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SEVENTH INTERIM TECHNICAL PROGRESS REPORT
TO
MANUFACTURING TECHNOLOGY LABORATORY
DIRECTORATE OF MATERIALS
AND PROCESSES
AFSC AERONAUTICAL SYSTEMS DIVISION

TUNGSTEN FORGING DEVELOPMENT PROGRAM

CONTRACT No. AF 33(600)41629

30 NOVEMBER 1962

MATERIALS PROCESSING DEPARTMENT
TAPCO
A DIVISION OF
Thompson Ramo Wooldridge Inc.
CLEVELAND 17, OHIO

ASD TR 7-797 (VII)

ASD INTERIM REPORT 7-797 (VII)
December 1962

TUNGSTEN FORGING DEVELOPMENT PROGRAM

E. J. Breznyak
F. N. Lake

Materials Processing Department
TAPCO a division of
THOMPSON RAMO WOOLDRIDGE INC.

Contract: AF 33(600)-41629
ASD Project: 7-797

ASD Project Engineer: L. C. Polley

Seventh Interim Technical Progress Report
5 September 1962 - 30 November 1962

Large diameter centrifugally cast W-2%Mo billets have been reproducibly extruded to yield sound forging billet stock. The forging process previously developed for structural tungsten forgings has been successfully extended to thin section non-structural components in the form of a cup shape. Forging parameters have been defined. Evaluation of the W-2%Mo thin section forgings indicates process reproducibility. Ductile-brittle transition temperature and high temperature tensile properties are reported.

MANUFACTURING TECHNOLOGY LABORATORY
DIRECTORATE OF MATERIALS AND PROCESSES
AFSC Aeronautical Systems Division
United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT - SUMMARY

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Large diameter centrifugally cast W-2%Mo billets have been reproducibly extruded to yield sound forging billet stock.

The forging process previously developed for structural tungsten forgings has been successfully extended to thin section non-structural components in the form of a cup shape. Process parameters such as-forging temperatures, starting forging billet microstructure, number of forging blows, and lubrication practice have been defined. Evaluation of W-2%Mo thin section forgings produced indicates that superior surface finish, dimensional tolerances, and soundness can be reproducibly controlled by the process.

Ductile-brittle transition temperature and 3000°F, 4000°F, and 5000°F tensile properties of the W-2%Mo forgings are reported.

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NOTICES

FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF 33(600)-41629 from 5 September 1962 to 30 November 1962. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with the Materials Technology of TAPCO a division of Thompson Ramo Wooldridge Inc., Cleveland, Ohio was initiated under ASD Project 7-797, "Tungsten Forging Development". It is administered under the direction of Mr. L. C. Polley of the Manufacturing Technology Laboratory, Directorate of Materials and Processes, AFSC Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.

F. N. Lake of the Materials Processing Department, TAPCO a division of Thompson Ramo Wooldridge was the Engineer in charge. E. J. Breznyak was responsible for the execution of the program.

PUBLICATION REVIEW

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I INTRODUCTION

The use of tungsten for ultrahigh temperature components in aerospace vehicles is still a relatively new concept. Only since projected operating temperatures have reached 3000°F and above has the density of tungsten been viewed as anything but undesirable. The success of rocket nozzle engineers in designing around tungsten's density has further prompted a re-evaluation of the applicability of tungsten as a material for load carrying structural components.

The basic manufacturing method for aerospace structural components is forging. For tungsten, however, forging methods did not exist except as related to conversion steps in the lamp industry and as used for preliminary rocket nozzle shaping. For this reason the Aeronautical Systems Division, Manufacturing Technology Laboratory, initiated the present program with Thompson Ramo Wooldridge for the development of forging methods for tungsten and its alloys.

The principal objective of the program was the development of methods for producing tungsten forgings for structural use in aerospace vehicles. To accomplish this aim the program was originally divided into five phases consistent with the state-of-the-art and with the non-integrated nature of the refractory metal and forging industries. The objectives of each of these original five phases are summarized below:

Phase I State-of-the-Art-Analysis

An evaluation of the tungsten and forging industry state-of-the-art in order to satisfactorily plan the program for subsequent phases. This was completed and reported in the First Interim Technical Progress Report on 31 August 1960.

Phase II Billet Process Development

The development of processes for the production and conversion of sound tungsten ingots to quality forging bar stock. This was completed and reported in the Second Interim Technical Progress Report on 12 December 1960.

Phase III Development of the Forging Operation

The forging of tungsten billets to establish forging process parameters, controls, and tests for the controlled forging of tungsten. This was completed and reported in the Third and Fourth Interim Technical Progress Reports on 27 March and 27 May 1961 respectively.

Phase IV Forging Process Verification and Post-Forging Development

Forging tungsten to verify the developed process and the subsequent development of applicable post-forging operations. This was completed and reported in the Fifth Interim Technical Progress Report on 9 November 1961.

Phase V Final Pilot Production

Pilot production to demonstrate reliability of the developed process and of the forgings produced. This phase was successfully completed with Phase IV and also reported in the Fifth Interim Technical Progress Report.

That all of the program objectives were met is well documented (1-5). In addition, the original objectives of Phases III, IV, and V; i.e., those of development and pilot production verification of controlled precision forging methods for structural tungsten components, were accomplished within the boundaries of the third and the fourth phases. For these reasons the program has been modified and extended for adaptation of the developed technique to the continuing and more immediate problem of thin section, nonstructural tungsten shapes currently required by the rocket engine industry. The specific objectives of the revised fifth phase and the additional sixth phase are:

Phase V Development of Thin Section Forging Process

Extension of the developed forging process to controlled precision forging of thin section, nonstructural tungsten shapes having optimum properties.

Phase VI Verification of Thin Section Forging Process

Production of scaled-up thin section forgings to verify and demonstrate applicability of the process.

This Seventh Interim Technical Progress Report covers approximately the second half of the revised Phase V program effort.

II PHASE V PROGRAM

The objective of Phase V is adaptation of the process developed for structural forgings to thin section, nonstructural tungsten components presently required for aerospace applications. Although this phase is primarily a development effort from which forged hardware is to result, it may also be viewed as a combination of the first three program phases with the emphasis now placed upon nonstructural components rather than structural members. For example: (1) information regarding component configuration, required properties, and types of materials to be used is to be gathered and evaluated; (2) forging bar stock must be produced; and (3) the specific forging process for production of precision, thin section components must be developed.

Fortunately, the "universal structural" configuration concept utilized by TAPCO during the previous program phases has laid much of the basic ground work for the redirected effort. Thus, the following tasks are all scheduled for completion during the Phase V program:

1. Design of a Universal Thin Section configuration and tooling sequence representative of the basic forging variables involved in precision forging of nonstructural tungsten aerospace components.
2. Selection and procurement of the optimum tungsten-base material for nonstructural, ultrahigh temperature aerospace applications.
3. Extrusion to forging bar stock of the selected tungsten material.
4. Adaptation of the existing forging process to provide optimum properties in the thin section component.

Integration of these tasks into a single organized Phase V program is illustrated schematically in Figure 1.

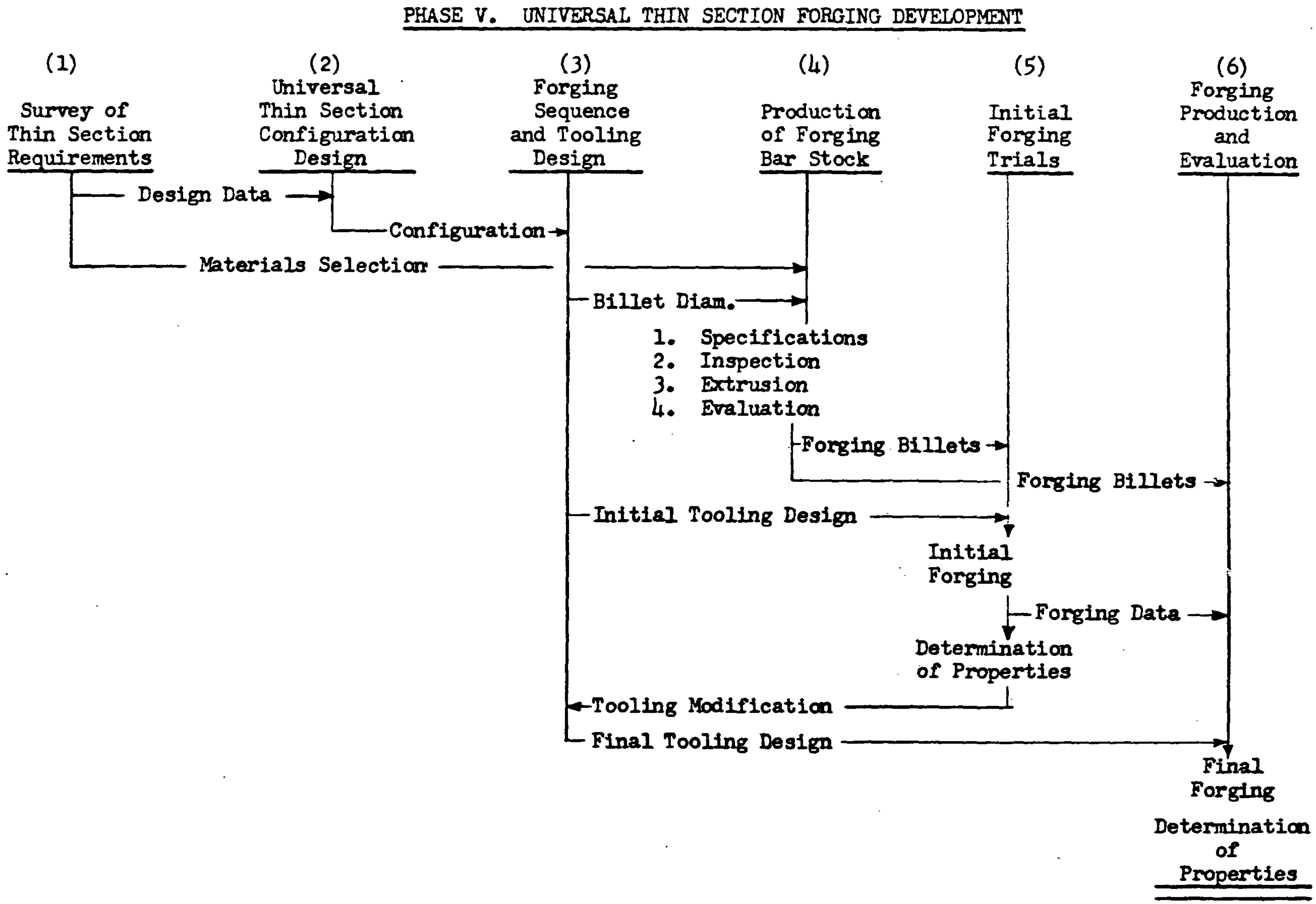


Figure 1. Plan of Operations and Programming for Phase V.

III PRODUCTION OF FORGING BAR STOCK

A. Extrusion Billet Procurement

To complete the Phase V requirements for forging billet stock, three additional arc-melted and centrifugally cast W-2%Mo extrusion billets were procured from the Oregon Metallurgical Corporation. The billets were produced in accordance with Processing and Material Specification No. 2135-7, previously reported (1). The processing and extrusion data and extrusion results for these billets are discussed in the following sections:

B. Inspection

1. Surface

TAPCO inspection of the cast extrusion billets indicated an O.D. surface finish range of 60-80 RMS, well within the 100 RMS maximum limit specified. Super zyglo fluorescent penetrant inspection performed at both Oremet and TAPCO revealed no surface discontinuities. TAPCO fluorescent penetrant inspection was performed to MIL-6866.

2. Ultrasonic Testing

Vendor ultrasonic testing results indicated all three extrusion billets to be free from internal defects. These results were confirmed by duplicate testing performed by TAPCO.

3. Chemical Analysis

Certified chemical analyses of the extrusion billets were supplied by Oremet. These analyses are listed in Table I. Since the analyses were well within the limits specified and because final billet acceptance was contingent on a specified carbon and oxygen limit in the extruded stock (1), the vendor analyses were not duplicated by TAPCO. Ultimate billet acceptance would be confirmed only after TAPCO analysis for carbon and oxygen in the extruded bar stock proved to be within the specified limit.

C. Extrusion

During Phase V a total of four arc-melted and centrifugally cast W-2%Mo billets were converted to forging billet stock. The results of the previously reported (1) 6" diameter billet extrusion attempt proved to be significantly successful in that extrusion sectioning and conditioning provided four sound, cold-worked billets for forging trials.

TABLE I

Chemical Analysis(1) of Centrifugally Cast W-2% Extrusion Billets

Element	Billet No. 6-2 Analyses	Billet No. 6-3 Analyses	Billet No. 6-4 Analyses
C	40 ppm	20 ppm*	30 ppm
O	20 ppm*	20 ppm	20 ppm*
H	2 ppm	4 ppm	1 ppm*
N	1 ppm*	1 ppm*	10 ppm
Mo	2.5%	2.2%	2.1%
Al	10 ppm*	15 ppm	10 ppm
Cr	5 ppm*	5 ppm*	5 ppm*
Co	5 ppm*	5 ppm*	5 ppm*
Cu	2 ppm*	2 ppm*	2 ppm*
Fe	20 ppm	15 ppm	20 ppm
Mg	2 ppm*	2 ppm	10 ppm
Mn	1 ppm*	1 ppm*	1 ppm*
Ni	1 ppm*	7 ppm	1 ppm*
Pb	5 ppm*	5 ppm*	5 ppm*
Si	20 ppm*	20 ppm*	20 ppm*
Sn	5 ppm*	5 ppm*	5 ppm*
Ti	5 ppm	20 ppm	5 ppm
V	5 ppm*	5 ppm*	5 ppm*
W	Balance	Balance	Balance

(1) Analysis supplied by vendor (Oremet)

* Indicates value shown is lowest quantitative result obtainable through standardization at Oremet of the techniques utilized for W-2%Mo. Techniques specified are listed in Appendix I, Sixth Interim Technical Progress Report.

The general extrusion appearance, however, outlined various areas requiring further processing refinement, i.e., the degree of surface tearing, nose burst, and pipe depth. Since such surface imperfections not only influence the ultimate billet yield per extrusion but also tend to initiate longitudinal extrusion cracking, the processing route of the three remaining billets was altered to evaluate the function of several parameters on the resultant extruded surface.

