Drip-Melting Operation



a. Explosion-Proof Control Room



b. Bottom Tap 8-Inch Diameter Arc Furnaces

Figure 3. Views Showing Facilities Developed for Arc Melting of Tantalum and Tungsten Alloy Ingots from 2-7/8 Inches to 8 Inches in Diameter by a Maximum Height of 27 Inches with Maximum Electrode Length of 90 Inches

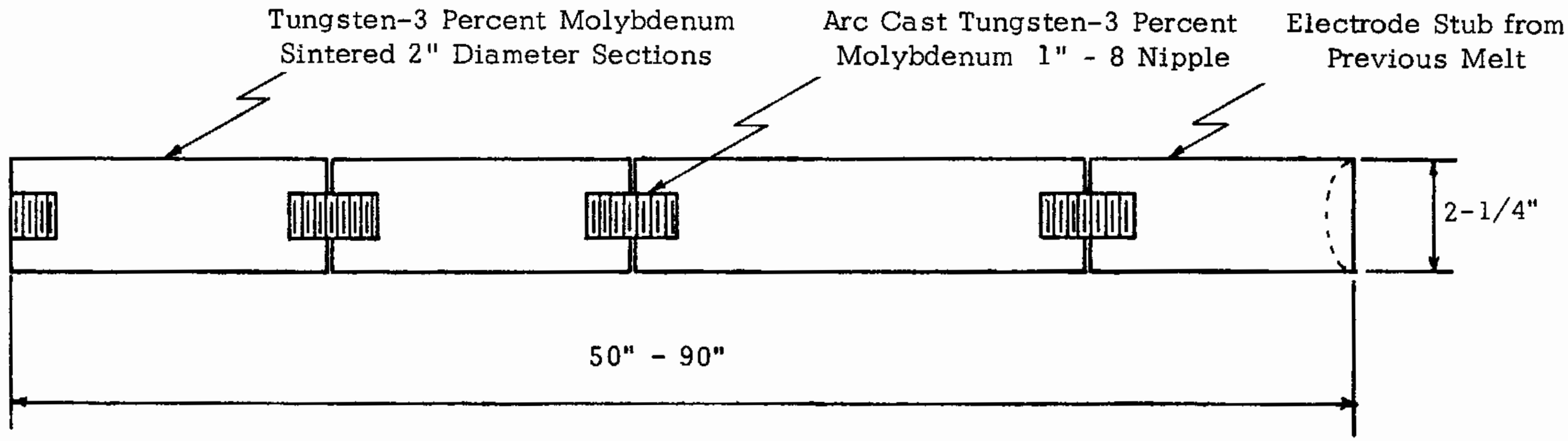


Figure 4. Mechanical Joining for Obtaining 100- to 500-Pound Tungsten Electrodes

Figure 5. Side View of 6.55-Inch Billet Extruded to 4 Inches with Split Iron Can - Extrusion 434

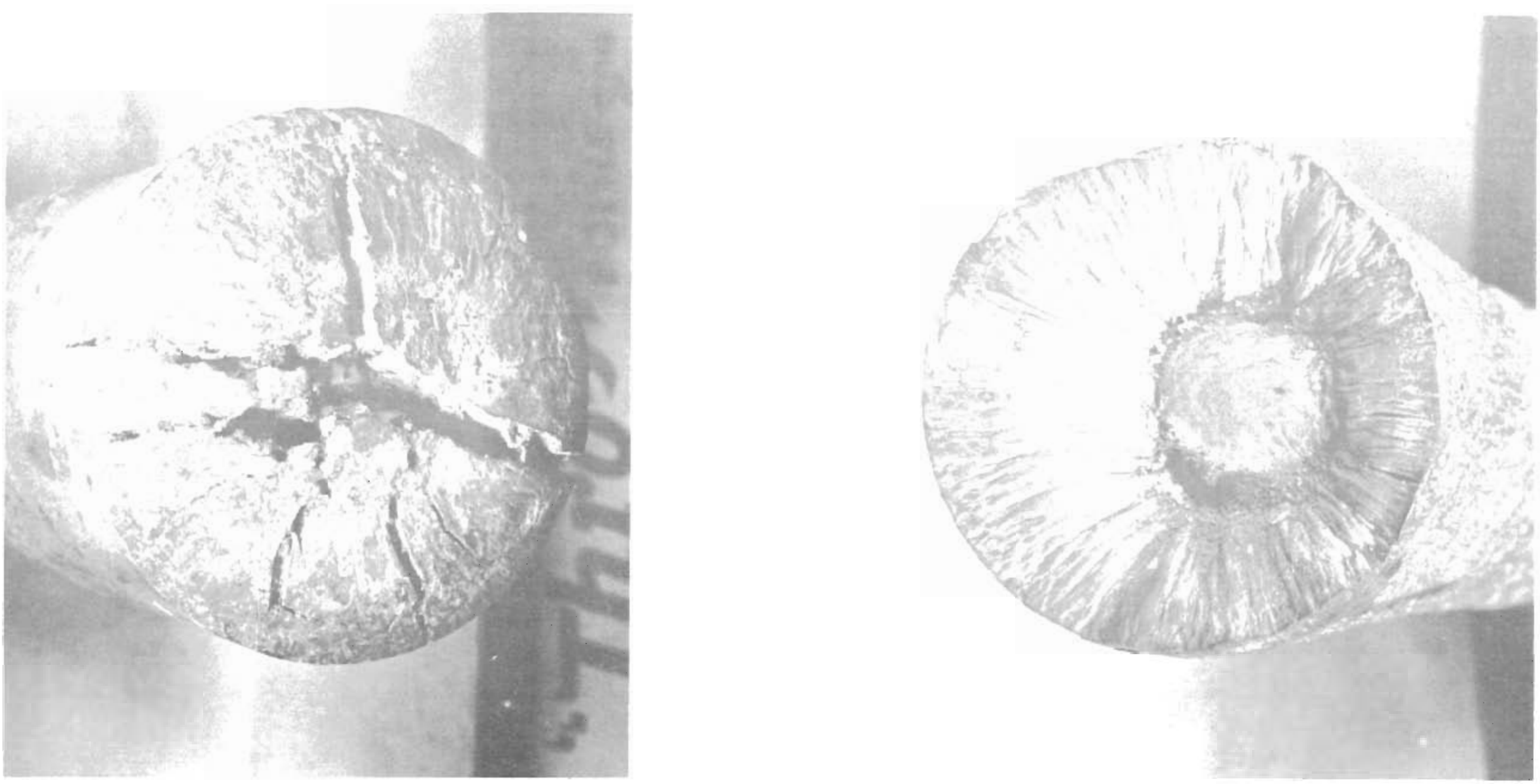


Figure 6. Nose and Tail Views of Extrusion 434

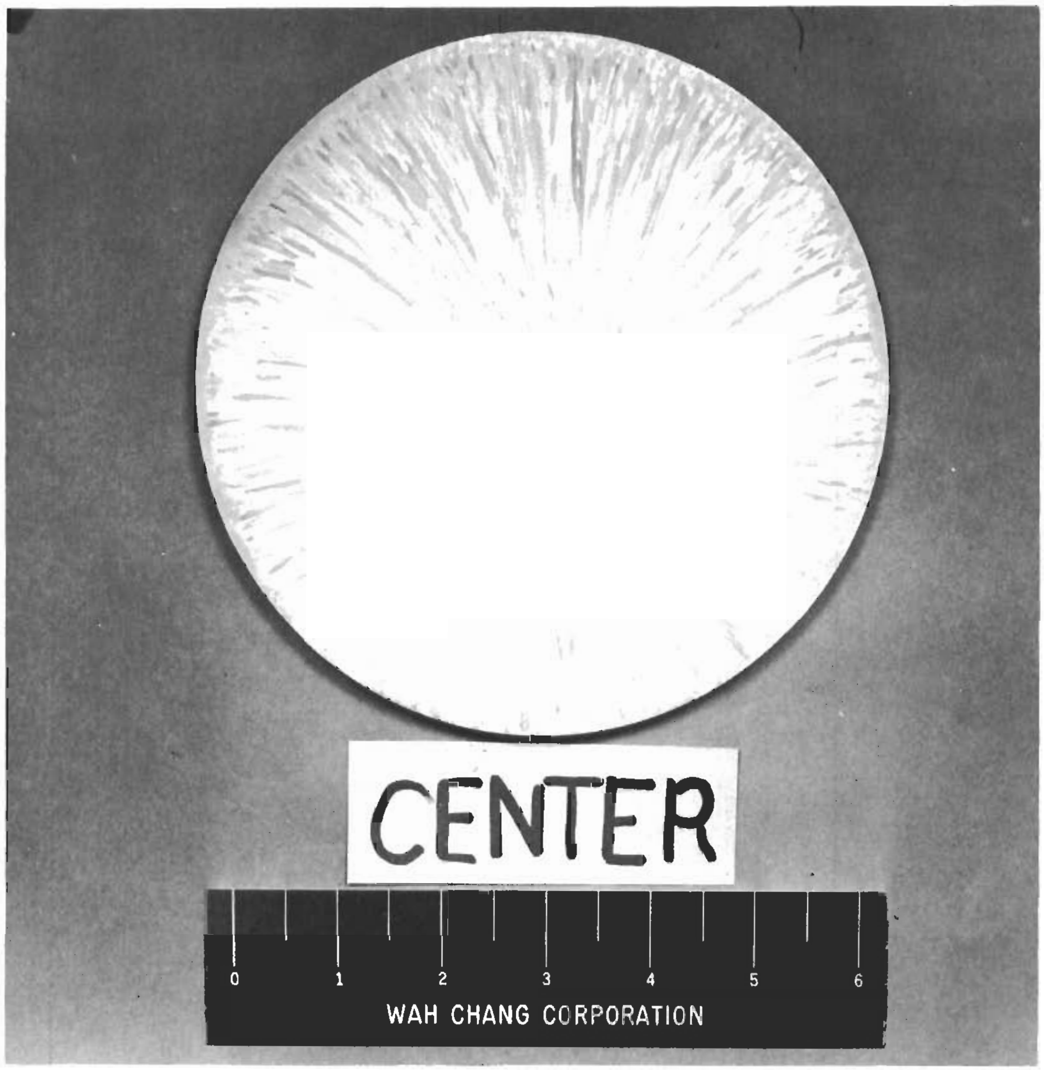


Figure 7. Center Ingot Slice from Tungsten-3 Percent Molybdenum 6.55-Inch Ingot Supplied by Climax Molybdenum

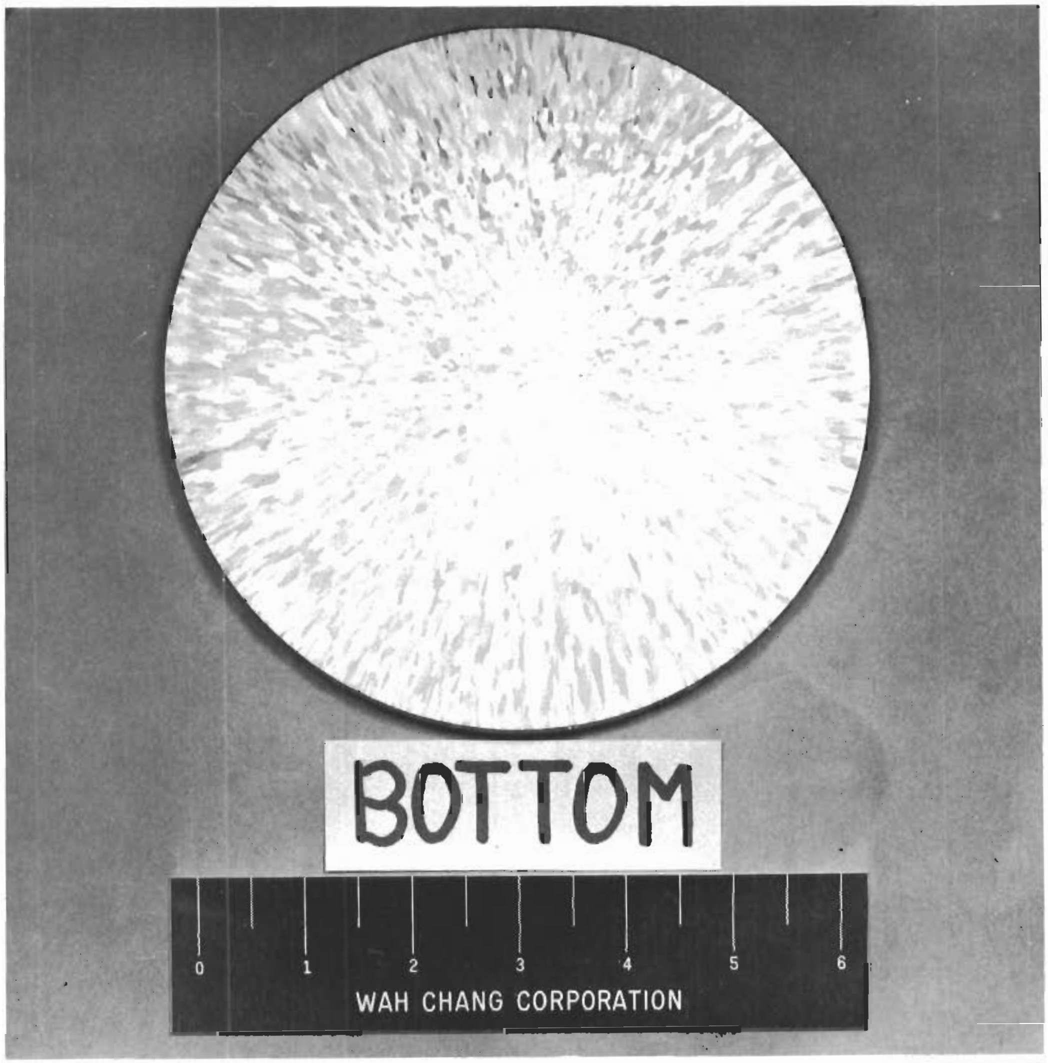
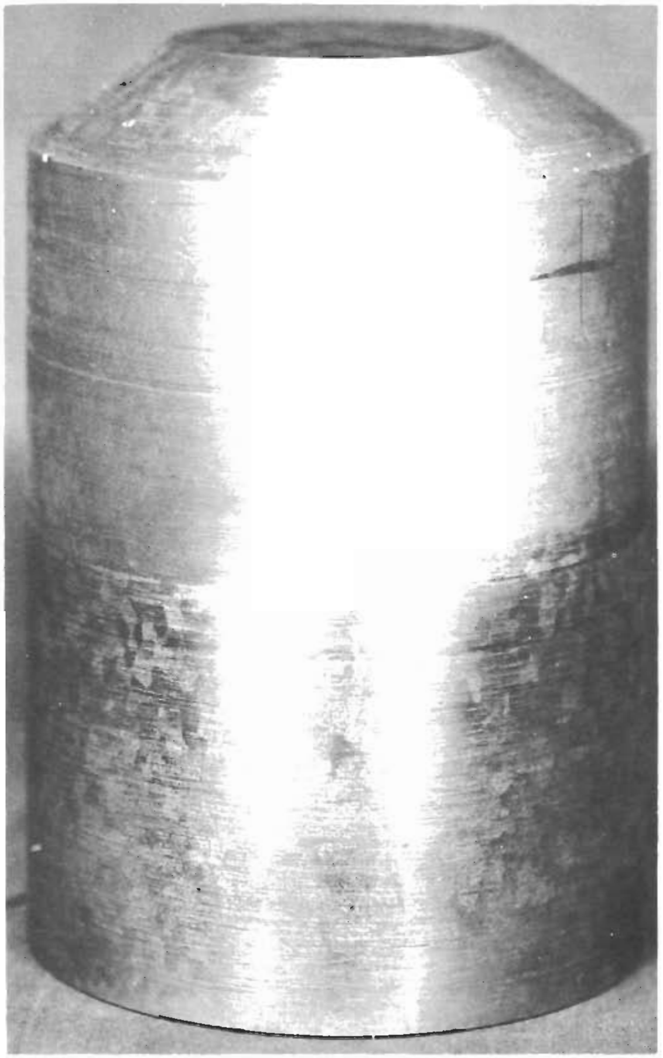
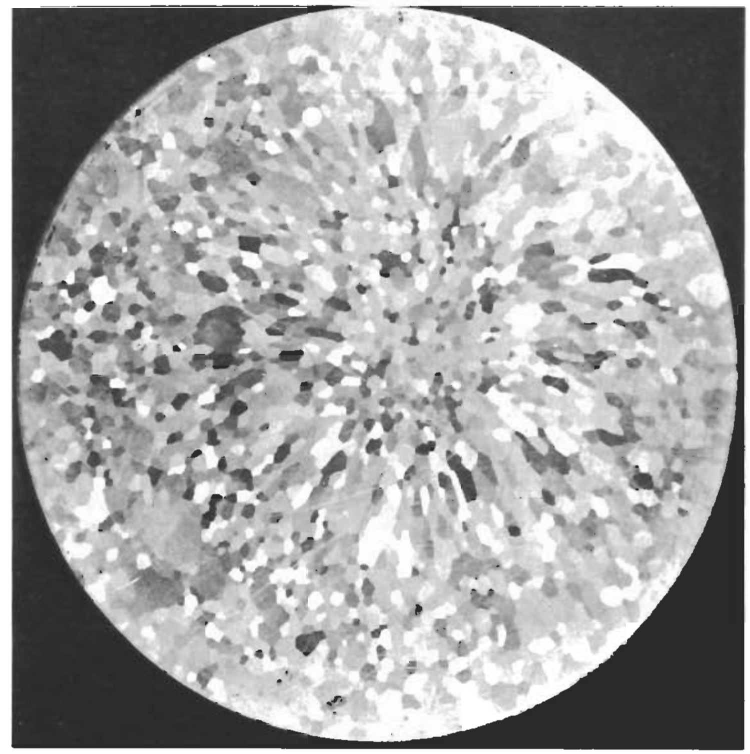


Figure 8. Bottom Ingot Slice from Tungsten-3 Percent Molybdenum 6.55-Inch Ingot Supplied by Climax Molybdenum





Bottom Mag. 1X Approx.

Etchant: 70% HNO_3 + 30% HF

Mag. 1X Approx.

Figure 9. Surface and Macrostructure of As-Received Extrusion Billet from Heat AF-3694

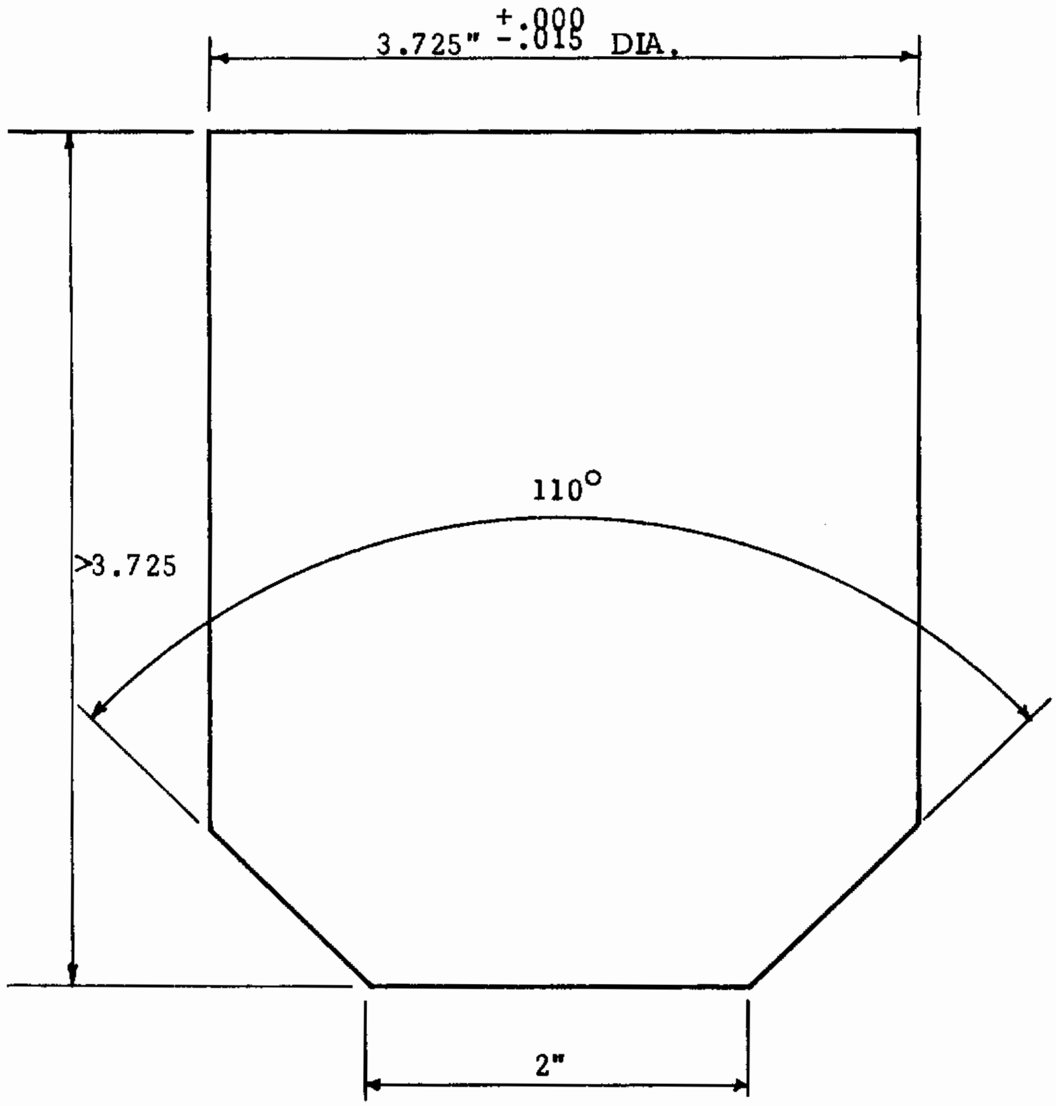


Figure 10. Dimensional Sketch of Extrusion Billet

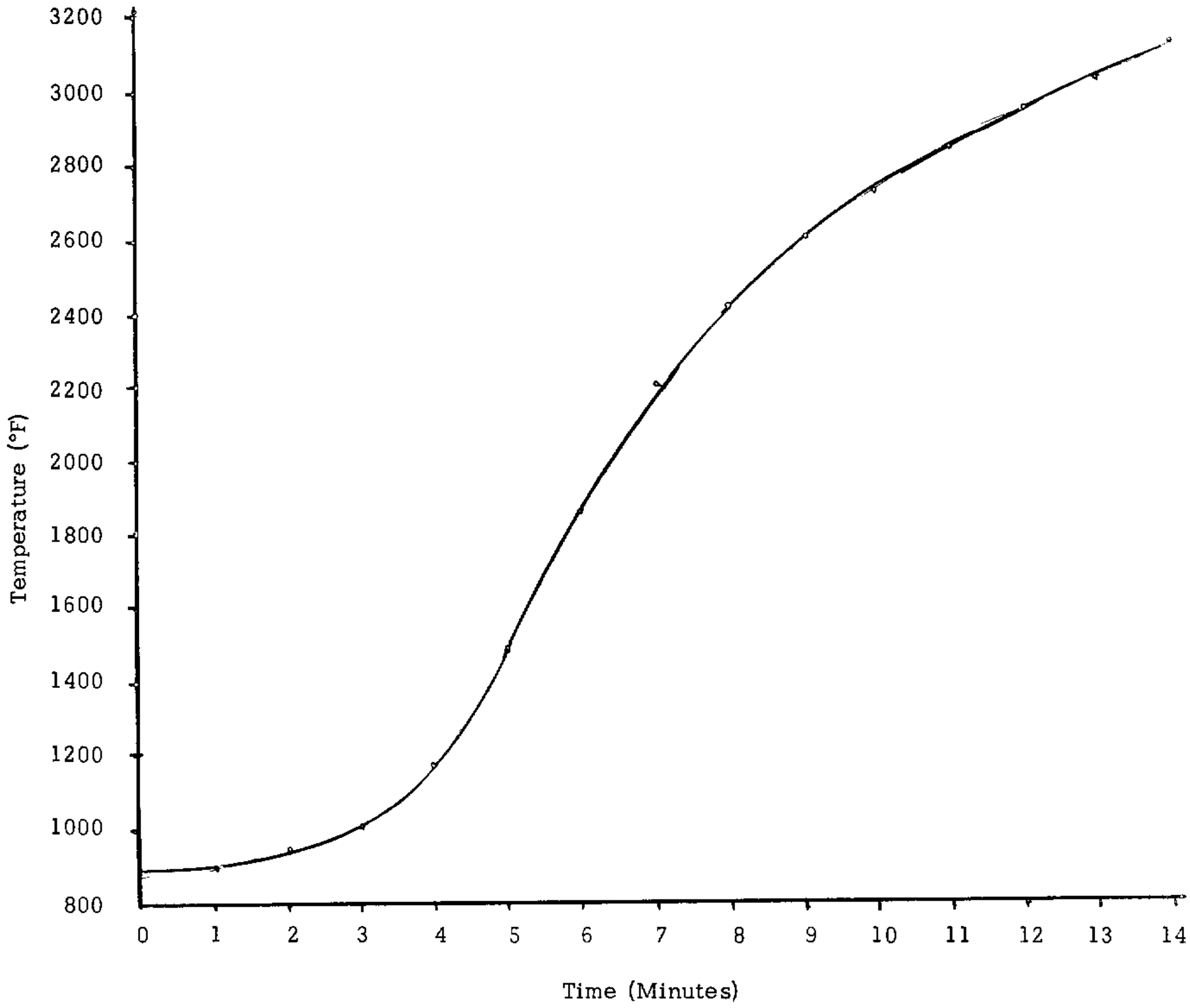


Figure 11. Temperature Versus Time for Tungsten-3 Percent Molybdenum Extrusion Billet W16

Part No.	Open Dim.	Dim. Y
E	1.165*	.744
D	1.040	.773
C	.955	.792
B	.970	.789

* OPEN DIMENSION OVER SIZE TO ALLOW FOR .020 INCH COATING

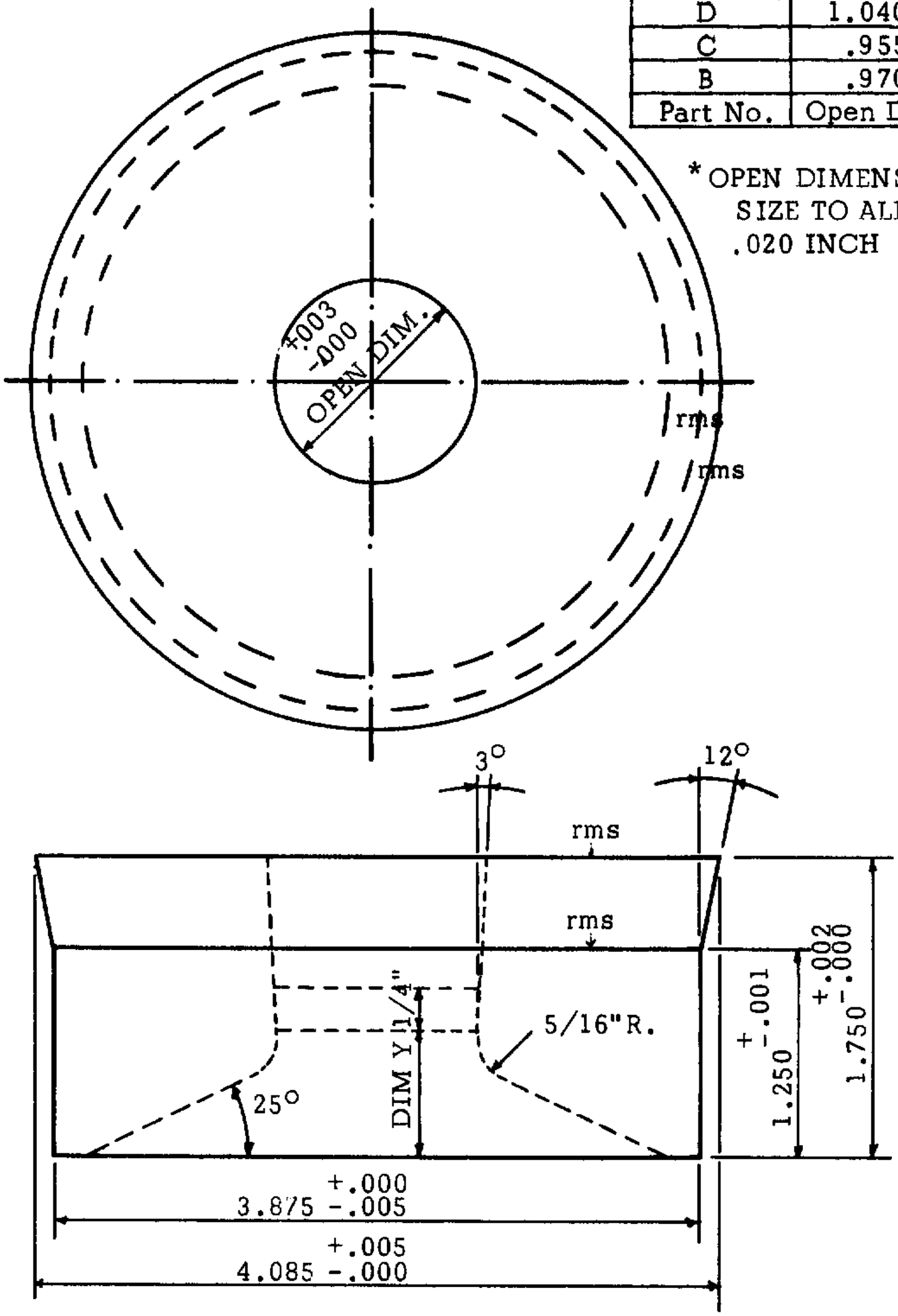


Figure 12. Extrusion Die Design for Solid Rounds

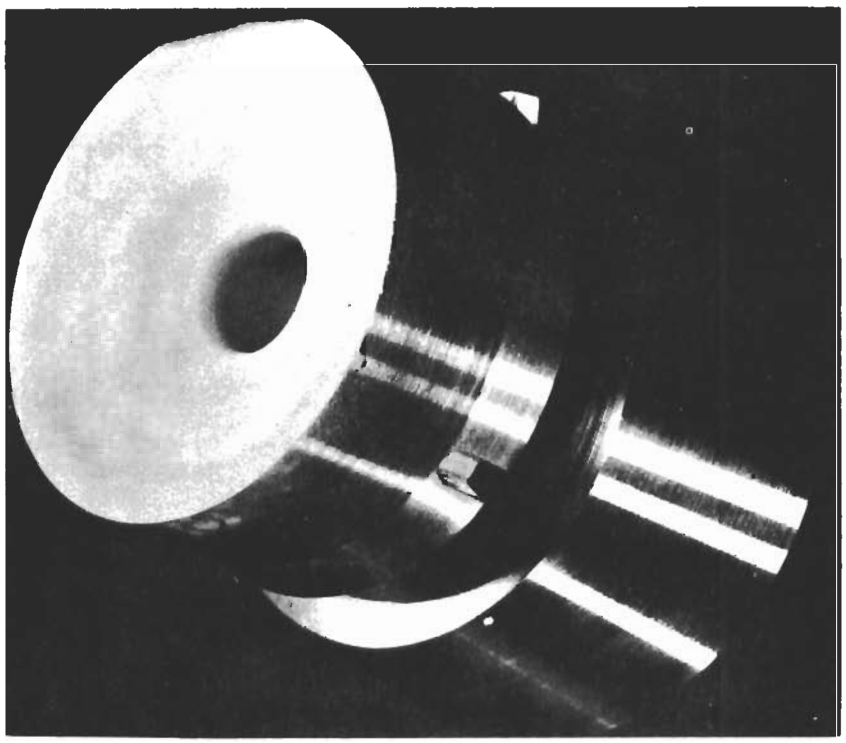


Figure 13. As-Coated Die and Spacer

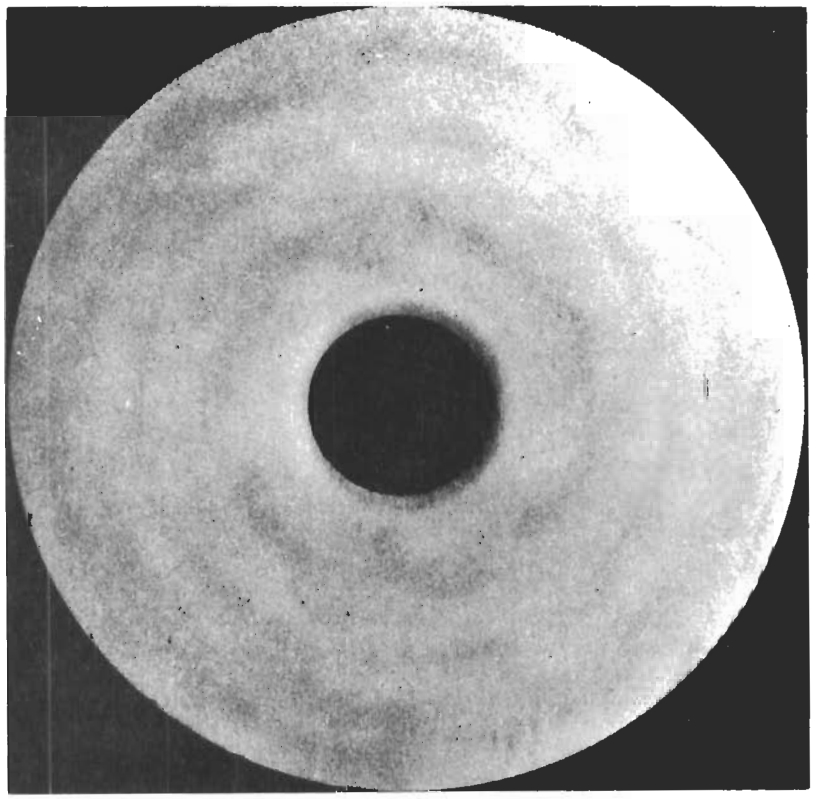
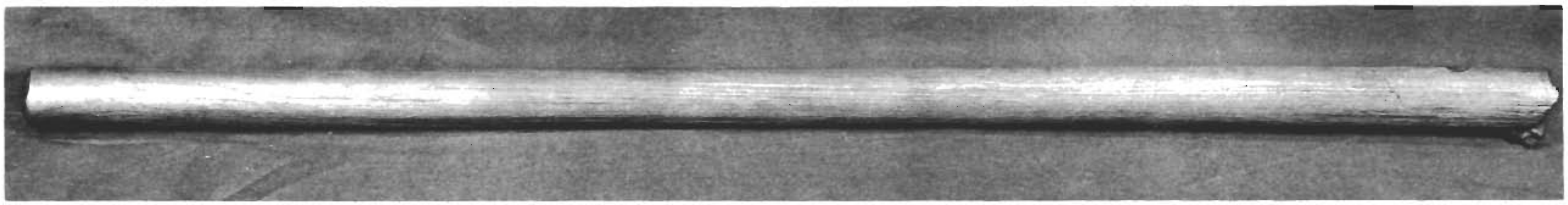