Appendix I contains the modified extrusion work statement issued to and approved by Du Pont for extrusion Nos. 6-3 and 6-4. For a direct comparison, the processing and extrusion data of all four 6" diameter billet extrusions are recorded in Table II. The processing divergence of the latter three extrusions from the first trial (extrusion No. 6-1) are detailed below:

1. Billet Configuration

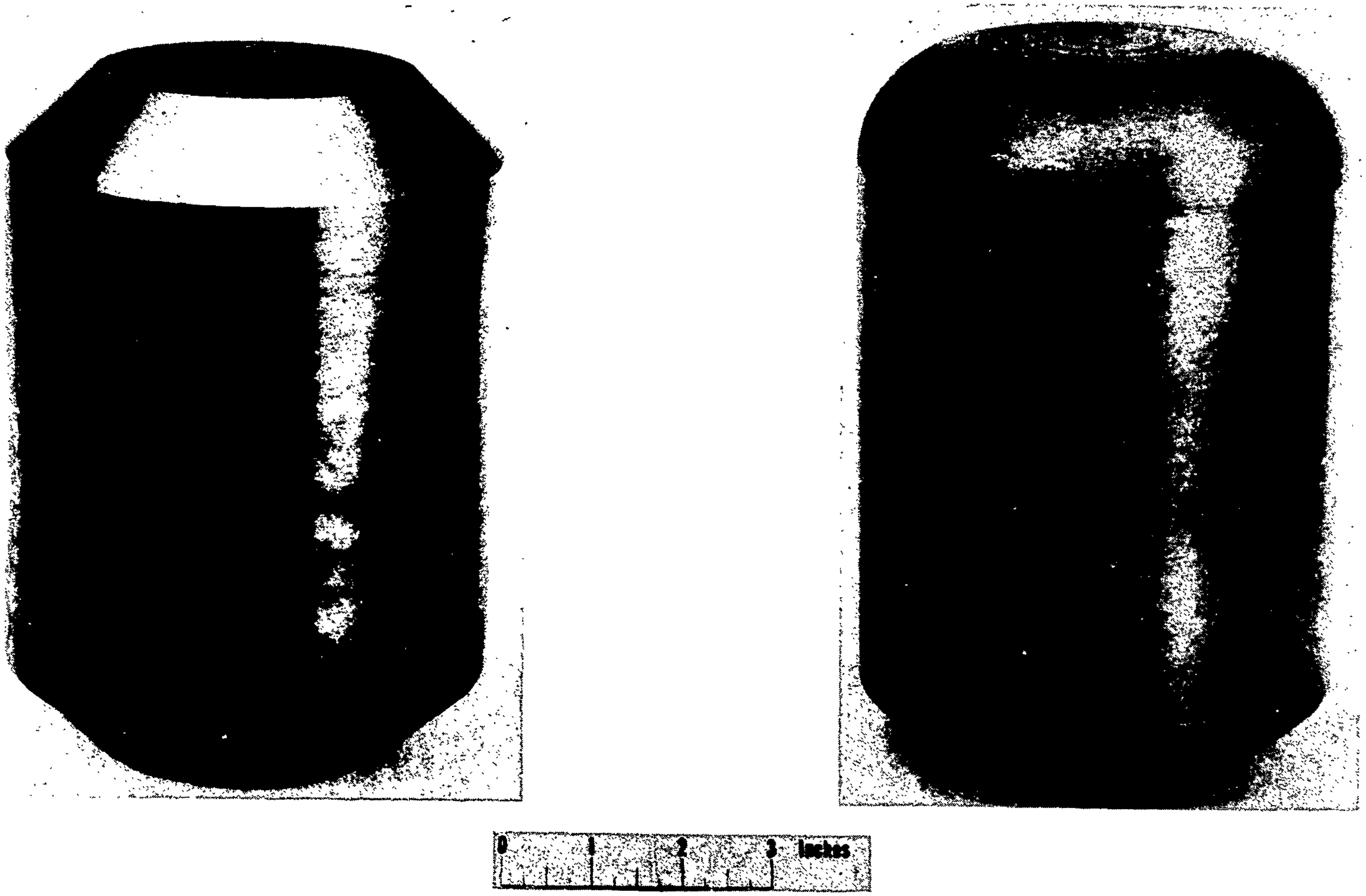
The butt side of the billets for the latter three extrusions was ground to a 1" x 45° chamfer. This type of butt configuration has demonstrated a significant reduction of pipe depth at lower extrusion speeds in a Bu Weps sponsored TAPCO program involving powder tungsten extrusions (2). The billet nose configuration for extrusion Nos. 6-3 and 6-4 were altered from 1" x 45° chamfer to a 1-1/2" radius, a change incorporating the representative nose geometry of the 3" diameter billet extrusions performed during the earlier phases of this program (3, 4, 5). These billet configurations are shown for extrusion No. 6-2 and extrusion Nos. 6-3, 6-4 in Figures 2a and 2b respectively.

2. Extrusion Temperature

The irregular die wash exhibited in extrusion No. 6-1 coupled with previously reported TAPCO data (4, 5) indicated the probability of improved die coating effectiveness with slightly decreased extrusion temperatures. The extrusion billet temperatures were, therefore, progressively lowered from the initial 3400°F used for extrusion No. 6-1 to 3250°F for extrusion Nos. 6-2 and 6-3, and 3150°F for extrusion No. 6-4.

3. Lubrication Practice

Du Pont recommended Sejournet lubrication practice was utilized for the first two extrusions (Nos. 6-1 and 6-2). The remaining two billets (Nos. 6-3 and 6-4) were extruded bare according to established TAPCO lubrication practice, using only a commercial molybdenum disulfide grease swabbed on the liner interior prior to extrusion.



06587-2 (a) Extrusion No. 6-2

06587-1 (b) Extrusion Nos. 6-3 and 6-4

PRE-EXTRUSION BILLET PREPARATION

FIGURE 2

TABLE II

Extrusion Data for Centrifugally Cast W-2%Mo Billets

Billet No.	6-1	6-2	6-3	6-4
Billet Weight (pounds)	145.4	146.5	158.8	149.2
Billet Nose Configuration	1" x 45° Chamfer	1" x 45° Chamfer	1-1/2" Radius	1-1/2" Radius
Billet Butt Configuration	Flat	1" x 45° Chamfer	1" x 45° Chamfer	1" x 45° Chamfer
Heating Method	3000 Cycle Induction	3000 Cycle Induction	3000 Cycle Induction	3000 Cycle Induction
Heating Atmosphere	Argon	Argon	Argon	Argon
Heating Time to Temperature	17 Minutes	12 Minutes	11 Minutes	10 Minutes
Temperature (Shawmeter)	3400°F	3250°F	3250°F	3150°F
Soak Time at Temperature	12 Minutes	21 Minutes	15 Minutes	20 Minutes
Lubrication Practice	Current Du Pont Sejournet	Current Du Pont Sejournet	TAPCO - Bare Molydag Swab	TAPCO - Bare Molydag Swab
Transfer Time	46 Seconds	40-45 Seconds	51 Seconds	38 Seconds
Die Configuration	Du Pont 90° Included Entrance Angle	Du Pont 90° Included Entrance Angle	TAPCO 120° Included Entrance Angle	TAPCO 120" Included Entrance Angle
Die Coating	0.030" Flame Sprayed ZrO_2	.030" Flame Sprayed ZrO_2	.040" Plasma Sprayed	.055" Plasma Sprayed
Pre-Ext. Die Orifice Diameter	3.033"	3.031"	3.015"	3.005"
Land Diameter	None	None	2.944	2.937
Die Temperature	750°F	750°F	750°F	750°F
Container Temperature	850°F-900°F	850°F-900°F	850°F-900°F	850°F-900°F
Press Throttle Setting	40% of Maximum	40% of Maximum	40% of Maximum	40% of Maximum
Breakthrough Pressure	144,000 psi	125,000 psi	142,000 psi	145,000 psi
Extrusion Constant "K"*	105,000 psi	91,800 psi	103,000 psi	104,500 psi
Average Run Pressure	131,000 psi	122,000 psi	142,000 psi	136,000 psi
Ram Speed	16"/sec.	15.2"/sec.	11.5"/sec.	11.5"/sec.
Post Ext. Die Orifice Diameter	3.091"	3.082"	3.286"	3.057"
Total Die Wash	0.058"	0.051"	0.271"	0.052"
Extrusion Diameter-Lead	3.060"	3.058"	3.015"	3.023"
Extrusion Diameter-Mid-point	3.071"	3.055"	3.042"	3.038"
Extrusion Diameter-Butt	3.085"	3.050"	3.148"	3.038"
Pipe Depth	4-1/2"	2-21/32"	4-1/2"	4-3/4"

* $P = "K" \ln \frac{A_1}{A_2}$ Where P = extrusion breakthrough pressure
K = extrusion constant
A_1 = upset billet cross sectional area
A_2 = extrusion cross sectional area

4. Die Configuration

Du Pont recommended die configuration was utilized for the first two extrusions while TAPCO developed die practice was applied to the remaining two extrusions. The basic die design difference are shown in Figure 3a and 3b. Du Pont die design utilizes a 90° included die entrance angle as compared to TAPCO design of an included die entrance angle of 120°, a more generously radiused throat, and a slightly greater relief angle.

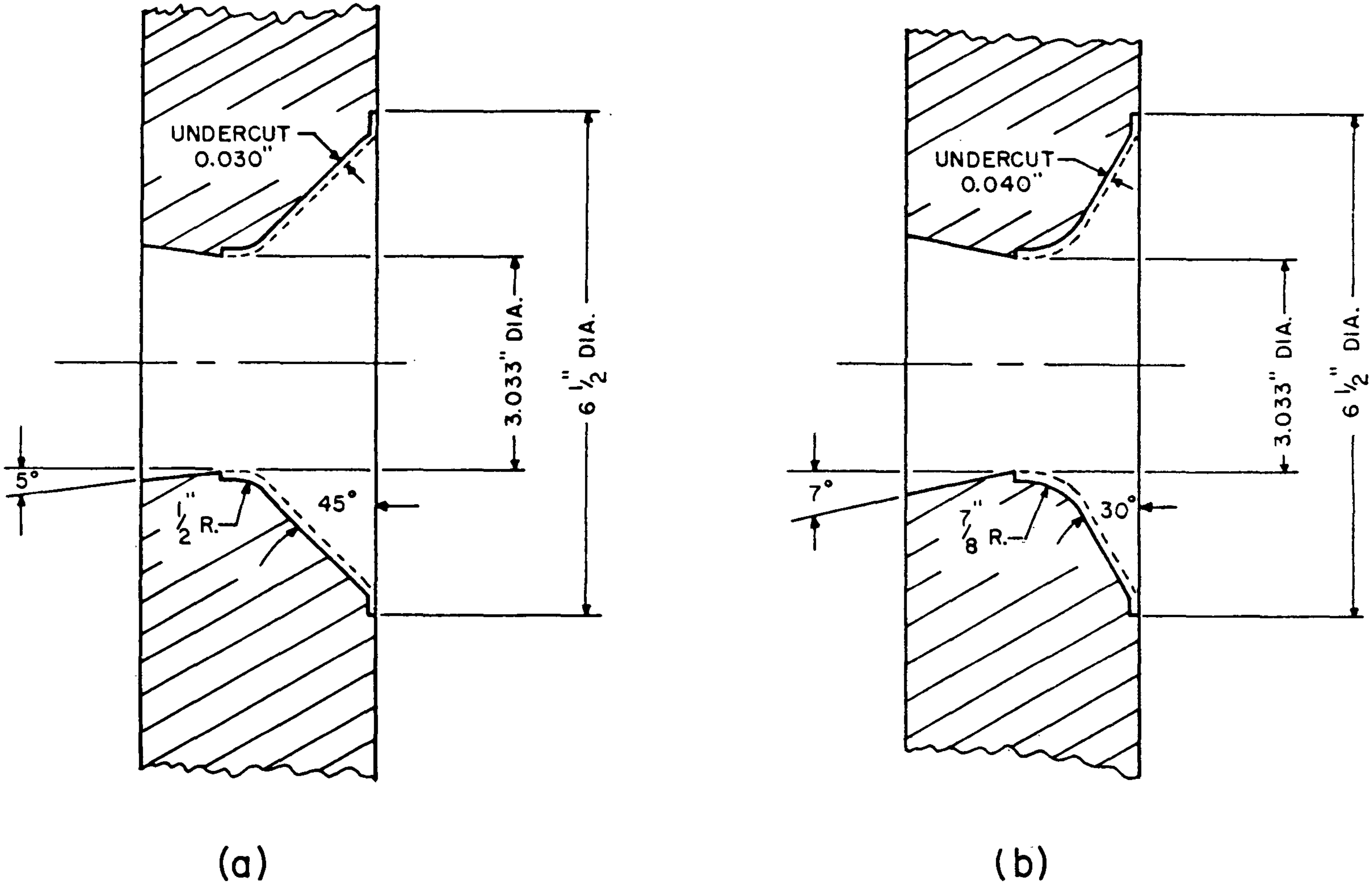
5. Die Coating

Du Pont flame sprayed ZrO_2 extrusion die coating practice was utilized for the first two extrusions while the established TAPCO plasma sprayed coating was utilized for the last two extrusions. Coating thickness of the flame sprayed dies was .030" as compared to plasma coating thicknesses of .040" and .055" for extrusion Nos. 6-3 and 6-4 respectively.

In summary, extrusion Nos. 6-1 and 6-2 were extruded basically in accordance with TAPCO practice with Du Pont recommended exceptions as noted in the preceding report (1). With deletion of these exceptions, extrusion Nos. 6-3 and 6-4 represent in total the direct scale-up of TAPCO extrusion practice established during the extrusion of 50 nominal 3" diameter billets in program Phases II, III, and IV.

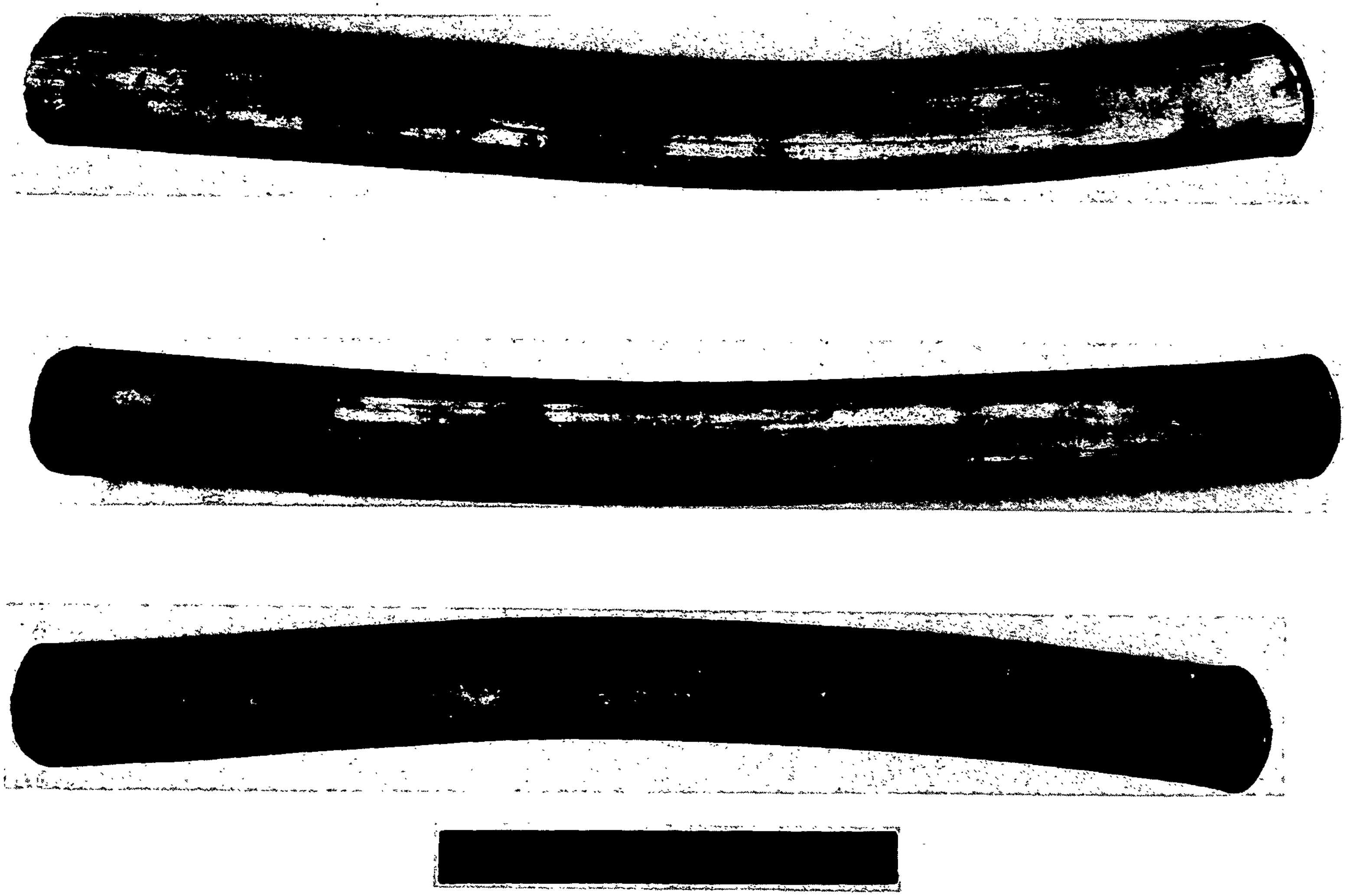
The centrifugally cast W-2%Mo billets are shown in the as-extruded condition in Figures 4 and 5. Extrusion of billet Nos. 6-2 and 6-4 was performed to work statement conditions without incident. However, during the extrusion of billet No. 6-3, the exiting extrusion rammed into the run-out stop chute in a non-concentric manner, hitting the tube edge. This caused the extrusion to be thrown into the air end over end, and to land butt side first on the floor. Fortunately, the subsequent extrusion inspections showed the stock to be sound. The only defects which could be firmly attributed to the extrusion's mishap were cracks near the butt end oriented approximately 45° from the extrusion axis (Figure 8).

Extrusion No. 6-4 exhibited a longitudinal crack which propagated forward from the butt end approximately eleven inches. This indicates that the extrusion temperature of billet No. 6-4 (3150°F) was marginally low. The crack, similar to those previously observed during low temperature extrusion of arc melted tungsten (6), apparently defines a 3200°F temperature minimum for the cast W-2%Mo and the processing route followed.



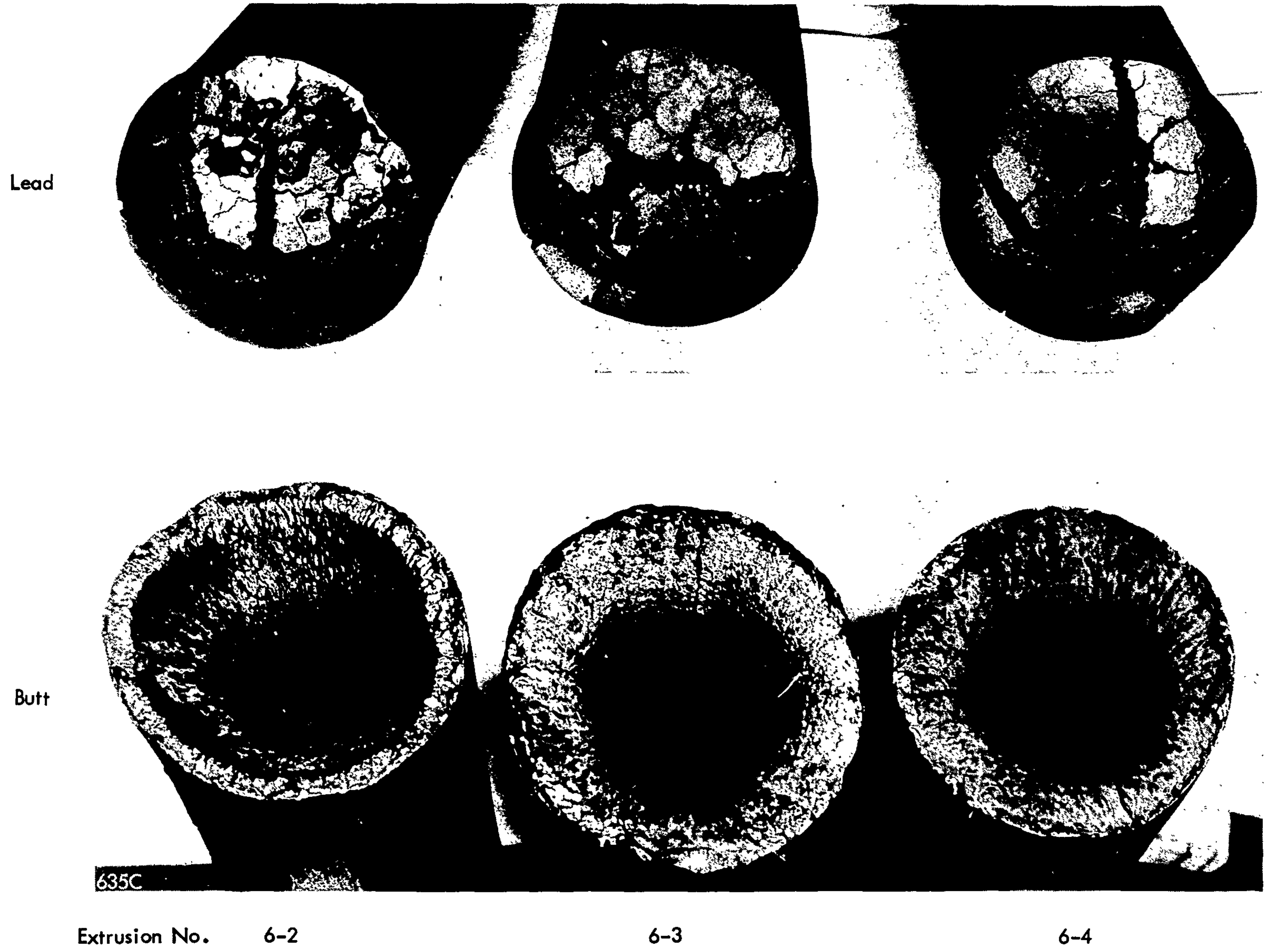
DIE SECTION CONFIGURATIONS: (a) DuPONT, AND (b) TAPCO

FIGURE 3



SURFACE APPEARANCE OF EXTRUSION NOS. 6-2, 6-3 AND 6-4

FIGURE 4



LEAD AND BUTT APPEARANCE OF EXTRUSION NOS. 6-2, 6-3 AND 6-4

FIGURE 5

The combined effect of plasma coated dies with temperature reductions illustrates the progressively improved extrusion O.D. surface appearance (Figure 4). The plasma-coated die coated to .055" thickness proved effective in that the resultant die wash (.052") for extrusion No. 6-4 was both uniform and restricted to the plasma coating, leaving the die material intact (Figures 6 and 7). The effects of billet nose and butt geometry, i.e., 1-1/2" radius nose and 1" x 45° butt chamfer, did not appear to produce any significant changes in the severity of nose burst and pipe depth compared to extrusion No. 6-1. It should be noted, however, that these latter extrusions were processed at somewhat lower temperatures. The data and results suggest that, an optimum processing route cannot be recommended from the four 6" diameter billet extrusions attempted thus far, however, the following factors have shown to significantly contribute to improved extrusion surfaces:

1. Plasma-coated dies of 0.055" minimum coating thickness.

2. Extrusion temperature range of 3200-3250°F.

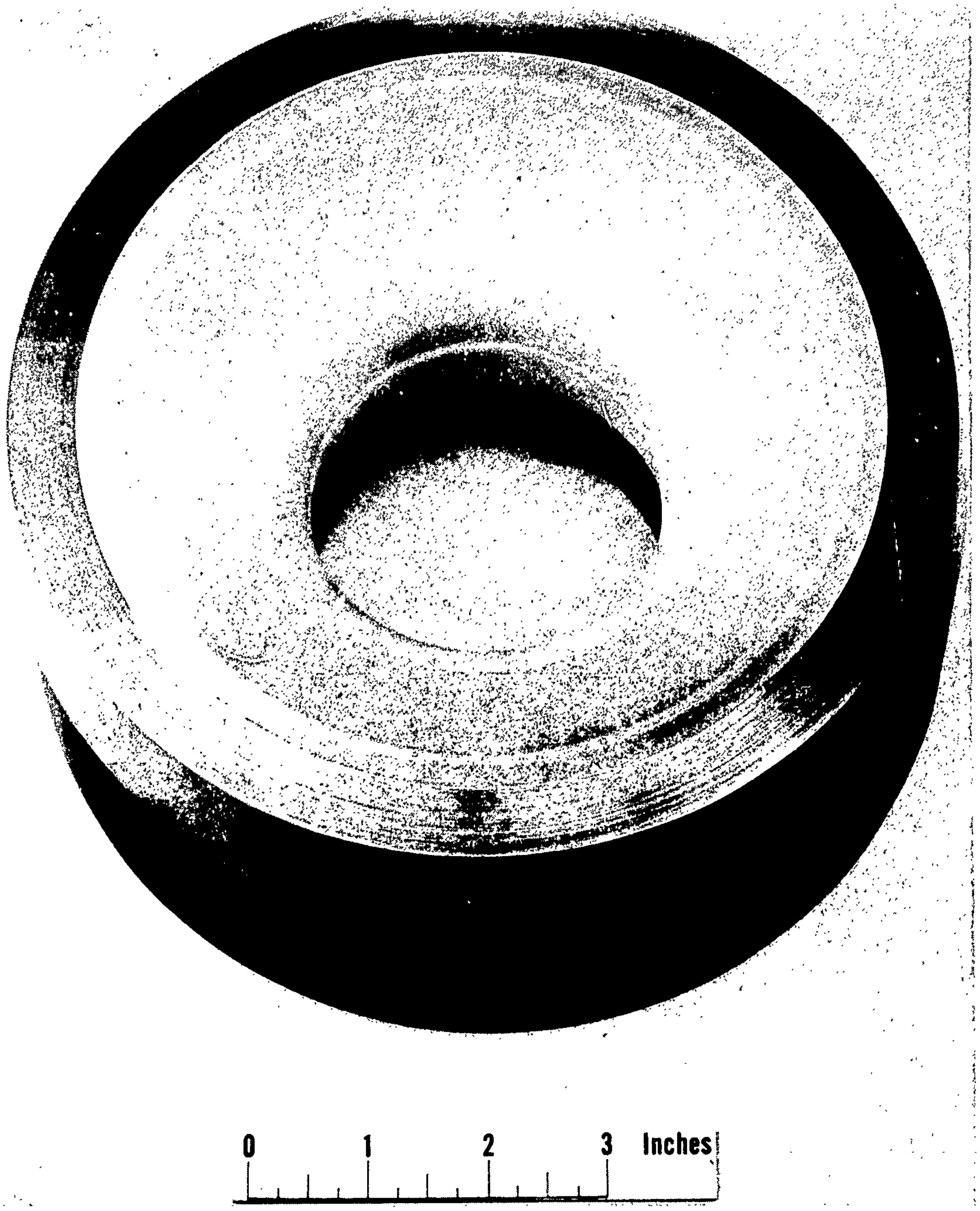
3. Bare billet lubrication practice.

D. Post Extrusion Evaluation

The as-extruded and sand-blasted extrusion Nos. 6-2, 6-3, and 6-4 were sectioned at TAPCO as illustrated in Figure 8. The crack observed in extrusion No. 6-4 required a large butt cropping and thereby limited the billet yield for this extrusion to three. A total of eleven sections were prepared by grinding to 20-pound forging billets. Billet No. 6-3A sectioned from the dropped extrusion was observed to be cracked about 3/4" inward from the lead face. During the grinding operation this crack propagated the entire section length. However, this billet was used in the subsequent forging trials as discussed in Section IV-D. The results of forging billet quality control evaluations and of metallurgical evaluation of the thin slices from extrusion lead, butt, and mid-point positions are discussed below:

1. Forging Billet Evaluation

Fluorescent penetrant inspection results of the forging billets ground to the required 2-3/4" diameter are listed in Table III. Billet surface defects were comparatively slight in relation to the first extrusion (No. 6-1) forging billet yield and, therefore, only slight grinding touchup was required to complete the billet surface conditioning.

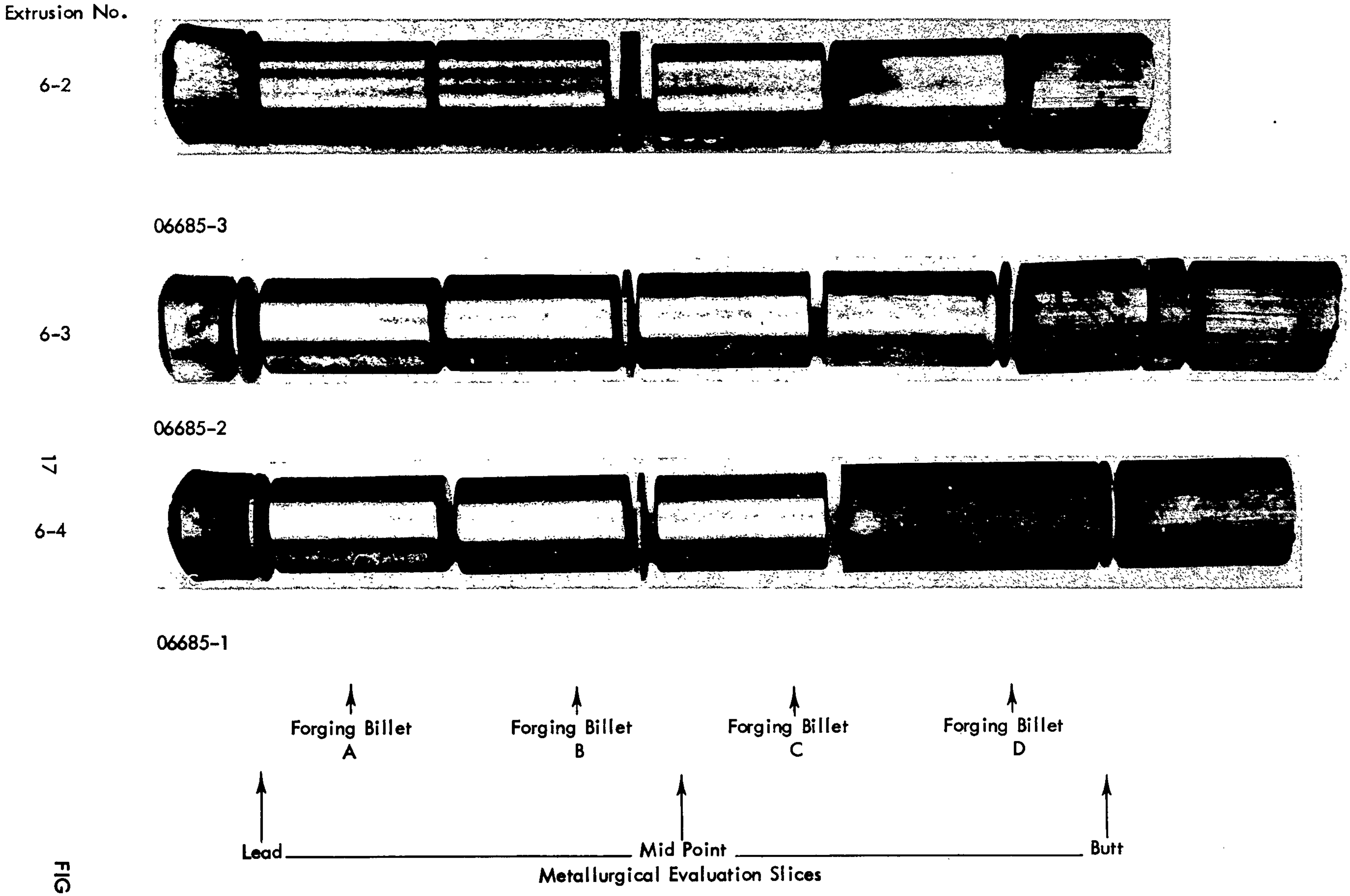


UNUSED PLASMA COATED TAPCO EXTRUSION DIE IDENTICAL TO THAT IN FIGURE 7

FIGURE 6

DIE USED FOR EXTRUSION No. 6-4. WHITE AREAS SHOW WHERE PLASMA COATING WAS DELIBERATELY CHIPPED AFTER EXTRUSION TO DETERMINE EXTENT OF DIE WASH

FIGURE 7



UTILIZATION OF EXTRUSION NOS. 602, 603, and 6-4

FIGURE 8

TABLE III

Fluorescent Penetrant Inspection Results for W-2%Mo Forging Billets

Extrusion and Section No. (1)	Results
6-2A	Sound surface
6-2B	Sound surface
6-2C	Small pits on sidewall extending from butt end toward lead end approximately 1-1/2" long.
6-2D	2 thin longitudinal cracks approximately 1/2" long extending from butt end.
6-3A	5 small longitudinal cracks approximately 1/2" long extending from lead end. One of these cracks propagated the full length of billet during machining clean-up.
6-3B	Sound surface
6-3C	Small pits extending from butt end 1/2" long.
6-3D	Sound surface
6-4A	One thin longitudinal crack approximately 3/8" long extending from lead end.
6-4B	Sound surface
6-4C	Sound surface
6-4D	Extrusion was cracked from lead end of position D to butt end. (Section was not ground)

(1) See Figure 8 for billet section identification

Ultrasonic testing results showed the repaired billets to be sound within previously reported limits (3, 4) except for billet No. 6-3A which, because of the magnitude of the visual crack, was not repaired.

2. Chemical Analysis

The center slices of each extrusion were carefully prepared and analyzed for carbon and oxygen as outlined in the previous report (1). The reported results of the commercial testing laboratory, as recorded in Table IV, indicated these interstitial levels to be well within the TAPCO specification limits for the extruded stock (60 ppm maximum each for carbon and oxygen) and thereby confirmed the final billet acceptance. The report showed a marked decrease of the interstitial level (up to 50%) as compared to extrusion No. 6-1.

3. Structure - Macroexamination

The transverse macrostructures of these extrusions were taken at lead, mid-point, and butt positions as shown in Figures 9, 10, and 11. In some instances the macrostructures shown represent the actual ground forging billet faces at the respective positions indicated (note the radiused edge). An exaggerated "nose" effect can be seen in the lead sections of extrusion Nos. 6-2 and 6-3. The similarity of the uniform structures exhibited by both mid-point and butt sections of all three extrusions indicate the butt croppings adequately removed all signs of the "pipe" effect. Extrusion No. 6-4 (extruded at lowest temperature 3150°F) appeared to have the most uniformly worked structure (Figure 11).