Figure 14. Linde Plasma Arc Sprayed Extrusion Die with Zirconia



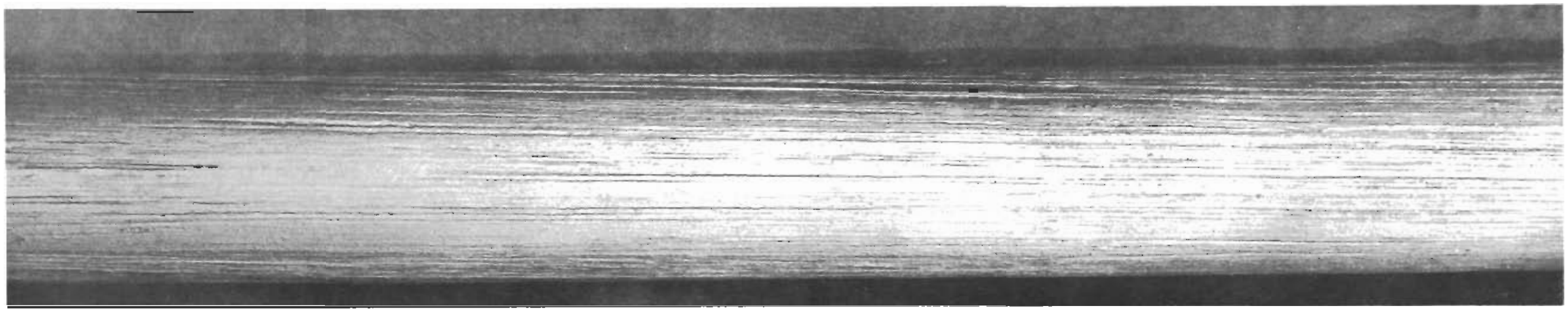
Nose

Mag. 1/4X

Extrusion 1

Billet Code W1
Billet Heating Temperature 4000°F
Reduction Ratio 11.6:1

Figure 15. Tungsten-3 Percent Molybdenum Extrusion from Heat AF-3814-A



Sandblasted | Mag. 1X

Extrusion 1

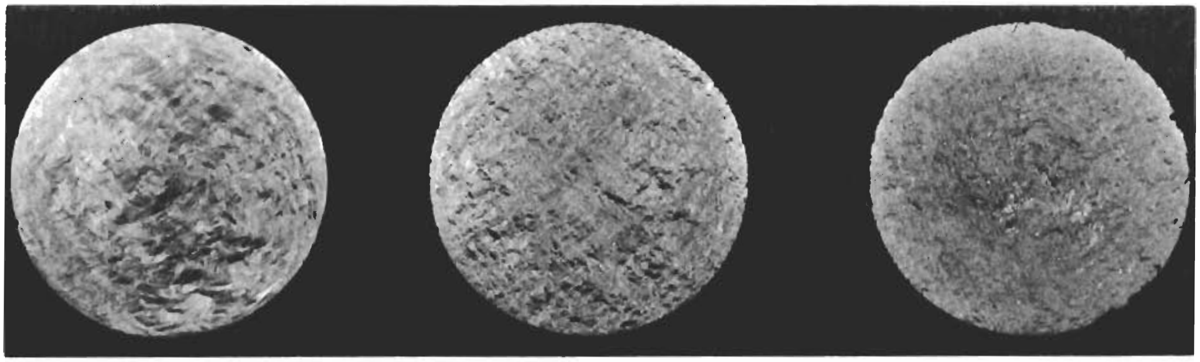
Billet Code W1
Billet Heating Temperature 4000°F
Reduction Ratio 11.6:1

Sandblasted | Mag. 1X

Extrusion 2

Billet Code W2
Billet Heating Temperature 4000°F
Reduction Ratio 16.9:1

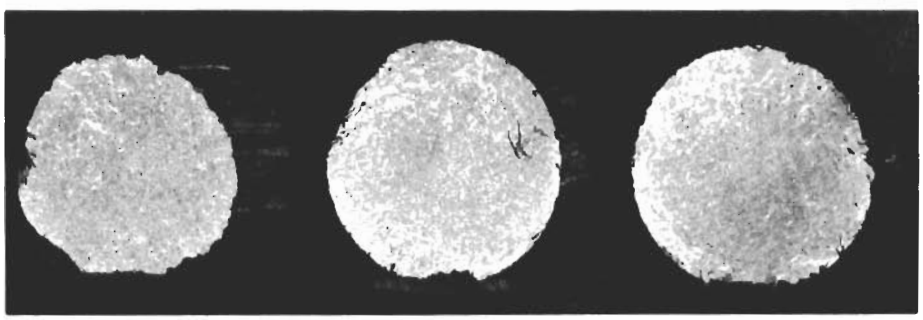
Figure 16. Surface Appearance of Tungsten-3 Percent Molybdenum Extrusions from Heat AF-3814



Front Middle Back

Extrusion 1

Billet Code W1
Billet Heating Temperature 4000°F
Reduction Ratio 11.6:1

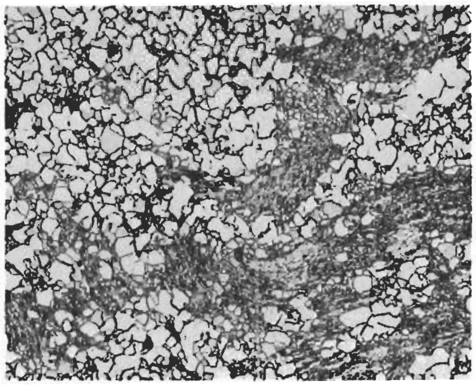


Front Middle Back

Extrusion 2

Billet Code W2
Billet Heating Temperature 4000°F
Reduction Ratio 16.9:1

Figure 17. Transverse Macrostructures of Front, Middle, and Back of Tungsten-3 Percent Molybdenum Round Extrusions 1 and 2 (Magnification: approximately 1-1/2X)

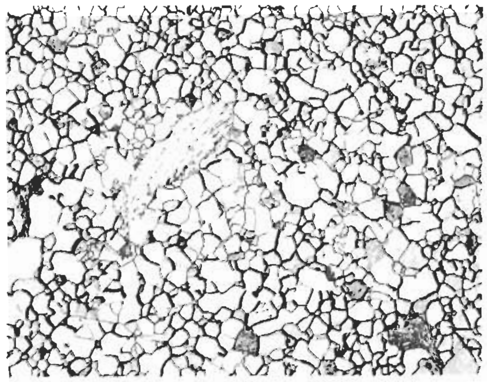


Extrusion 1

Billet Code W1
Billet Heating Temperature 4000°F
Reduction Ratio 11.6:1

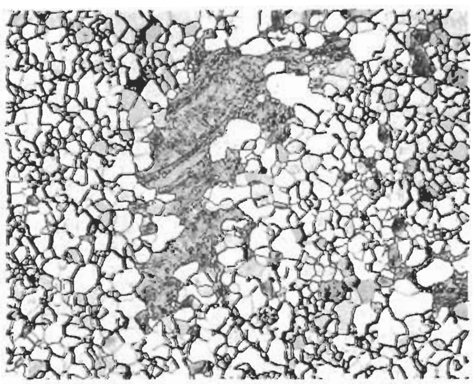
Extrusion 2

Billet Code W2
Billet Heating Temperature 4000°F
Reduction Ratio 16.9:1



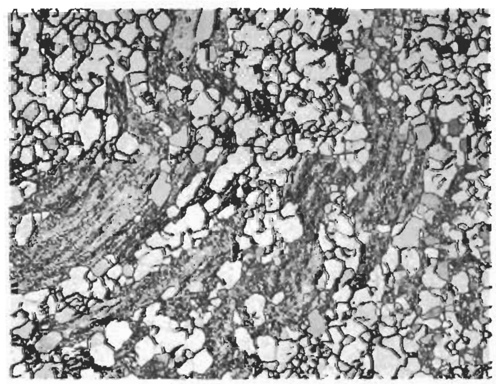
Extrusion 3

Billet Code W3
Billet Heating Temperature 3500°F
Reduction Ratio 17.1:1



Extrusion 4

Billet Code W4
Billet Heating Temperature 4000°F
Reduction Ratio 16.9:1



Extrusion 5

Billet Code W5
Billet Heating Temperature 3200°F
Reduction Ratio 12.9:1

Figure 18. Transverse Macrostructures at Center of Tungsten-3 Percent Molybdenum Round Extrusions (Magnification Before Reproduction 150X)

DW1

DW2

Die Code	Extrusion	Billet Heating Temperature (°F)	Die I.D. Before Extrusion (Inches)	Die I.D. After Extrusion (Inches)
DW1	1	4000	1.140	1.149-1.150
DW2	2	4000	0.944	1.058-1.102

Figure 19. Die Appearance After Extrusion of Tungsten-3 Percent Molybdenum Alloy

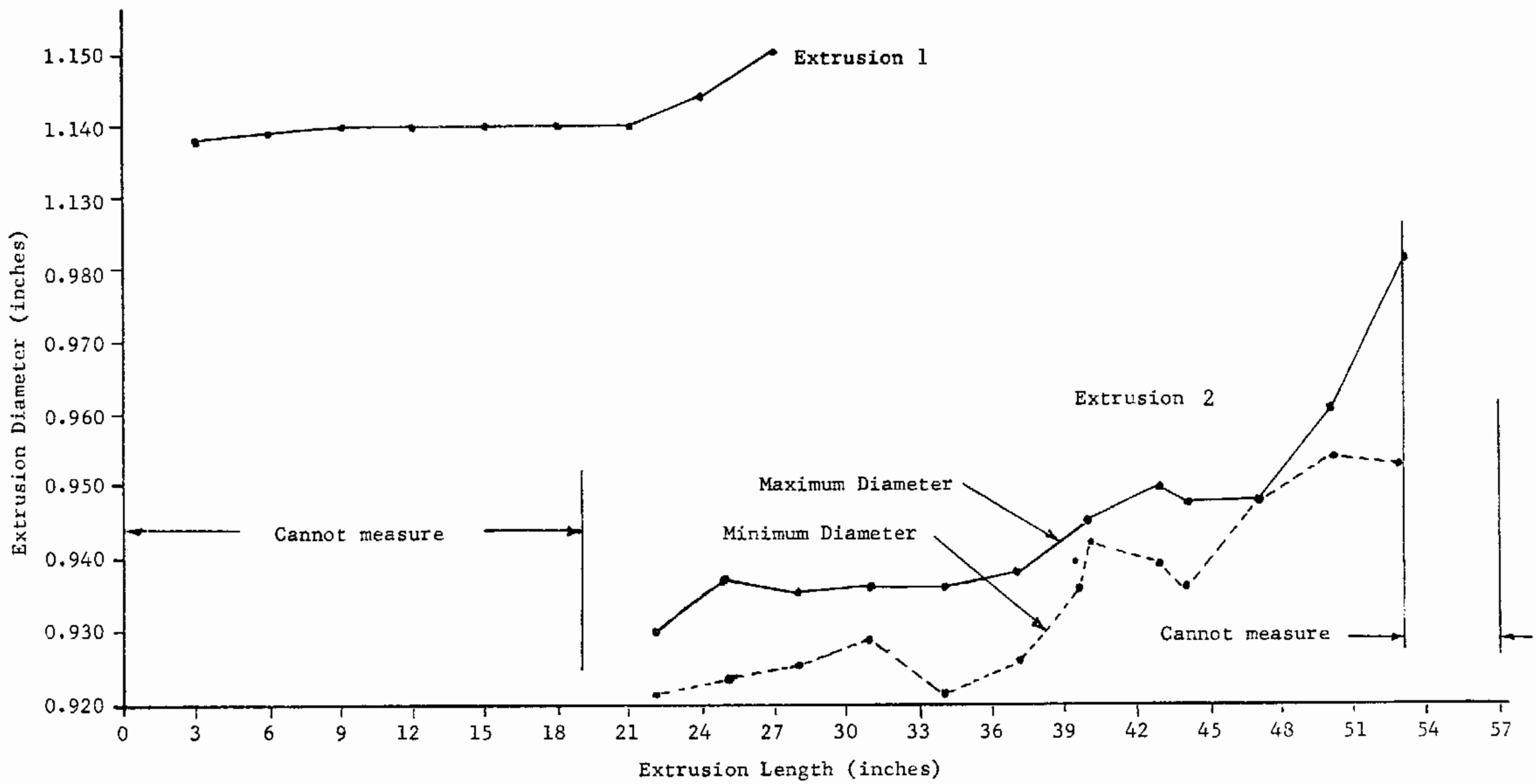


Figure 20. Extrusion Diameter Versus Extrusion Length for Extruded Solid Rounds of Tungsten-3 Percent Molybdenum

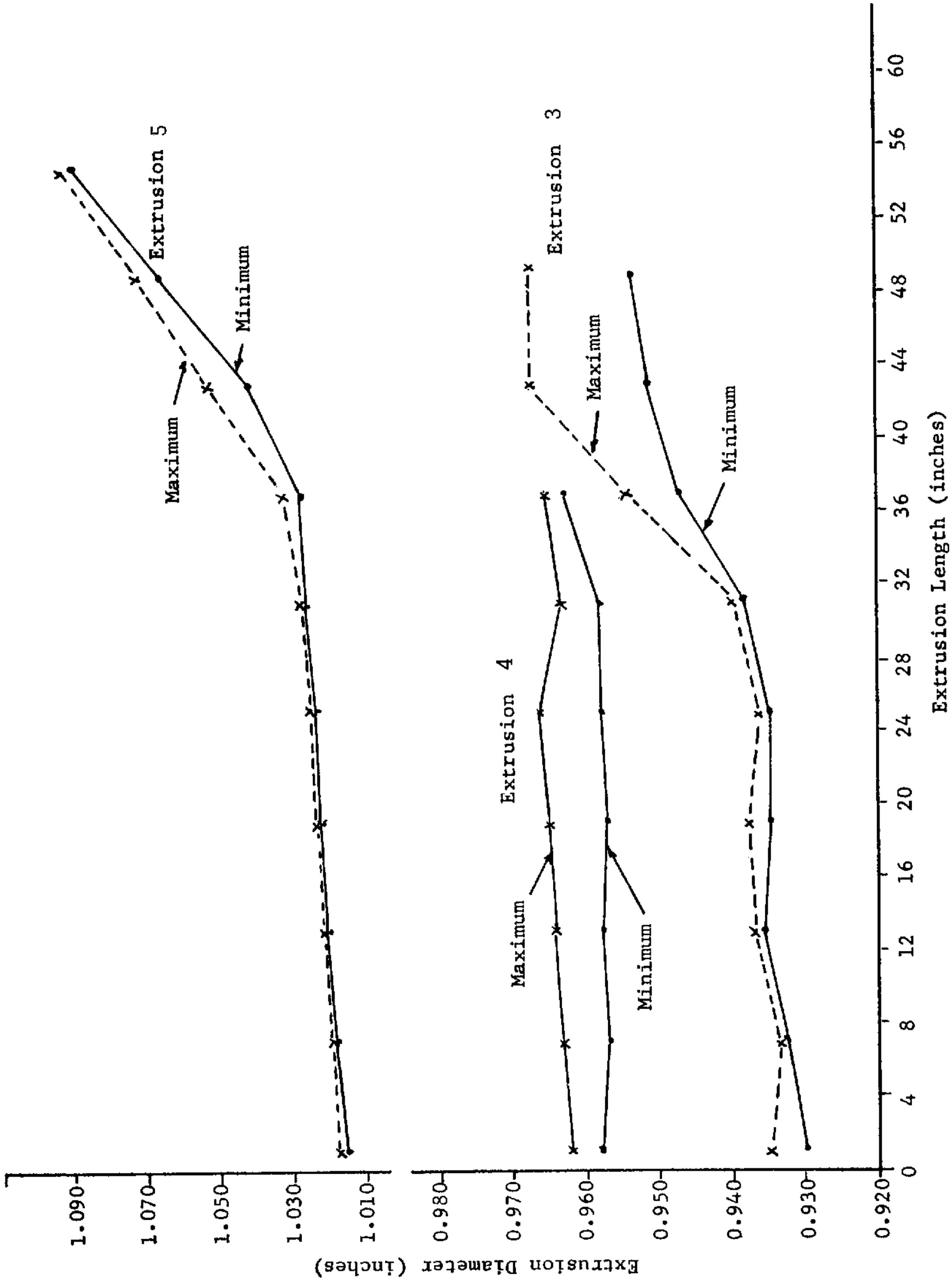


Figure 21. Extrusion Diameter Versus Extrusion Length for Extrusions 3, 4, and 5

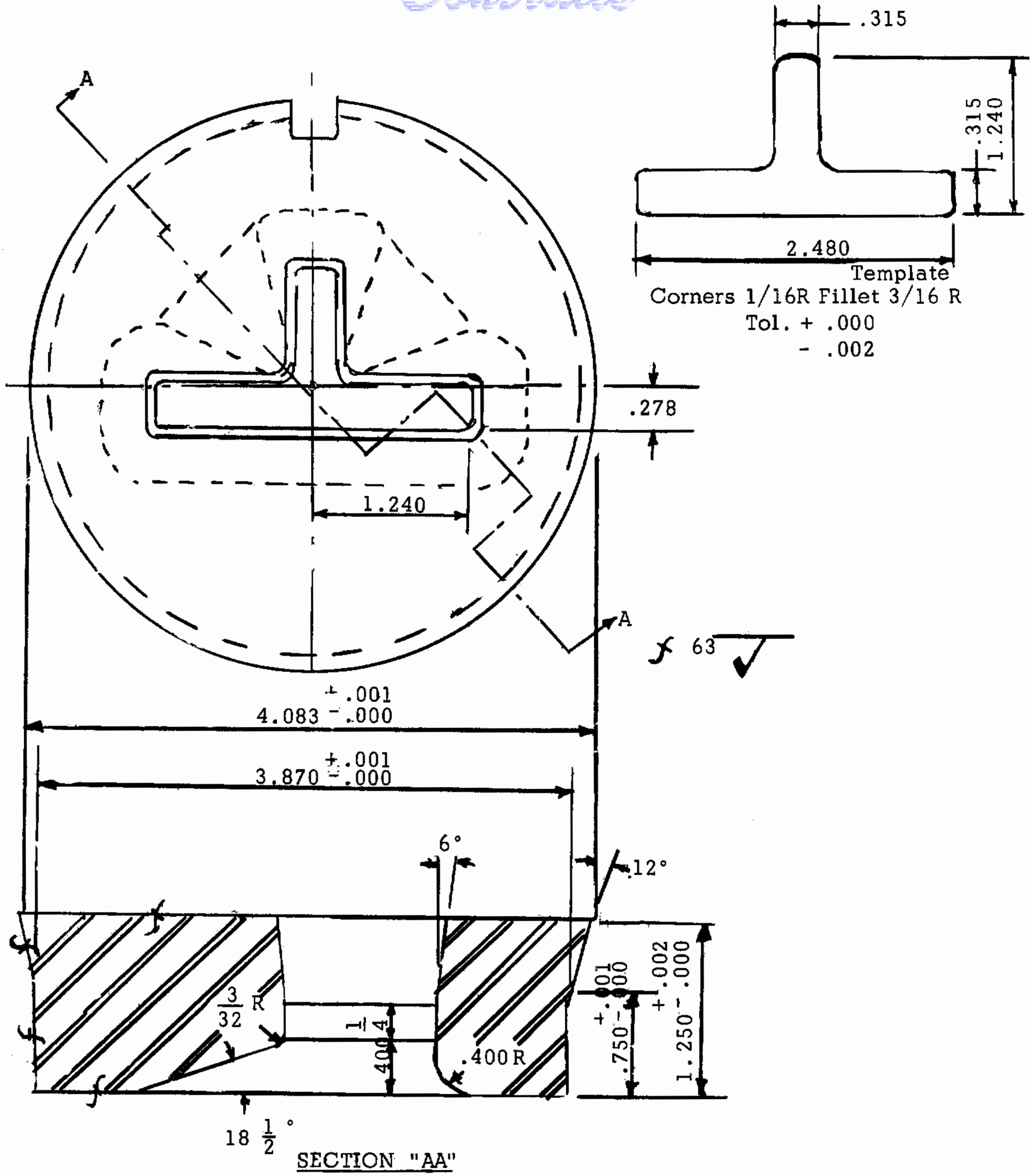


Figure 22. Modified Flat-Face Die Design for Die Codes DW11, DW12, and DW13

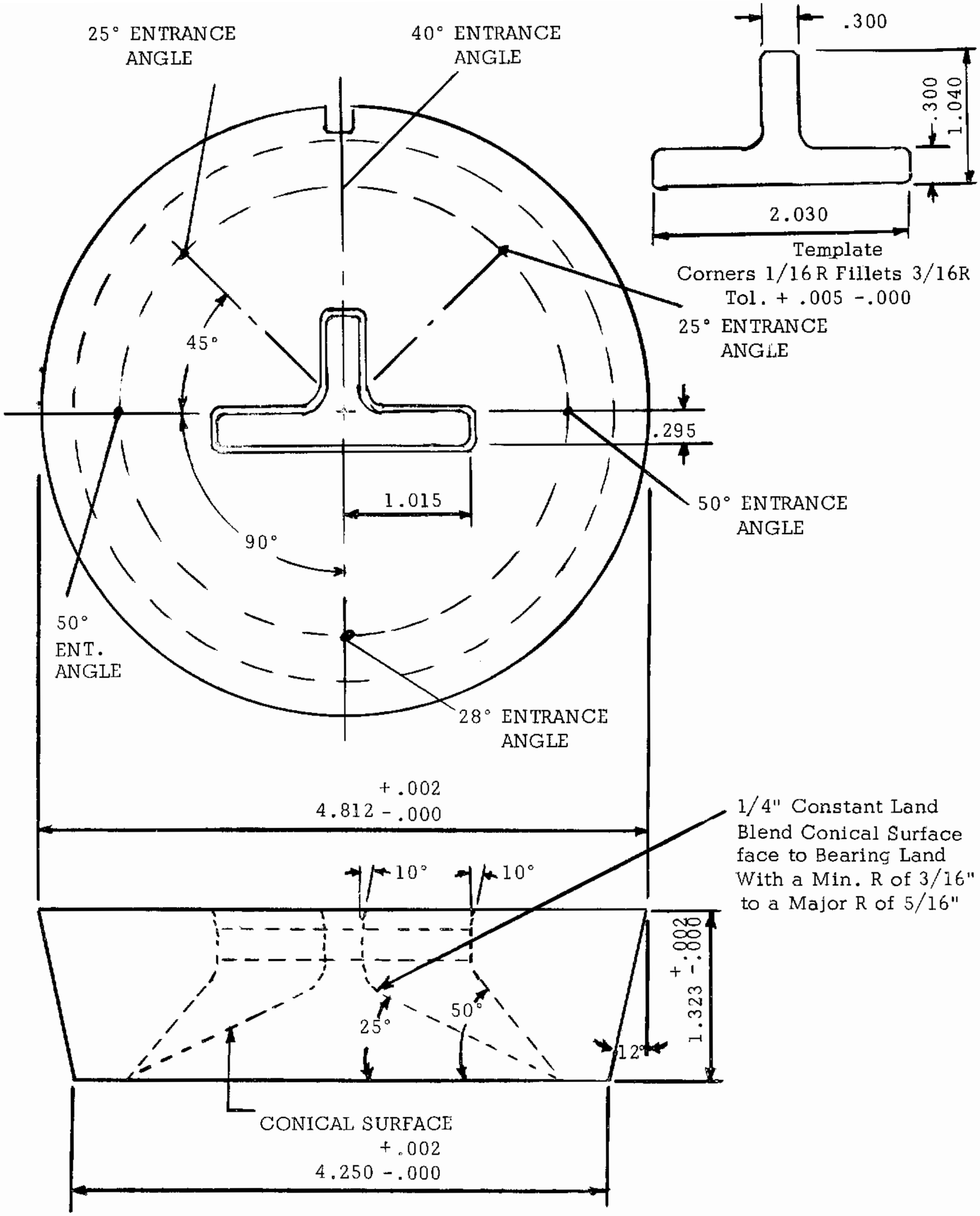


Figure 23. Conical Die Design for Die Codes DW14, DW15, DW16, DW17, and DW18

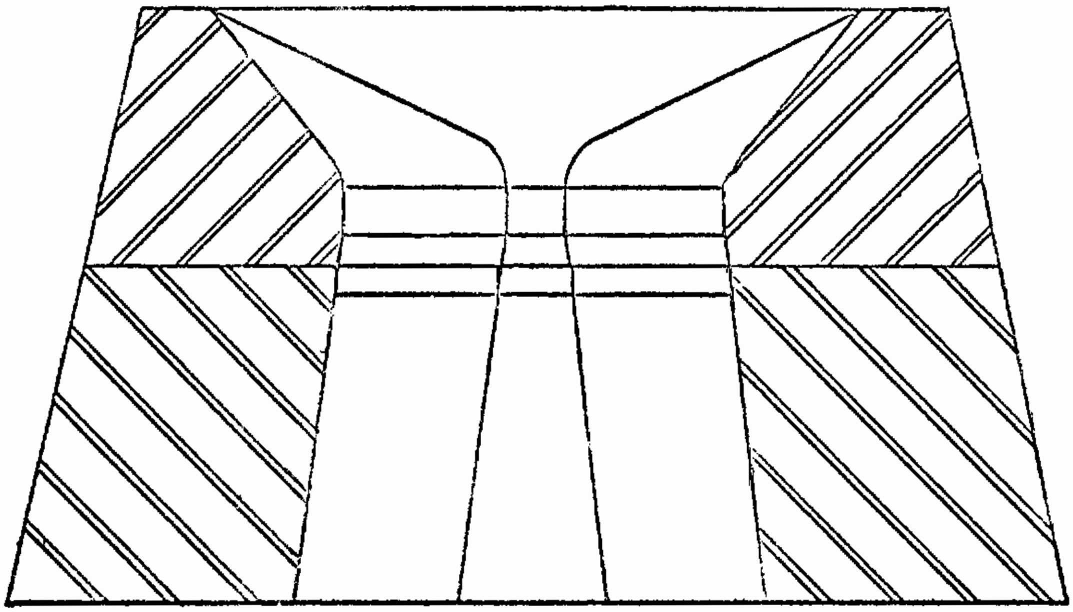


Figure 24. Full-Taper O.D. Design with Short Exit Relief Angle and Zero Spacer Clearance