4. Structure - Microexamination

The longitudinal microstructures taken from the mid-point metallurgical evaluation slices are reproduced in Figure 12 for extrusion Nos. 6-2, 6-3, and 6-4. These W-2%Mo microstructures represent the results of billet extrusion temperatures of 3250°F and 3150°F at nominal 4 to 1 extrusion ratios followed by stress relief heat treatments of one hour at 2400°F. In each case a cold worked structure is retained with no evidence of recrystallization.

A further comparison of the center sections of all four 6" billet extrusions of the centrifugally cast W-2%Mo reveals a consistently reproducible microstructure within the entire extrusion temperature ranges attempted (3400°F-3150°F).

TABLE IV

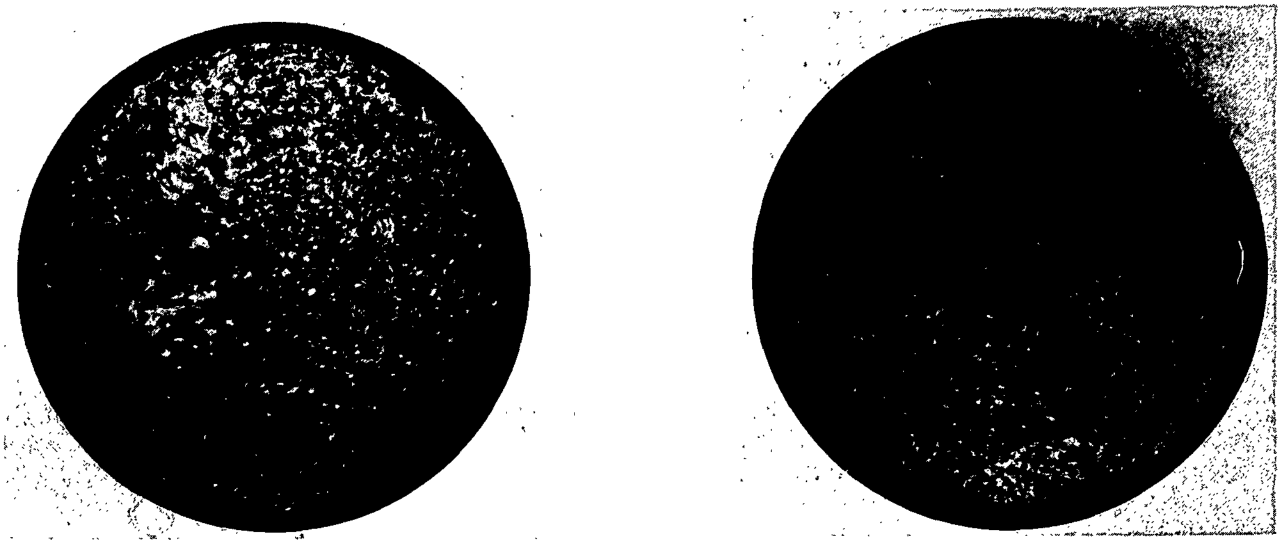
Carbon and Oxygen Analysis of W-2%Mo Extrusions

Extrusion No.	Determination No.	Carbon[1] (ppm)	Oxygen[2] (ppm)
6-2	1	20	13
	2	20	12
	3	21	13
	Average	20	13
6-3	1	29	7
	2	27	12
	3	27	9
	Average	28	9
6-4	1	29	11
	2	32	18
	3	33	17
	Average	31	15

(1) Leco Conductometric

(2) Inert Gas Fusion

Analyses performed by Crobaugh Testing Laboratory, Cleveland, Ohio.



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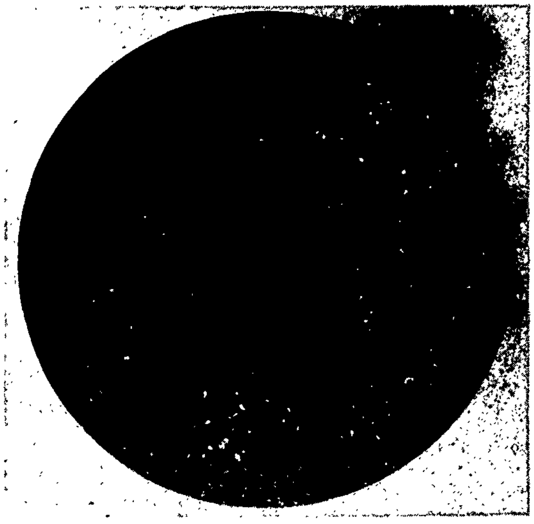
Lead

06678-5

Butt



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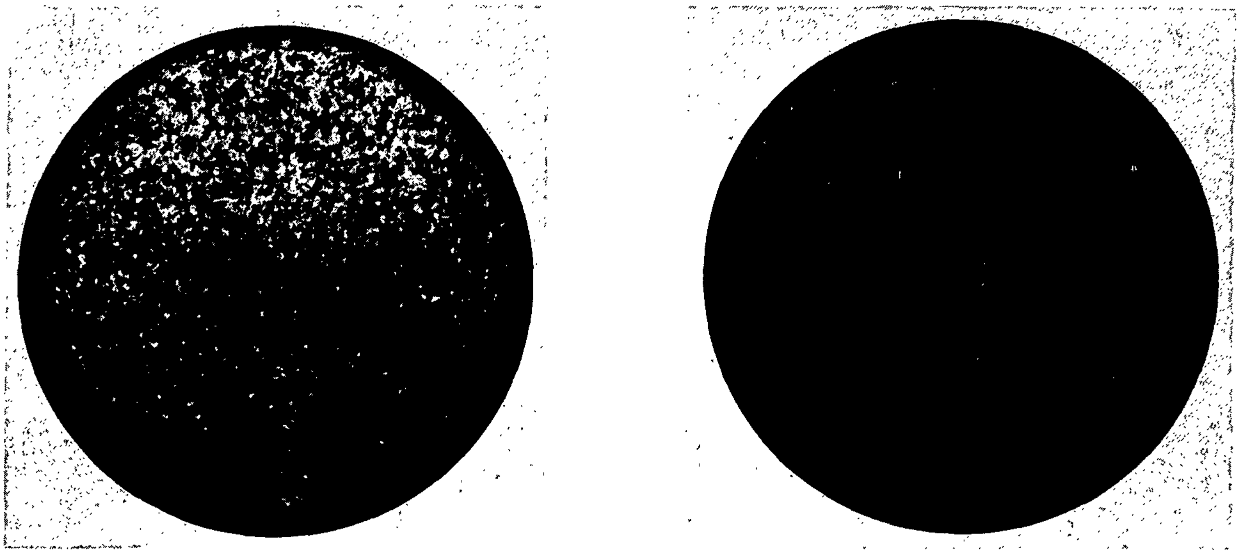
Center

TRANSVERSE MACROSTRUCTURE OF EXTRUSION 6-2. ACTUAL SIZE

FIGURE 9



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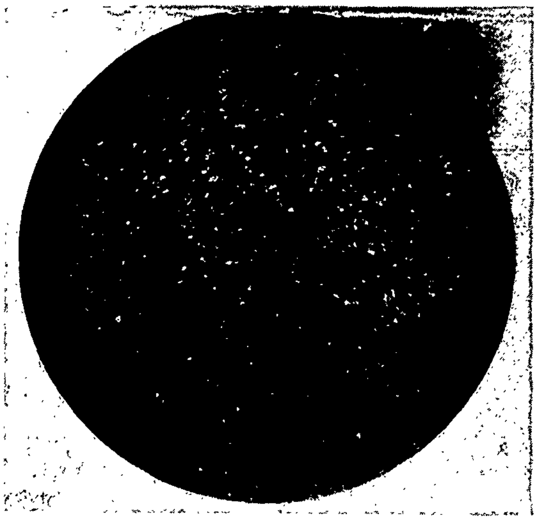
Lead

06678-4

Butt



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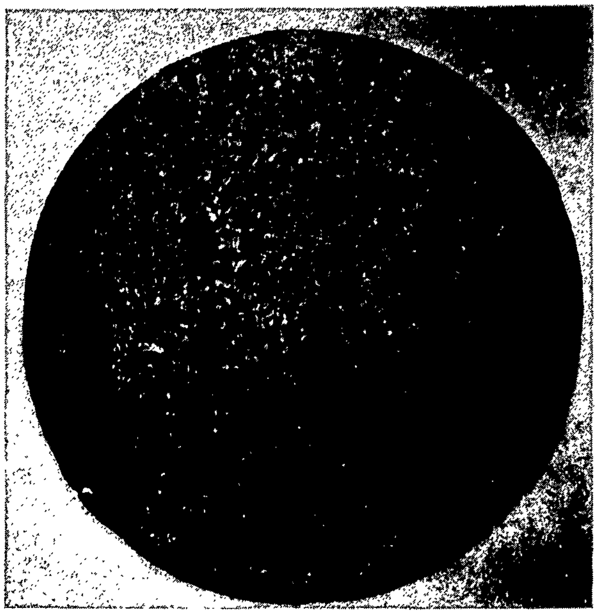
Center

TRANSVERSE MACROSTRUCTURE OF EXTRUSION 6-3. ACTUAL SIZE

FIGURE 10

06678-5

Butt



06678-3

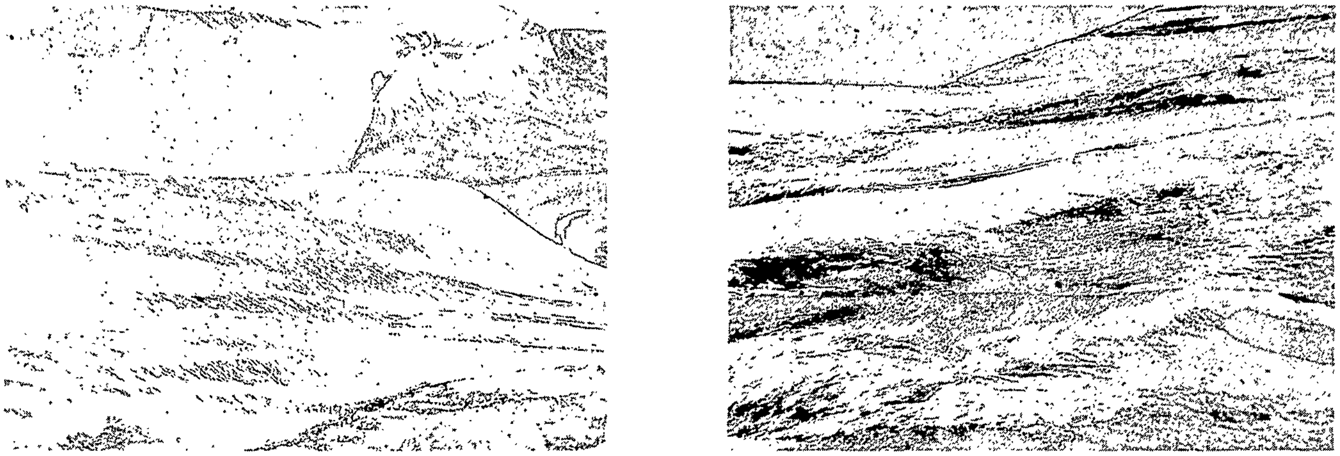
Lead

06666-3

Center

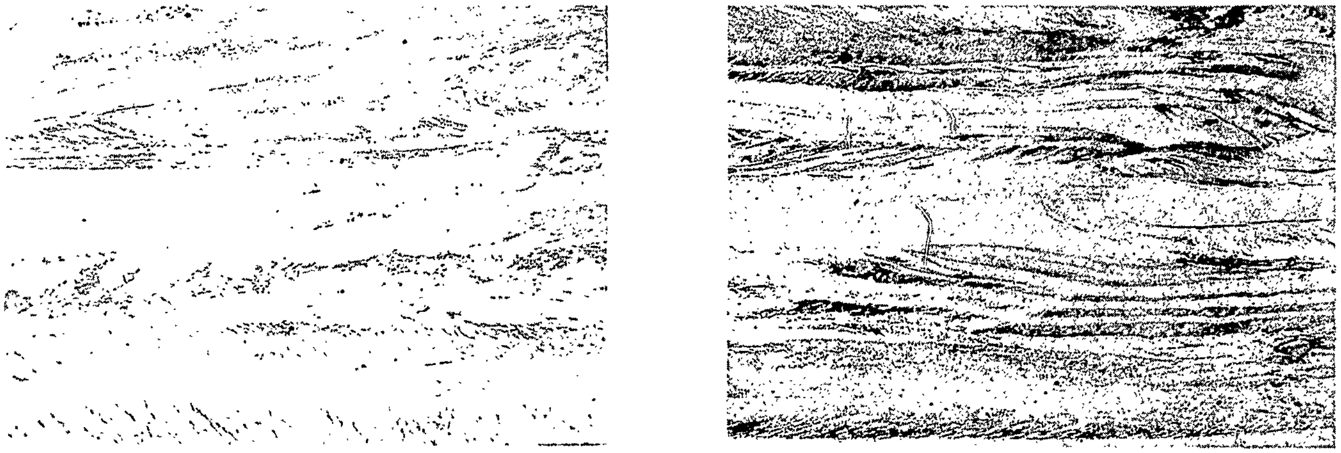
TRANSVERSE MACROSTRUCTURE OF EXTRUSION 6-4. ACTUAL SIZE

FIGURE 11



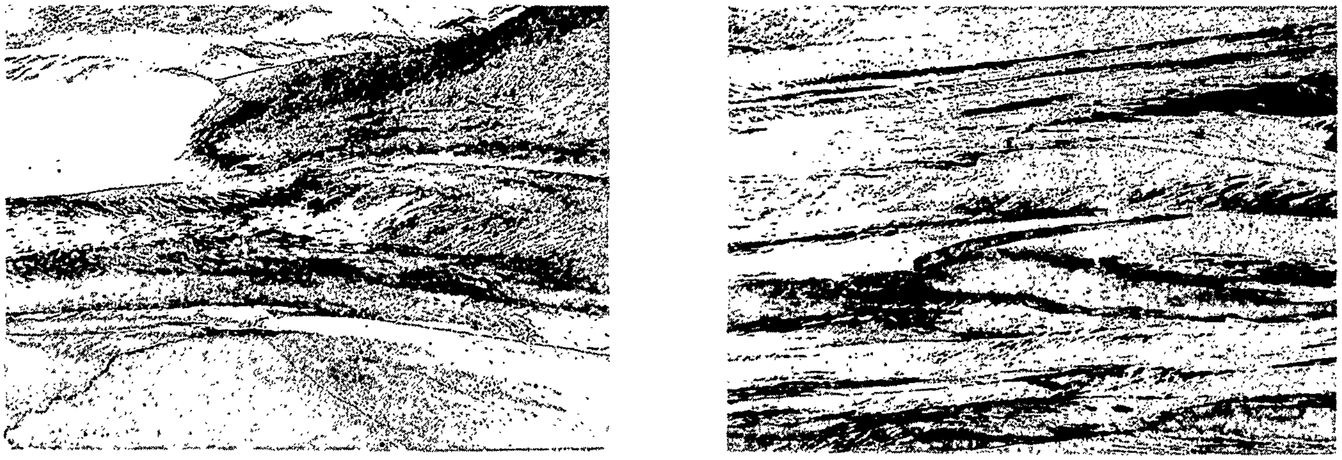
No. 6-2 Near Surface

No. 6-2 Center



No. 6-3 Near Surface

No. 6-3 Center



No. 6-4 Near Surface

No. 6-4 Center

LONGITUDINAL MICROSTRUCTURES AT THE CENTER AND NEAR THE SURFACE OF EXTRUSION NOS. 6-2, 6-3, AND 6-4 - 50X FIGURE 12

5. Hardness

Hardness values taken by a traverse across the transverse lead, mid-point, and butt sliced of the extrusions recorded in Table V indicated similar results observed for extrusion No. 6-1, i.e., slightly lower hardnesses for the extrusion centers at the mid-point and butt sections and conversely slightly higher hardnesses for extrusion centers at the lead end ("nose" effect).

6. Recrystallization Temperature

A preliminary study to aid in determining proper forging and stress relief temperatures previously reported (1) indicated the initiation of the one hour recrystallization temperature in the extruded stock to be in excess of 2700°F. Further one hour heat treatments at 2900°F, 3000°F, and 3100°F established the one hour 100% recrystallization temperature to be at approximately 3100°F. Hardness measurements taken on the near surface and center portions of the heat treated specimens confirm the microstructure observations. These hardness values plotted with the corresponding microstructures as a function of temperature are shown in Figure 13.

7. Yield

Fifteen 20 pound forging billets were conditioned from the four W-2%Mo extrusions. The 300 pound forging billet recovery produced from the total extrusion billet weight of 600 pounds represents a yield of 50%. This overall yield can be regarded as relatively high when considering such factors as:

a) low l/d extrusion billets utilized,
b) low reduction ratios required,
c) resultant metal loss due to nose, butt, and evaluation croppings, and
d) range of processing parameters investigated.

TABLE V

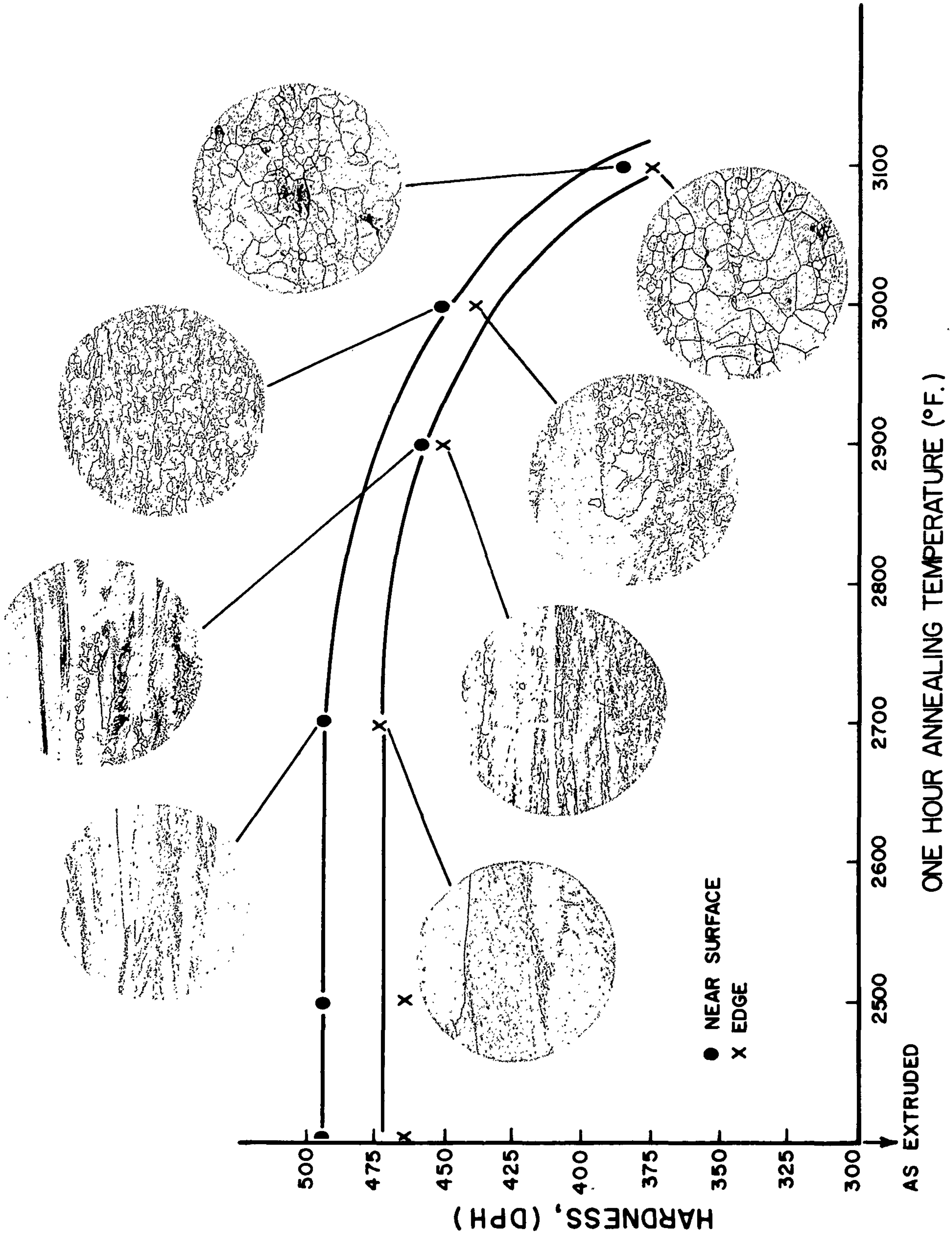
Hardness$^{(1)}$ Across Transverse Sections of W-2%Mo

Extrusion No. 6-2

Location Number (2)	Lead Section Hardness - Rc	Mid-Section Hardness - Rc	Butt Section Hardness - Rc
1	42	42	43
2	42.7	42	43.7
3	43.7	42.3	40.7
4	43.7	41.7	41.5
5	42.8	41.8	42.2
6	44	41	43.2
7	44.3	41.3	43.8
8	44.3	41.3	44
9	44.3	43	43.7
10	44.7	43	44
11	43.7	43.2	44.3
12	42	43	44
Average	43.5	42.1	43.2
	Extrusion No. 6-3		
1	44	43	45.1
2	44	43.5	42
3	43	43	41.2
4	42.8	43.3	41.7
5	42	42.2	41
6	44	40.3	42
7	44	41.0	44.3
8	45	41.8	43.8
9	44.7	42.3	42.2
10	45	43	43
11	45	43.3	44
12	44	43	44.6
Average	43.5	42.5	42.9
	Extrusion No. 6-4		
1	45	44	44.2
2	44.7	43.2	43.7
3	43.7	42.8	44
4	43.7	42.7	42.5
5	45.3	41.8	43.3
6	44.7	42.5	43.3
7	44.7	42.2	42.7
8	44	41.7	43.5
9	44.8	41.7	43.5
10	44.7	43.3	43.1
11	44.7	44	43.5
12	44.9	44	44
Average	44.6	42.8	43.4

(1) Each value represents the average of a minimum of four good readings.

(2) Location numbers refer to a linear traverse with 1/4" spacing across the traverse faces of the "Metallurgical Evaluation Slices" shown in Figure 8. Thus numbers 1 and 12 represent material close to the extrusion surface, numbers 6 and 7 represent centrally located material, etc.



RECRYSTALLIZATION OF EXTRUDED W-2% Mo CENTRIFUGALLY CAST STOCK

FIGURE 13

IV DEVELOPMENT OF UNIVERSAL THIN SECTION FORGING

A. Component, Sequence, and Tooling Design

The universal thin section forging configuration and the five stage sequence designed to produce the configuration are reproduced from the previous report in Figures 14 and 15. The forging volumes required to fill each stage of the closed die sequence established starting billet dimensions at 2-3/4 inch diameter by 4-7/8 inch long, (28.7 in.^{3}).

1. Upsetting

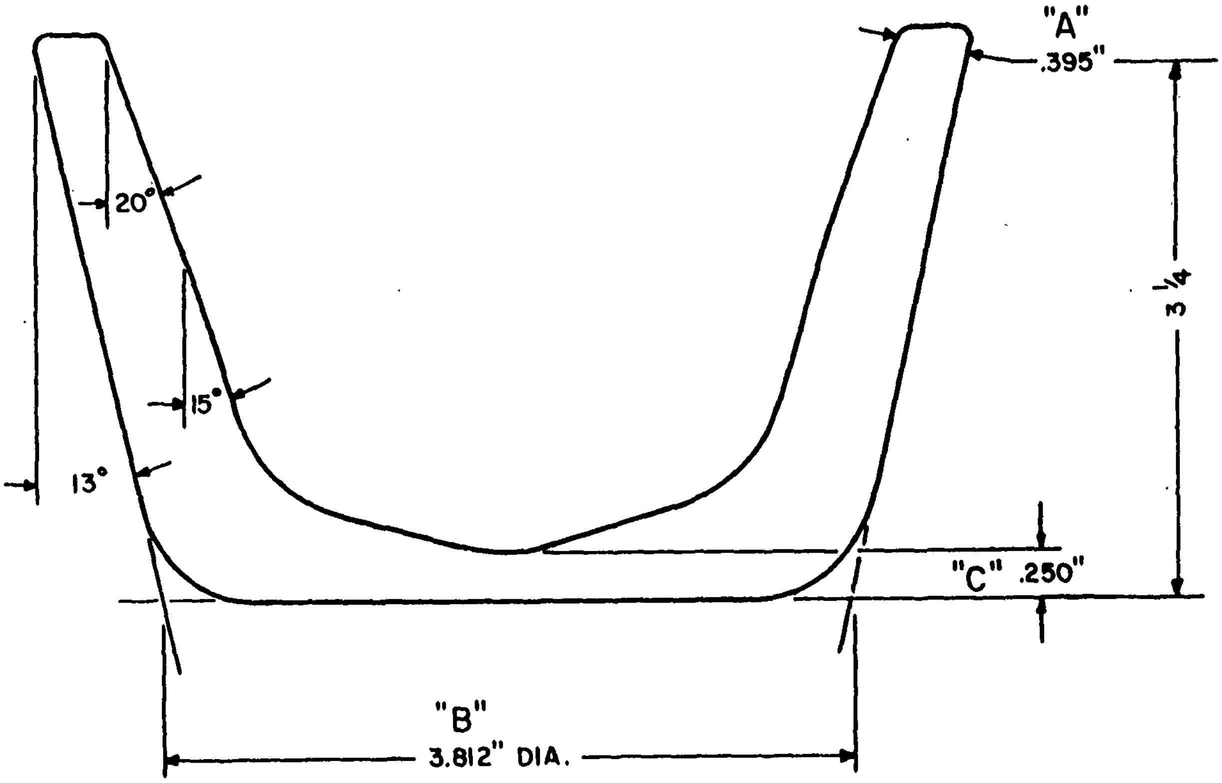
The two stage upsetting sequence was designed to distribute the metal laterally, thus increasing the diameter for the back extrusion operations (Figure 15). The tooling design was unusual in that proper billet locating required fastening the flat punches to the press bed while the die, secured to the ram, struck the upsetting blow. The die utilized for the second upset was the same die used in the subsequent back extrusion operations.

2. Back Extrusion (Blockdown, Semi-Coin, and Coin)

The three back extrusion operations were designed to provide the vertical metal flow required to attain both the desired side-wall height and the properly oriented cold worked grain structure. The die for these operations was used as a loading locator since the same die formed the second upset configuration. Therefore, this die was secured to the press bed, and the punch attached to the ram forced the metal flow vertically upward.

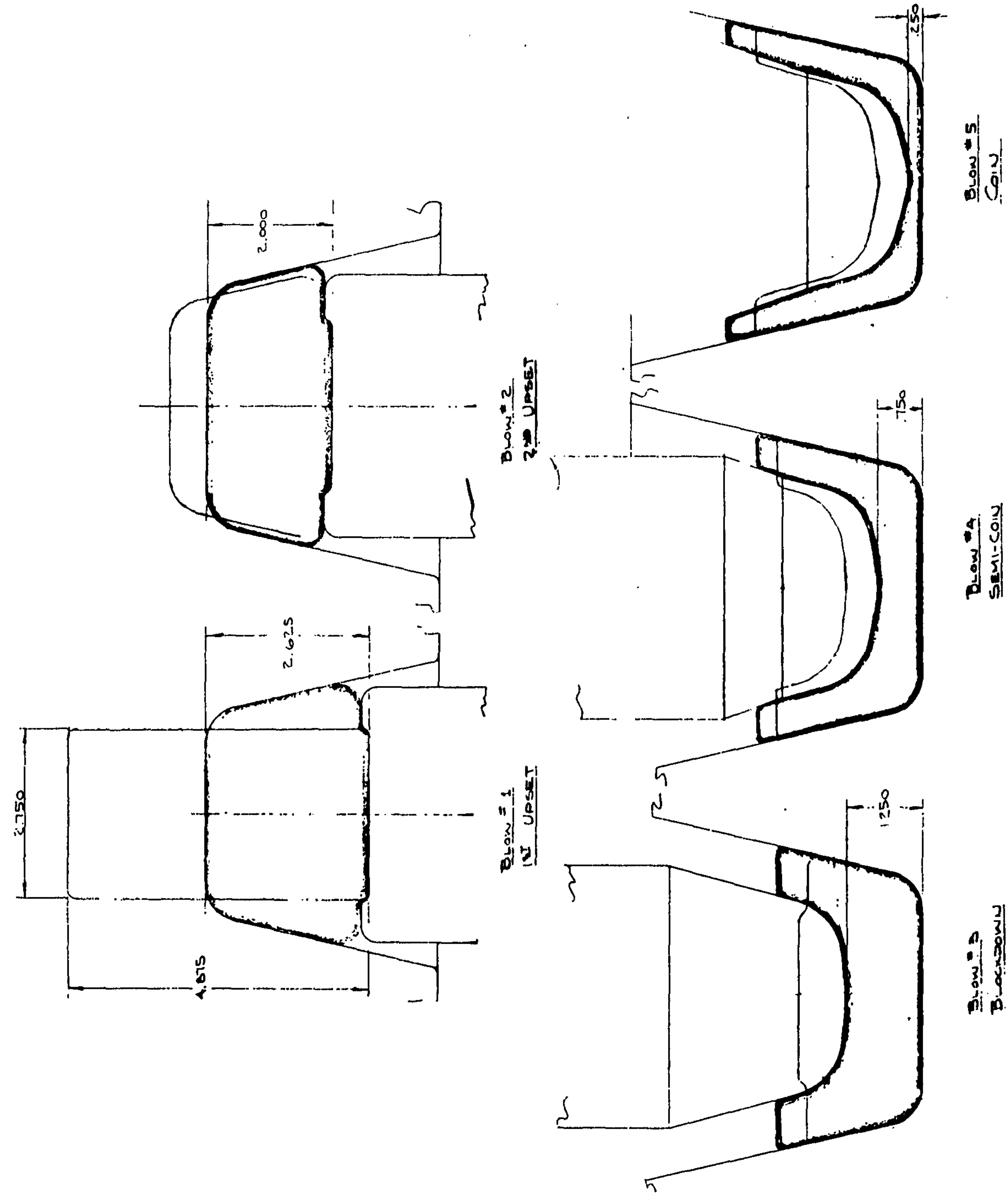
B. Heating and Forging Equipment

A commercial electric box furnace purged with argon to minimize oxidation was used for heating. Optical pyrometer readings taken during the initial forging trials were shown to be within ± 20°F of duplicate Chromel-Alumel thermocouple reading for the forging temperature range utilized (2050°F-2500°F). The total heating time to forging temperatures was established at 30 minutes. The maximum forging temperatures utilized (2500°F) were considerably lower than the recrystallization of the extruded stock (above 2700°F), therefore the workpieces were returned to the furnace and were retained for 30 minutes at the forging temperature for a temperature equalization. The possibility of thermal stress cracking was minimized by burying the workpiece in silocel and allowing a slow cool through the ductile-brittle transition temperature.



CROSS SECTION OF "UNIVERSAL THIN SECTION" OF FORGING CONFIGURATION

FIGURE 14



FORGING SEQUENCE FOR "UNIVERSAL THIN SECTION" CONFIGURATION

FIGURE 15

Pressure requirements necessitated the use of a 4000 ton mechanical crank press, shown in Figure 16. The press utilizes a 12" stroke and is equipped with a mechanism capable of vertical tooling adjustment to 0.001".