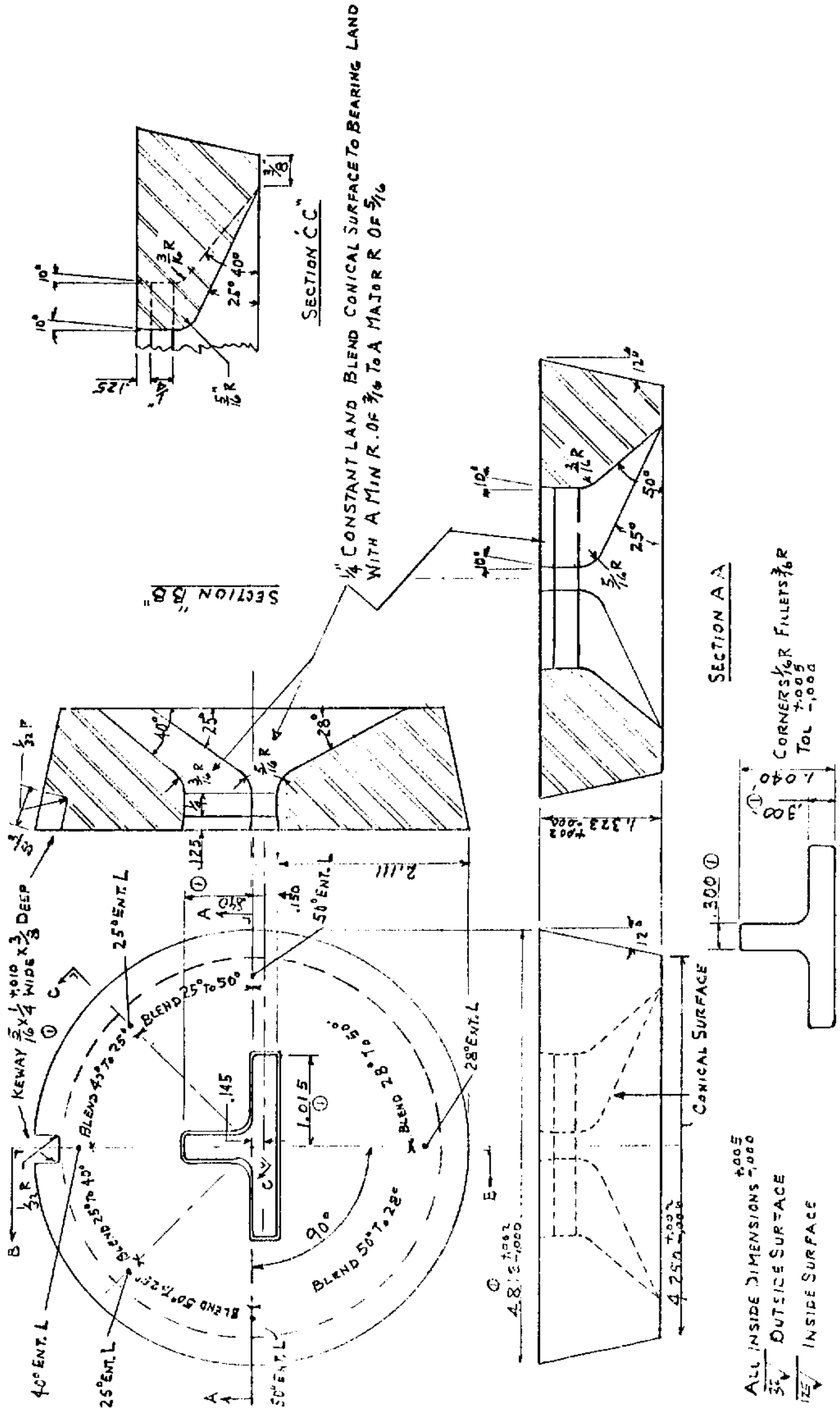


Figure 25. Die Design B-0442

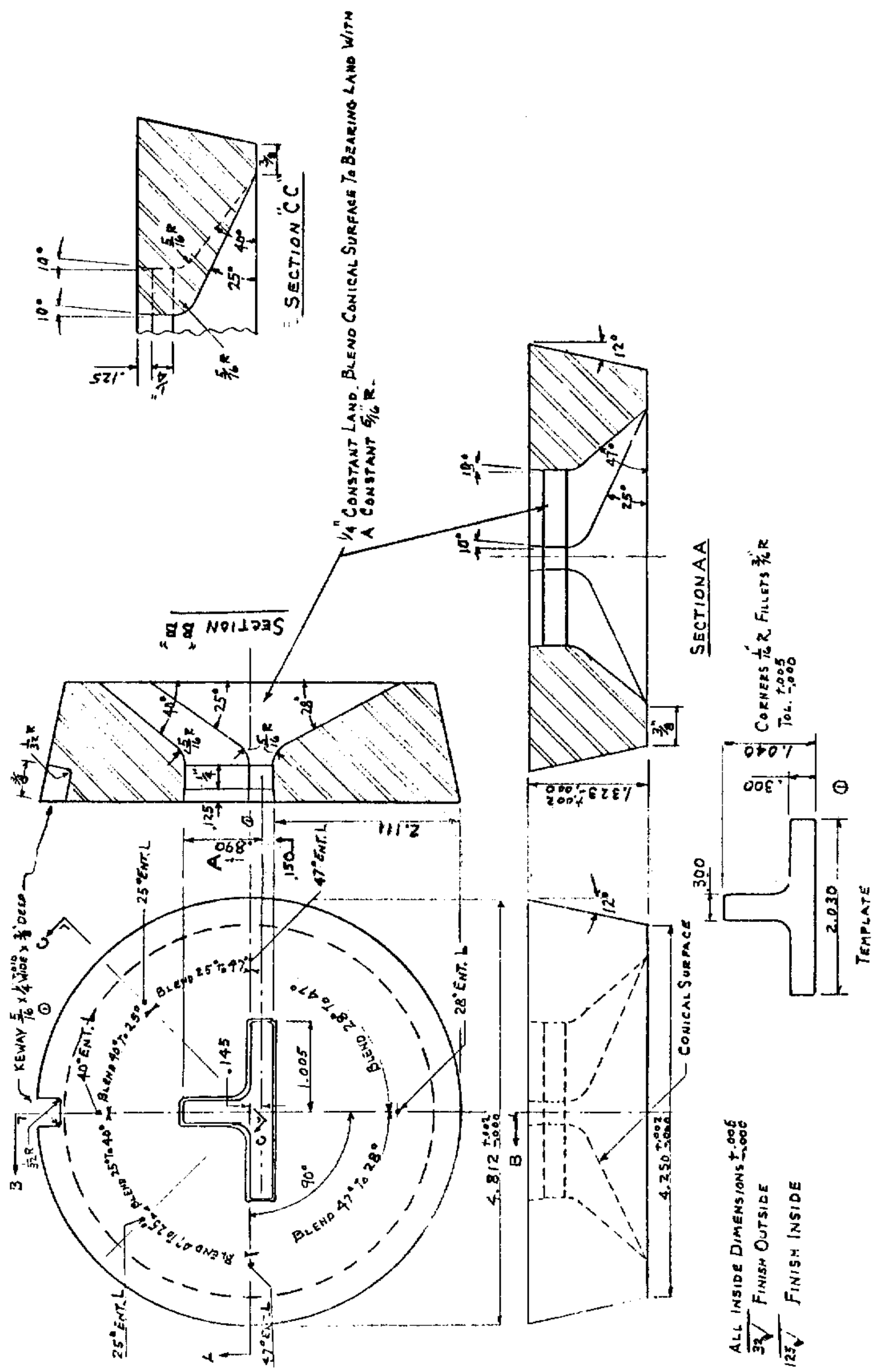


Figure 26. Die Design B-0443

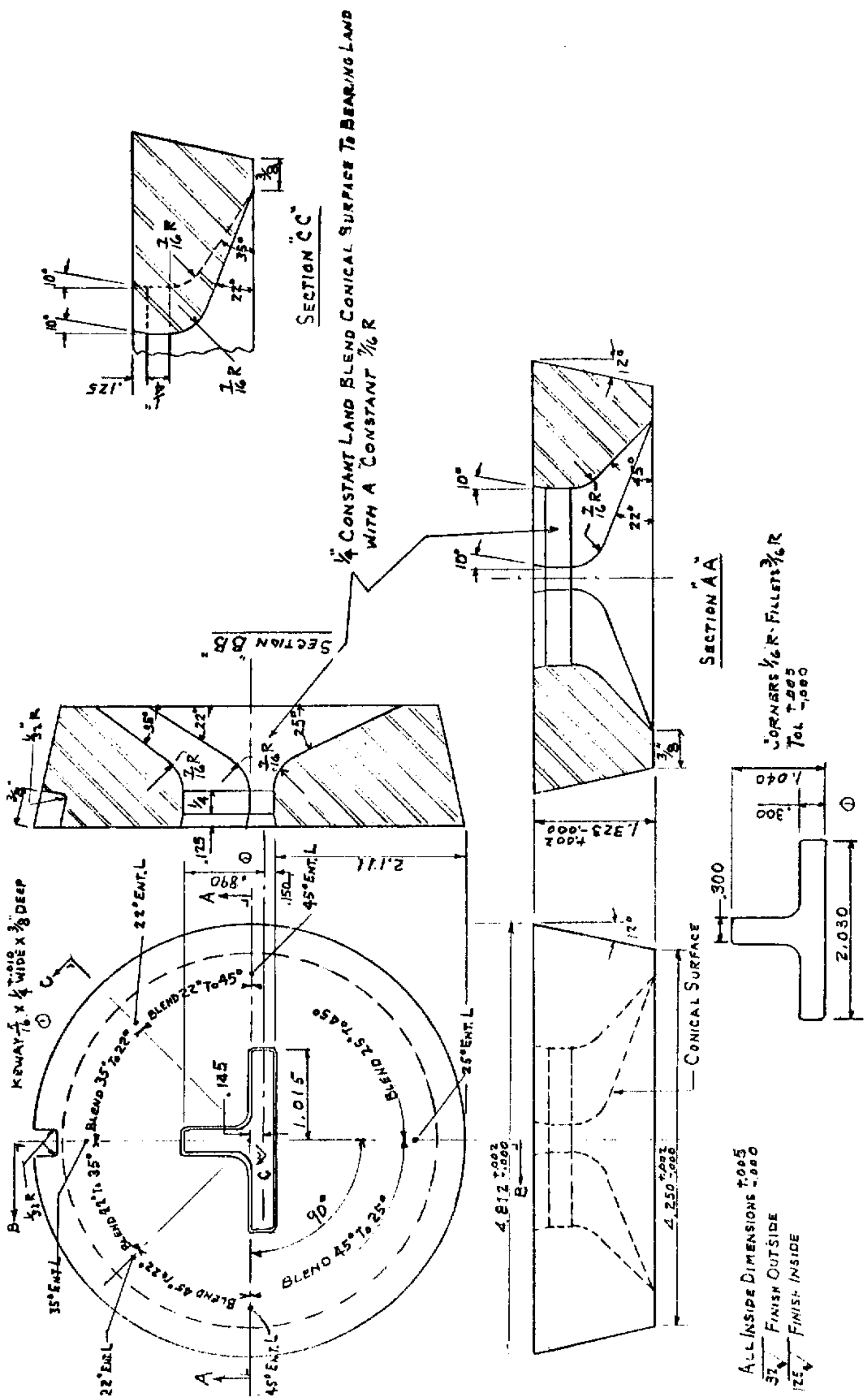


Figure 27. Die Design B-0444

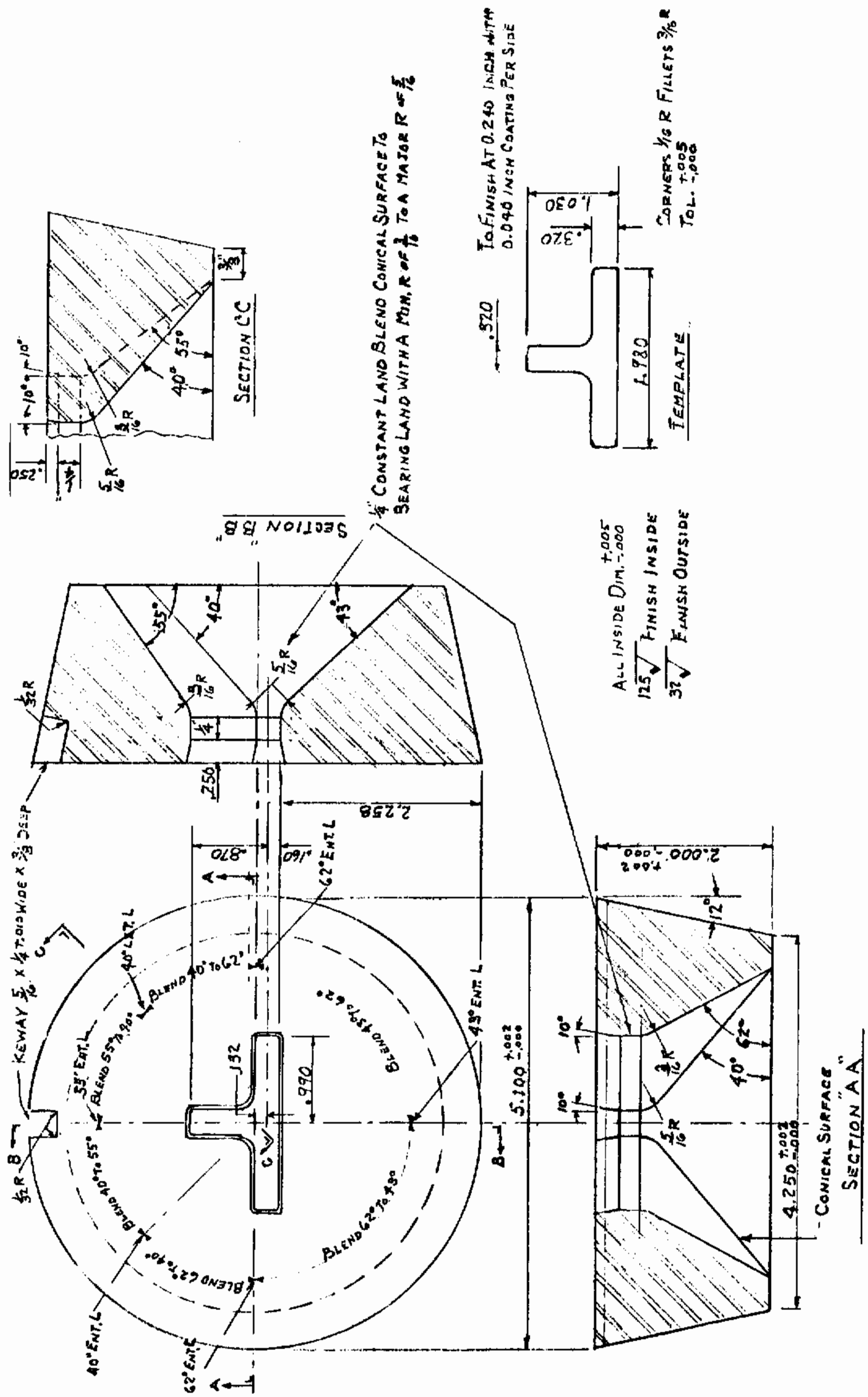


Figure 28. Die Design B-0482

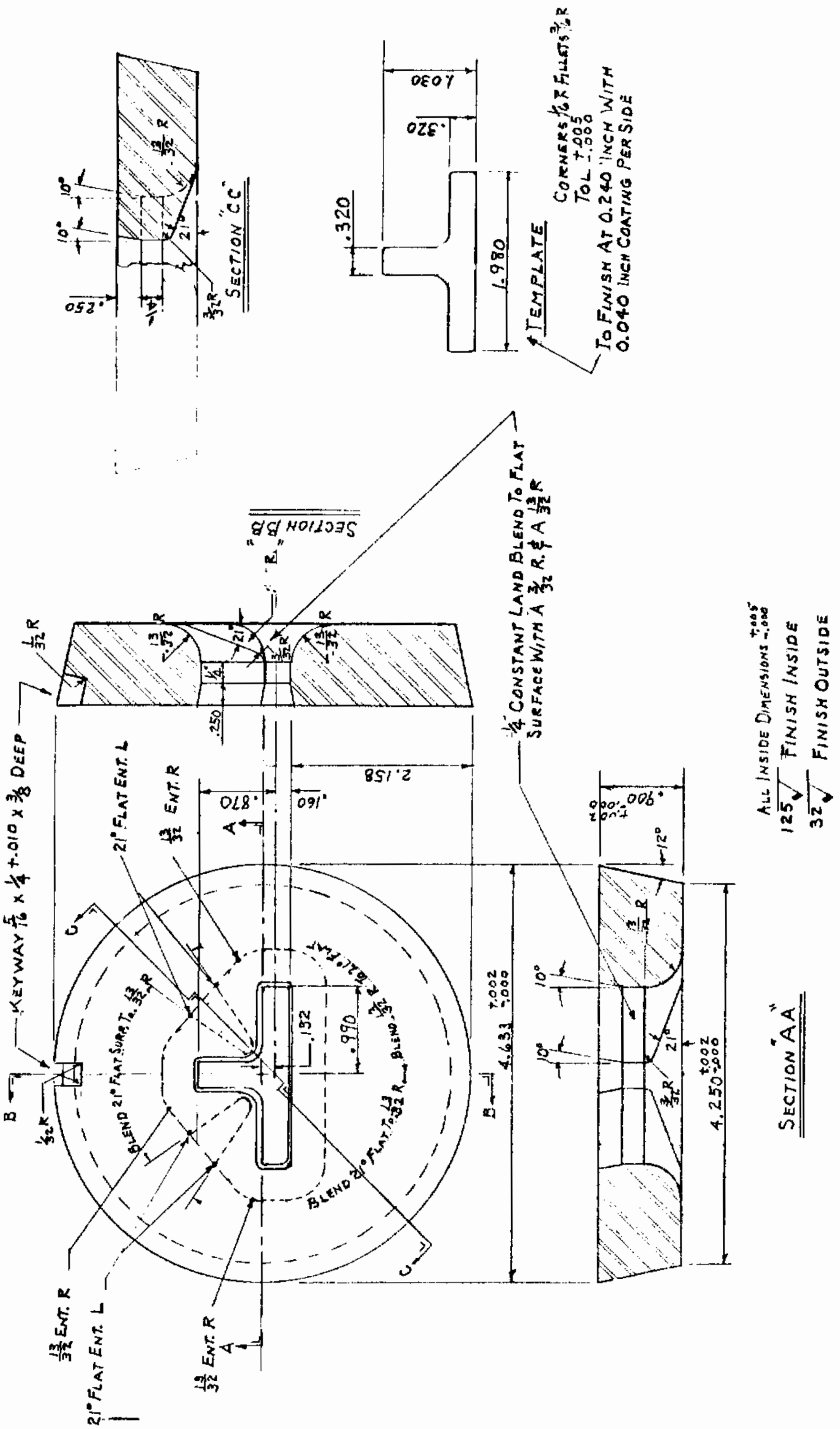


Figure 29. Die Design B-0486

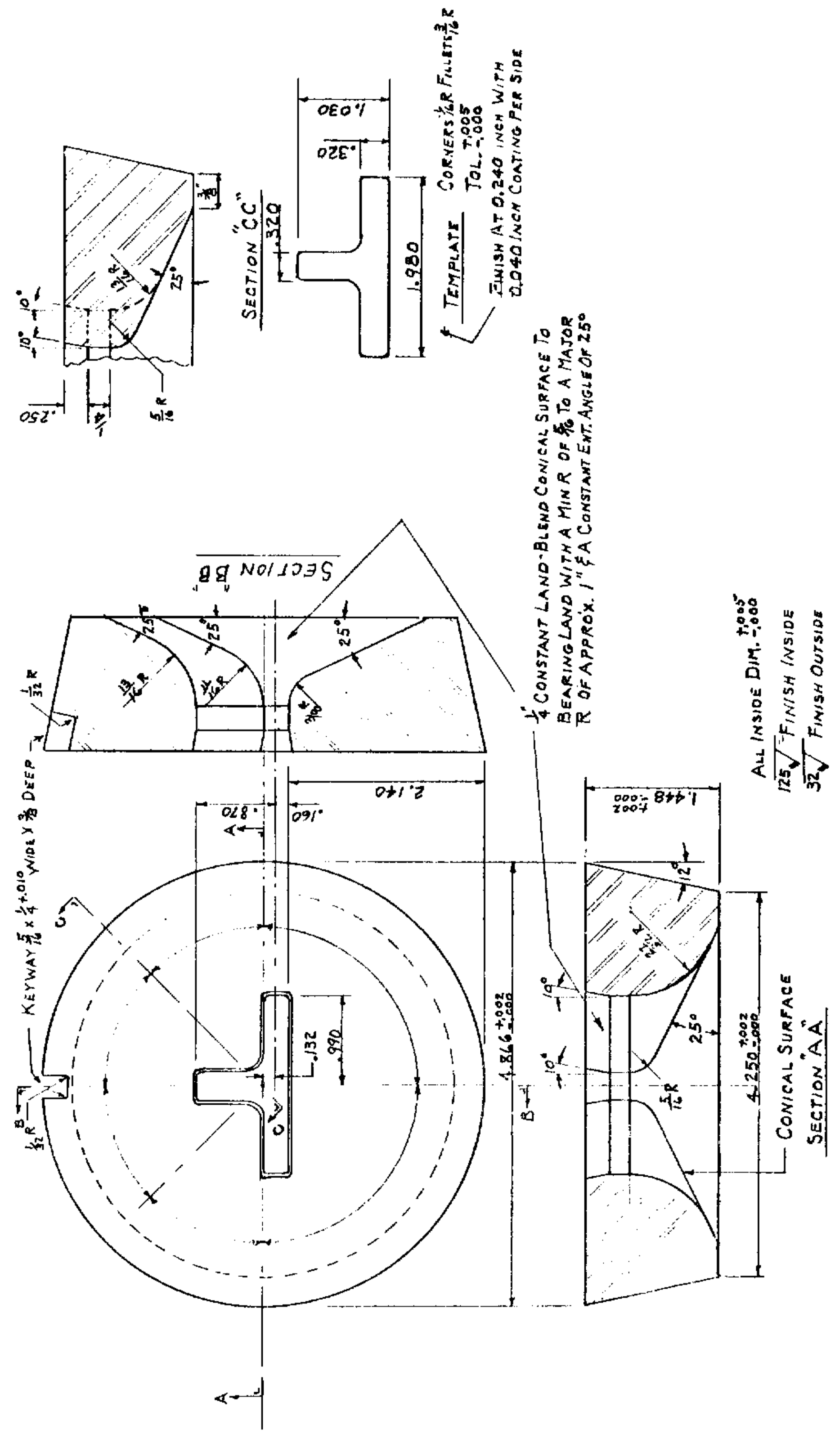


Figure 30. Die Design B-0490

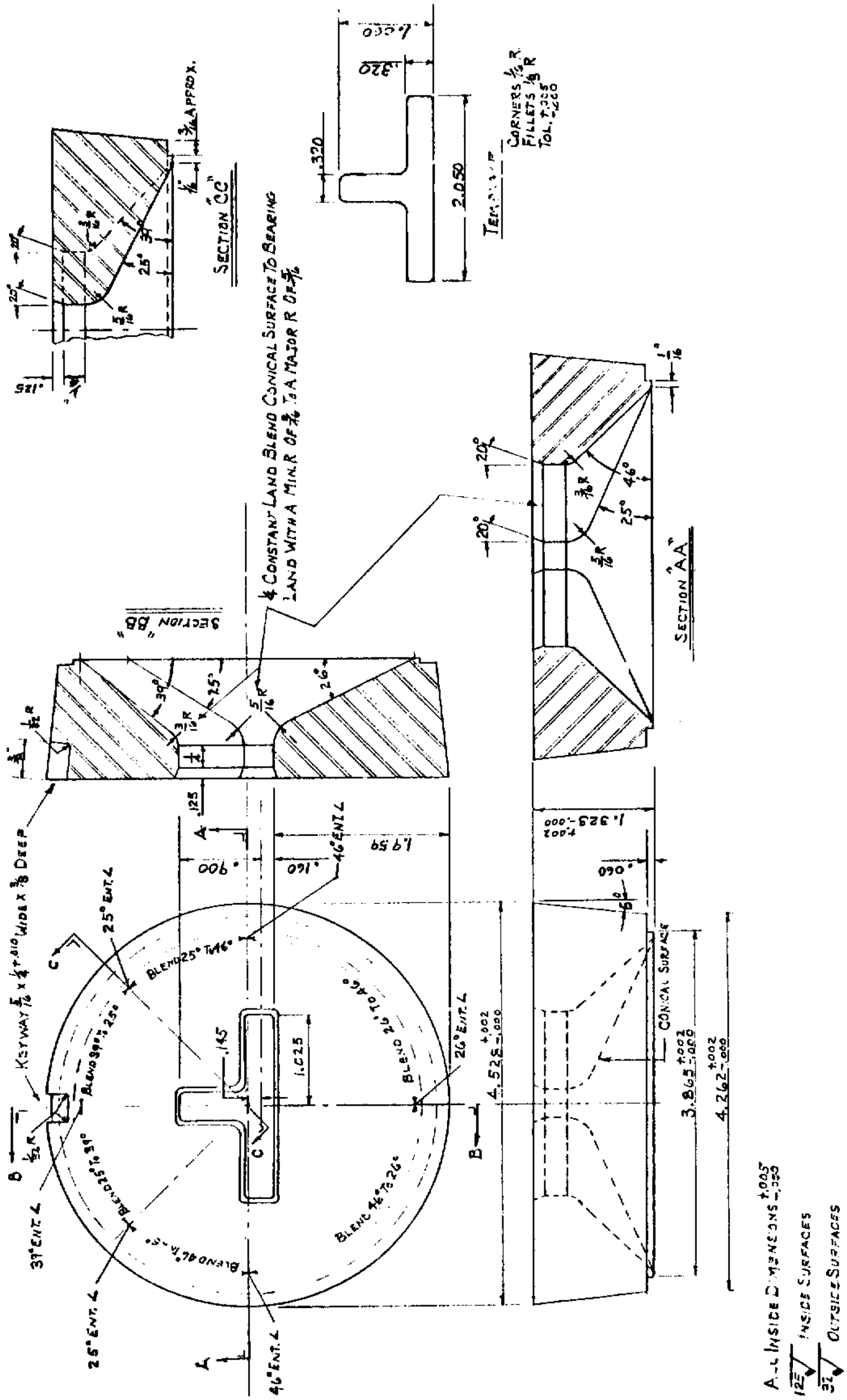


Figure 31. Die Design B-0506

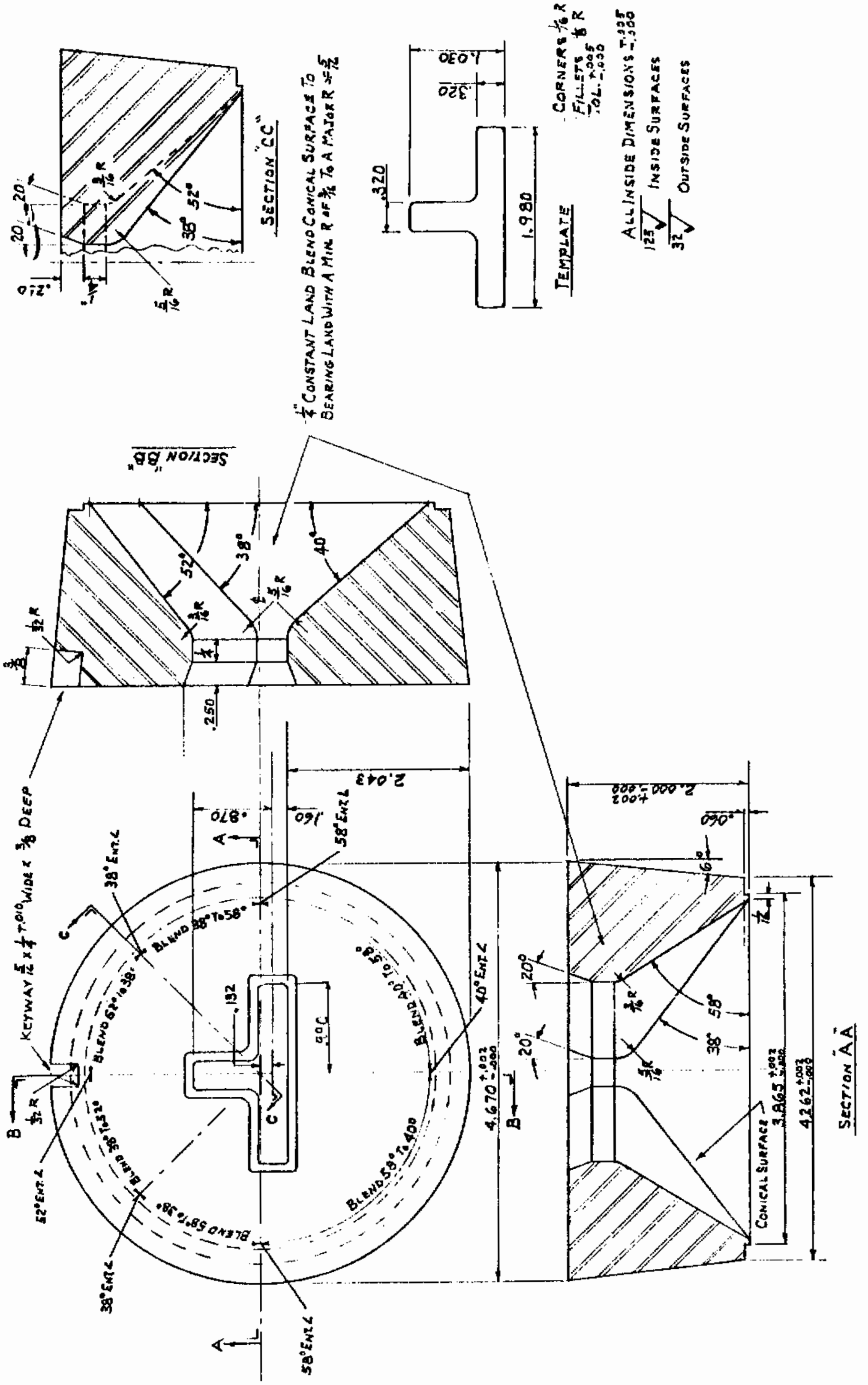


Figure 32. Die Design B-0508

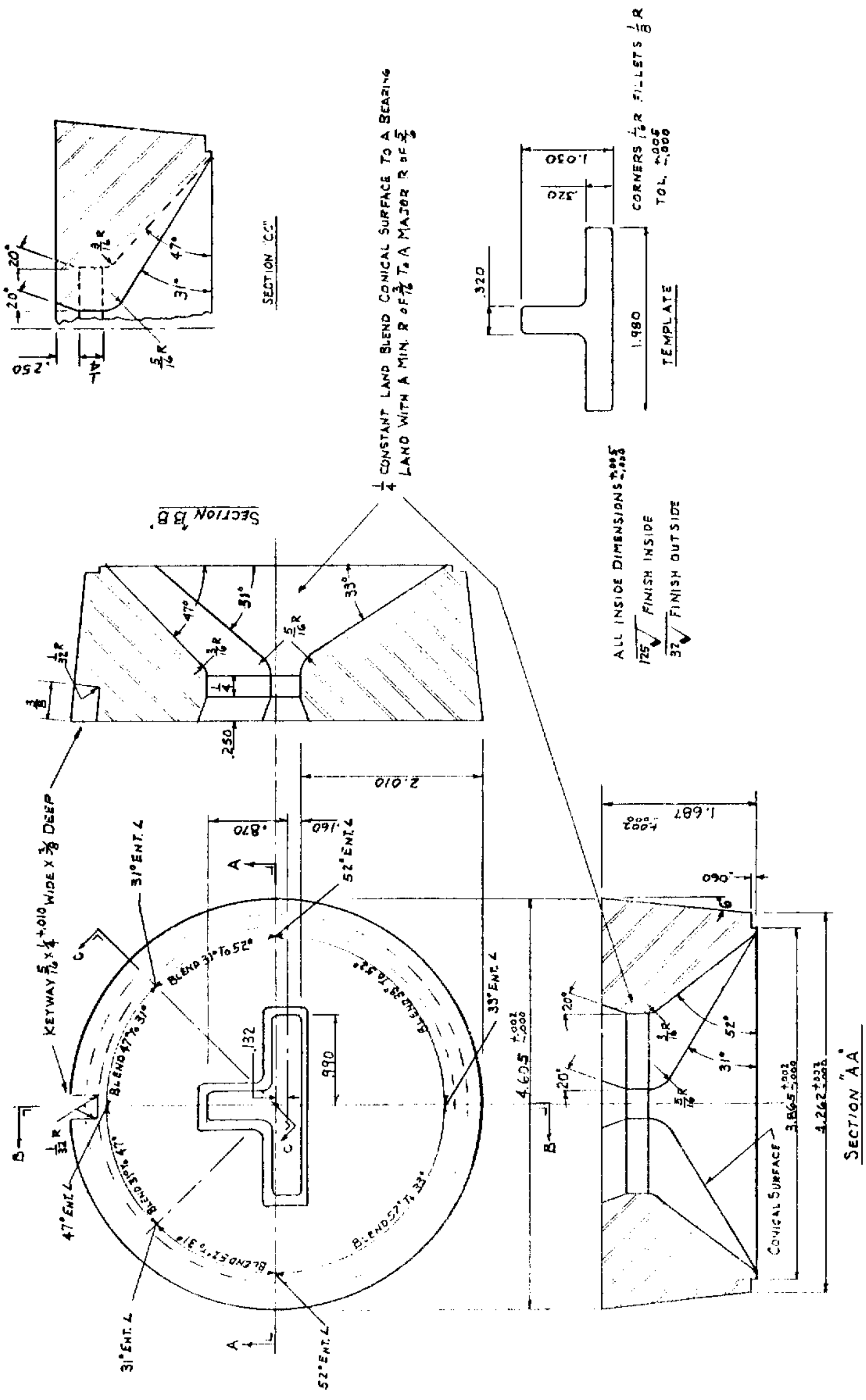


Figure 33. Die Design B-0510

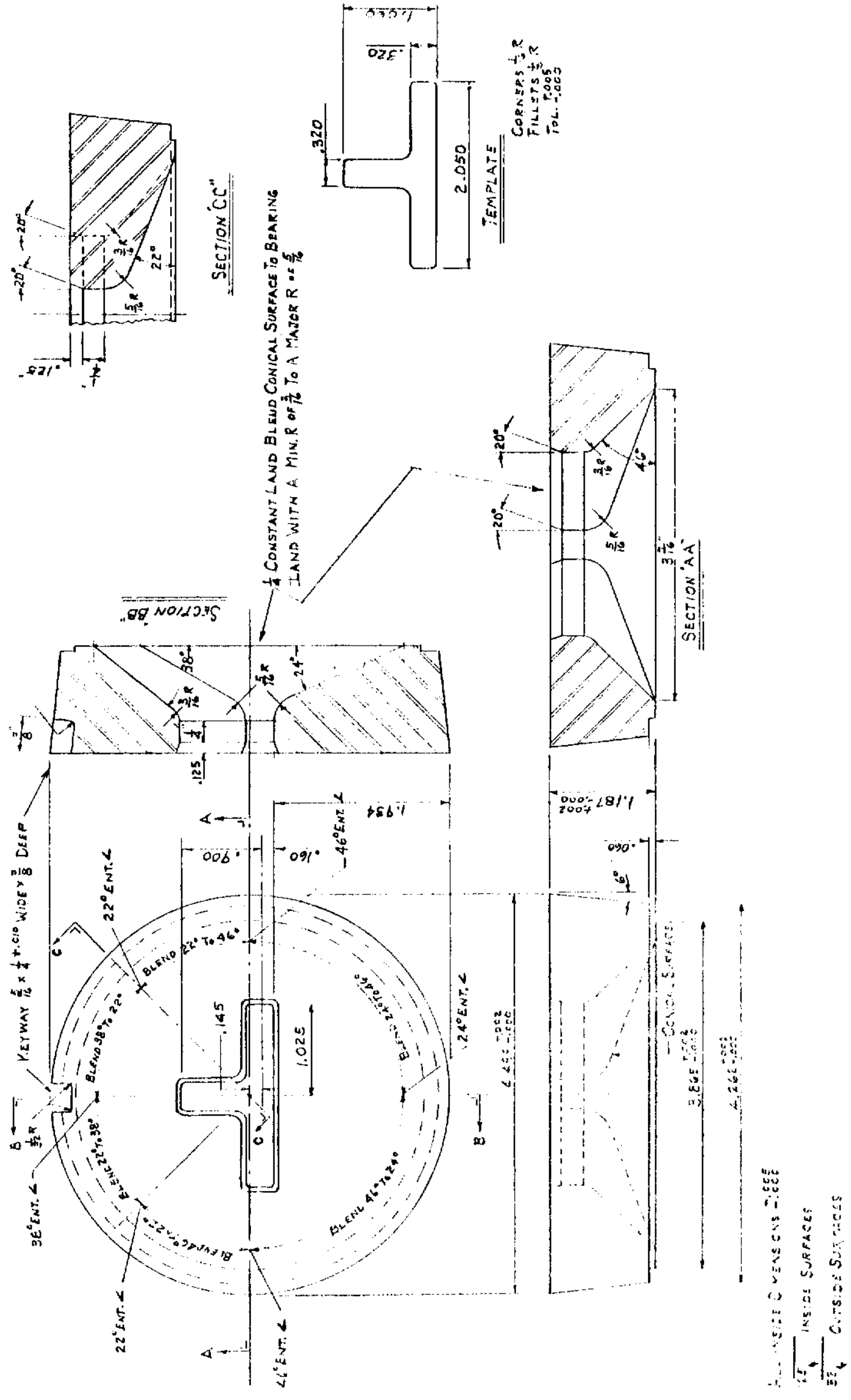


Figure 34. Die Design B-0540

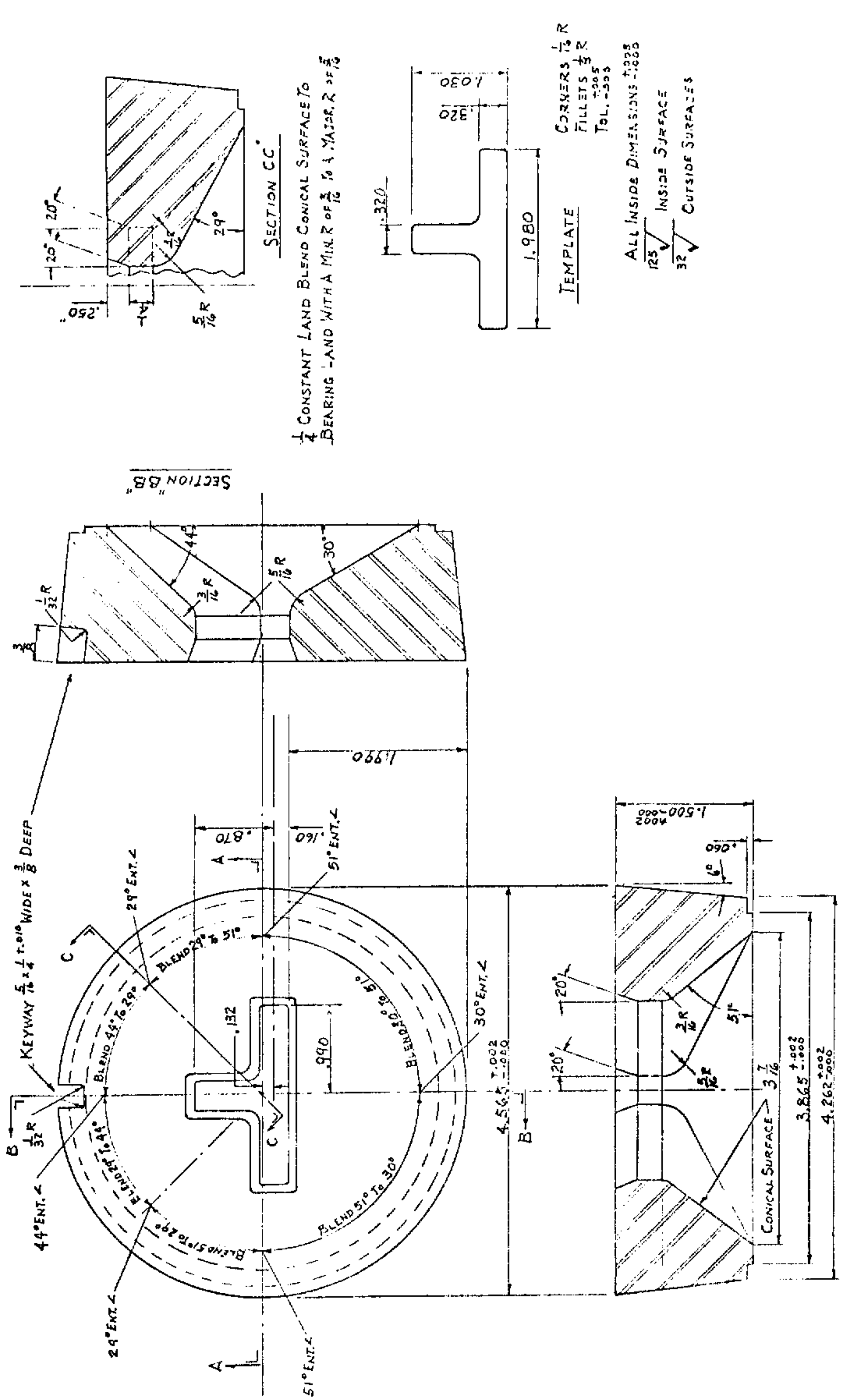


Figure 35. Die Design B-0542

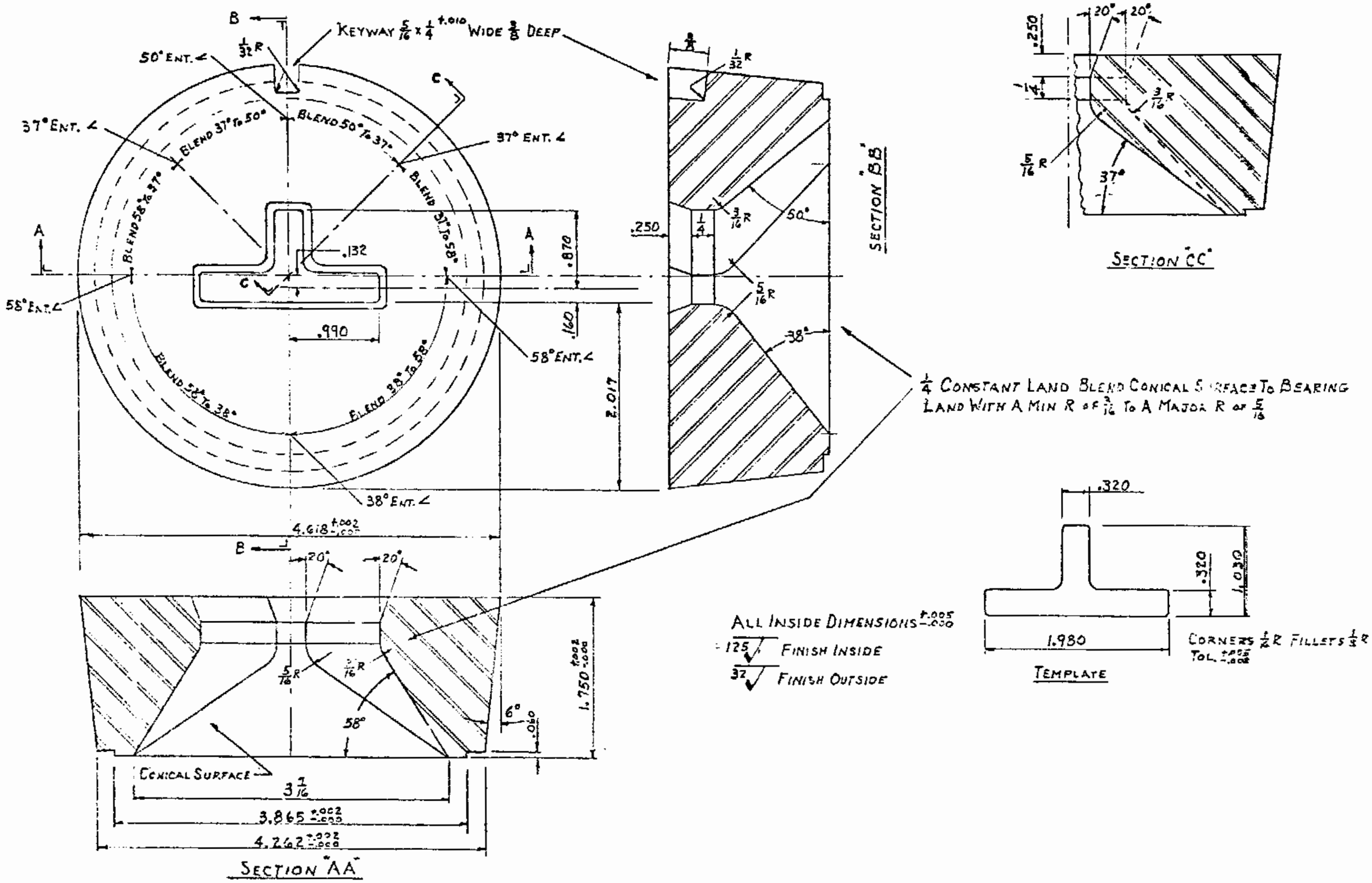
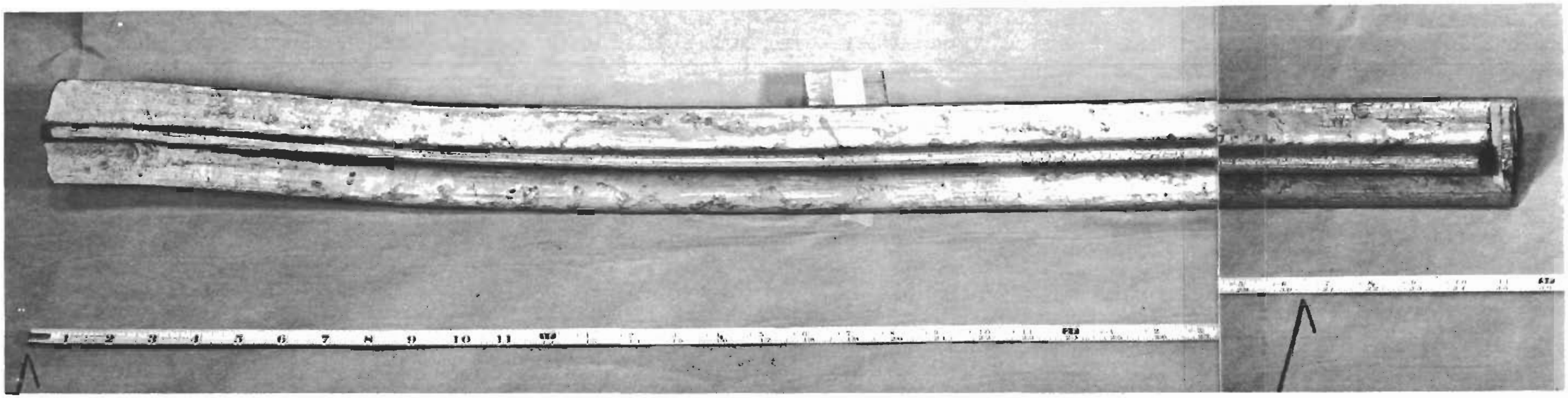