C. Sequence Metal Flow Evaluation

Prior to the W-2%Mo forging trials, tests were conducted for preliminary evaluation of the metal flow pattern produced by the tooling sequence. Four right cylinders of low carbon steel turned to the proper dimensions, grooved on the outer diameters to form a 1/4 inch square grid pattern, and concentrically press fitted together comprised the starting billet. Five such billets were assembled and forged at 1800°F, producing the configurations at each stage shown in Figure 17. These billets were then sectioned to evaluate the distribution of metal flow produced, as shown in Figure 18. The flow patterns produced indicate:

1. Sidewall metal flow is uniform with flow lines parallel to the punch and sidewall.

2. The cup bottom is formed by the center billet core while the cup sidewalls are formed by the elongated outer rings.

3. Lapping or tearing tendencies are not apparent at the tooling radii.

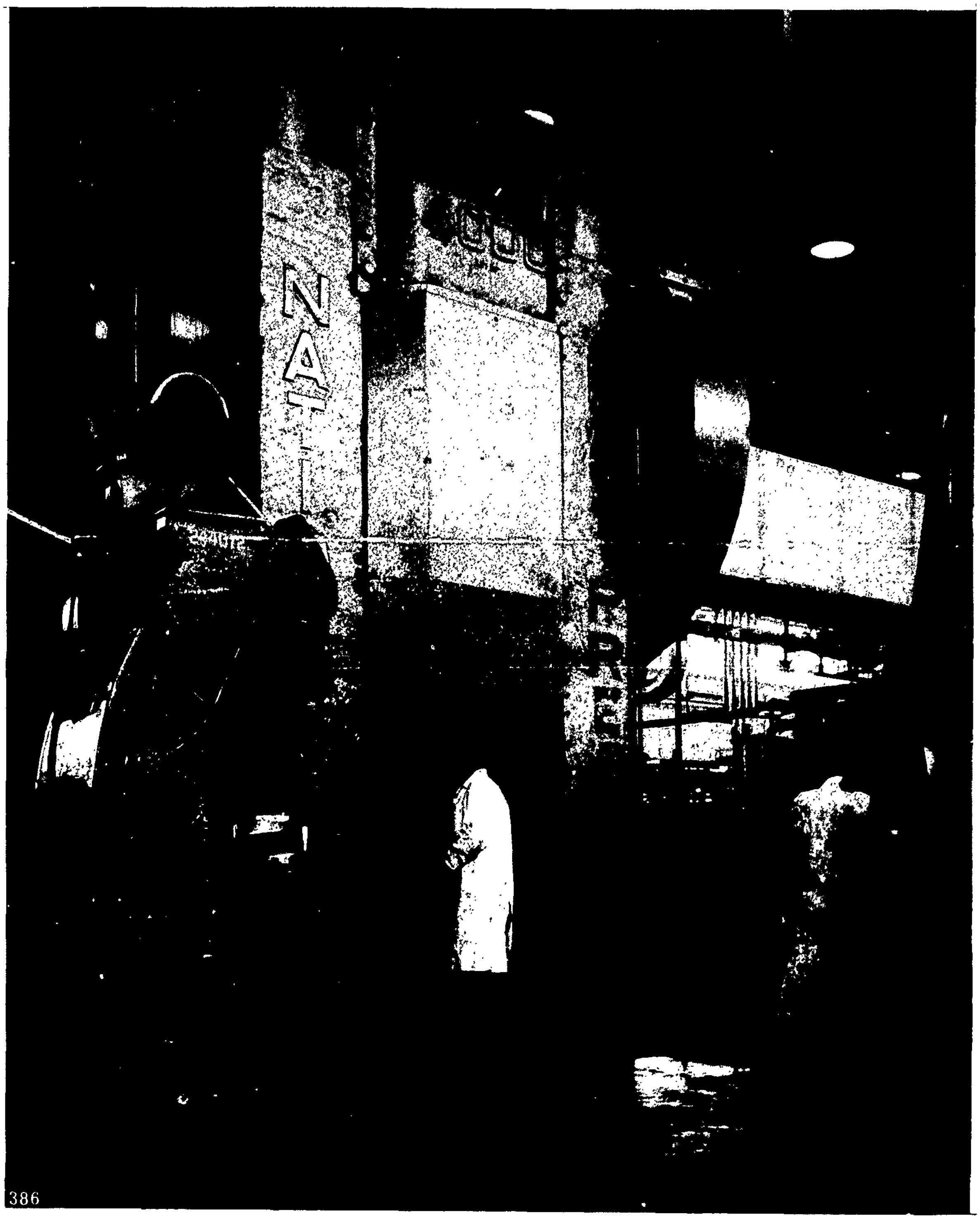
It should be noted that, although usefull for qualitative tooling evaluation, such results derived from hot worked steel cannot be definitively translated to the metal flow characteristics of the more deformation resistant W-2%Mo cold worked through the same sequence.

D. Forging Development

The W-2%Mo forging trials were separated into two forging runs as shown schematically in Figure 1. The function of the initial forging trials was to confirm the tooling design and to provide a set of standard forging conditions which could be evaluated and used as a baseline for further forging development. The second forging run was utilized to evaluate a small production run and to determine the effect of pertinent processing variables, e.g., forging temperature, lubrication practice, number of forging blows, and starting billet microstructure on the workpiece forgeability and the final forged properties. These forging procedures and results are discussed below:

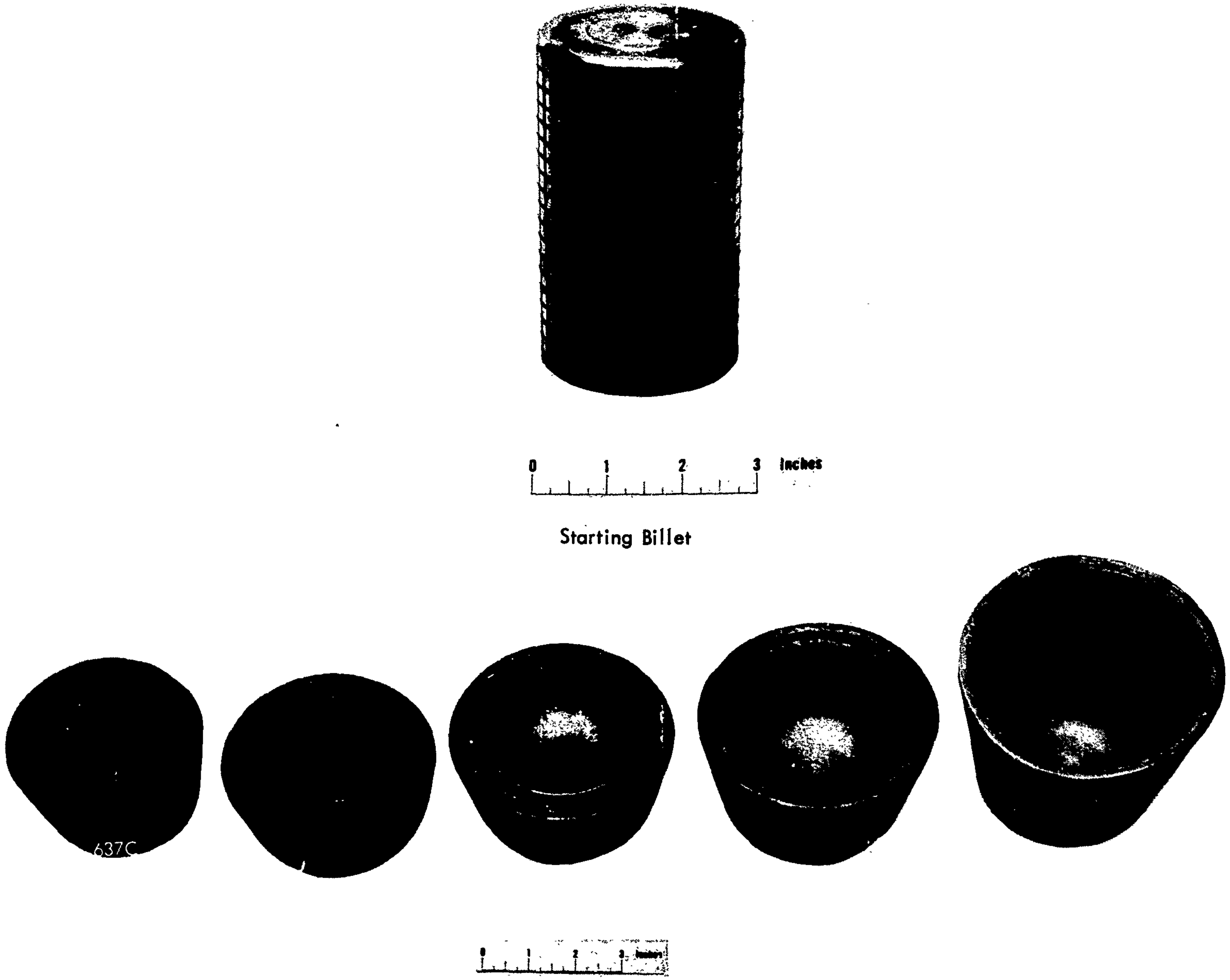
1. Initial Forging Trials

The four forging billets conditioned from W-2%Mo extrusion No. 6-1 supplied the required stock for the initial forging trials. Low carbon steel bar stock machined to the starting forging billet



4000-Ton High Speed Crank-Type Press.

FIGURE 16



Starting Billet

Upset No. 1 Upset No. 2 Blockdown Semi-Coin Coin

CONFIGURATIONS PRODUCED THROUGH FIVE STAGE FORGING SEQUENCE

FIGURE 17

Upset No. 1

Upset No. 2

Blockdown

Semi-Coin

Coin

GRIDDED STEEL BILLETS SECTIONED AT EACH SEQUENCE STAGE

FIGURE 18

size provided the setup pieces for preliminary adjustment of tooling concentricity alignment and shut heights.

The punch and die inserts were preheated and maintained within the temperature range 275°F to 375°F. A prior TAPCO internal forging program (7) with a related but less severe forging configuration revealed excellent resultant as-forged surfaces from the lubricity afforded by the tungsten oxide formed on the workpiece surface during heating. Therefore, "bare" workpiece lubrication practice was adopted for these forging efforts. A thin coating of colloidal graphite lubricant was applied to the tooling surface prior to each blow.

An analysis of the earlier forging development in this program plus the added background of related TAPCO tungsten forging programs (7-10) prompted initial selection of the following temperatures for each stage of the sequence:

Upset No. 1 - 2350°F
Upset No. 2 - 2300°F
Blockdown - 2250°F
Semi-Coin - 2200°F
Coin - 2200°F

After the tooling setup for a particular forging stage was complete, one tungsten piece was forged by the procedures described in Section IV-C. If, after sand blasting, visual inspection showed the workpiece to be sound, the remaining W-2%Mo pieces would be struck at the same temperature. Inspection showed the first tungsten piece struck at each forging stage to be sound; therefore, all four forging billets were struck at the temperatures selected for the standard forging conditions. Forging data are listed in Table VI.

The forging surface irregularities visually observed upon completion of each forging blow (see Table VI) were repaired manually with an air grinder. The repaired areas were then critically re-examined by red dye penetrant inspection. A summary of the observations is as follows:

a) Upset No. 1 - The severest surface roughness was exhibited after this operation by all workpieces. The shallow intergranular surface cracking observed was attributed to the large unrestrained lateral movement (45% upset) prior to die sidewall contact and support. A solution suggested was the addition of an intermediate upsetting operation to reduce the severity of the first upset. However, since the shallow irregularities produced were readily repairable the addition of

TABLE VI

Initial Forging Trials of W-2%Mo Extruded Billet Stock and Results

Upset No. 1

Billet No.	Forging Temp. (°F) (1)	Tooling Temp. (°F) Punch	Tooling Temp. (°F) Die	Upset Height (in.)	Condition of Forging
6-1A	2340°	320°	320°	2.668" (2)	Rough sidewall surface
6-1B	2345°	325°	325°	2.628"	Rough surface
6-1C	2345°	325°	325°	2.618"	One small crack in repaired area plus crack 180° opposite in flash area
6-1D	2345°	325°	325°	2.630"	One small crack in flash area

Upset No. 2

Billet No.	Forging Temp. (°F) (1)	Tooling Temp. (°F) Punch	Tooling Temp. (°F) Die	Upset Height (in.)	Condition of Forging
6-1A	2300°	320°	300°	2.167" (2)	Better surfaces, tearing in flash zone and small tears in radius
6-1B	2295°	290°	290°	2.165"	Better surfaces, tearing in flash zone and small tears in radius
6-1C	2290°	300°	275°	2.160"	Better surfaces, small tears in radius
6-1D	2305°	280°	280°	2.160"	Better surfaces, small tears in radius

(1) Optical temperature determinations (see Section IV-C)

(2) W-2%Mo billets used for tooling setup.

TABLE VI (continued)

Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F) Punch	Tooling Temp. (°F) Die	Upset Height (in.)	Condition of Forging
		Blockdown			
6-1A	2250°	320°	290°	1.310"(2)	Good surfaces one crack in previously repaired area (radius)
6-1B	2250°	280°	280°	1.300"	One crack in radius
6-1C	2250°	290°	310°	1.301"	Several small tears in previously repaired area (flash area)
6-1D	None				
		Semi-Coin			
6-1A	2200°	300°	375°	.745"(2)	Good surface, slight tearing in O.D. radius
6-1B	2200°	300°	375°	.743"	Good surface, slight tearing in O.D. radius
6-1C	2200°	320°	375°	.743"	Good surface, slight tearing in O.D. radius
		Coin			
6-1A	None				
6-1B	2205°	300°	290°	.338"(2)	Excellent surface, slight tearing in O.D. radius
6-1C	2210°	375°	350°	.328"	Excellent surface, slight tearing in O.D. radius

(1) Optical temperature determinations (see Section IV-C)
(2) W-2%Mo billets used for tooling setup

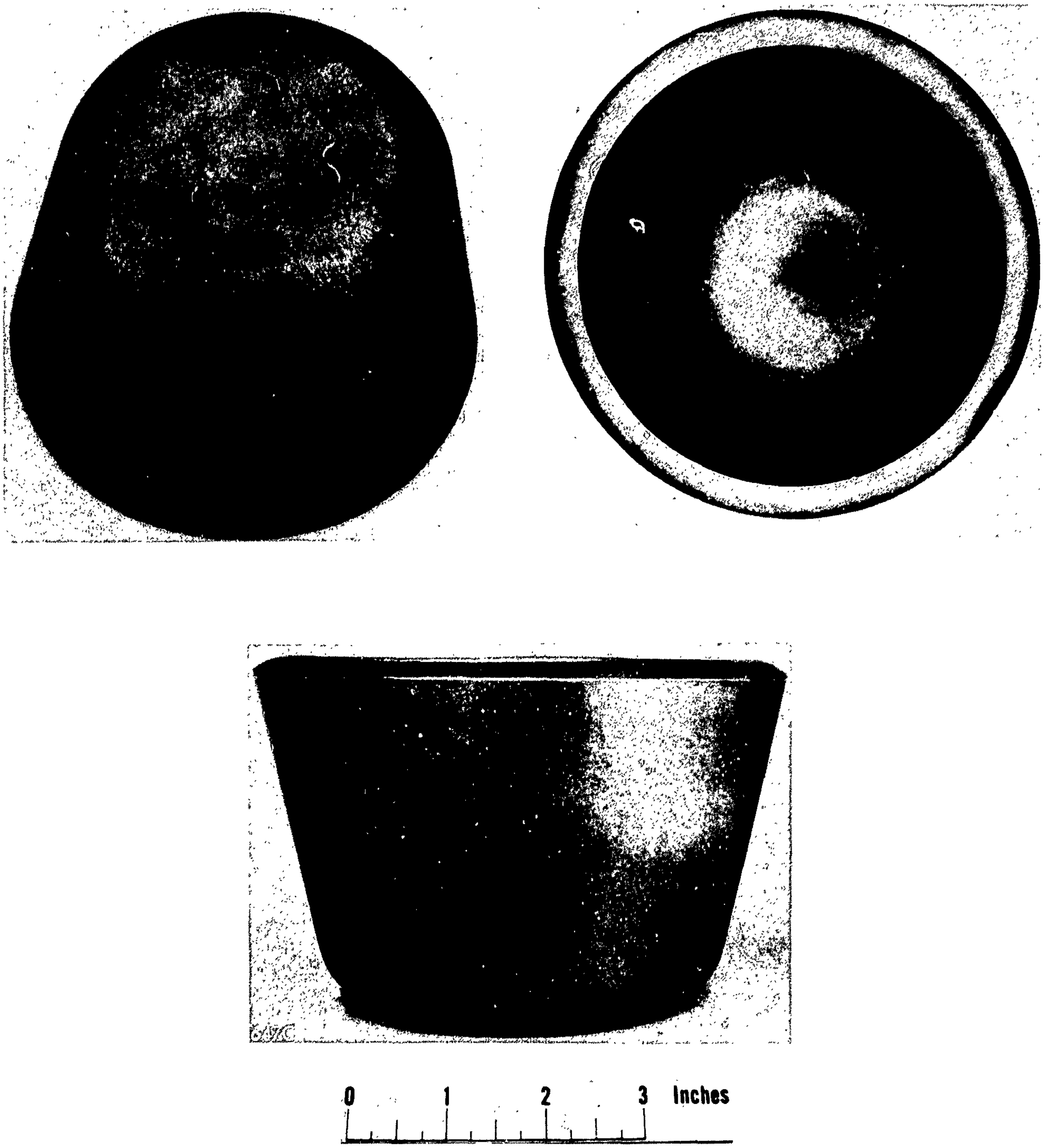
a sixth forging operation was not economically practical. Slight flashing over the punch sidewall also produced minor surface tears in this zone.

b) Upset No. 2 - The general surface appearance was greatly improved over the previous blow. The only irregularities encountered were slight surface tears in the flash zone and bottom radius.

c) Back Extrusion (Blockdown, Semi-Coin, and Coin) - The sidewall surface condition of each piece improved as it progressed through the back extrusion operations, as shown by the completed coined forging in Figure 19. The punch and die contours provided complete workpiece support throughout the forging strokes. Also shown in Figure 19 are the minor internal and external surface tears on the bottom radii observed after each of the back extrusion operations. The macrostructure of the coined section (Figure 20) shows the fibrous structure to be both oriented normal to and terminated on the outer radius surface. The radial surface tearing on the outer radius can be related to the metal flow which moves in a direction transverse to the orientation of the structure. The circumferential tears on the inner radius can be attributed to surface shearing due to insufficient workpiece lubricity.

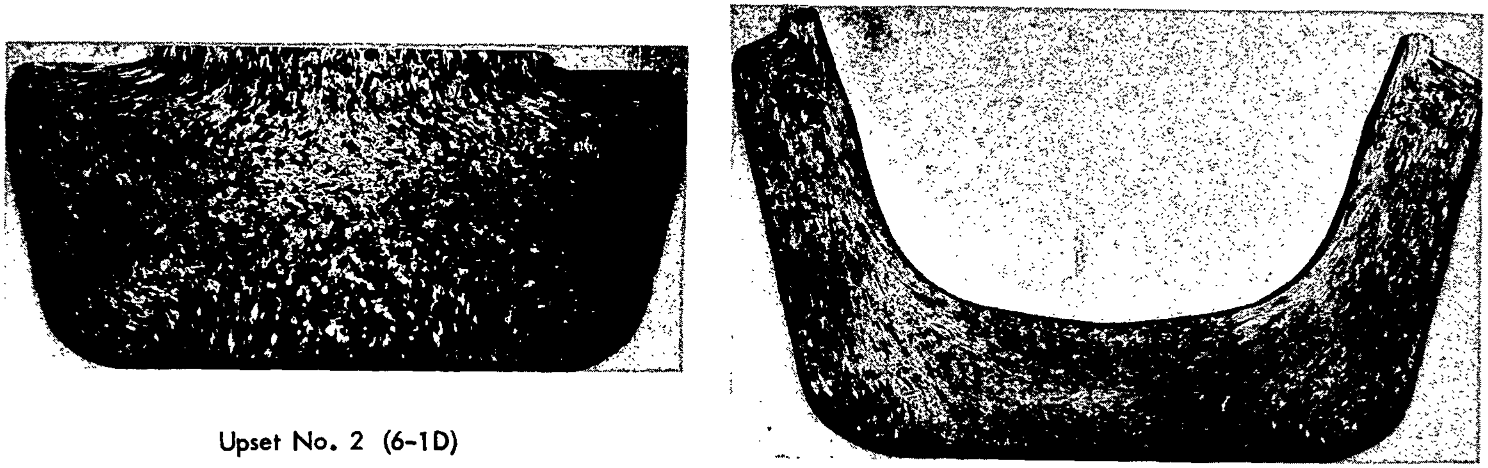
Forged W-2%Mo billets were dropped out at various stages of the sequence to evaluate both the metal flow produced by the sequence and the effect of the selected forging temperatures on microstructure. Forging Nos. 6-1D and 6-1A were dropped out after upset No. 2 and semi-coin, respectively. Center-section macrostructures of these sequence stages together with that of the coin stage are shown in Figure 20. The severity of the work imparted to the center of the workpiece by the back extrusion operations is clearly demonstrated. Note that in this case the metal flow produced in the W-2%Mo forgings is similar to the flow lines observed in the preliminary gridded steel analysis (Figure 18). The lesser worked extrusion centers form the cup bottom and, conversely, result in the most severely worked structure. Note also the lack of work in the upset section in areas bounded by the "X" flow pattern and the frictional restraint of top and bottom tooling contact surfaces.

The problems encountered during the previous forging development of the W-15%Mo universal "structural" component were solved basically by tooling refinement in which such variables as flash modes, restricting draft angles, die sticking, die fill, and minimum corner radii were all systematically balanced to produce the resultant complicated forging. During initial forging trials



FORGING NO. 6-1B, W-2% Mo AS COINED AND SANDBLASTED

FIGURE 19



Upset No. 2 (6-1D)

Semi-Coin (6-1A)

Coin (6-1C)

MACROSTRUCTURES OF W-2% Mo FORGINGS AT VARIOUS STAGES OF THE SEQUENCE

FIGURE 20

of the universal thin section forging, such difficulties were not encountered because of the design simplicity associated with the configuration produced; i.e., component symmetry, large sidewall tapers, and generous radii. In addition, the observed metal flow produced by this sequence verified the original design concept, thus tooling modifications were not required for the subsequent forging run.

2. Final Forging Trials

With the initially selected forging conditions established as successful, the remaining eleven forging billets produced were processed during the final forging development trials by the schedule recorded in Table VII. The parameters investigated and the observed results are outlined below:

a) Process Verification

Five billets were forged using the standard forging conditions to verigy reproducibility (billet Nos. 6-2B, 6-2A, 6-4B, 6-3B, and 6-3C). Billet Nos. 6-3C and 6-4B were forged only through semi-coin because of the possibility of future performance testing of nozzle inserts which could be machined from this configuration. The surfaces produced during the initial forging trials were duplicated by these five billets as shown in Figure 21. Billet No. 6-2B cracked during upset No. 2. No cause could be attributed for the cracking. The billet was, however, forged through the sequence as a backup piece for the forging evaluation studies. Minor radial surface tearing on the outer radius was observed as previously noted in Initial Forging Trials.

b) Starting Billet Microstructure

Billet No. 6-4C was recrystallized prior to forging. The 3000°F - 1 hour recrystallized structure is shown in Figure 13. This 70% recrystallized structure was selected in preference to more fully recrystallized structures because of the grain coarsening produced at the necessarily higher recrystallization temperatures. The temperature sequence varied from that initially selected only in the upset No. 1 temperature, which was increased to 2500°F. All surfaces of the billet required considerable conditioning at each stage of the sequence. The coined forging is shown in Figure 22. Note the severe intergranular cracking in the outer radius as compared to the tears in this region observed for workpieces forged from as-extruded stock (Figure 19).

TABLE VII

Final Forging Trials and Results

Upset No. 1

Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F)		Upset Height (in.)	Condition of Forging
		Punch	Die		
6-2B	2345°	290°	300°	2.630"(2)	3 radial cracks, flash area
6-2A	2340°	300°	350°	2.615"	O.K.
6-4B	2340°	300°	350°	2.620"	O.K.
6-3B	2340°	300°	350°	2.615"	Very rough surface
6-3C	2340°	300°	350°	2.610"	O.K.
6-4C	2520°	290°	325°	2.615"	Widely scattered small radial cracks
6-4A	2520°	290°	325°	2.615"	2 radial cracks, flash area
6-3D	2310°	290°	310°	2.610"	O.K.
6-3A	2340°	300°	310°	2.620"	Large radial side wall crack
6-2D	2340°	300°	310°	2.615"	"
6-2C	Omit				

(1) Optical temperature determinations (see Section IV-C
(2) W-2%Mo billets used for set up

TABLE VII (continued)

Upset No. 2

Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F)		Upset Height (in.)	Condition of Forging
		Punch	Die		
6-2B	2300°	300°	300°	2.110(2)	1 large radial crack on sidewall
6-2A	2300°	300°	300°	2.110"	Good surface
6-4B	2300°	300°	300°	2.110"	Good surface
6-3B	2300°	300°	300°	2.110"	Good surface
6-3C	2300°	300°	300°	2.110"	Good surface
6-4C	2300°	300°	300°	2.110"	Many small radial cracks
6-4A	2515°	300°	300°	2.108"	Good surface
6-3D	2235°	290°	220°	2.113"	Good surface
6-3A	2315°	320°	220°	2.110"	Badly cracked on sidewall
6-2D	2315°	320°	220°	2.111"	Badly cracked
6-2C	2375°	320°	290°	2.112"	Several large radial tears on sidewall

(1) Optical temperature determinations (see Section IV-C)
(2) W-2%Mo billets used for set up

TABLE VII (continued)

Blockdown

Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F) Punch	Die	Bottom Web Thickness (in.)	Condition of Forging
6-2B	2250°	300°	300°	1.216"	1 deep crack as before
6-2A	2250°	300°	300°	1.214"	Good surface
6-4B	2260°	-	-	1.215"	Good surface
6-3B	2260°	300°	290°	1.299"(2)	Good surface
6-3C	2260°	-	-	1.218"	Good surface
6-4C	2260°	-	-	1.213"	Very large radial cracks in radius
6-4A	2515°	300°	300°	1.203"	Large radial cracks in radius
6-3D	2170°	300°	300°	1.217"	Good surface
6-3A	2250°	300°	300°	1.217"	Badly cracked half way thru
6-2D	2250°	300°	300°	1.217"	Cracked very badly
6-2C	Omit				

(1) Optical temperature determinations (see Section IV-C)
(2) W-2%Mo billets used for set up

TABLE VII (continued)

Semi-Coin

Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F)		Bottom Web Thickness (in.)	Condition of Forging
		Punch	Die		
6-2B	2200°	350°	375°	.736"	1 crack side-wall otherwise O.K.
6-2A	2210°	375°	375°	.735"	Excellent side-wall surface
6-4B	2210°	375°	375°	.737"	Small moderate radius tears, excellent side-wall surface
6-3B	2200°	350°	375°	.736"	Small moderate radius tears, excellent side-wall surface
6-3C	2200°	350°	375°	.732"	Small moderate radius tears, excellent side-wall surface
6-4C	2200°	350°	375°	.749(2)	Tears in radius, same areas re-paired in block-down
6-4A	2510°	390°	350°	.732"	Tears in radius, same areas re-paired in block-down
6-3D	2120°	390°	300°	.734"	1 large tear in radius
6-3A	2210°	375°	375°	.738"	Badly cracked (omit coin)
6-2D	2210°	375°	375°	.736"	Cracked as before
6-2C	2260°	325°	325°	.732"	Bad chip on bottom, cracked on O.D. from uspet No. 2

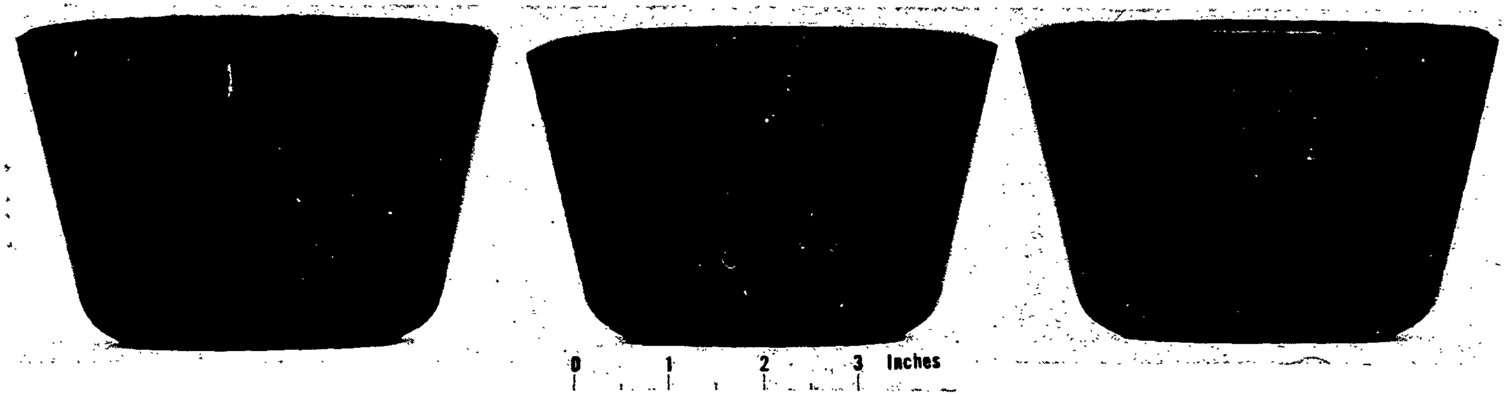
(1) Optical temperature determination (see Section IV-C)
(2) W-2%Mo billets used for tooling set up

TABLE VII (continued)

Coin

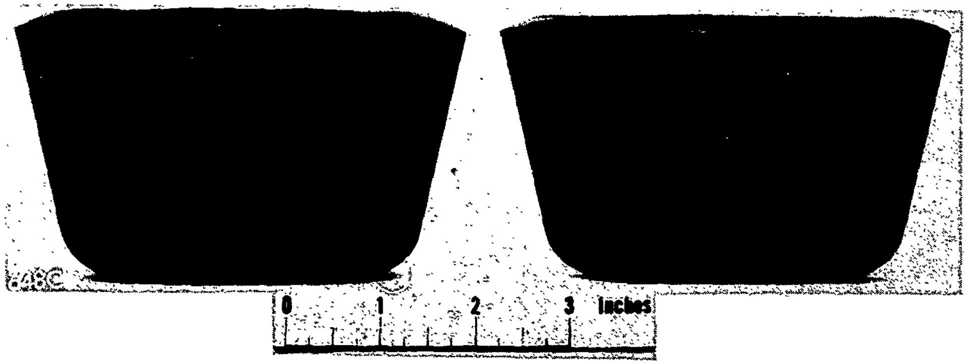
Billet No.	Forging(1) Temp. (°F)	Tooling Temp. (°F) Punch	Die	Bottom Web Thickness (in.)	Condition of Forging
6-2B	2200°	350°	375°	.306"	Figure 21
6-2A	2210°	380°	300°	.352"(2)	Figure 21
6-4B	Omit				Figure 21
6-3B	2200°	350°	375°	.308"	Figure 21
6-3C	Omit				Figure 21
6-4C	2215°	300°	300°	.306"	Figure 22
6-4A	2510°	290°	290°	.300"	Good sidewall surface mod. tears in O.D. radius
6-3D	2055°	290°	300°	.309"	Good sidewall surface mod. tears in O.D. radius
6-3A	Omit				Piece was sectioned
6-2D	2210°	380°	300°	.387"(2)	Figure 24b
6-2C	2215°	300°	300°	.308"	Figure 23

(1) Optical temperature determination (see Section IV-C).
(2) W-2%Mo billets used for tooling set up.



No. 6-2B No. 6-2A No. 6-3B

COINED

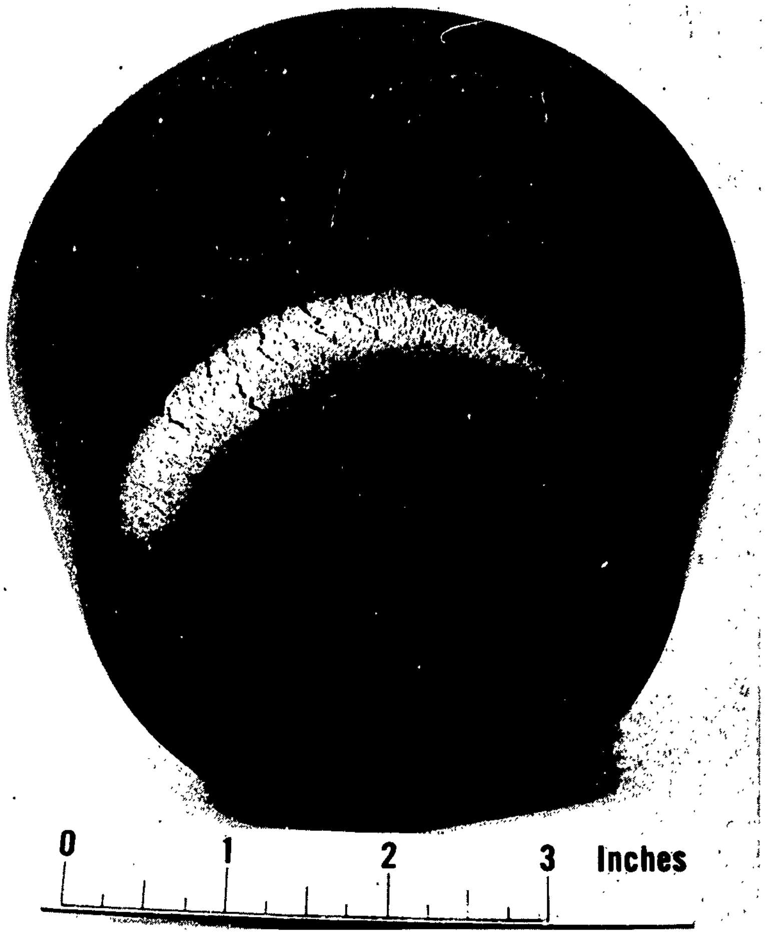


No. 6-3C No. 6-4B

SEMI-COINED

SURFACE APPEARANCE OF FIVE BILLETS FORGED FOR PROCESS VERIFICATION

FIGURE 21



No. 6-4C

SURFACE APPEARANCE OF COINED FORGINGS FOR RECRYSTALLIZATION STARTING BILLET

FIGURE 22

c) High Forging Temperature

The effect of higher forging temperatures within the cold working range of W-2%Mo was investigated using billet No. 6-4A. This billet was forged at 2500°F through each sequence stage. Observed forgeability was comparable to billet No. 6-4C, i.e., the in-process conditioning was similarly extensive for all surfaces. The sidewall surface appearance of the workpiece was comparable to those produced by the standard forging conditions. Similar but deeper radial surface tearing was observed in the outer radius region.

d) Low Forging Temperature

Billet No. 6-3D was processed at temperatures below those initially established, ranging from 2300°F for the initial upset to 2050°F for the final coin blow (see Table VII).