Figure 36. Die Design B-0544



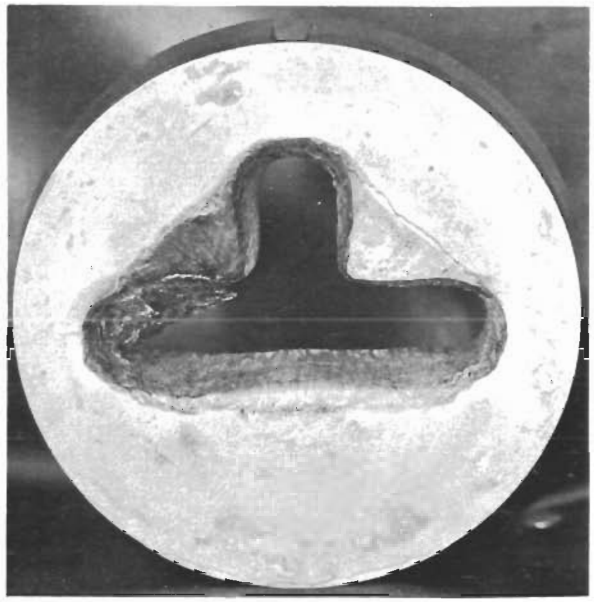
Nose

Mag. 1/3X

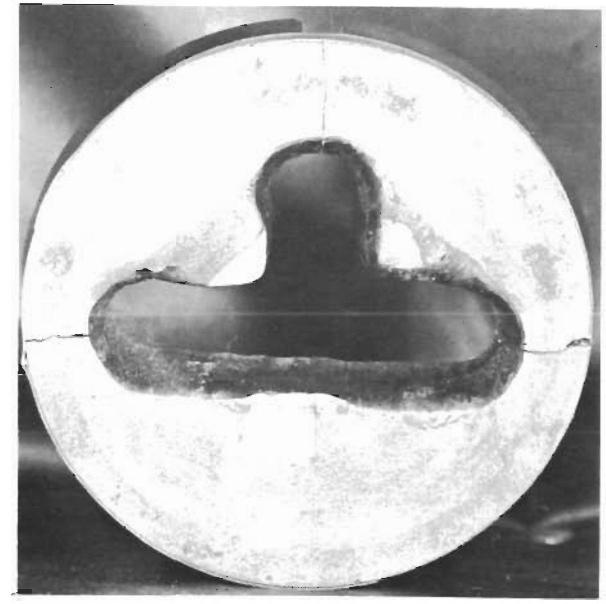
Extrusion 13

Billet Code W13
Billet Heating Temperature 3100°F
Reduction Ratio 12.7:1

Figure 37. Extruded "T" Shape of Tungsten-3 Percent Molybdenum from Heat AF-4364-B

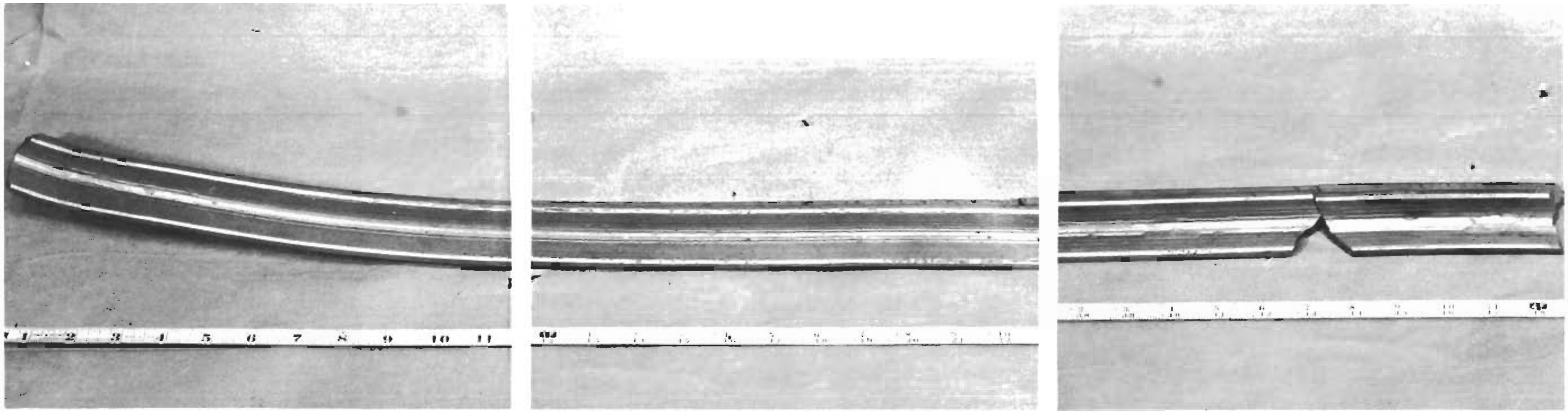


DW12



DW13

Figure 38. Die Appearance After Extrusion of "T" Shapes of As-Cast Tungsten-3 Percent Molybdenum - DW12 and DW13
(Magnification Approximately 3/4X)

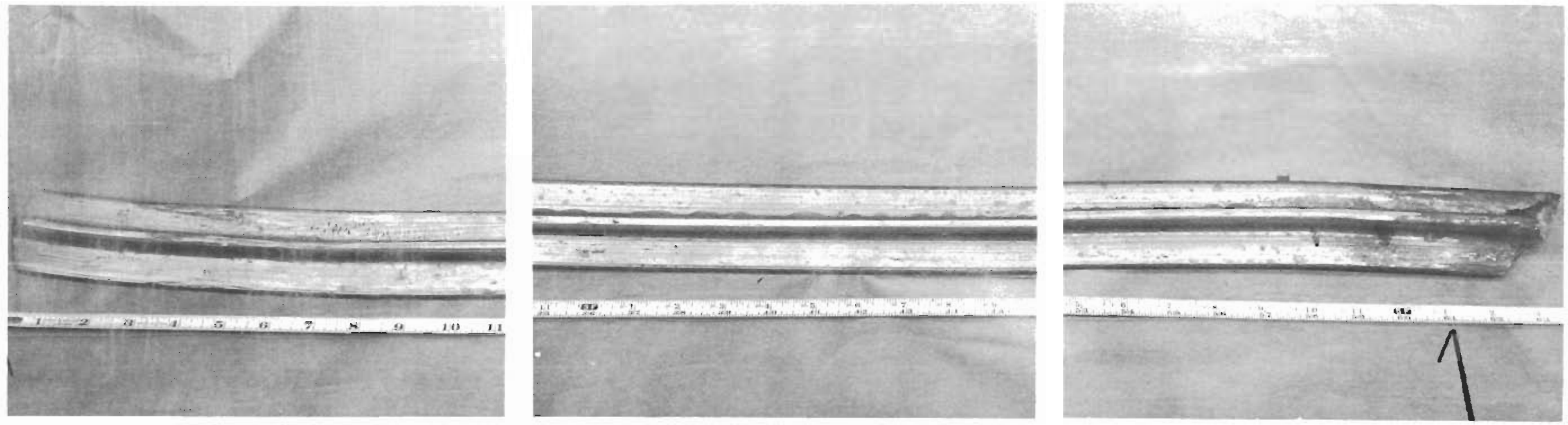


Front Middle Back

Extrusion 14

Billet Code W14
Billet Heating Temperature 3100°F
Reduction Ratio 17.9:1

Figure 39. Extruded "T" Shape of Tungsten-3 Percent Molybdenum from Heat AF-4578-A
(Magnification 1/3X)

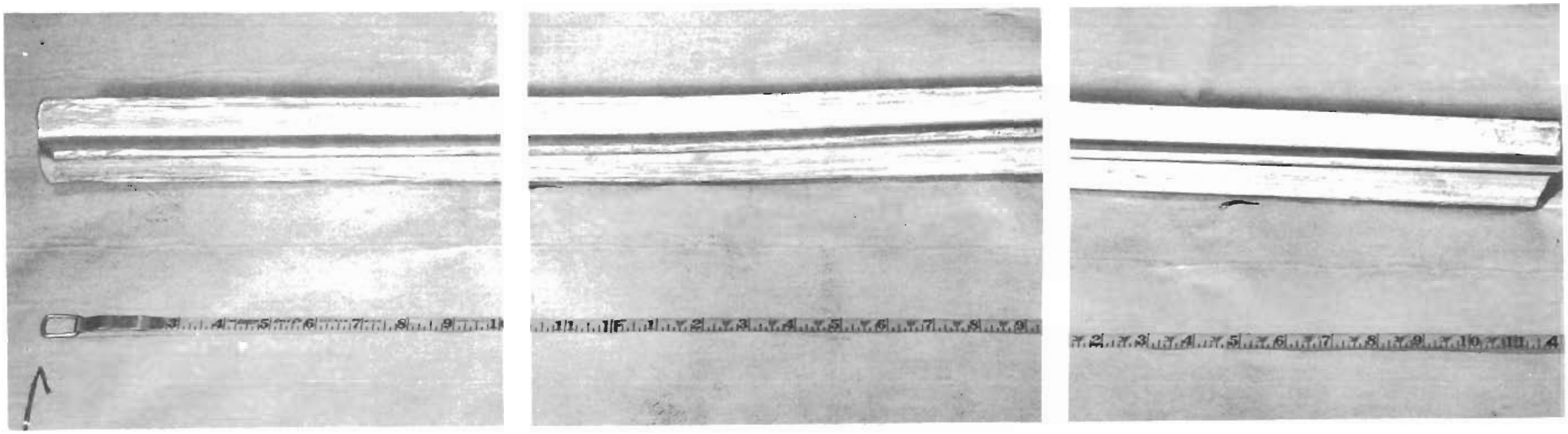


Front Middle Back

Extrusion 15

Billet Code W15
Billet Heating Temperature 3100°F
Reduction Ratio 17.9:1

Figure 40. Extruded "T" Shape of Tungsten-3 Percent Molybdenum from Heat AF-4578-B (Magnification 1/3X)



Front

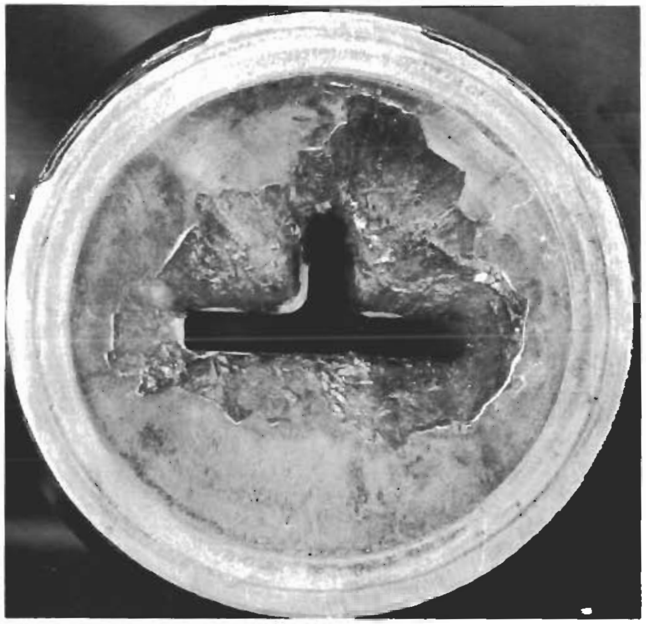
Middle

Back

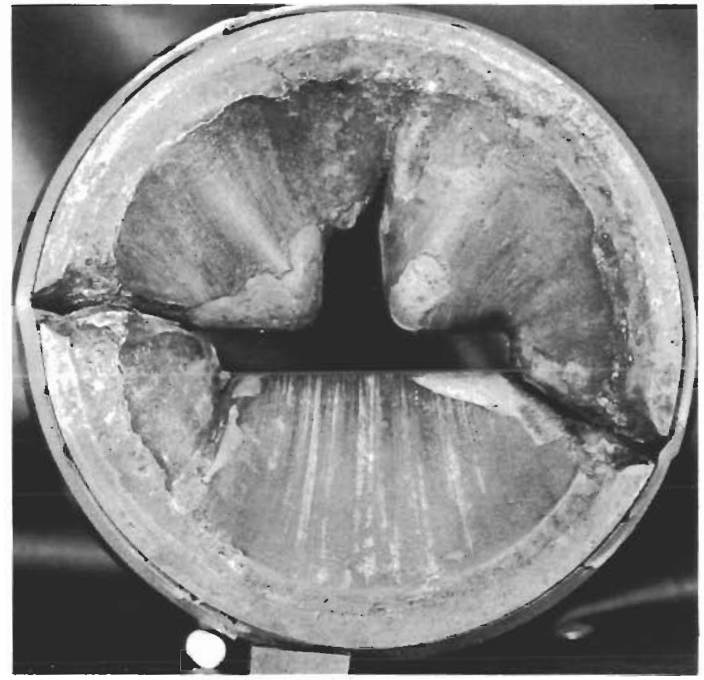
Extrusion 16

Billet Code W16
Billet Heating Temperature 3100°F
Reduction Ratio 17.9:1

Figure 41. Extruded "T" Shape of Tungsten-3 Percent Molybdenum from Heat AF-4604
(Magnification 1/3X)



DW17



DW18

Figure 42. Die Appearance After Extrusion of "T" Shapes of As-Cast Tungsten-3 Percent Molybdenum - DW17 and DW18 (Magnification Approximately 3/4X)

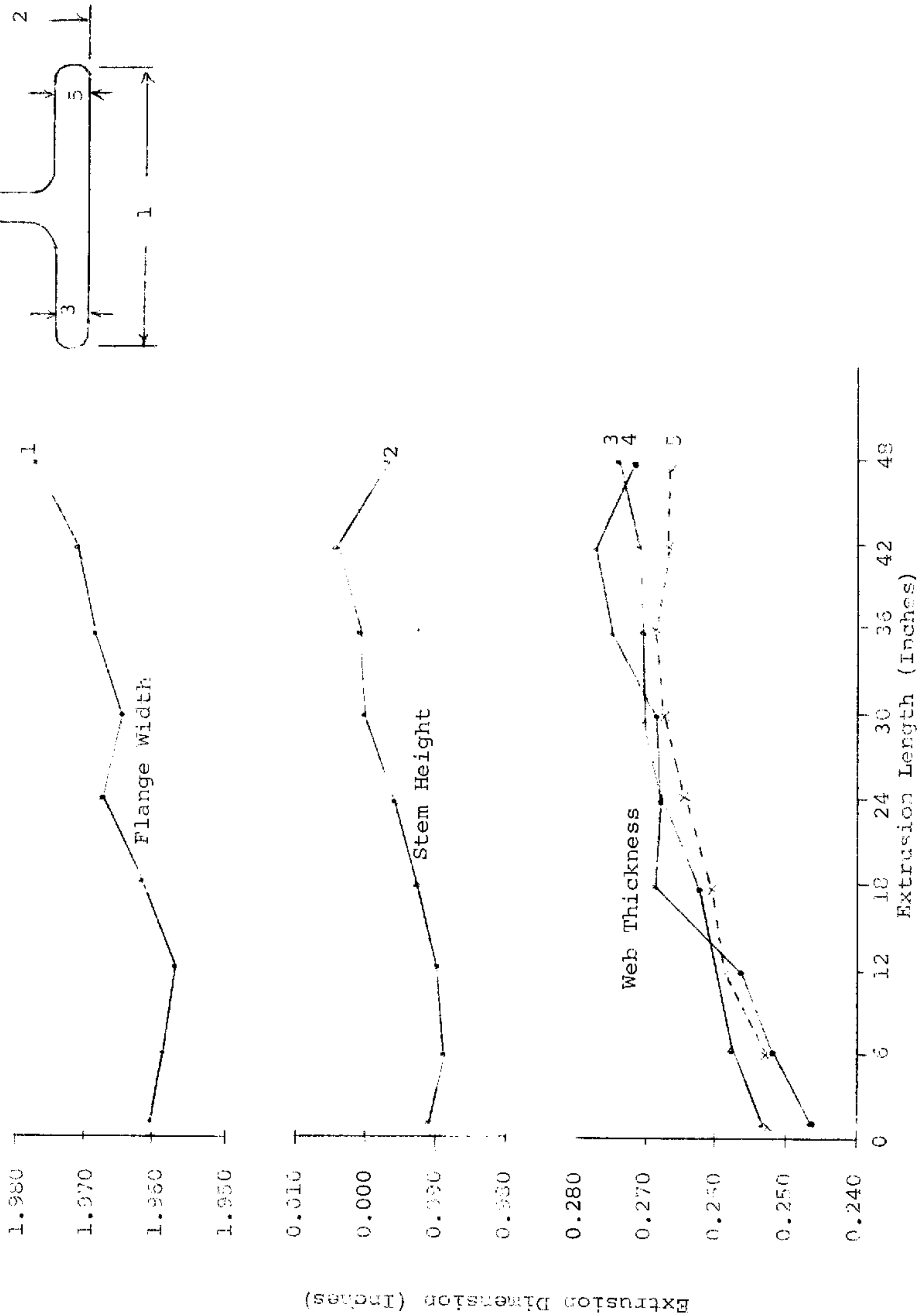


Figure 43. Extrusion Dimension Versus Extrusion Length for Extrusion 14

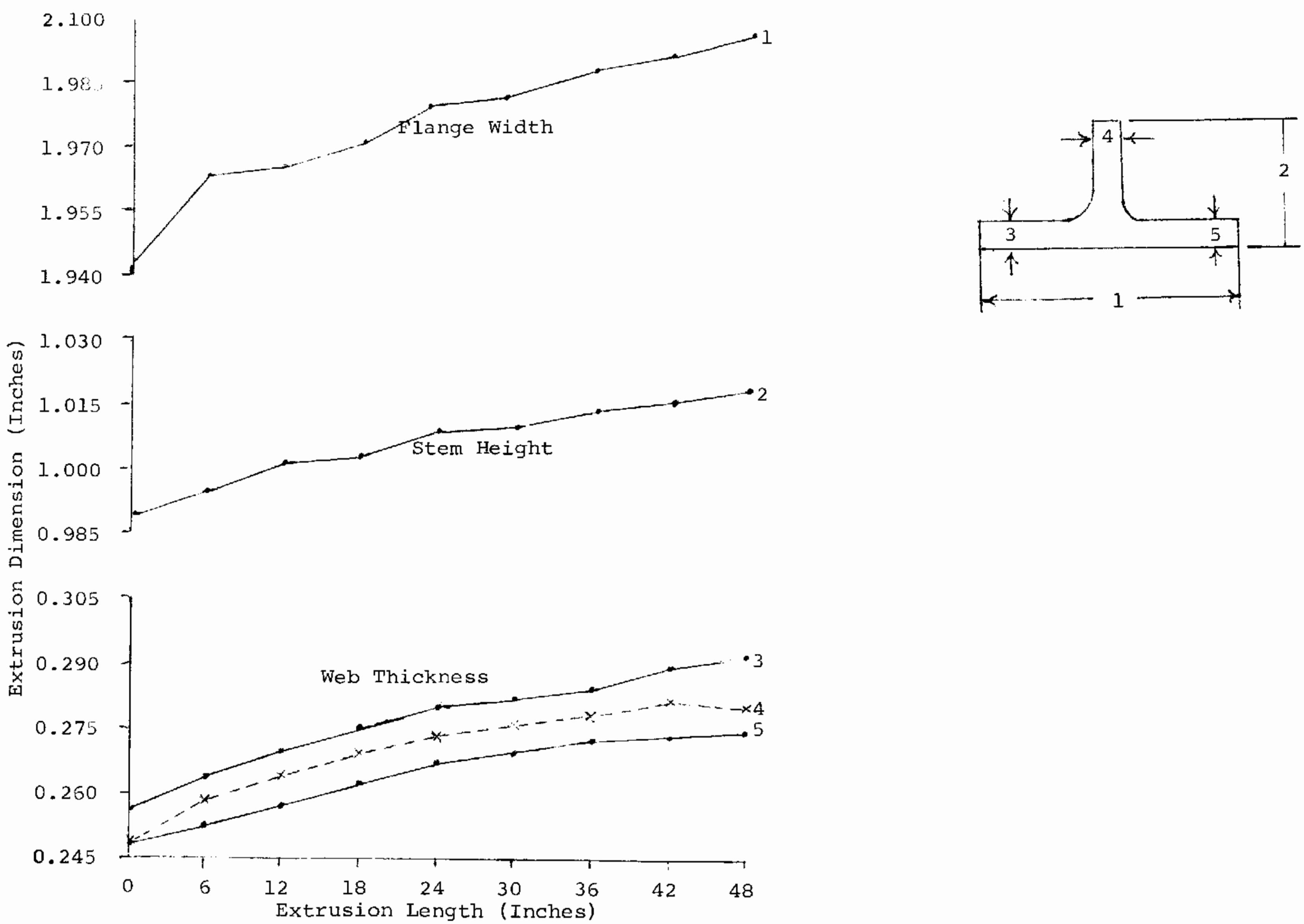


Figure 44. Extrusion Dimension Versus Extrusion Length for Extrusion 16

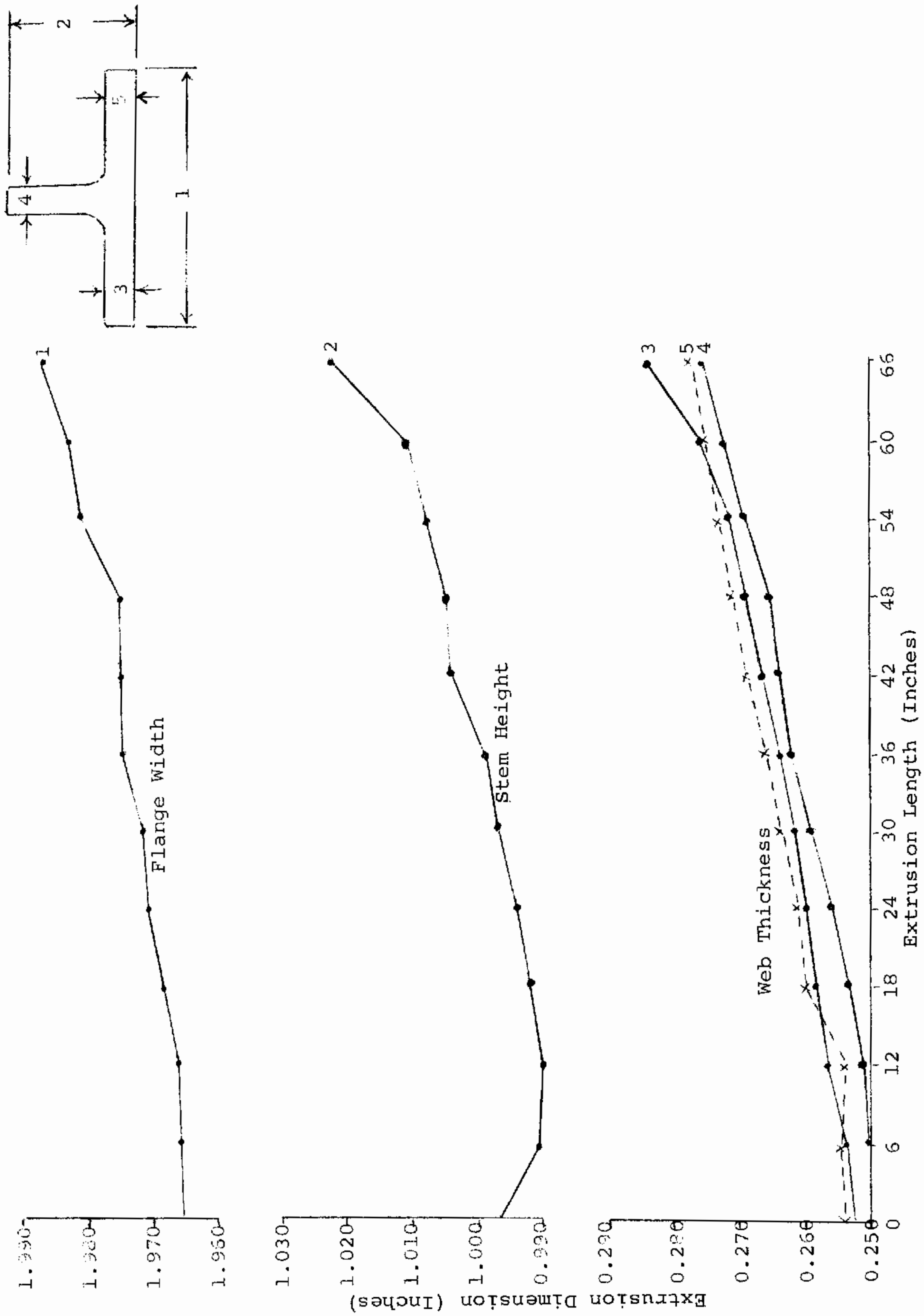


Figure 45. Extrusion Dimension Versus Extrusion Length for Extrusion 17

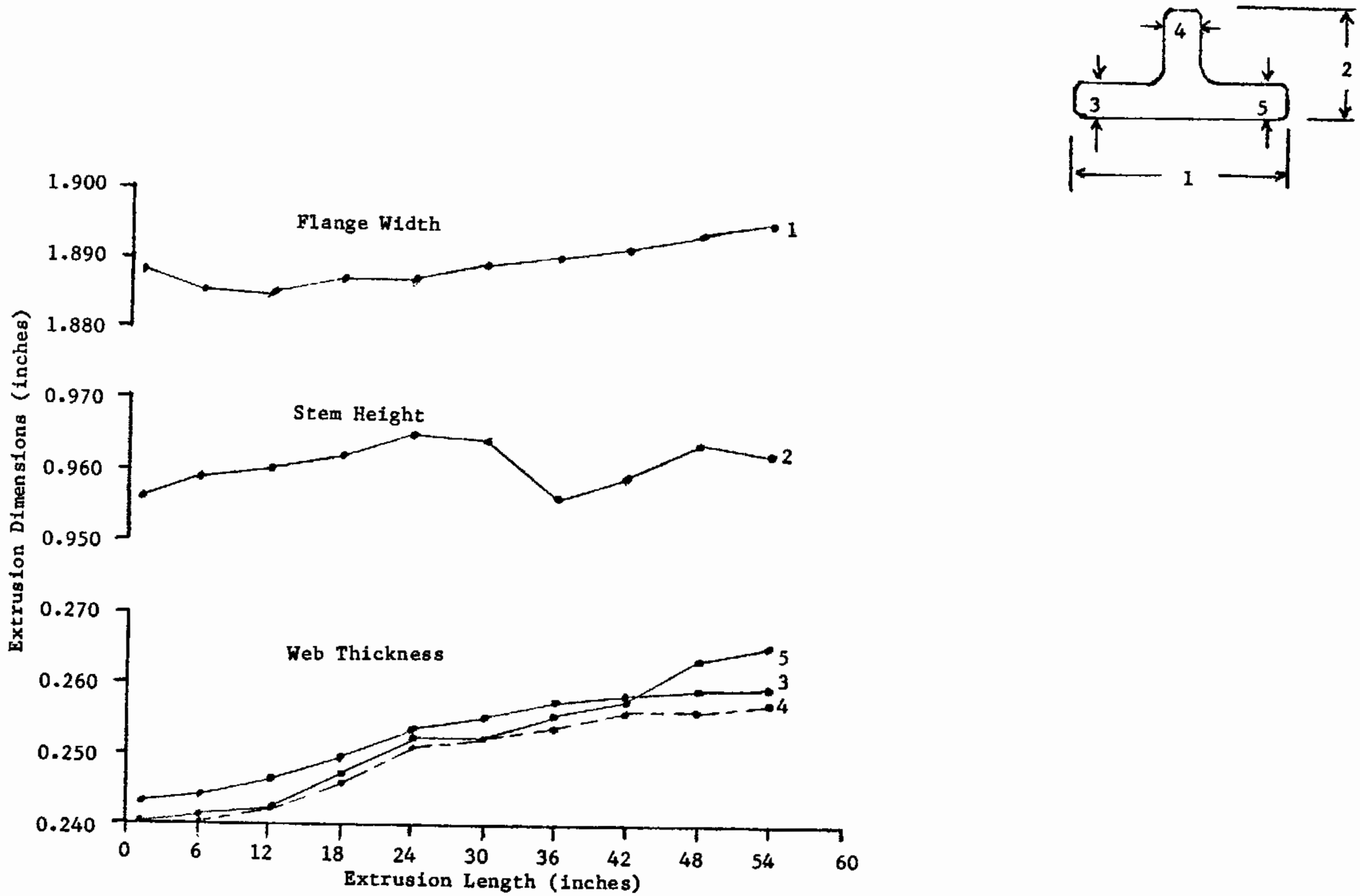


Figure 46. Extrusion Dimension Versus Extrusion Length for Extrusion 23

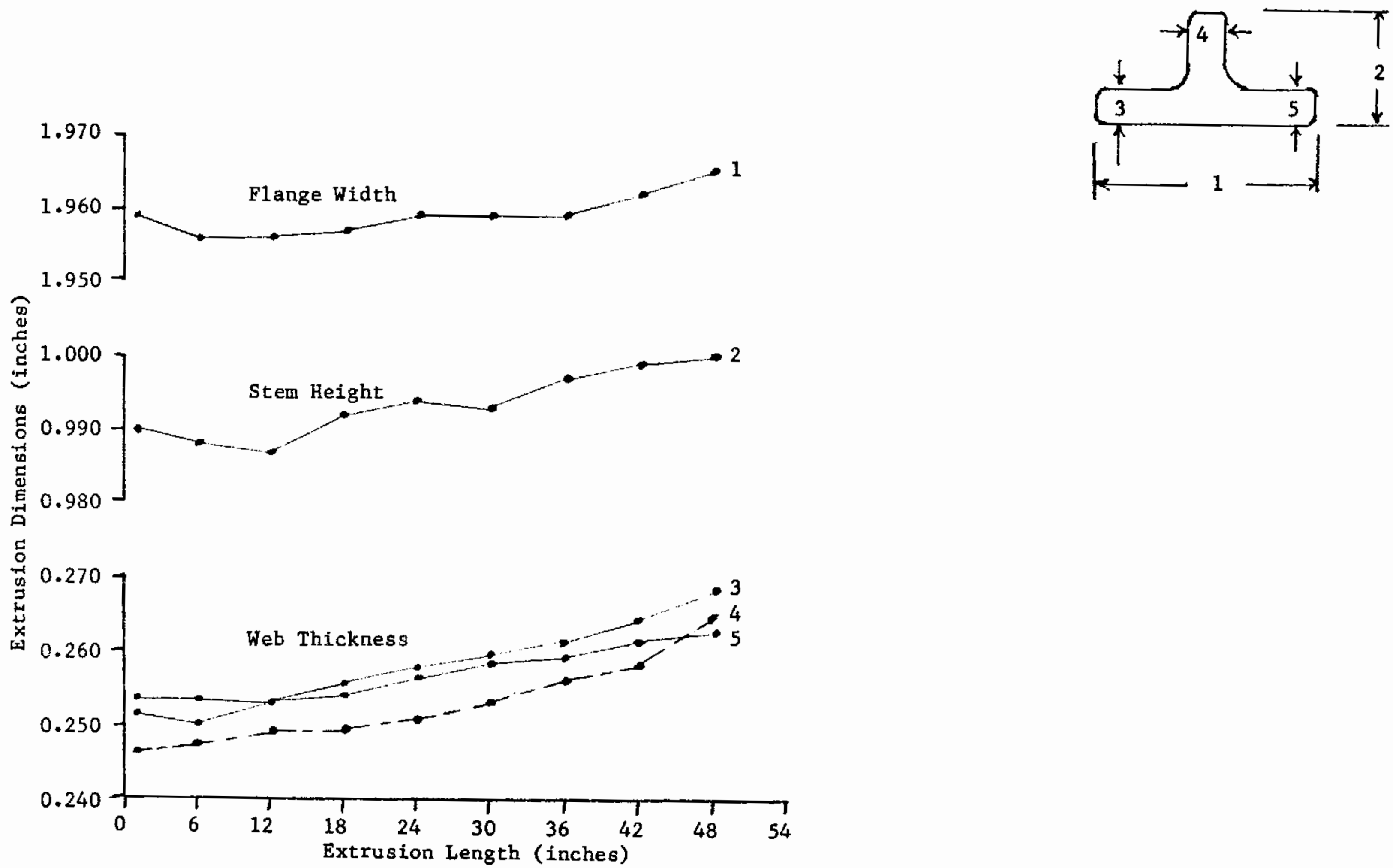


Figure 47. Extrusion Dimension Versus Extrusion Length for Extrusion 24

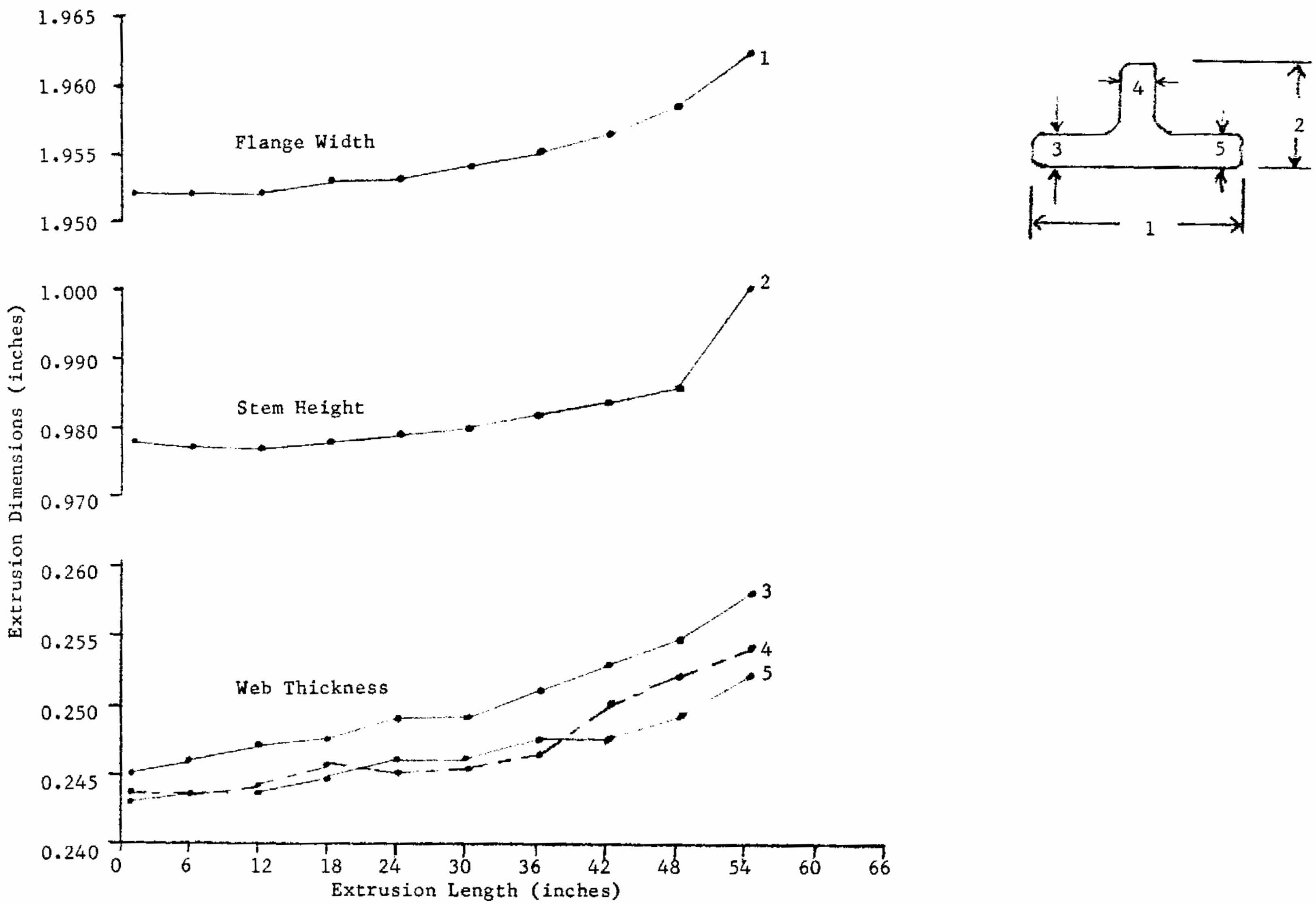


Figure 48. Extrusion Dimension Versus Extrusion Length for Extrusion 36

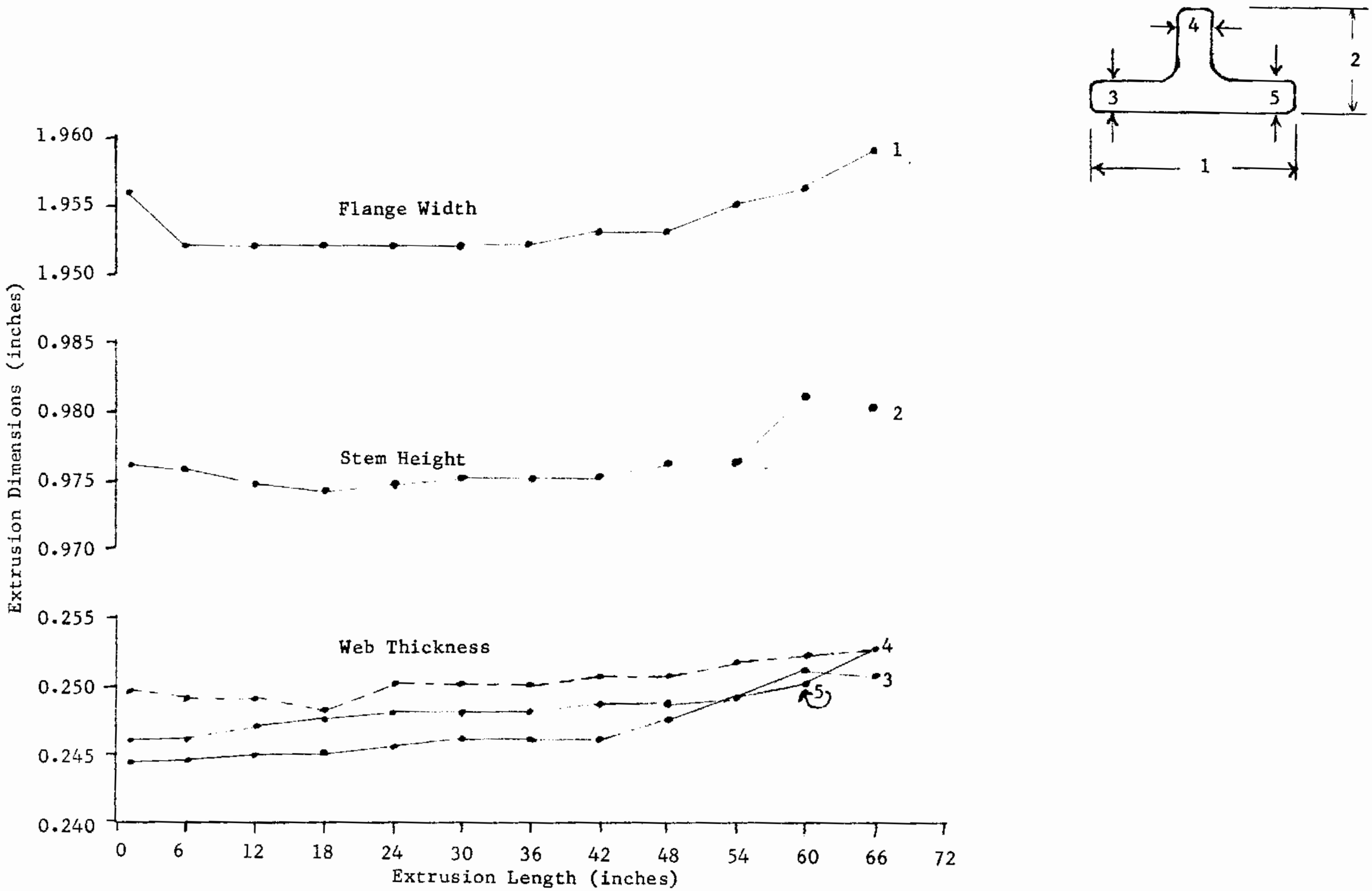


Figure 49. Extrusion Dimension Versus Extrusion Length for Extrusion 44

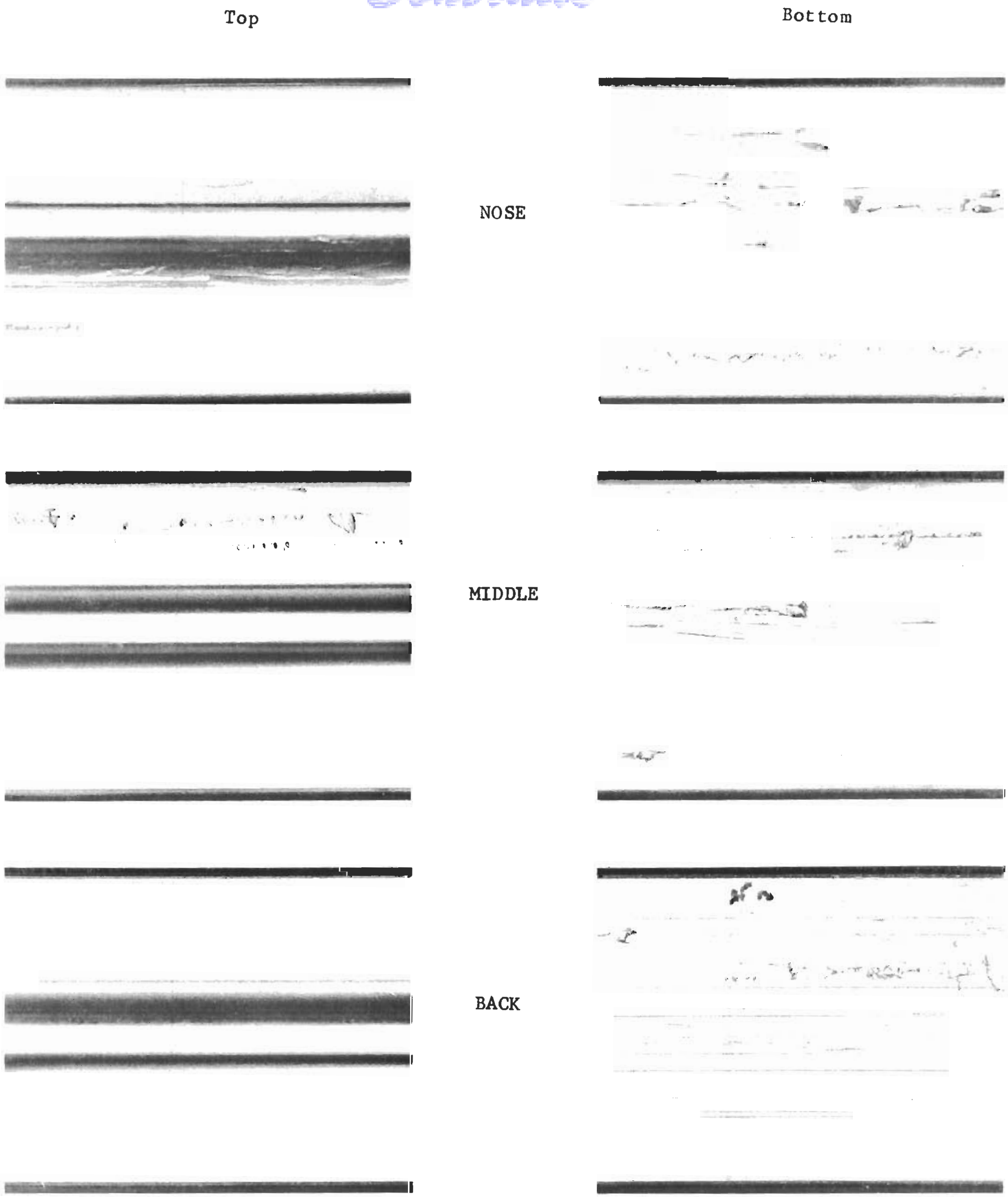


Figure 50. As-Extruded Surface of Arc Cast Tungsten-3 Percent Molybdenum Extrusion 36 (Billet Code W29) (Magnification 1-1/4X)

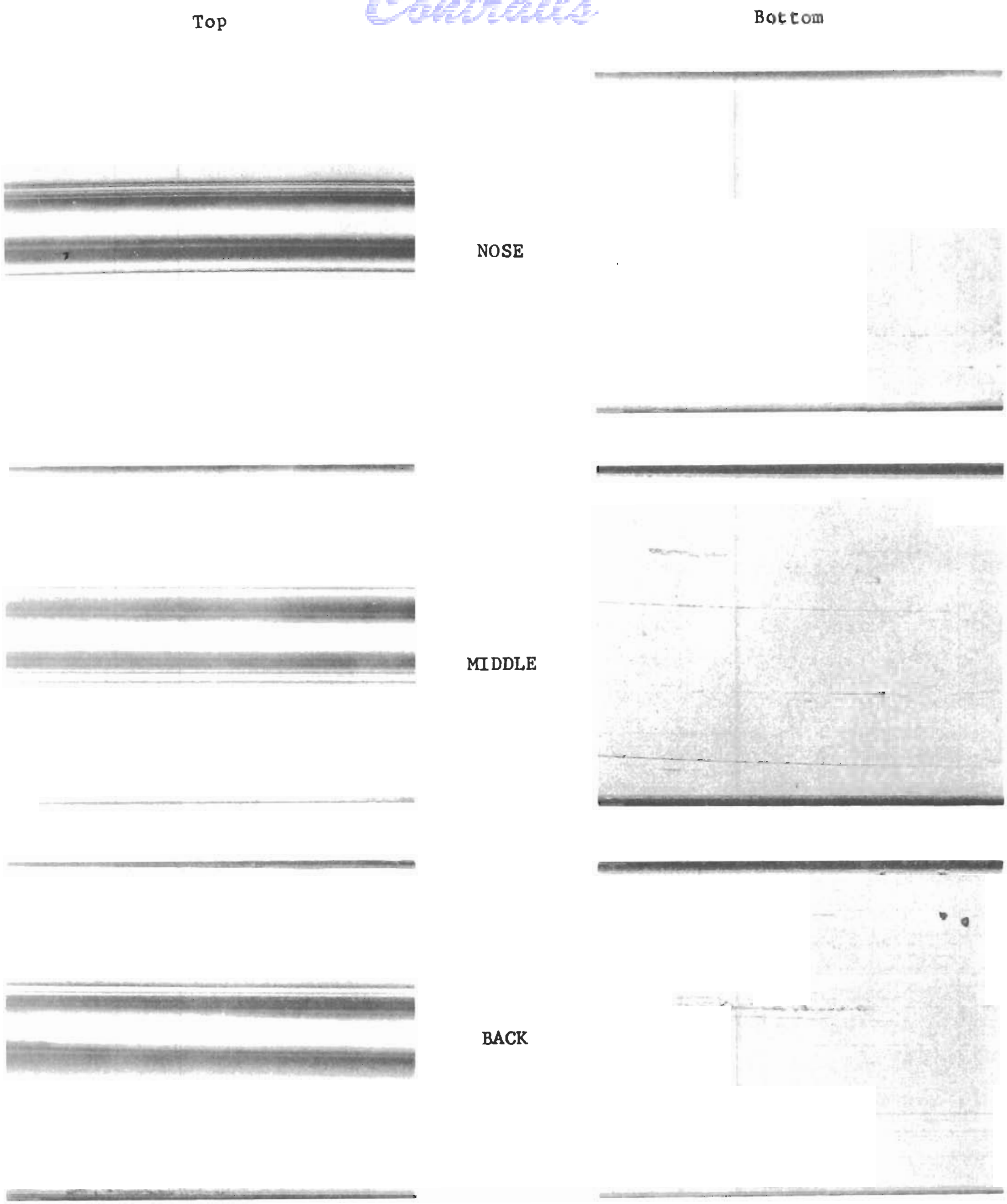
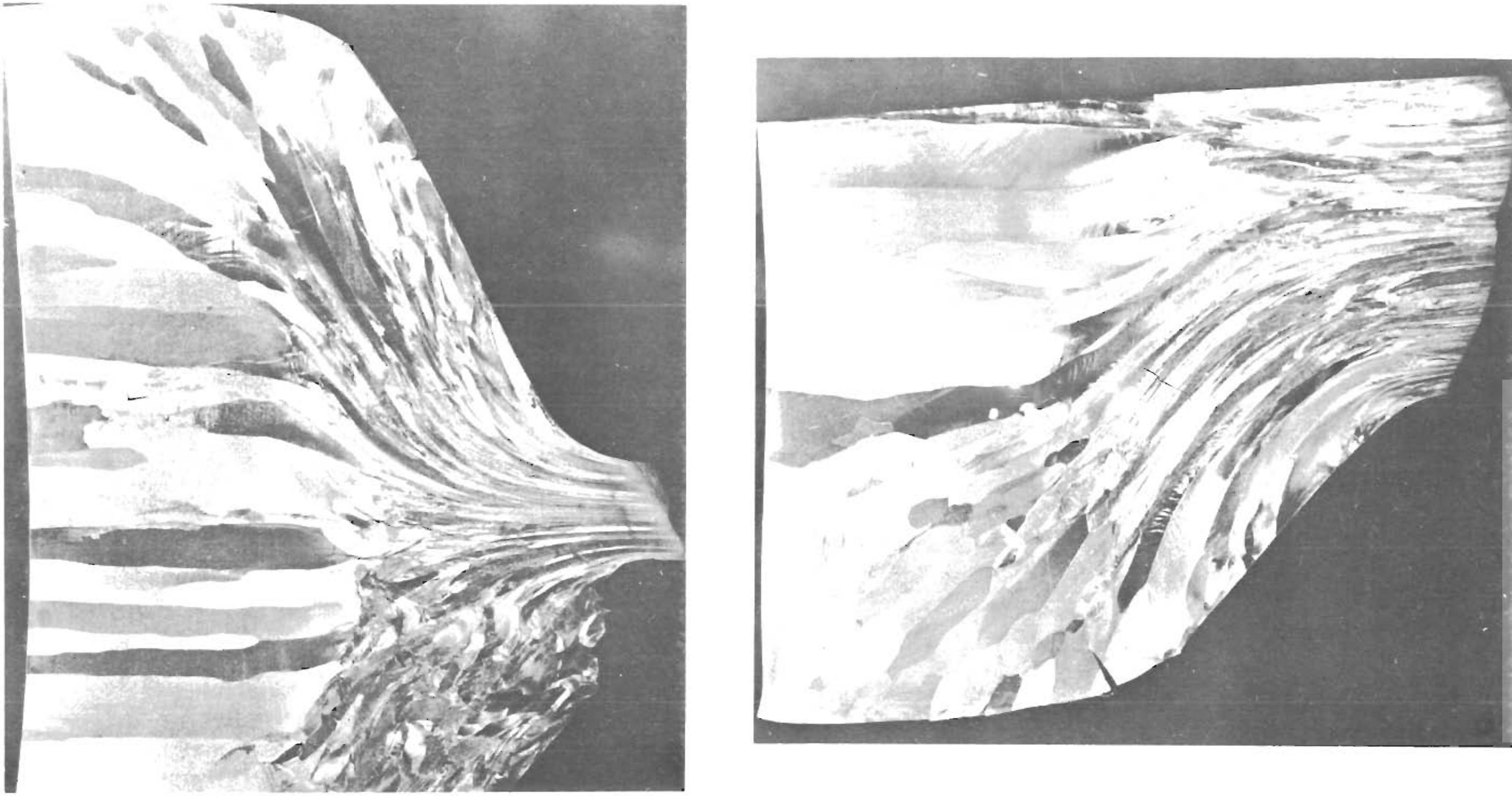


Figure 51. As-Extruded Surface of Arc Cast Tungsten-3 Percent Molybdenum
Extrusion 44 (Billet Code W23)
(Magnification 1-1/4X)



Extrusion 14

Billet Code W14
Billet Heating Temperature 3100°F
Reduction Ratio 17.9:1

Figure 52. Cross-Sectional View of Billet Cracking During Entry to the Die (Magnification 1-1/2X)

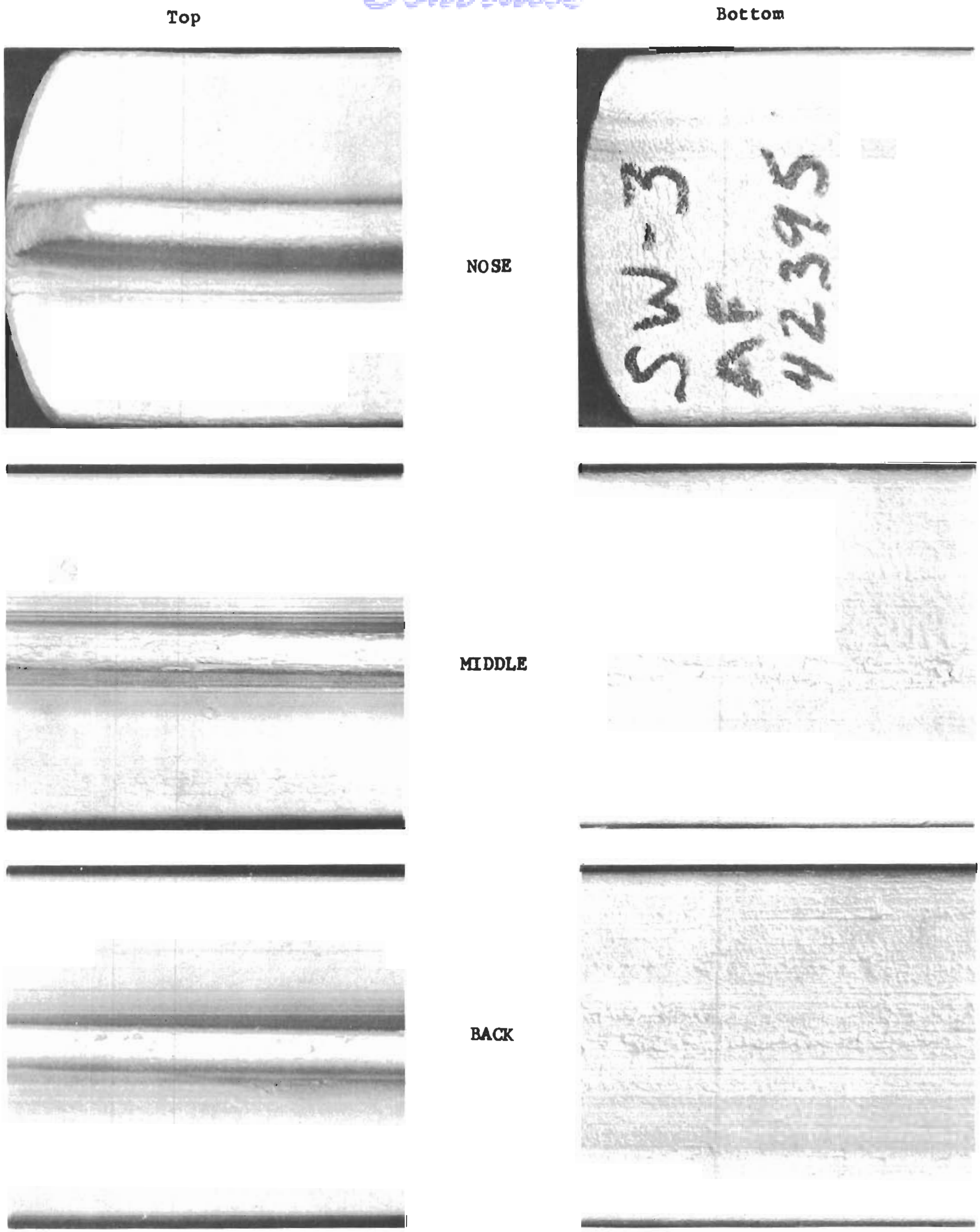


Figure 53. As-Extruded Surface of Pressed and Sintered Tungsten-3 Percent Molybdenum Extrusion 25 (Billet Code SW3) (Magnification 1-1/2X)

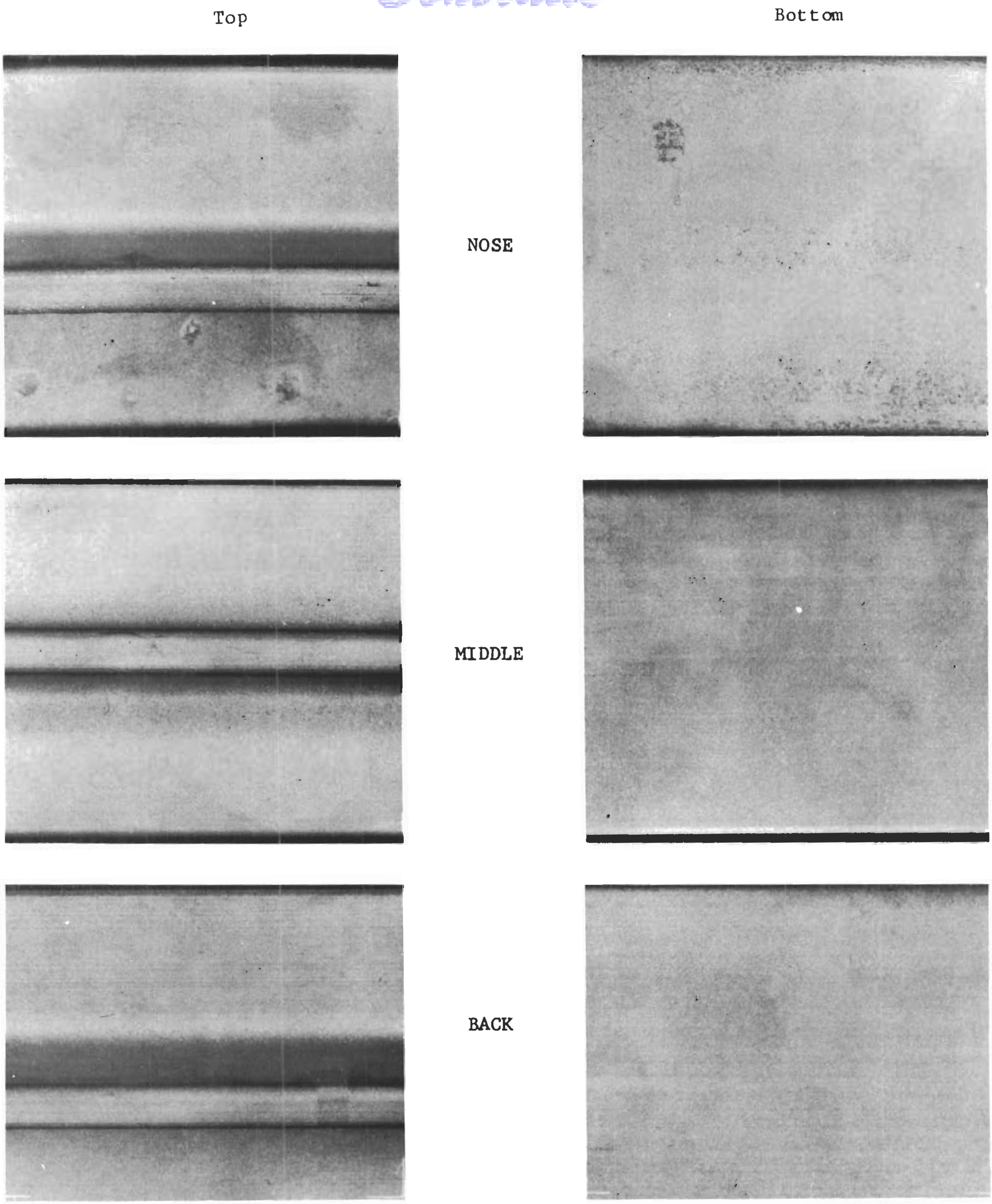


Figure 54. As-Extruded Surface of Pressed and Sintered Tungsten-3 Percent Molybdenum Extrusion 33 (Billet Code SW11) (Magnification 1-1/2X)

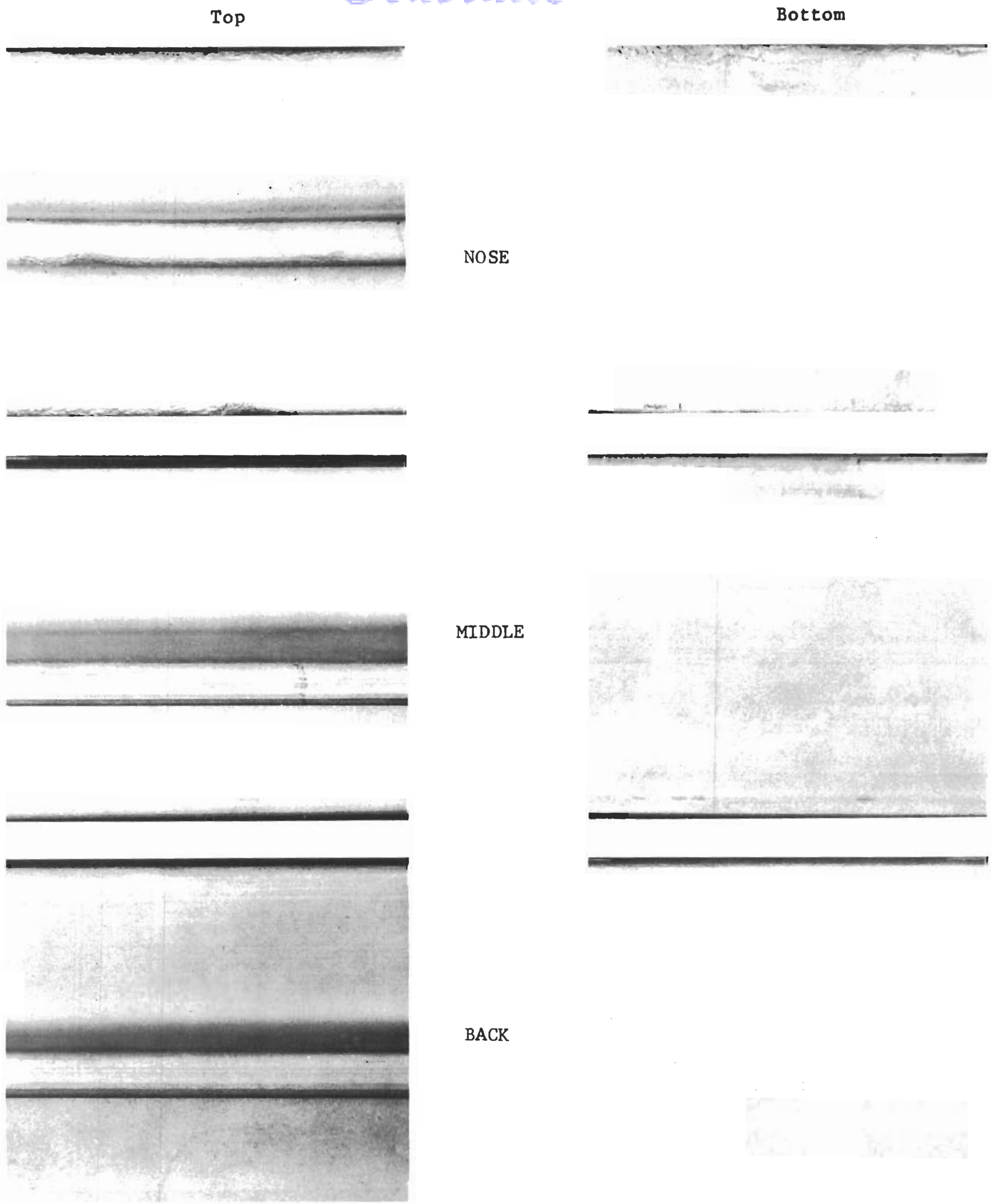


Figure 55. As-Extruded Surface of Pressed and Sintered Tungsten-3 Percent Molybdenum Extrusion 35 (Billet Code SW10) (Magnification 1-1/2X)

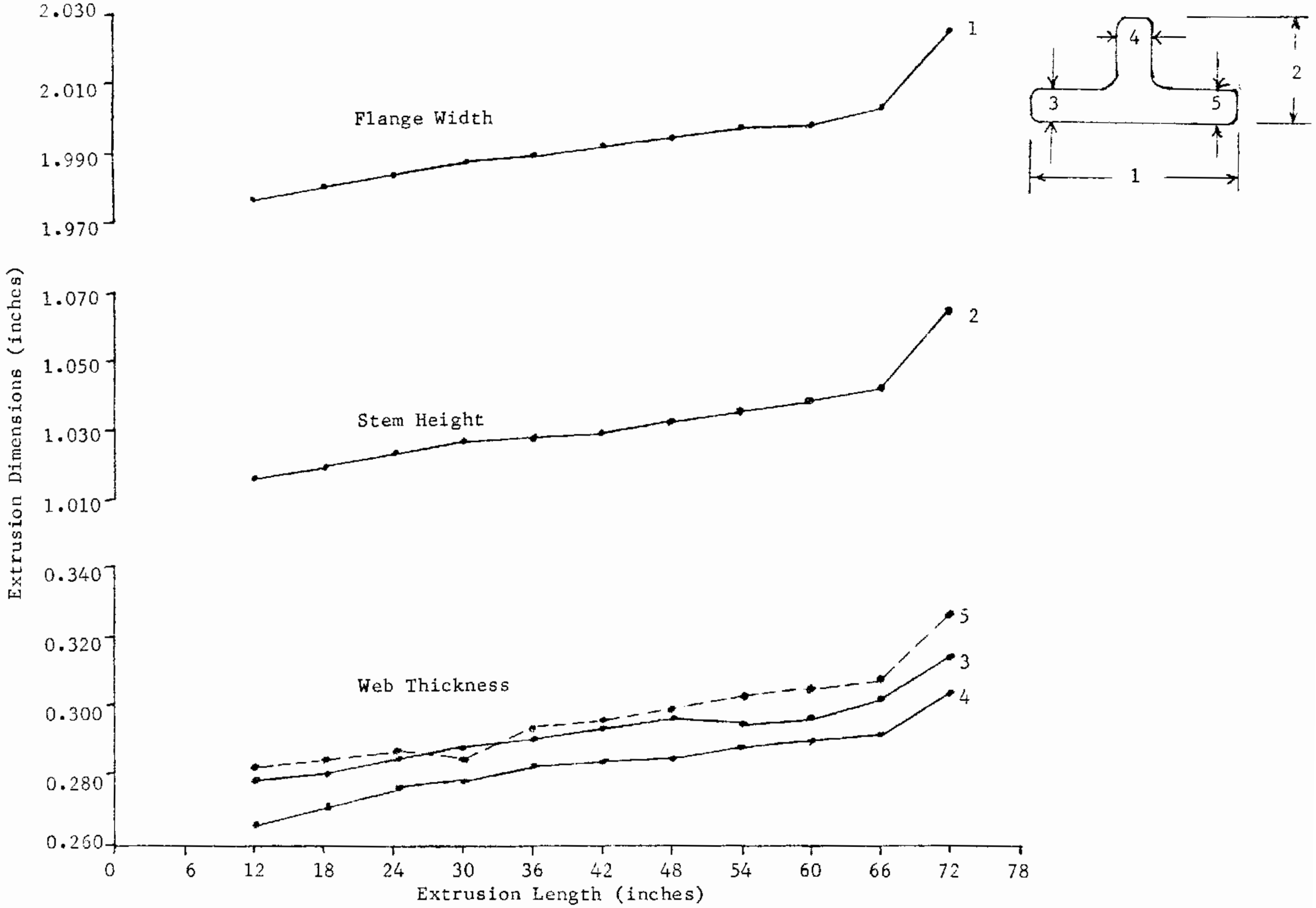


Figure 56. Extrusion Dimension Versus Extrusion Length for Extrusion 22

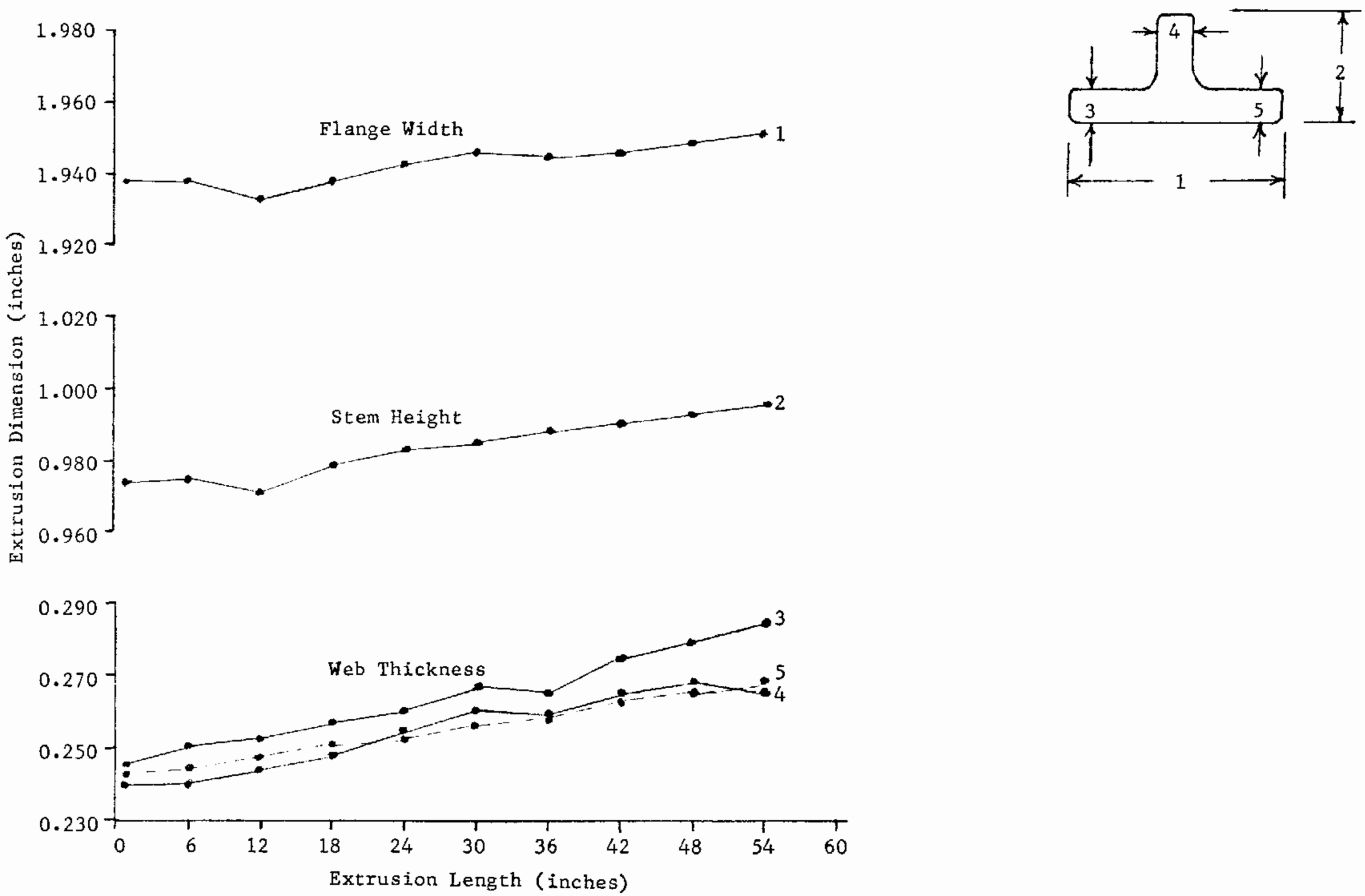


Figure 57. Extrusion Dimension Versus Extrusion Length for Extrusion 25

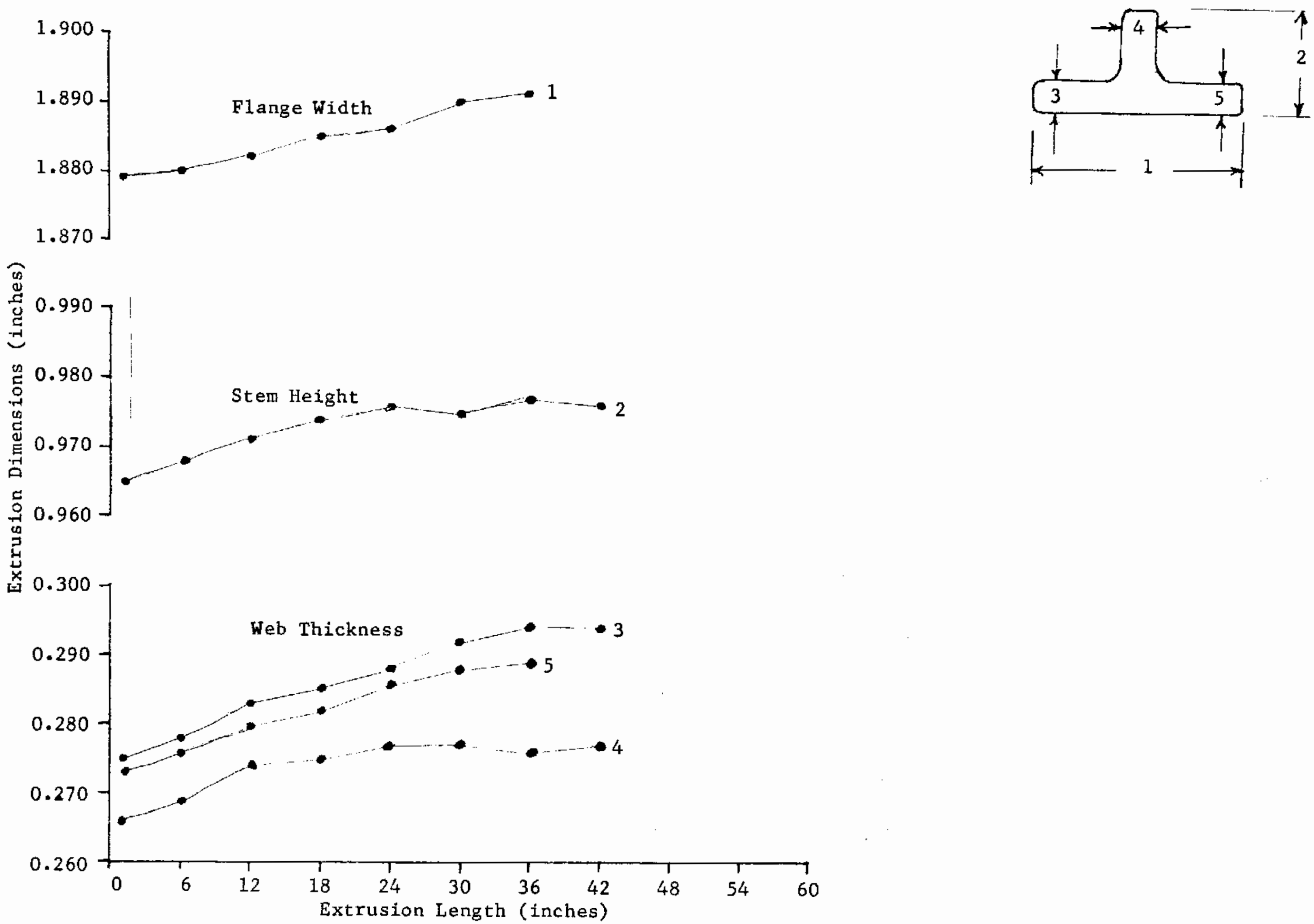
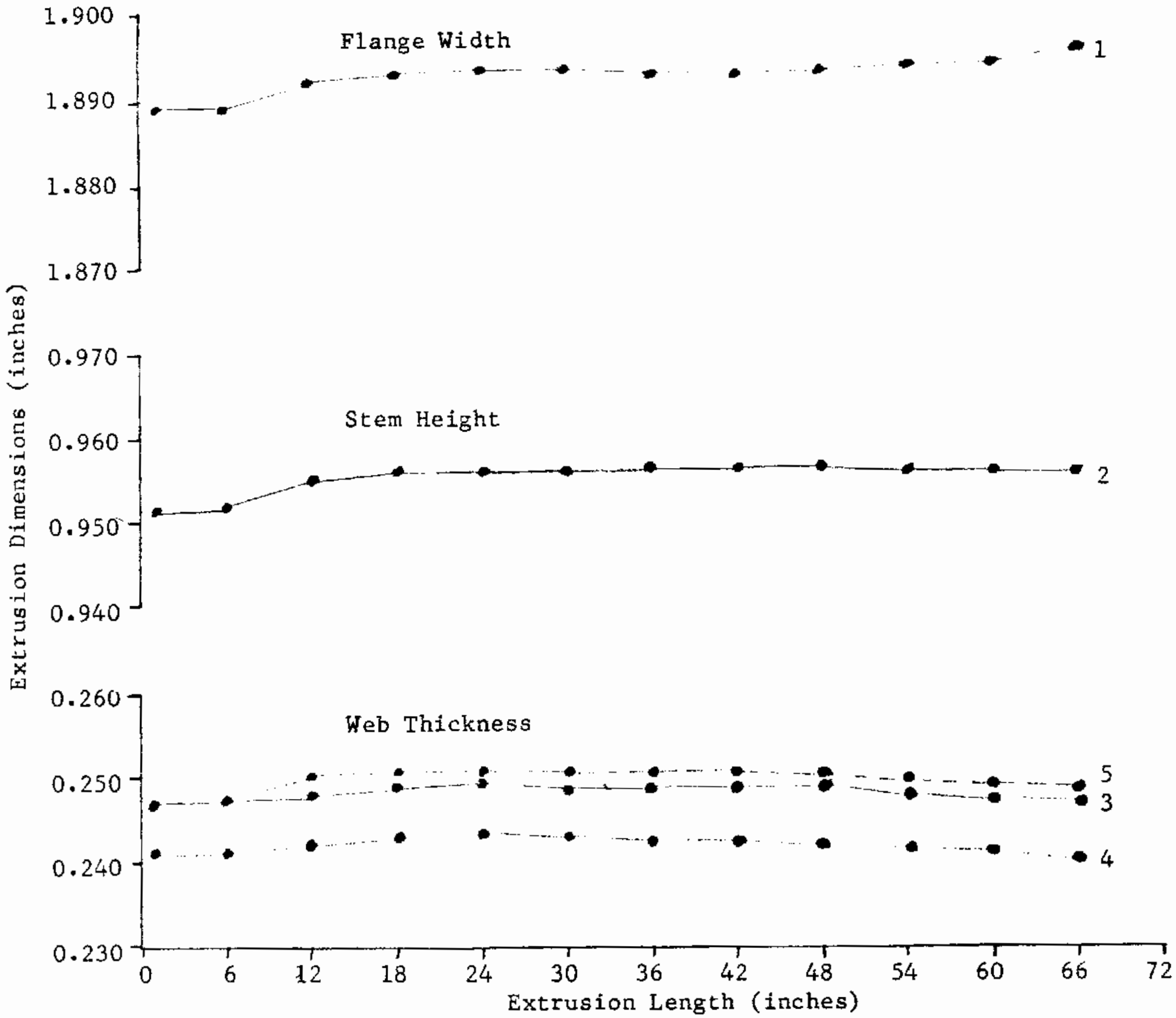


Figure 58. Extrusion Dimension Versus Extrusion Length for Extrusion 26.



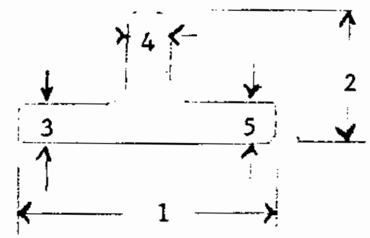


Figure 59. Extrusion Dimension Versus Extrusion Length for Extrusion 33

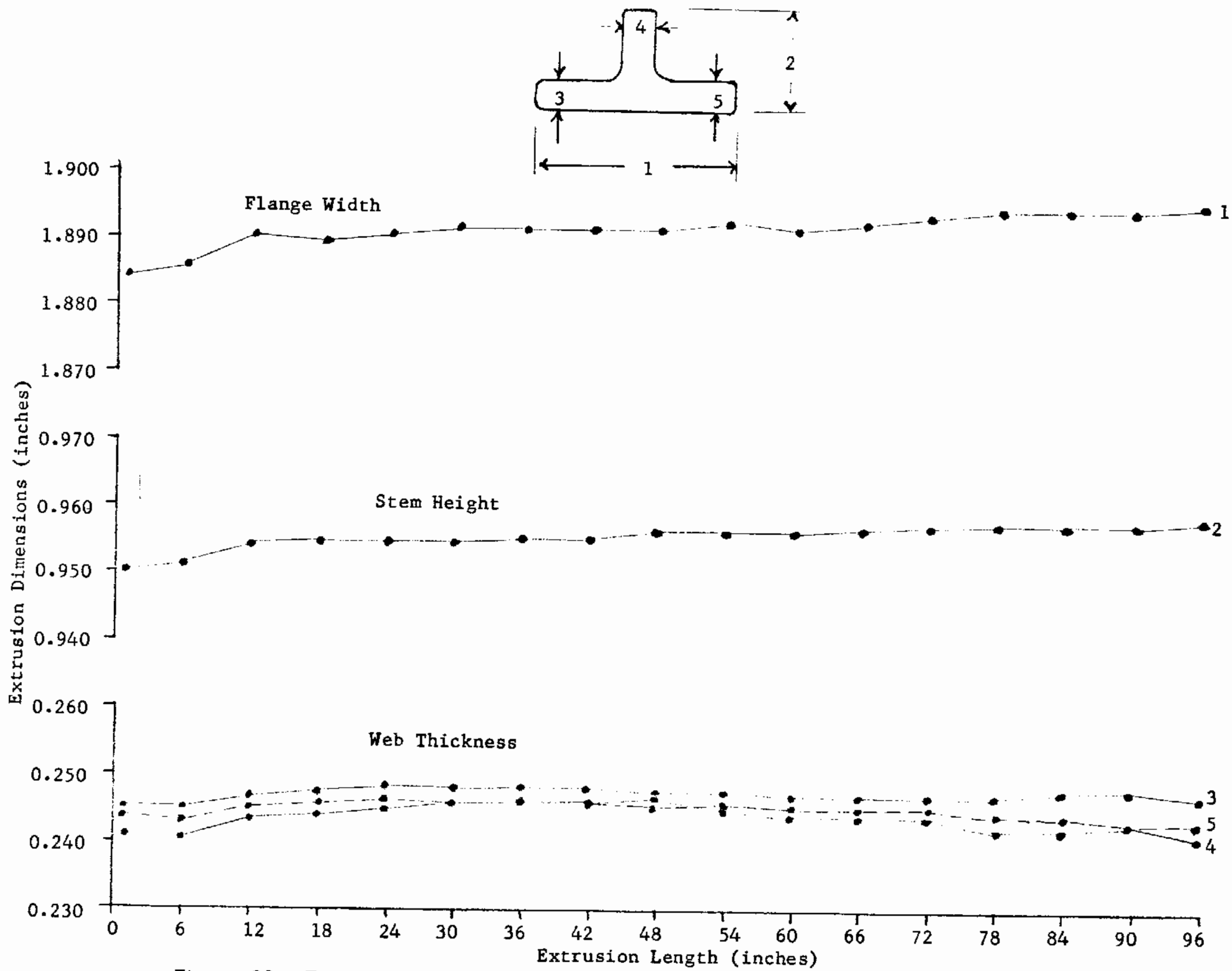
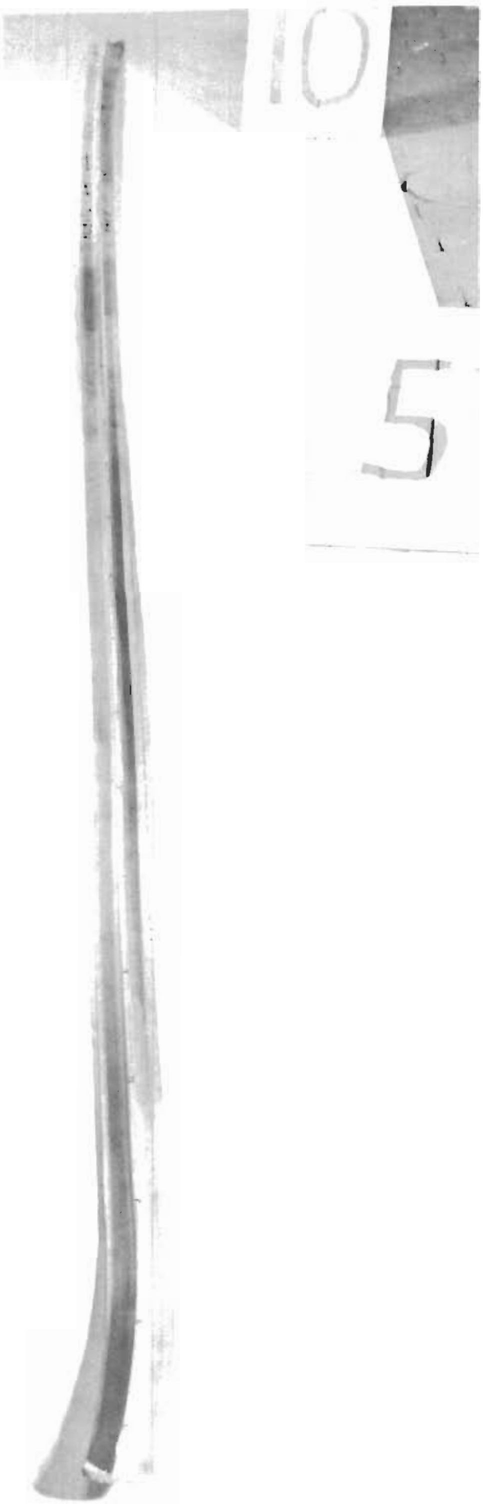
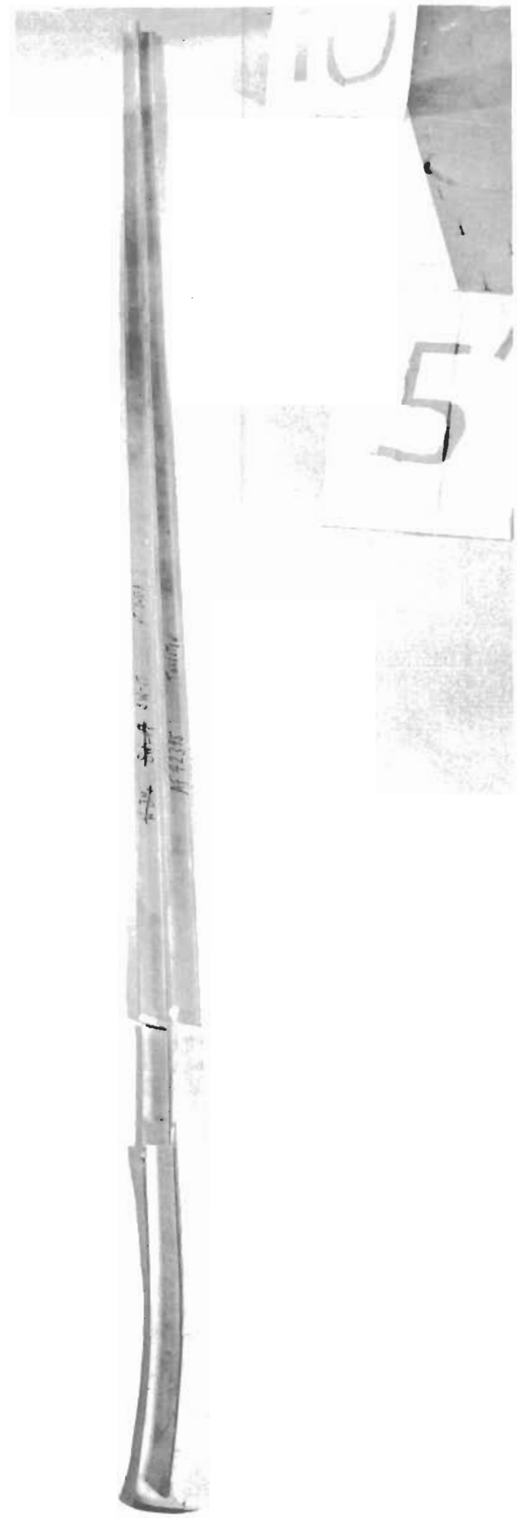


Figure 60. Extrusion Dimension Versus Extrusion Length for Extrusion 35





Nose

Extrusion 40

Billet Code SW16
Billet Heating Temperature 3720°F
Reduction Ratio 19:1

Extrusion 41

Billet Code SW17
Billet Heating Temperature 3720°F
Reduction Ratio 19:1

Figure 61. Extruded "T" Shapes of Pressed and Sintered Tungsten

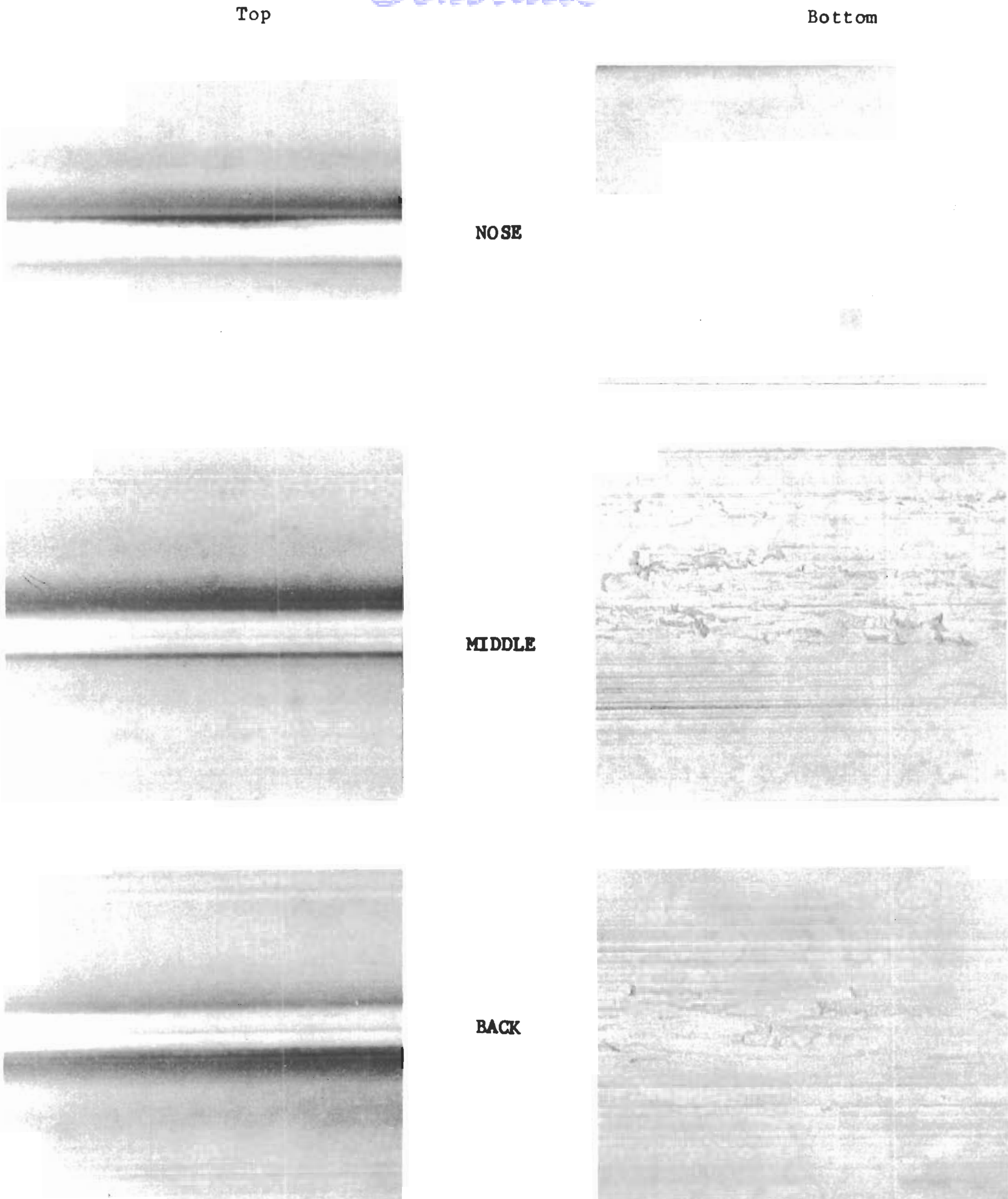


Figure 62. As-Extruded Surface of Full-Length Pressed and Sintered Tungsten Extrusion 38
(Magnification 1-1/2X)

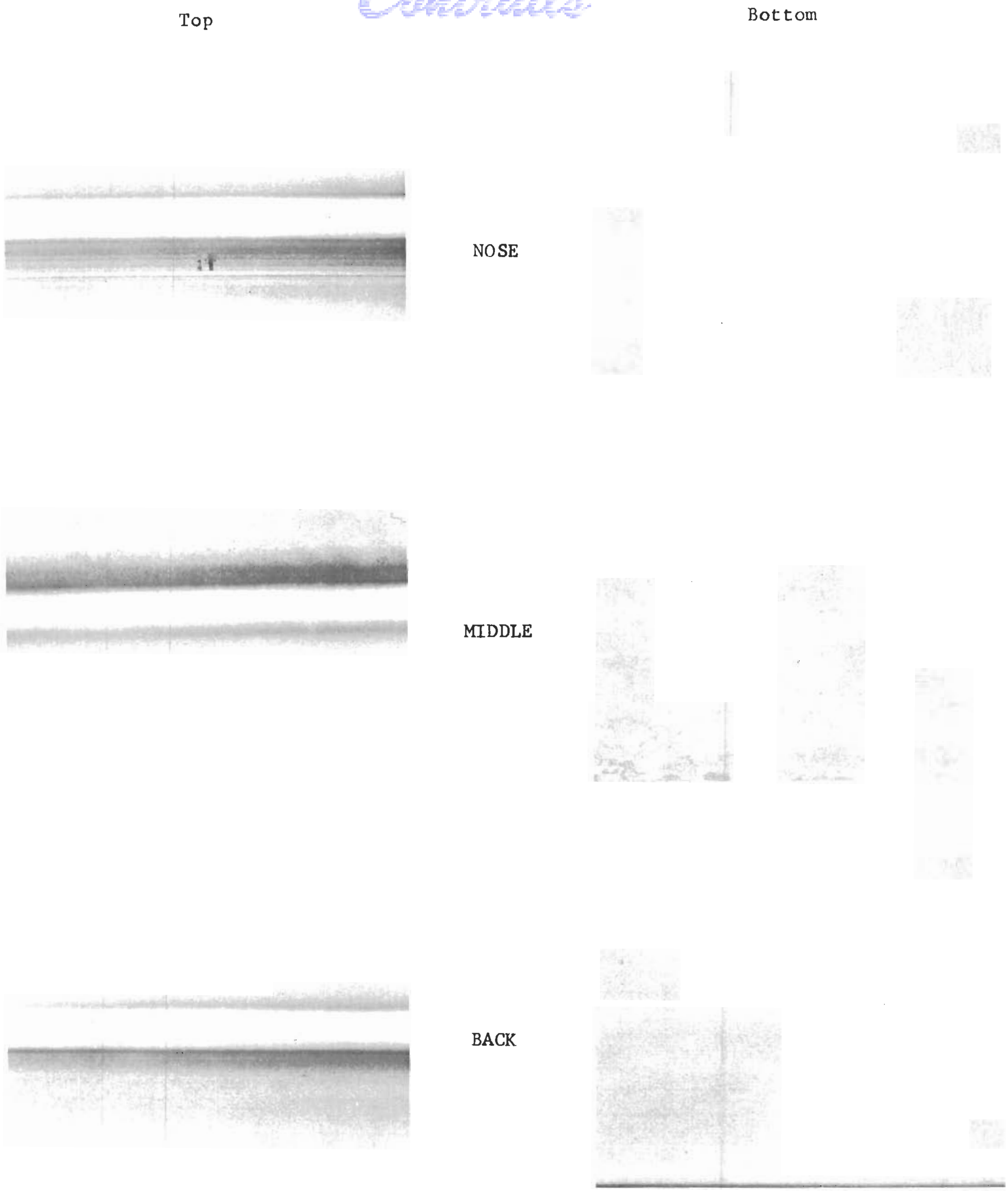


Figure 63. As-Extruded Surface of Full-Length Pressed and Sintered Tungsten Extrusion 40
(Magnification 1-1/2X)

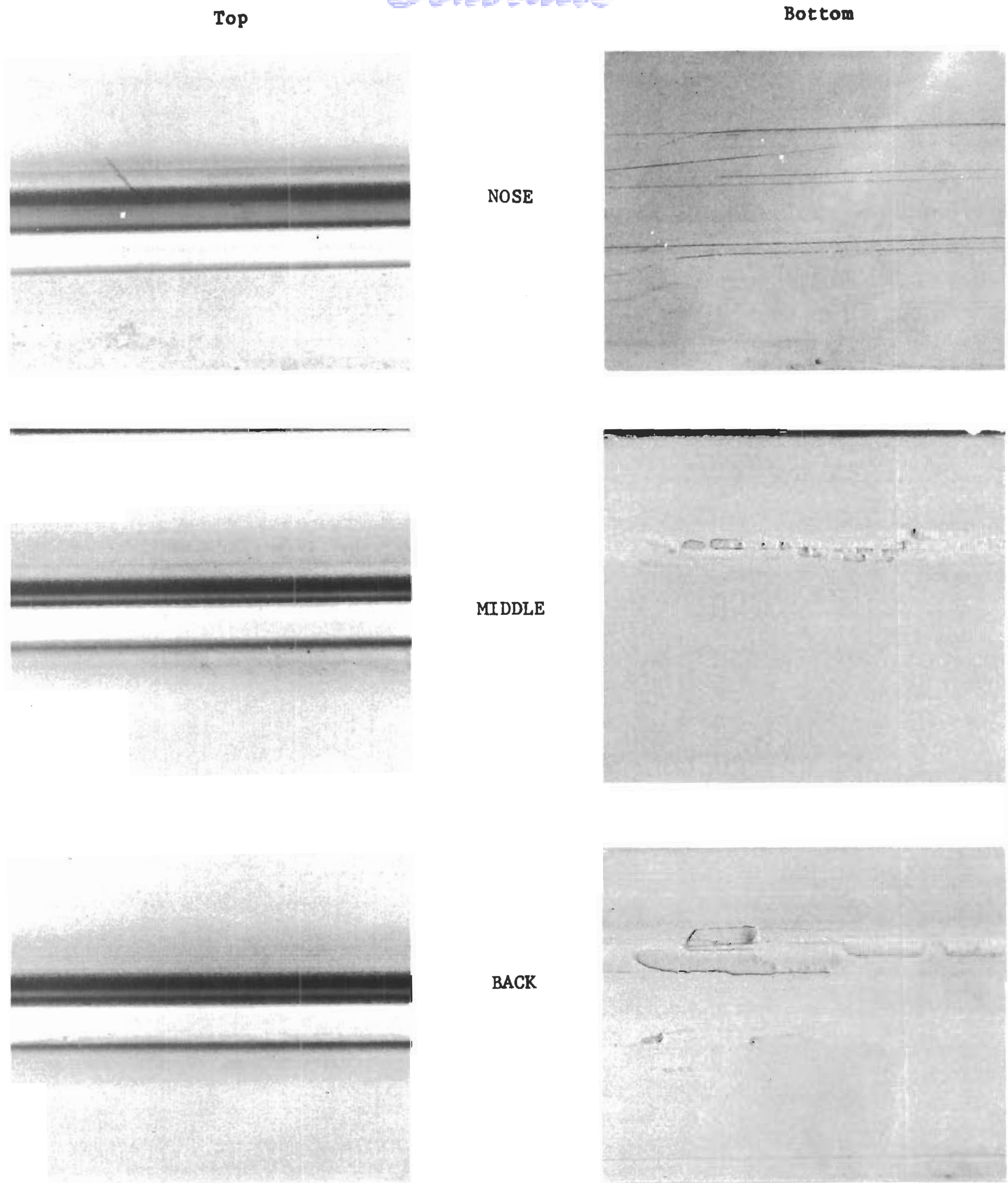


Figure 64. As-Extruded Surface of Full-Length Pressed and Sintered Tungsten Extrusion 41
(Magnification 1-1/2X)

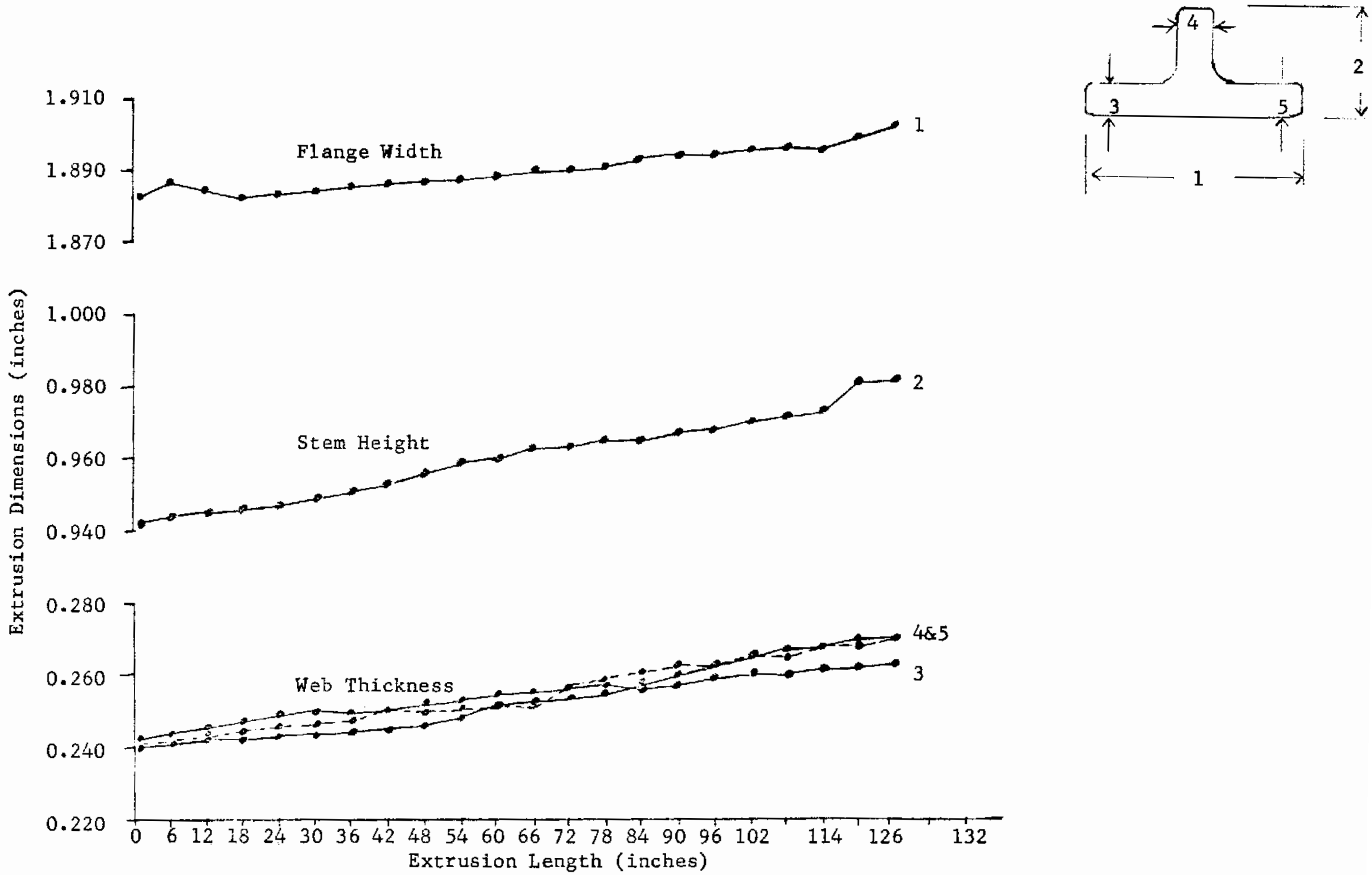


Figure 65. Extrusion Dimension Versus Extrusion Length for Extrusion 38

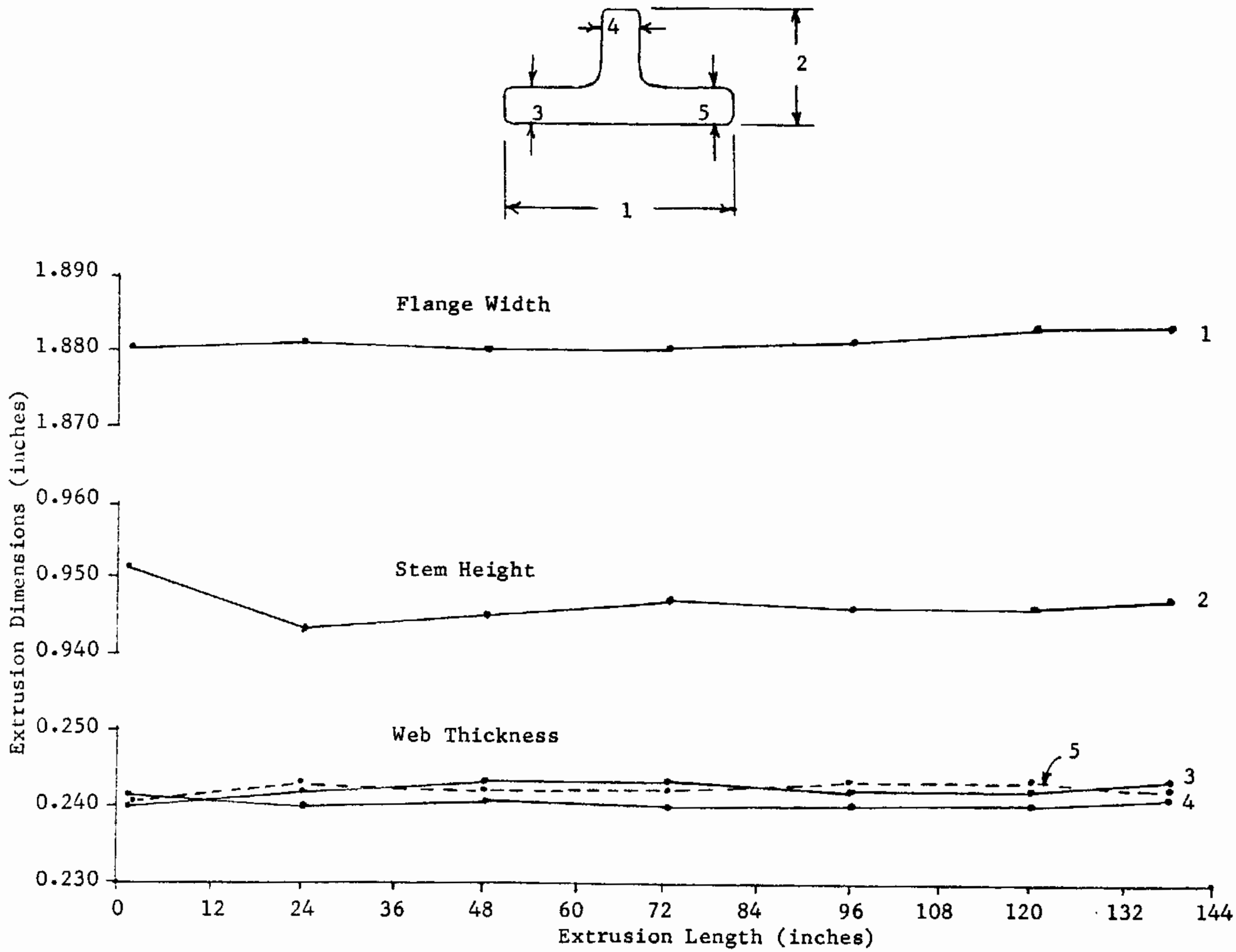


Figure 66. Extrusion Dimension Versus Extrusion Length for Extrusion 40

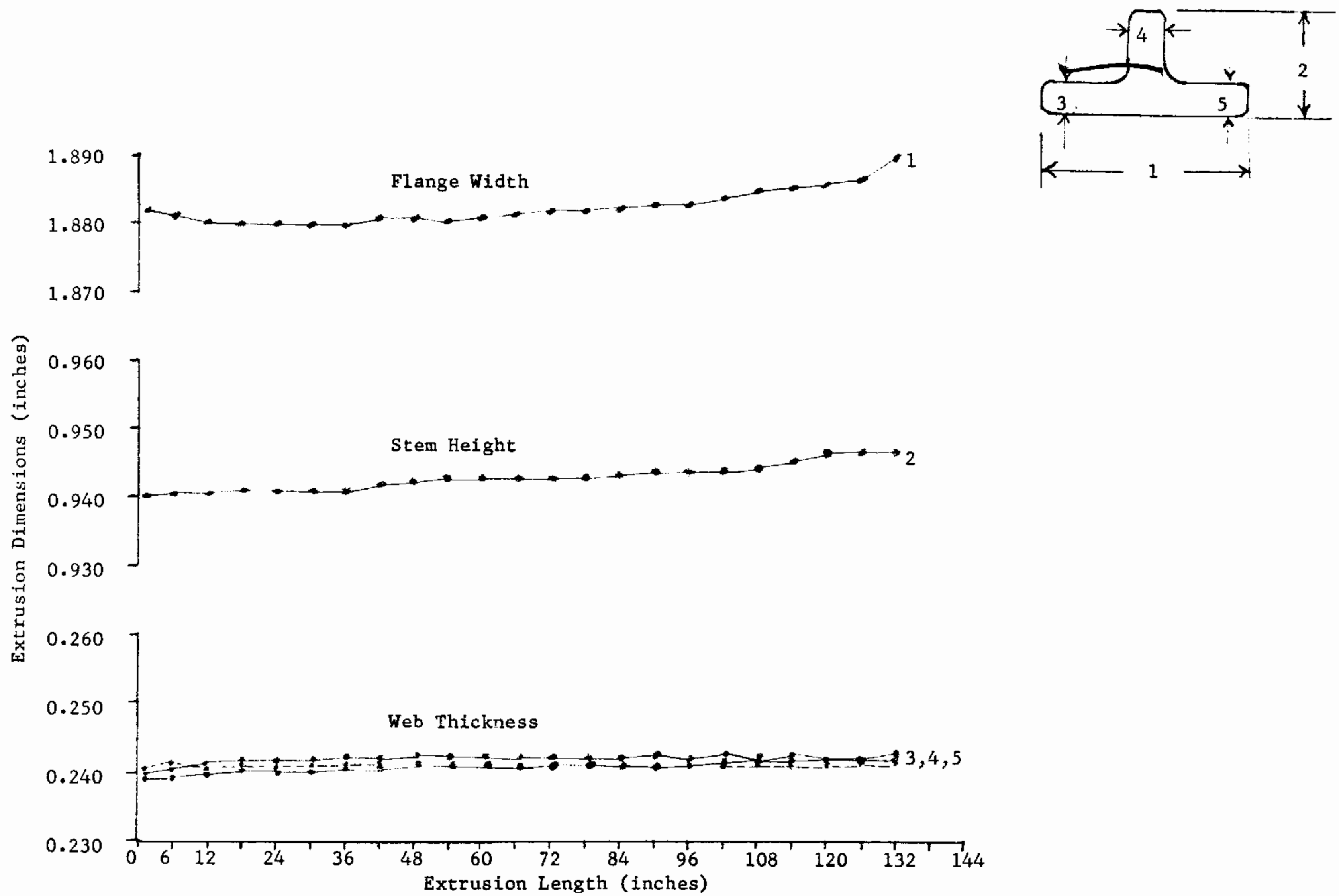
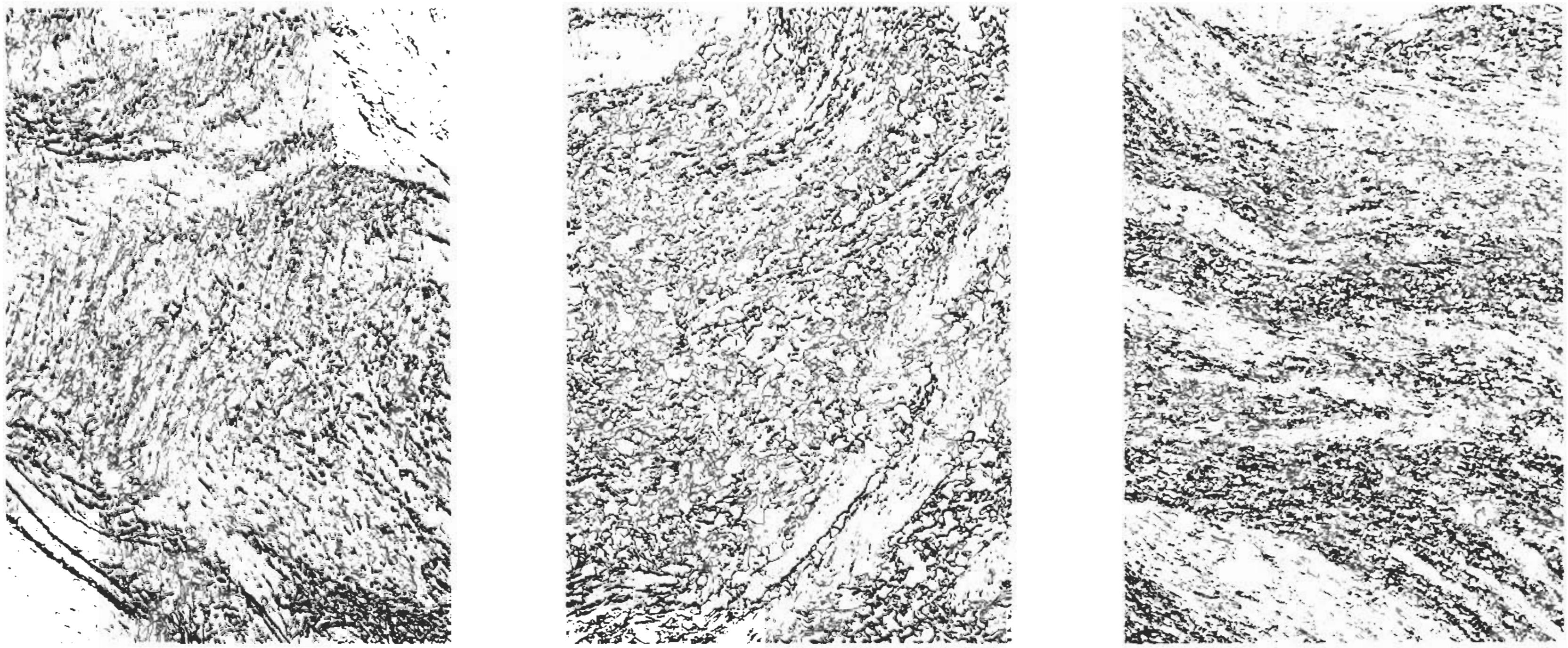


Figure 67. Extrusion Dimension Versus Extrusion Length for Extrusion 41



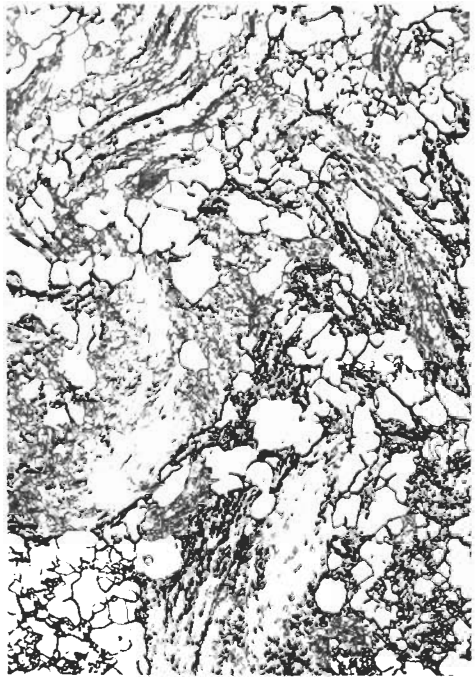
Front Middle Back

Etchant: 1-1/2% NaOH Electrolytic

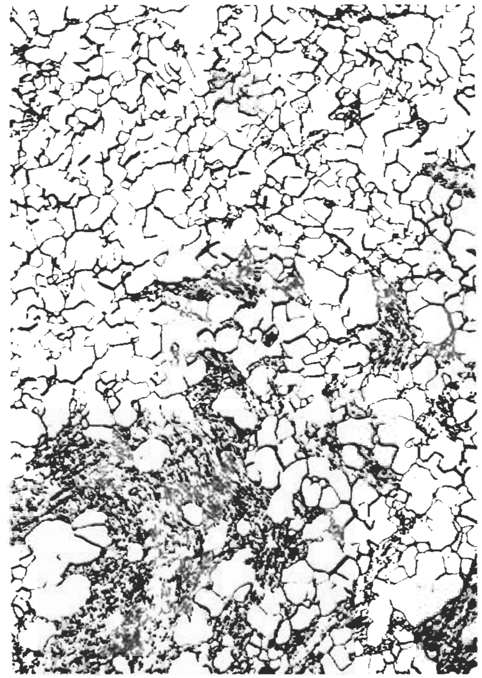
Extrusion 23

Billet Code W25
Billet Heating Temperature 3200°F
Reduction Ratio 17.9:1

Figure 68. Transverse Microstructures at Front, Middle, and Back of As-Cast Tungsten-3 Percent Molybdenum "T" Extrusion from Heat 5-4665-B (Magnification 150X)



Front



Middle

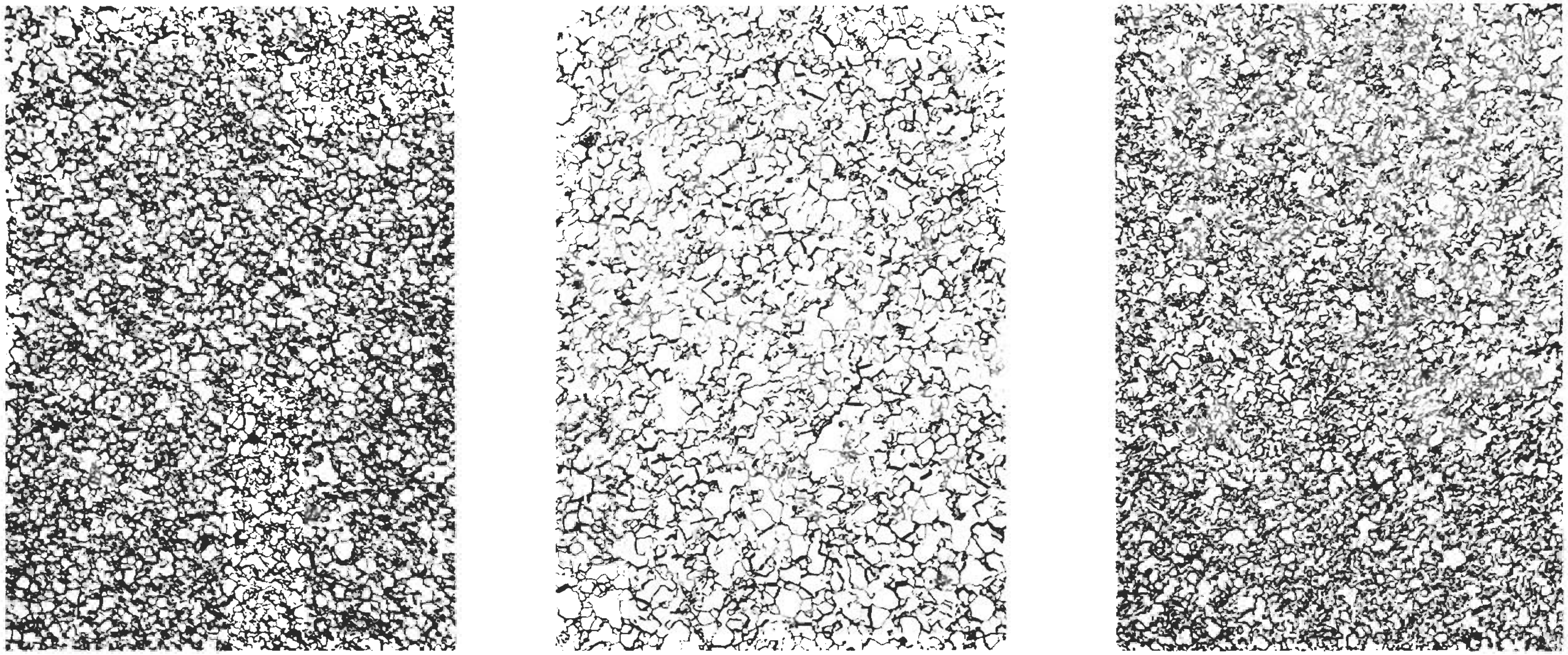
Back

Etchant: 1-1/2% NaOH Electrolytic

Extrusion 24

Billet Code W22
Billet Heating Temperature 3200°F
Reduction Ratio 18.4:1

Figure 69. Transverse Microstructures at Front, Middle, and Back of As-Cast Tungsten-3 Percent Molybdenum "T" Extrusion from Heat 5-4354-A (Magnification 150X)



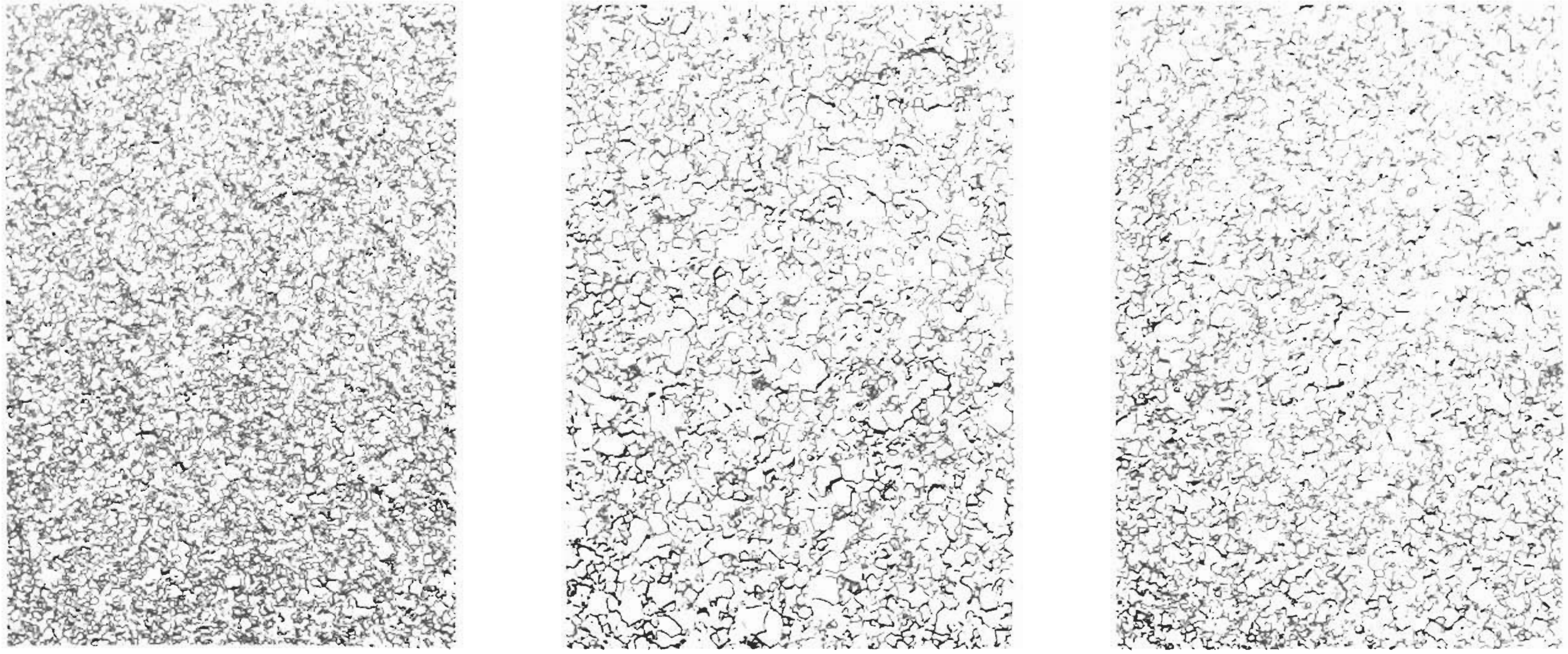
Front Middle Back

Etchant: 1-1/2% NaOH Electrolytic

Extrusion 22

Billet Code SW1
Billet Heating Temperature 3200°F
Reduction Ratio 18.7:1

Figure 70. Transverse Microstructures at Front, Middle, and Back of Pressed and Sintered Tungsten-3 Percent Molybdenum "T" Extrusion from Heat SW1
(Magnification 150X)



Front Middle Back

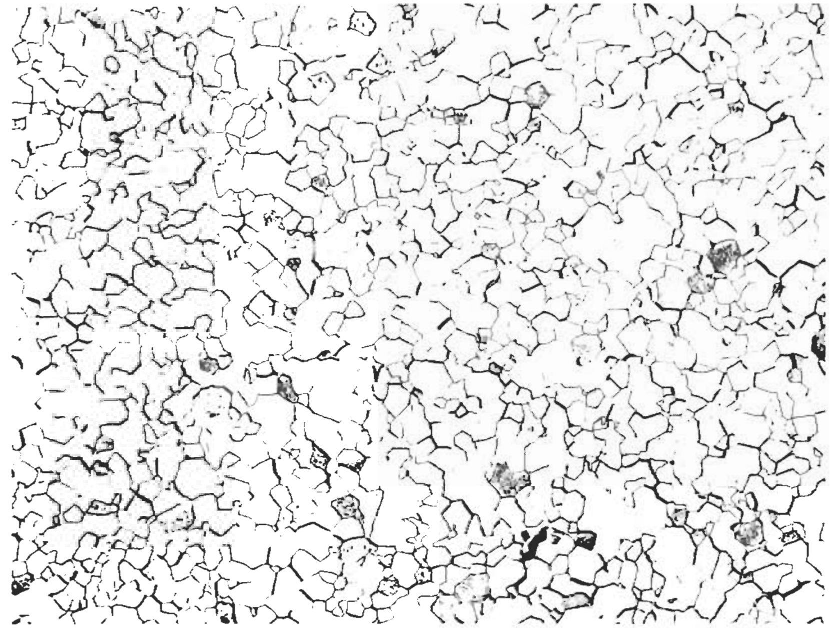
Etchant: 1-1/2% NaOH Electrolytic

Extrusion 26

Billet Code SW4
Billet Heating Temperature 3500°F
Reduction Ratio 18.5:1

Figure 71. Transverse Microstructures at Front, Middle, and Back of Pressed and Sintered Tungsten-3 Percent Molybdenum "T" Extrusion from Heat SW4 (Magnification 150X)

Note: Short black lines are believed to be cracks introduced during cutting.



Front

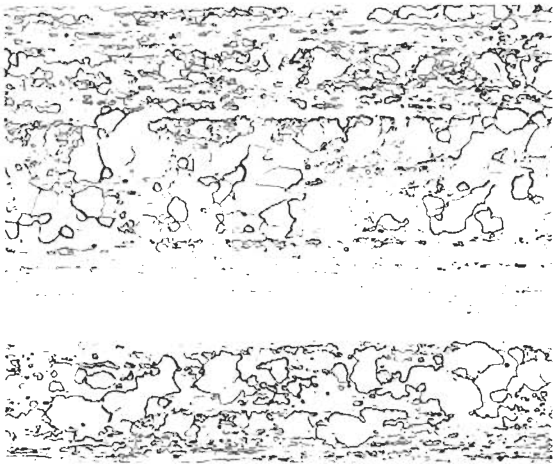
Back

Etchant: 1-1/2% NaOH Electrolytic

Extrusion 41

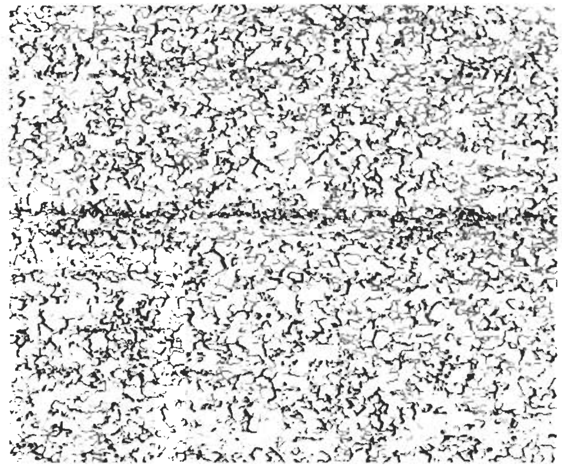
Billet Code SW17
Billet Heating Temperature 3720°F
Reduction Ratio 19:1

Figure 72. Transverse Microstructures at Front and Back of Pressed and Sintered Tungsten "T"-Shaped Extrusion from Heat SW5-A (Magnification 150X)



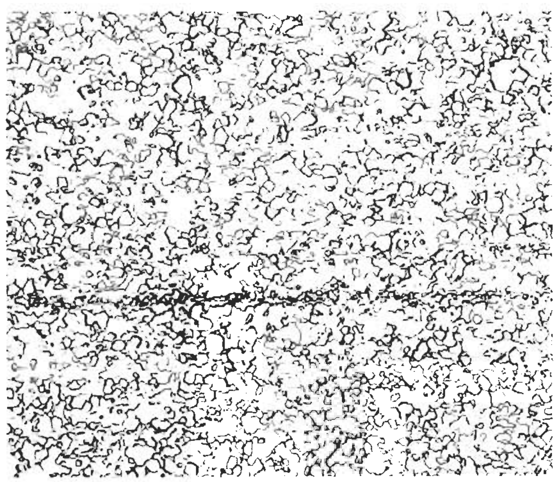
Extrusion 24
Arc Cast Tungsten-3 Percent
Molybdenum

Billet Code W22
Billet Heating Temperature 3200°F
Reduction Ratio 18.4:1



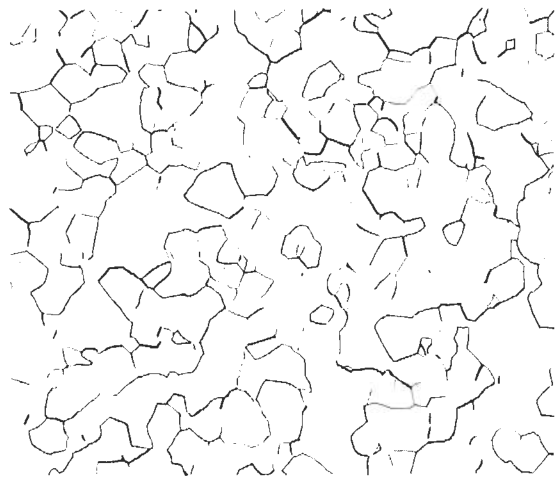
Extrusion 22
Pressed and Sintered Tungsten-3
Percent Molybdenum

Billet Code SW1
Billet Heating Temperature 3200°F
Reduction Ratio 18.7:1



Extrusion 35
Pressed and Sintered Tungsten-3
Percent Molybdenum

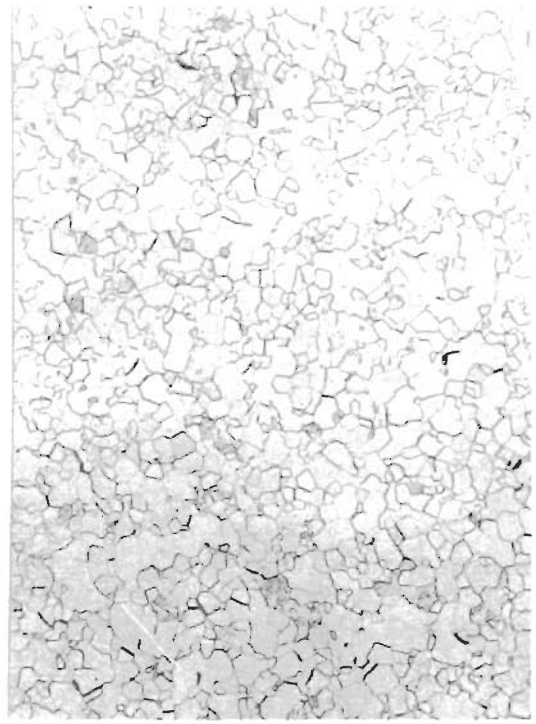
Billet Code SW10
Billet Heating Temperature 3650°F
Reduction Ratio 18.4:1



Extrusion 41
Pressed and Sintered Tungsten

Billet Code SW17
Billet Heating Temperature 3720°F
Reduction Ratio 19.2:1

Figure 73. Longitudinal Microstructures at Back Sections of "T" Extrusions
(Magnification 150X)



1800°F - 1 Hour
Vickers Hardness 431

2400°F - 1 Hour
Vickers Hardness 416

Etchant: 1-1/2% NaOH Electrolytic

Extrusion 35

Billet Code SW10
Billet Heating Temperature 3650°F
Reduction Ratio 18.4:1

Figure 74. Effect of Heat Treatment on the Transverse Microstructure at the Back Location of Pressed and Sintered Tungsten-3 Percent Molybdenum "T" Extrusion from Heat SW10 (Magnification 150X)

Bend Test Specimen

Test Temperature (F)	Angle at Fracture (°)
1200	55
1400	78
1500	84
1525	88
1550	90
1575	90
1590	90
1600	90

Transition Temperature (bracketed between 1550 and 1575)

Figure 75. Bend Transition Tests of Extrusion 35
(Magnification 2/3X)

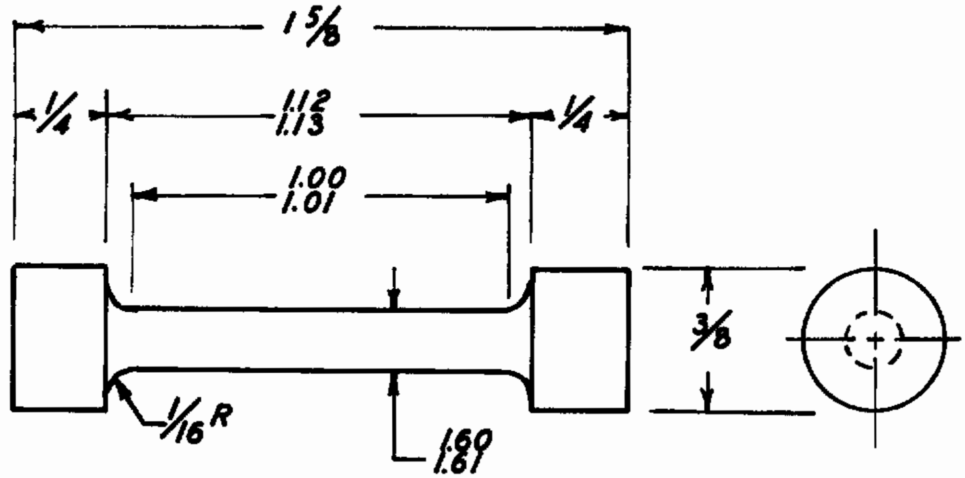


Figure 76. Specimen Design for Tensile Testing

TABLE 1

TYPICAL ANALYSES OF C-5, C-10, AND C-40 TUNGSTEN POWDER
(PARTS PER MILLION)

Element	C-5	C-10	C-40
Al	<10	<10	<10
C	10	30	10
Co	<10	<10	<10
Cr	10	<10	<10
Cu	<10	<10	<10
Fe	90	65	80
Mg	<10	<10	<10
Mn	<10	<10	<10
Mo	70	50	80
Ni	10	<10	15
O	1480	900	440
Pb	<10	<10	<10
Si	<10	<10	<10
Sn	<10	<10	<10

TABLE 2

CHEMICAL ANALYSES OF INDIRECT-RESISTANCE HYDROGEN PRESINTERED AND ELECTRON BEAM SINTERED ROUND BARS
(PARTS PER MILLION)

Element	Hydrogen Presintered	Electron Beam Sintered
Al	<20	75
B	1	1
C	100	60
Cd	<5	<5
Co	<20	<20
Cr	<20	<20
Cu	50	<40
Fe	125	<100
H	10	3.2
Mg	<20	<20
Mn	<20	<20
Mo	3.30%	3.30%
N	44	29
Ni	35	<20
O	550	100
Pb	20	<20
Si	80	<100
Sn	50	<20
Ti	<150	<20
V	<20	<20
Zn	<20	<20

TABLE 3

CHEMICAL ANALYSIS OF ELECTRON BEAM DRIP-MELTED TUNGSTEN-3 PERCENT MOLYBDENUM, HYDROGEN SINTERED BAR
(PARTS PER MILLION)

Element	Sample 1	Sample 2
Al	<20	<20
B	0.4	0.4
C	<30	<30
Cd	<5	<5
Co	<20	<20
Cr	<20	<20
Cu	<40	<40
Fe	<100	<100
H	1.7	1.6
Mg	<20	<20
Mn	<20	<20
Mo	0.66%	1.35%
N	20	24
Ni	20	<20
O	80	60
Pb	<20	<20
Si	<100	<100
Sn	<20	<20
Ti	<20	<20
V	<20	<20
Zn	<20	<20

TABLE 4

SUMMARY OF INGOT MELTING PARAMETERS

Melting Sequence	Ingot Material and Heat	Ingot Description Diameter (Inches)	Ingot Description Weight (Lbs)	Starting Electrode Form	Load Weight (Lbs) Electrode	Load Weight (Lbs) Base	Maximum Pressure During Melting (Micron)	Melting Power Amp	Melting Power Volt	Melting Rate (lbs/min)	Remarks
1	4.5-3628 W-3%Mo	4.5	36.8	3/4" x 3/4" indirect sintered, 83% density, 4 bar cluster welded	91.0	18.0	125 during startup	7,500	34	2.3	Electrode broke near stinger stub 9 min. after inception of melting
2	4.5-3573 W	4.5	57.4	1/2" x 1/2" direct sintered, 94% density, 8 bar cluster welded	80.2	20.0	1000 near end of melting run	7,500	33	1.1	Electrode broke near stinger at start of melt. Electrode rewelded and melting continued until insufficient cooling and outgassing raised pressure to 1000.
3	4.5-3646 W-3%Mo	4.5	41.5	3/4" x 3/4" indirect sintered, 85% density, 4 bar cluster welded	90.2	18.0	1000 near end of melting run	7,500	26	2.0	As pressure raised to 1000 the arc had to be shortened and electrode was inadvertently stuck into ingot top and broke off
4	4.5-3594 W	4.5	101.0	1/2" x 1/2" direct sintered, 94% density, 5 bar cluster welded	90.0	17.0	50 near middle of melting run	6,500	36	2.4	Excellent ingot obtained, very solid base and small shrink pipe
5	4.5-3693 W-3%Mo	No yield		Raw--isostatic pressed round bar with swaged W-rod as center	84.4	16.8	200 during startup	---	---	---	Electrode stuck to base at startup and crucible burnthrough occurred
6	5-3770 W-3%Mo	5	98.8	2" diameter indirect sintered, 83% density, mechanically joined	103.0	16.0	100 near end of melting run	7,500	31	2.0	Excellent ingot obtained, very solid base, fine grained ingot. No shrink pipe.
7	5-3769 W-3%Mo	5	35.9	1/2" x 1/2" indirect sintered, 94% density, 5 bar cluster welded	133.5	16.0	20 during startup	8,000	30	1.8	Electrode broke and stuck to ingot top
8	4.5-3814 W-3%Mo	4.5	107.4	Quartered arc melted ingot	103.8	15.0	300	7,500	28	2.3	Used for extrusion billets W1 and W2
9	5-3870 W-3%Mo	5	102.5	Quartered arc melted ingot	99.1	15.0	18	8,000	28	3.8	Used for extrusion billet W8-11
10	5-3871 W-3%Mo	5	155.1	2-1/2" diameter sintered bars mechanically joined	157.6	15.0	55	8,000	27	1.5	Used for extrusion billets W6 and W7
11	5-3977 W-3%Mo	5	140.7	2-1/2" diameter sintered bars mechanically joined	133.9	15.0	25	8,000	30	3.1	Used for extrusion billets W3 and W4

continued....

TABLE 4 (continued)

SUMMARY OF INGOT MELTING PARAMETERS

Melting Sequence	Ingot Material and Heat	Ingot Description Diameter (Inches)	Ingot Description Weight (Lbs)	Starting Electrode Form	Load Weight (Lbs) Electrode	Load Weight (Lbs) Base	Maximum Pressure During Melting (Micron)	Melting Power Amp	Melting Power Volt	Melting Rate (lbs/min)	Remarks
12	5-3978 W-3%Mo	5	147.4	2-1/2" diameter sintered bars mechanically joined	140.7	15.0	75	8,000	28	1.3	Used for extrusion billet W5
13	5-4186 W-3%Mo	5	148.0	2-1/2" diameter sintered bars mechanically joined	151.7	15.0	100	9,000	32	2.3	Used for extrusion billets W27 and W28
14	5-4354 W-3%Mo	5	167.8	2-1/2" diameter sintered bars mechanically joined	155.9	15.0	10	9,000	30	3.1	Used for extrusion billets W22 and W26
15	4.5-4364 W-3%Mo	4.5	139.0	2-1/2" diameter sintered bars mechanically joined	127.4	13.0	25	8,000	25	1.7	Used for extrusion billets W12 and W13
16	5-4578 W-3%Mo	5	169.4	2-1/2" diameter sintered bars mechanically joined	177.8	15.0	300	9,800	33	1.9	Used for extrusion billets W14 and W15
17	5-4604 W-3%Mo	5	106.0	2-1/2" diameter sintered bars mechanically joined	145.4	15.0	900	10,000	30	2.1	Used for extrusion billet W16
18	5-4519 W-3%Mo	5	162.5	2-1/2" diameter sintered bars mechanically joined	152.9	15.0	125	10,500	30	2.4	Used for extrusion billets W29 and W30
19	5-4620 W-3%Mo	5	147.4	2-1/2" diameter sintered bars mechanically joined	158.6	15.0	40	10,000	30	2.5	Used for extrusion billets W17 and W18
20	5-4621 W-3%Mo	5	148.5	2-1/2" diameter sintered bars mechanically joined	140.0	15.0	60	11,000	31	2.0	Used for extrusion billets W23 and W24
21	5-4622 W-3%Mo	5	159.4	2-1/2" diameter sintered bars mechanically joined	152.3	15.0	35	11,000	30	4.1	Used for extrusion billets W19 and W20
22	5-4663 W-3%Mo	5	157.1	2-1/2" diameter sintered bars mechanically joined	147.3	15.0	700	10,000	30	4.1	Used for extrusion billets W21 and W25

TABLE 5

EVALUATION INGOT PHYSICAL PARAMETERS

No.	Ingot No.	Hardness Traverse (R_C) Longitudinal		Hardness Traverse (R_C) Transverse		Sidewall Cleanup (Radius)	Depth of Base To Sound Metal Center	Depth of Base To Sound Metal Sidewall	Depth of Shrink Pipe
1	5-3769	17		23.5					
	W-3%Mo	33		31.0					
		24		40	Center	1/2"	3/4"	1-3/8"	5/8"
		34		30					
		14	Top	29.5					
2	4.5-3646	25		18					
	W-3%Mo	35		26					
		32		34.5	Center	3/8"	1"	1-3/4"	1/2"
		31.5		26					
		31.5	Top	18					
3	4.5-3573	24		25					
	W	28		24.5					
		23		26.5	Center	1/4"	1"	2-1/2"	None
		36		24					
		37.5	Top	23					
4	4.5-3628	31		35					
	W-3%Mo	33		21					
		33		15	Center	1/4"	1"	2-3/8"	1"
		31		24					
		32	Top	31					

TABLE 6

CHEMISTRY OF DESTRUCTIVELY EVALUATED INGOTS
(PARTS PER MILLION)

Element	Ingot 5-3769	Ingot 4.5-3646	Ingot 4.5-3573	Ingot 4.5-3628	Ingot 5-3770
Al	<20	<20	<20	<20	<20
B	<1	<1	<1	<1	<1
C	35	<30	<30	<30	<30
Cd	<5	<5	<5	<5	<5
Co	<20	<20	<20	<20	<20
Cr	<20	<20	<20	<20	<20
Cu	<40	<40	<40	<40	<40
Fe	<100	<100	<100	<100	<100
H	9	4.6	5	9	2.8
Mg	<20	<20	<20	<20	<20
Mn	<20	<20	<20	<20	<20
Mo	3.4%	3.5%	3.5%	3.4%	3.3%
N	60	63	26	18	19
Ni	<20	<20	<20	<20	<20
O	80	70	<50	<50	<50
Pb	20	35	<20	<20	<20
Si	<100	<100	<100	<100	<100
Sn	<20	<20	<20	<20	<20
Ti	<20	<20	<20	<20	<20
V	<20	<20	<20	<20	<20
Zn	<50	<50	<50	<50	<50

TABLE 7

CHEMICAL ANALYSES OF TUNGSTEN POWDER USED FOR POWDER METALLURGY BILLETS (PARTS PER MILLION)

Element	C8-133	C10-118	C40-103
Al	<10	<10	<10
C	70	27	40
Co	<10	<10	<10
Cr	<10	<10	25
Cu	<10	<10	<10
Fe	50	25	70
Mg	<10	<10	<10
Mn	<10	<10	<10
Mo	30	15	150
Ni	<10	15	30
O	820	320	300
Pb	<10	<10	<10
Si	<10	<10	<10
Sn	<10	<10	<10

TABLE 8

CHEMICAL ANALYSIS OF CLIMAX TUNGSTEN-3 PERCENT MOLYBDENUM EXTRUSION BILLETS (PARTS PER MILLION)

Element	Wah Chang Corporation Starting Tungsten Powder	Climax Molybdenum Final Ingot (Center)
Al	-	<10
B	-	<1
Ca	<40	15
C	60	150
Cr	<20	<10
Co	-	<5
H	4.9	<1
Fe	125	30
Mo	<500	3.3%
Ni	20	<1
N	35	<1
O	900	<4
Pb	-	1
Si	-	<20
Sn	-	<1

TABLE 9

ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM EXTRUSION BILLETS
FOR ROUND SOLID EXTRUSIONS

Billet Code No.	Heat No.	Size (Inches) Diameter	Length	Weight (Pounds)	Nose Geometry*	Chemical Analysis: Molybdenum (%)	Parts Per Million: C	O	N	H
W1	AF-3814-A	3.500	4	21.4	110°	3.00	30	55	10	6
W2	AF-3814-B	3.500	3-1/2	25	110°	3.60	45	60	14	4
W3	AF-3977-A	3.725	3-11/16	26	1"R	2.90	<30	<50	6	3
W4	AF-3977-B	3.724	3-13/16	26.7	1"R	2.90	<30	<50	8	2.7
W5	AF-3978	3.724	4-7/8	34.7	1"R	3.00	<30	<50	6	2.8
W6	AF-3871-A	3.725	5-1/2	37.0	110°	2.10	<30	50	10	3.4
W7	AF-3871-B	3.725	5-1/4	35.4	110°	2.90	<30	70	11	3.1
W8	AF-3870	3.725	5-3/4	41.1	1"R	3.00	<30	50	12	4.2
W6-9	AF-3871-A	3.725	5-1/16	35.1	1"R	2.10	<30	50	10	3.4
W7-10	AF-3871-B	3.725	4-1/2	34.0	1"R	2.90	<30	70	11	3.1

* 110° indicates 100° bevel nose; 1"R indicates a 1-inch nose radius

TABLE 10

DIE DESIGN DATA FOR SOLID ROUND EXTRUSIONS

Die Code*	Surface Preparation	Hardness Rc	Die Coating**	Die I.D. Before Coating (Inches)	Die I.D. After Coating (Inches)	Average Thickness Of Coating (Inches)	Degree Conical Entry	Figure
DW1		52-54	Nichrome + ZrO_2	1.165	1.140		130	12
DW2		52-54	Nichrome + ZrO_2	0.955	0.944		130	12
DW3		52-54	Nichrome + ZrO_2	0.955	0.944		130	12
DM2-W4		58-60	Nichrome + ZrO_2	0.955	0.925		90	12
DW5		52-54	Nichrome + ZrO_2	1.165	1.144		130	12
DW6		52-54	Nichrome + ZrO_2	1.040	1.020		130	12
DW7		52-54	Nichrome + ZrO_2	1.040	1.019		130	12
DW5-8	Alumina grit blasted	52-54	Nichrome + ZrO_2	1.164	1.144	0.016	130	12
DM3-W9	Steel grit blasted + nitrided	58-60	Nichrome + ZrO_2	1.003	0.973	0.015	130	12
DM4-W10	Steel grit blasted + nitrided + sulfurized	58-60	Nichrome + ZrO_2	1.000	0.973	0.014	130	12

* Die material is Super DBL, high speed tool steel of M-36 type, having the following analysis:

C	Mn	Si	W	Cr	V	Mo	Ni	Co
0.82	0.41	0.47	5.30	3.95	1.78	4.32	0.04	7.65

** An initial flash coating of nichrome 0.002 to 0.003 inch was applied before applying 0.010 to 0.012 inch of zirconia, which was coated by using a plasma-arc spraying process.

TABLE 11

EXTRUSION DATA FOR ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM SOLID ROUNDS

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Billet Coating	Die Code	Die Glass Code	Reduction Ratio	Maximum Liner Pressure (ksi)	Minimum Liner Pressure (ksi)	Maximum Resistance To Deformation K (ksi)**	Minimum Resistance To Deformation K (ksi)**	Remarks
1	W1	4000	ALA-13, 11-41	DW1	ALB-14-56	11.6:1	194	177	79	72	Light nose cracks, shallow striations
2	W2	4000	ALA-13, 11-41	DW2	ALB-14-56	16.9:1	181	169	54	60	Surface damage, shallow striations
3	W3	3500	ALD-14, 11-41	DW3	AL-20(D)-56	17.1:1	197	190	70	67	Light nose cracks, shallow striations on front, tears on back
4	W4	3500	ALD-14, 11-41	DM2-W4	AL-20(D)-56	16.9:1	197	186	70	66	Severe nose cracks, shallow striations on front, tears on back
5	W5	3200	ALD-13, 11-41	DW6-5	AL-14(C)-56	12.9:1	188	184	74	72	Severe nose cracks, shallow and deep striations on surface
6	W6	3000	ALD-13, 11-41	DW7-6	AL-14(C)-56	14.8:1	---	---	---	---	No extrusion, billet dropped at furnace
7	W7	3000	ALD-15-41	DW7-6-7	AL-14(C)-56	14.8:1	208	---	>77	---	No extrusion, press blocked
8	W8	---	AL-11-45*	DW5-8	---	11.8:1	---	---	---	---	Cancelled, extrusion too low
9	W6-9	3200	ALD-22, 11-41	DM3-W9	AL-14(B)-56	15.4:1	195	192	59.6	47.2	Container released from die holder, 17 inches extruded, shallow striations and light glass rub-in
10	W7-10	---	AL-11-45*	DM4-W10	---	16.4:1	---	---	---	---	Cancelled

* Rolling coated (others spray coated)

** Calculated by $K = \frac{P}{\ln R}$, where P = Liner Pressure, R = Reduction Ratio

TABLE 12

FINAL EVALUATION RESULTS OF SOLID ROUND EXTRUSIONS OF ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Reduction Ratio	Front			Middle			Back	
				Micro	Macro	Rc	Micro	Macro	Rc	Micro	Macro
1	W1	4000	11.6:1	PR DG	C	43.1	PW DG	C	40.4	PW DG	C
2	W2	4000	16.9:1	PW DG	F	38.0	PW DG	F	37.5	PW DG	F
3	W3	3500	17.1:1	PW DG	F	38.4	PW DG	F	38.6	PR DG	C
4	W4	3500	16.9:1	PW DG	F	40.5	PW DG	F	40.5	PW DG	C
5	W5	3200	12.9:1	PR DG	C	43.9	PR DG	C	40.1	PR DG	C

W = 100 percent wrought structure

R = 100 percent recrystallization

DG = Duplex grain size

F = Fine grain macrostructure

C = Coarse grain macrostructure

PW = More than 50 percent of the microstructure in the recrystallized condition

PR = Less than 50 percent of the microstructure in the recrystallized condition

TABLE 13

ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM BILLETS FOR "T"-SHAPED EXTRUSIONS

(WAH CHANG ANALYSIS)

Billet Code	Ingot Heat	Size (Inches) Diameter	Size (Inches) Length	Weight (Pounds)	Chemical Analysis Molybdenum (%)	Parts Per Million C	O	N	H
W8-11	5-3870	3.725	5-3/4	41.1	3.00	<30	50	12	4.2
W12	4.5-4364-A	3.725	4-25/32	34.6	3.00	<30	<50	<5	2.0
W13	4.5-4364-B	3.725	4-7/8	34.3	3.00	<30	<50	<5	2.1
W14	5-4578-A	3.725	5-1/4	37.4	2.54	<30	90	32	2.0
W15	5-4578-B	3.725	5-1/8	36.5	3.07	<30	70	27	2.3
W16	5-4604	3.725	5-1/8	35.6	2.97	<30	50	4	1.6
W17	5-4620-A	3.725	5	35.5	2.82	<30	80	7	2.1
W18	5-4620-B	3.725	4-13/16	33.9	2.85	<30	60	10	2.3
W19	5-4622-A	3.725	4	34.9	3.62	40	<50	15	2.3
W20	5-4622-B	3.725	4	32.2	2.94	30	<50	15	2.4
W21	5-4665-A	3.725	4	34.3	2.76	<30	<50	20	2.1
W22	5-4354-A	3.725	3-7/10	27.5	2.75	80	<50	5	2.4
W23	5-4621-A	3.725	4	32.6	2.92	60	<50	5	2.3
W24	5-4621-B	3.725	4	32.0	3.40	40	<50	15	3.5
W25	5-4665-B	3.725	4	33.0	3.32	45	<50	15	2.5
W26	5-4354-B	3.725	3-4/5	28.3	3.10	60	<50	8	2.3
W27	5-4186-A	3.725	3-9/10	31.5	2.50	60	<50	15	1.5
W28	5-4186-B	3.725	3-4/5	29.3	3.05	55	<50	10	2.0
W29	5-4619-B	3.725	4-1/5	35.3	3.12	<30	<50	8	1.6
W30	5-4619-A	3.725	4-1/5	35.5	2.55	30	<50	12	1.2

NOTE: All billets in as-cast condition and with a 1-inch nose radius

TABLE 14

PRESSED AND SINTERED TUNGSTEN-3 PERCENT MOLYBDENUM BILLETS
FOR "T"-SHAPED EXTRUSIONS
(WAH CHANG ANALYSIS)

Billet Code	Heat	Size (Inches) Diameter	Length	Weight (Pounds)	Density* (%)
SW1	SW1	3.725	8	52.8	88.0
SW2	SW2	3.725	4-1/2	29.8	88.0
SW3	SW3	3.725		44.3	90.3
SW4	SW4	3.725		39.8	90.3
SW5	SW5	3.725		40.7	89.5
SW6	SW6	3.725	3-7/8	35.6	93.7
SW7	SW7	3.725	4-1/8	36.6	91.3
SW8	SW8	3.725	3-3/4	34.6	93.7
SW9	SW9	3.725	4	35.5	91.3
SW10	SW10	3.725	9-3/4	86.7	91.2
SW11	SW11	3.725	8-7/8	78.0	
SW12	SW12	3.725	11		

* Approximate percent of theoretical density

TABLE 15

PRESSED AND SINTERED TUNGSTEN BILLETS FOR "T"-SHAPED EXTRUSIONS
(WAH CHANG ANALYSIS)

Billet Code	Heat	Size (Inches) Diameter	Length	Weight (Pounds)	Density* (%)	Chemical Analysis (ppm) C	O	N	H
SW13	SW1-A	3.725	9	84.5	92.8	<30	<50	33	0.5
SW14	SW2-A	3.741	8-7/8	70.7		<30	<50	25	0.6
SW15	SW3-A	3.742	9	83.8		<30	<50	24	0.7
SW16	SW4-A	3.750	9	90.1	90.0	<30	80	10	1.0
SW17	SW5-A	3.755	9-1/8	82.4	90.45	<30	<50	16	1.0
SW18	SW6-A	3.749	8-7/8	70.6		30	<50	20	0.9

* Approximate percent of theoretical density

TABLE 16

DIE DESIGN DATA FOR "T"-SHAPED EXTRUSIONS

Die Code	Material	Hardness Rc	Surface Preparation	Coating Technique*	Average Thickness Of Coating (Inches)	Die Drawing	Figure
DW11	Atlas A (H21)	56	Alumina grit	Plasma-arc spray	0.015		22
DW12	ALX-6	42	Alumina grit	Plasma-arc spray + proprietary heat treatment	0.008		22
DW13	ALX	59	Alumina grit	Plasma-arc spray + proprietary heat treatment	0.008		22
DW14	Potomac M (H13)	49-52	Steel grit	Oxyacetylene spray	0.027		23
DW15	Potomac M (H13)	49-51	0.030" grooves + steel grit	Oxyacetylene spray	0.029		23
DW16	Potomac M (H13)	47-51	Steel grit	Oxyacetylene spray	0.027		23
DW17	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	0.028		23
DW18	Potomac M (H13)	47-51	Steel grit	Oxyacetylene spray	0.029		23
DW19,20	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0443	26
DW21,22	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0444	27
DW24,25	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0482	28
DW24,25	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0544	36
DW25	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0486	29
DW26,38	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0542	35
DW28,29, DM56	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0540	34
DW30	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0490	30
DW31,DM51	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0442	25
DW34,35 36,37	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0508	32
DW39	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0510	33
DM54	Potomac M (H13)	48-50	Steel grit	Oxyacetylene spray	**	B-0506	31

* Coating materials are nichrome and zirconia

** An undercoating of nichrome about 0.002 to 0.003 inch thick and final coating of about 0.040 inch thick stabilized zirconia were applied by the oxyacetylene flame spray process with solid rod feed. Careful inspection and measurements were made to insure a uniform proper thickness of coating on all internal surfaces.

TABLE 17

EXTRUSION DATA FOR ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM "T" SHAPES

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Die Code	Die Glass Code	Reduction Ratio	Maximum Liner Pressure (ksi)	Minimum Liner Pressure (ksi)	Maximum Resistance to Deformation* K (ksi)	Minimum Resistance to Deformation* K (ksi)	Remarks
11	W11	----	DW11	---	9.5:1	---	---	---	---	Cancelled
12	W12	3100	DW12	AL-15(A)-56	12.7:1	214	165	84.3	65.0	Severe die wash, poor extrusion
13	W13	3100	DW13	AL-15(A)-56	12.7:1	218	161	88.5	65.2	Severe die wash, poor extrusion
14	W14	3100	DW14	AL-20(D)-56	17.9:1	222	202	77.0	70.0	Striations and tears, glass rub-in on corners, fair dimensional run-out
15	W15	3100	DW37-W15	AL-14(B)-56	17.9:1	222	218	77.0	75.5	Striations, glass rub-in on flat surfaces, poor dimensional run-out
16	W16	3100	DW15	AL-12(F)-56	17.9:1	222	218	77.0	75.5	Light striations, deep furrows, light tears, orange peel on nose surface, fair dimensional run-out
17	W17	3200	DW17	AL-15(A)-56	17.9:1	218	202	75.5	70.0	Deep furrows, light glass rub-in, good dimensional run-out
18	W18	3200	DW18	AL-17(G)-56	18.4:1	218	214	88.4	86.6	Severe die wash, heavy die pick-up, poor dimensional run-out
19	W19	3200	DW19	AL-A-56	17.9:1	209	209	72.5	72.5	Partial extrusion - loss of container seal on die-holder

* Calculated by the formula $K = \frac{P}{\ln R}$, where P = Liner Pressure, R = Reduction Ratio

continued.....

TABLE 17 (continued)

EXTRUSION DATA FOR ARC CAST TUNGSTEN-3 PERCENT MOLYBDENUM "T" SHAPES

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Die Code	Die Glass Code	Reduction Ratio	Maximum Liner Pressure (ksi)	Minimum Liner Pressure (ksi)	Maximum Resistance to Deformation* K (ksi)	Minimum Resistance to Deformation* K (ksi)	Remarks
20	W21	3200	DW21	AL-A-56	18.5:1	206	---	70.6	---	Poor extrusion - loss of container seal on die-holder
23	W25	3200	DW25 B-0486	AL-K-56	17.9:1	222	217	77.0	75.2	54.5-inch extrusion - poor surface characterized by striations and pitting
24	W22	3200	DW22	AL-K-56	18.4:1	217	202	74.6	69.5	49-inch extrusion - poor surface characterized by striations and pitting
27	W20	3500	DW31	AL-A-56	19:1	---	---	---	---	No extrusion - billet cracked during upset and blocked press
35	W29	3700	DW28	AL-L-56	18.5:1	206	185	70.5	63.7	58-inch extrusion - poor surface characterized by striations and glass rub-in
43	W30	3350	DW39	AL-M-56	19:1	---	---	---	---	Billet heated but not extruded
44	W23	3360	DW29	AL-M-56	19:1	206	191	70.0	64.9	68-inch extrusion - some good surface, local striations

* Calculated by the formula $K = \frac{P}{\ln R}$, where P = Liner Pressure, R = Reduction Ratio

TABLE 18

EXTRUSION DATA FOR PRESSED AND SINTERED TUNGSTEN-3 PERCENT MOLYBDENUM AND TUNGSTEN "T" SHAPES

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Die Code	Die Drawing	Die Glass Code	Reduction Ratio	Maximum Liner Pressure (ksi)	Minimum Liner Pressure (ksi)	Maximum Resistance To Deformation K (ksi)*	Minimum Resistance To Deformation K (ksi)*	Remarks
Tungsten-3 Percent Molybdenum											
21	SW2	3050	DW20	B-0443	AL-J-56	17.9:1	>222	---	---	---	Press block, billet temperature too low
22	SW1	3200	DM51	B-0442	AL-J-56	18.7:1	222	210-222	75.8	71.6	Partial press block, 75-inch extrusion, poor surface quality characterized by deep striations and tears
25	SW3	3500	DW30	B-0490	AL-A-56	18.5:1	217	217-222	76.0	74.4	Partial press block (1/2-inch discard) 55-inch extrusion, poor surface quality
26	SW4	3500	DW24	B-0482	AL-A-56	18.5:1	217	216-222	76.0	74.0	Partial press block, 52-inch extrusion, poor surface quality
28	SW5	3500	DW25	B-0482	AL-L-56	19.2:1	218	---	---	---	Partial press block, 15-inch extrusion, fair surface quality
29	SW5	3500	DM54	B-0506	AL-L-56	18.7:1	222	---	---	---	Press block
30	SW7	3500	DW34	B-0508	AL-L-56	18.8:1	227	222	77.4	75.6	Partial press block, 38-inch extrusion, poor surface quality
33	SW11	3550	DW37	B-0508	AL-L-56	18.7:1	227	222	77.5	75.8	Partial press block, 70-inch extrusion, fair surface quality
34	SW12	3600	DW35	B-0508	AL-L-56	18.3:1	227	---	---	---	Press block, no extrusion
35	SW10	3650	DW36	B-0508	AL-L-56	18.4:1	216	212	74.2	72.8	106-inch extrusion, good surface quality, little glass rub-in
Tungsten											
37	SW13	3700	DW25	B-0544	AL-L-56	19:1	---	---	---	---	Heated to temperature but not extruded
38	SW14	3720	DW25	B-0544	AL-L-56	19:1	222	206	75.5	70.0	126-inch extrusion, fair surface with heavy striations
39	SW15	3740	DW24	B-0544	AL-M-56	19:1	217	190	73.8	64.5	Broken during handling at the press
40	SW16	3720	DW26	B-0542	AL-M-56	19:1	215	195	73.4	66.2	138-inch extrusion, excellent surface, striation in front billet area only four feet long
41	SW17	3720	DW38	B-0542	AL-M-56	19:1	206	190	70.0	64.5	134-inch extrusion, blisters due to billet defect
42	SW18	3720	DM56	B-0540	AL-M-56	19:1	195	191	56.6	65.0	Poor extrusion due to die coating failure

* Calculated by $K = \frac{P}{\ln R}$, where P = Liner Pressure, R = Reduction Ratio

TABLE 19

PROFILOMETER SURFACE MEASUREMENTS OF "T"-SHAPED EXTRUSIONS

Average RMS of High Peaks

Extrusion	Billet	Front						Middle						Back					
Sequence	Code	1	2	3	4	5	Avg.	1	2	3	4	5	Avg.	1	2	3	4	5	Avg.
Arc Cast Tungsten-3 Percent Molybdenum																			
23	W25	130	200	350	160	160	200	---	---	---	---	---	---*	260	120	160	190	150	176
24	W22	100	80	150	170	100	120	---	---	---	---	---	---*	110	120	140	120	140	126
36	W29	70	60	80	70	60	68	90	80	150	90	110	104	80	100	160	80	70	98
44	W23	89	90	90	70	90	84	70	70	80	70	80	74	90	90	80	80	75	79
Pressed and Sintered Tungsten-3 Percent Molybdenum																			
33	SW11	85	100	110	85	75	91	95	95	85	80	70	85	75	70	80	65	65	71
35	SW10	65	85	115	90	85	88	85	75	95	70	80	81	70	70	85	75	85	77
Pressed and Sintered Tungsten																			
38	SW14	85	105	170	60	95	103	220	160	250	150	120	180	250	230	265	450	130	265
40	SW16	80	90	90	70	85	83	75	70	95	60	80	94	80	60	95	50	95	94
41	SW17	90	100	70	80	70	82	90	80	70	100	80	84	80	90	80	60	70	76

* Extrusion too short for middle measurements

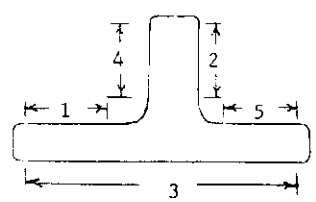


TABLE 20

HARDNESS MEASUREMENTS OF TUNGSTEN-3 PERCENT MOLYBDENUM "T"-SHAPED EXTRUSIONS STRESS RELIEVED FOR 45 MINUTES AT 1800°F (ROCKWELL C)

Extrusion Sequence	Billet Code	Billet Heating Temperature (°F)	Reduction Ratio	Front		Middle		Back	
				Range	Average	Range	Average	Range	Average
	Arc Cast								
24	W22	3200	18.4:1	39.1-43.8	41.2	39.4-41.2	40.3	39.3-42.1	40.9
44	W23	3360	19:1	43.3-45.2	44.3	41.1-43.4	42.2	43.1-44.5	43.9
	Pressed and Sintered								
25	SW3	3500	18.5:1	41.9-44.2	43.0	39.1-41.9	40.5	39.9-43.6	42.0
26	SW4	3500	18.5:1	42.0-43.0	42.3	39.1-41.5	40.1	40.0-42.1	41.1
33	SW11	3550	18.7:1	43.1-45.0	44.0	---	---*	42.0-44.8	43.2
35	SW10	3650	18.4:1	40.2-44.0	42.0	38.5-41.1	39.5	40.8-43.5	41.8

* Extrusion too short for middle measurements

TABLE 21

HARDNESS MEASUREMENTS OF TUNGSTEN-3 PERCENT MOLYBDENUM "T"-SHAPED EXTRUSIONS
STRESS RELIEVED FOR 45 MINUTES AT 1800°F
(DPH - 10 KG)**

Extrusion Sequence	Billet Code	Material	Billet Heating Temperature (°F)	Reduction Ratio	Front		Middle		Back	
					Range	Average	Range	Average	Range	Average
17	W-17	Arc cast tungsten-3 percent molybdenum	3200	17.9:1	387-437	411	394-425	408	429-450	441
24	W-22	Arc cast tungsten-3 percent molybdenum	3200	18.4:1	370-446	405	354-437	387	363-425	385
44	W-23	Arc cast tungsten-3 percent molybdenum	3360	19.0:1	421-450	436	405-437	419	401-441	429
22	SW-1	Pressed and sintered tungsten-3 percent molybdenum	3200	18.7:1	370-417	396	366-413	383	387-425	406
26	SW-4	Pressed and sintered tungsten-3 percent molybdenum	3500	18.5:1	370-455	406	354-405	388	380-405	396
41	SW-17	Pressed and sintered tungsten	3720	19.2:1	360-394	377	---	---*	330-383	358

* Extrusion too short for middle measurements

** Average of 14 readings. Locations of the cross-section on which DPH measurements were taken are shown on the sketch at right.

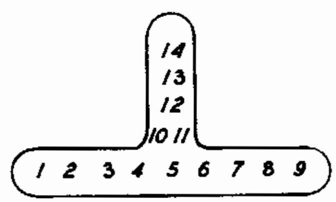


TABLE 22

TENSILE TEST RESULTS OF SPECIMENS TAKEN FROM EXTRUSION 35
PRESSED AND SINTERED TUNGSTEN-3 PERCENT MOLYBDENUM
"T"-SHAPED EXTRUSION

Temperature (°F)	Condition*	Direction**	Ultimate Strength (ksi)	0.2% Yield Strength (ksi)	% Elongation
Room (1)	A	T	--	--	--
Room (1)	A	L	--	--	--
Room (2)	B	T	--	--	--
Room (2)	B	L	--	--	--
2400	C	T	32.6	23.9	24
2400	C	L	37.7	25.2	68
2650 (3)	C	T	9.88	7.53	16
2650	C	L	15.3	12.8	27
3000	C	T	9.80	7.53	44
3000	C	L	11.5	8.73	64

* A - Stress relieved 45 minutes at 1800°F prior to preparation by grinding

B - Stress relieved 45 minutes at 1800°F before and after preparation by grinding

C - Stress relieved 1 hour at 2400°F prior to preparation by grinding

** T - Transverse

L - Longitudinal

(1) Broken during preparation

(2) Broken during initial loading

(3) Premature failure due to internal cracking

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