Low temperature processing indicated improvement over the high temperature forging, i.e., considerably less in-process conditioning was required. Except for a large radial tear in the O.D. radius observed after the semi-coin operation, the low temperature forgeability was comparable to that for workpieces forged by the standard conditions. The coined workpiece sidewall surface appearance was also comparable to that for standard workpieces; however, more extensive radial tearing was observed in the outer radius.

e) Forging Sequence Variation

A three-blow sequence was investigated with billet No. 6-2C in which the upset No. 1 and the blockdown operations were omitted. The omission of upset No. 1 (a total upset of 59%) resulted in non-repairable cracking during the single upsetting operation. Further omission of the blockdown operation resulted in punch sticking during the semi-coin operation. The time taken to pry the workpiece loose resulted in rapid cooling to a black heat. The sidewall and radius cracking are shown in Figure 23.

f) Lubrication Practice

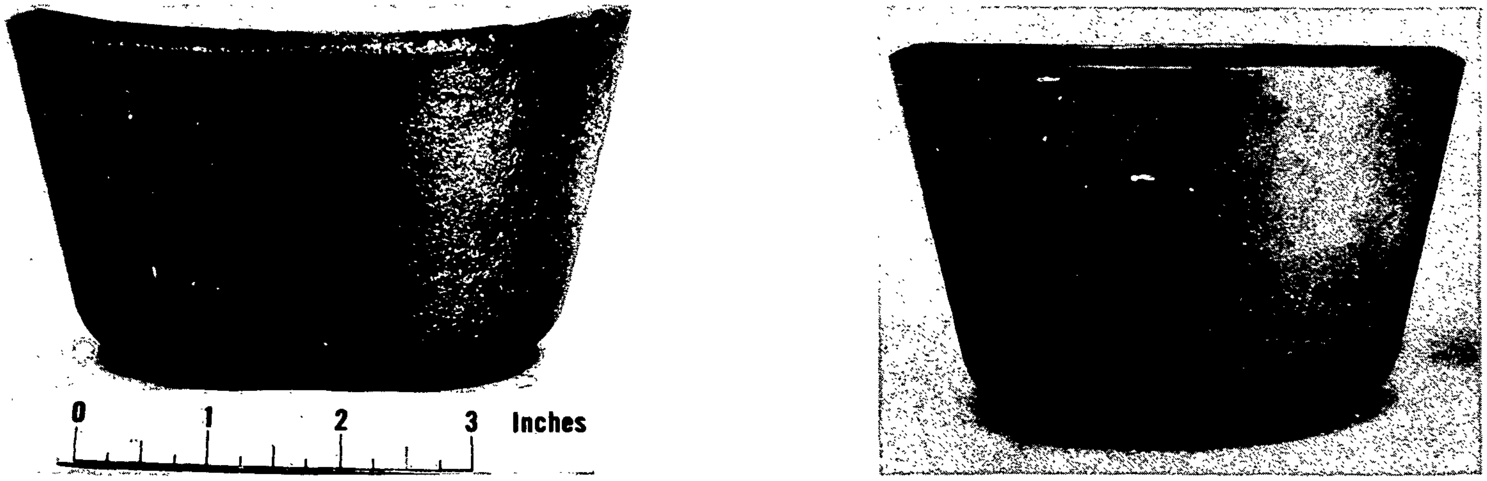
The two remaining billets, Nos. 6-3A and 6-2D, which were cracked during extrusion and extensively repaired, (Table III), were used to compare the "bare" forging lubrication practice

No. 6-2C

SURFACE APPEARANCE OF COINED FORGING FOR FORGING SEQUENCE REDUCED TO THREE STAGES

FIGURE 23

with workpiece lubricants previously used and described (5). The surface comparison of the coated forging (billet No. 6-2D) with "bare" lubrication practice is shown in Figure 24a and 24b. Obviously the coating, used effectively during the universal structural forging development, is inadequate at the slightly higher temperatures used for the thin section component.



(b) No. 6-2D

(a) No. 6-1B

SURFACE APPEARANCE OF COINED FORGING FOR (a) 'BARE' BILLET LUBRICATION PRACTICE AND (b) COATED BILLET LUBRICATION PRACTICE

FIGURE 24

V FORGING EVALUATION

A. Yield

The starting weight for the W-2%Mo forging billets was a nominal 20 pounds as compared to the average final coined forging weight of 19.1 pounds. The resultant 95.5% forging yield is exceptionally high. It should be noted, however, that the metal losses occurred solely by in-process surface conditioning and oxidation. Flash pattern scrap was precluded by the tooling design.

B. Dimensions

The coined forgings from the final forging trials were inspected for deviation from design dimensions at the locations shown in Figure 14. Position "A" thickness was located at a height of 3-1/4 in. from the cup bottom and was checked at four 90° rotated positions. The dimensions of the six positions checked are recorded in Table VIII. The high deviation from the design web thickness (C) for forging No. 6-2A was observed after forging with tooling adjusted vertically to yield a 0.250 in. web thickness for steel setup billets. The minimum tooling shut height was designed to 0.200 in. for the "C" dimension, thus the allowable vertical tooling adjustment at this setup position was 0.050 in. The tooling shut height was subsequently adjusted to this minimum web thickness limit and the remaining W-2%Mo forgings were struck. The deviations recorded for web thickness "C" and bottom diameter (B) reflect the inability of the tooling setup to compensate for the high resistance to deformation of thin wall tungsten forgings. These data will be programmed into future tooling designs.

A comparison of the last six forging produced reveals the dimensional reproducibility achieved; i.e., the cup bottom diamter dimensions are within 0.010 in. and the web thickness values are within 0.008 in. The cup sidewall thicknesses (A) were all within the 0.395 in. maximum dimension targeted for this position; however, the greatest dimensional variation at this location among the six forging was 0.024 in.

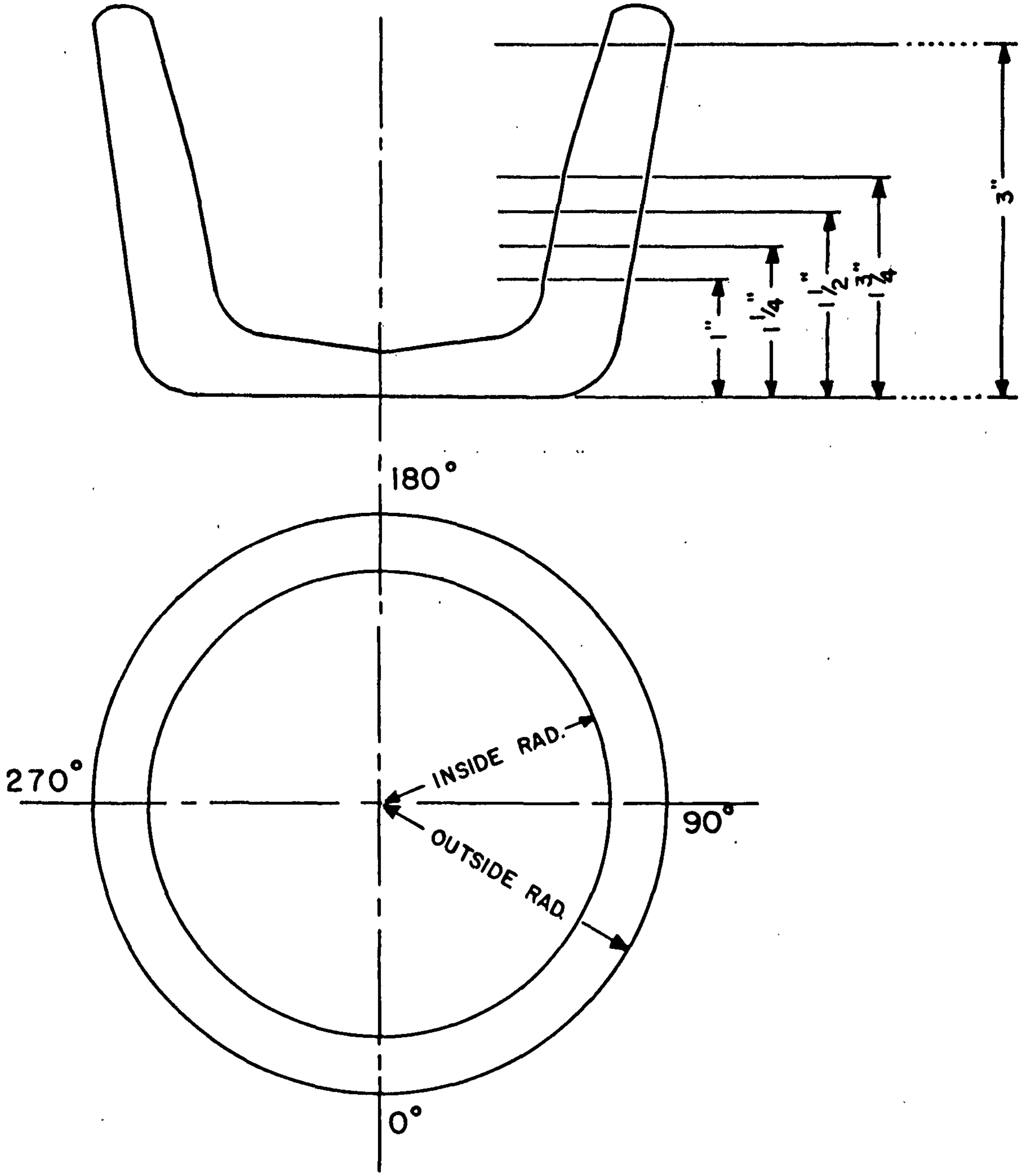
Of importance for a final forging design is the determination of the minimum forging envelope required for machining a critical tolerance component. The primary factors determining the minimum forging envelope for a thin section forging are surface finish, dimensional accuracy and reproducibility, and component concentricity. To determine the latter for the universal thin section forgings, coined forging No. 6-2A was selected at random, brushed with Dykem layout ink, and scribed for concentricity measurements at the 1/4 in. intervals shown in Figure 25. The forging was located on the outer sidewall in a lathe chuck, rotated and measured for concentricity with an indicator. The measurements

TABLE VIII

Dimensions of Coined Forgings from Final Forging Trials

Forging Billet No.	"A" Dimension (in.)(1)					Web Thickness "C" (in.)			Bottom Diameter "B" (in.)		
	Design Dimensions	0°	90°	180°	270°	Design Dimensions	Measured	Deviation	Design Dimensions	Measured	Deviation
6-2A(2)	.395	.412	.409	.402	.407	.250	.352	.102	3.812	3.840	.028
6-2D(2)	.395	.417	.409	.401	.400	.250	.394	.144	3.812	3.840	.028
6-2B	.395	.372	.394	.379	.394	.250	.306	.056	3.812	3.840	.028
6-2C	.395	.390	.388	.387	.376	.250	.308	.058	3.812	3.840	.028
6-3B	.395	.392	.387	.386	.378	.250	.308	.058	3.812	3.830	.018
6-4A	.395	.377	.369	.386	.370	.250	.300	.050	3.812	3.840	.028
6-4C	.395	.393	.388	.382	.379	.250	.306	.056	3.812	3.840	.028

(1) Taken at a constant sidewall height of 3.250 (see Figure 14).
(2) Used as W-2%Mo set up pieces.



DIMENSIONS TAKEN FOR CONCENTRICITY MEASUREMENTS OF COIN FORGING NO. 6-2A (See Table VIII)

FIGURE 25

recorded at each 90° rotation are tabulated in Table IX. The outer sidewall concentricity varied by 0.002 in. while the inner sidewall concentricity variations increased to 0.030 in. Based on these results and subsequent surface finish measurements, an adequate forging envelope would consist of approximately 0.010 in. and 0.040 in. on the outer and inner forging walls respectively. Improved alignment mechanisms for future forging efforts will be evaluated for the reduction of the inner sidewall concentricity variation.

C. Surface Finish

Post forging surface conditioning of the forged W-2%Mo components consisted of a light sandblast to remove a thin film of surface oxide. Figure 24a illustrates the representative surface finish obtained by "bare" workpiece lubrication practice for the universal thin section forgings. Sidewall surface finish readings for such forgings ranged from 40 to 60 RMS. Coated billet lubrication practice (Nos. 6-3A and 6-2D shown in Figure 24b) resulted in surface finish readings of 150 to 200 RMS.

D. Non-Destructive Testing

Super zyglo fluorescent penetrant inspection revealed no additional surface discontinuities other than those discussed in Section IV-E, Figures 23-25. Surface tearing in the regions of the punch and die radius, which were observed prior to zyglo inspection, were the only detectable surface discontinuities in the sound forgings.

The application of ultrasonic testing to the universal thin section forging was investigated. A meaningful test procedure could not be devised. Both shear beam and normal-to-surface ultrasonic testing of the thin wall coined forgings were precluded by near surface "dead areas".

Eddy current techniques are presently being utilized at TAPCO for the inspection of thin section titanium forgings. The applicability of these testing techniques to the thin walled W-2%Mo forging is being investigated.

E. Macrostructure

Macrostructure of the W-2%Mo thin section forging, as related to sequence and tooling design, has been previously discussed (Section IV-D). Further observation of the coined section macrostructure shown in Figure 20 reveals that the metal flow near the inner sidewall follows a convergent-divergent path corresponding to the throat configuration of a nozzle insert, thus minimizing interruption of flow lines during insert machining.

TABLE IX

Concentricity Measurements of Coined Forging No. 6-2A

Height on Sidewall (in)	0° Position*		90° Position		180° Position		270° Position	
	O. R.(1)	I. R.(2)	O. R.	I. R.	O. R.	I. R.	O. R.	I. R.
1	0	0	+.001	-	+.001	-	.000	-
1-1/4	0	0	+.002	+.021	.000	-.010	+.001	-.030
1-1/2	0	0	+.002	+.018	+.001	-.010	+.001	-.028
1-3/4	0	0	+.002	+.013	+.001	-.012	+.001	-.025
2	0	0	+.001	+.008	.000	-.013	.000	-.020
2-1/4	0	0	+.001	+.004	.000	-.014	+.001	-.017
2-1/2	0	0	+.001	+.001	+.001	-.011	+.001	-.011
2-3/4	0	0	+.001	-.005	+.002	-.016	+.001	-.010
3	0	0	+.001	-.005	+.002	-.012	+.001	-.002

* 0° Position set to 0 at each sidewall height
(1) O.R. = concentricity deviation of the outer radius
(2) I.R. = concentricity deviation of the inner radius
(See Figure 25)

F. Microstructure

To determine the cumulative effect of the forging process on the W-2%Mo workpiece microstructure, upset No. 2, semi-coined, and coined forgings processed by the standard forging conditions were sectioned and prepared for metallographic examination. In addition, all coined forgings whose processing deviated from the standard conditions were similarly prepared.

The as-forged microstructures and the DPH hardness values of the upset No. 2 section are shown in Figure 26. The shaded area represents a relatively heavily worked region, while the clear areas reflect hardness values and microstructures comparable to the as-extruded stock, as anticipated from the macrostructure.

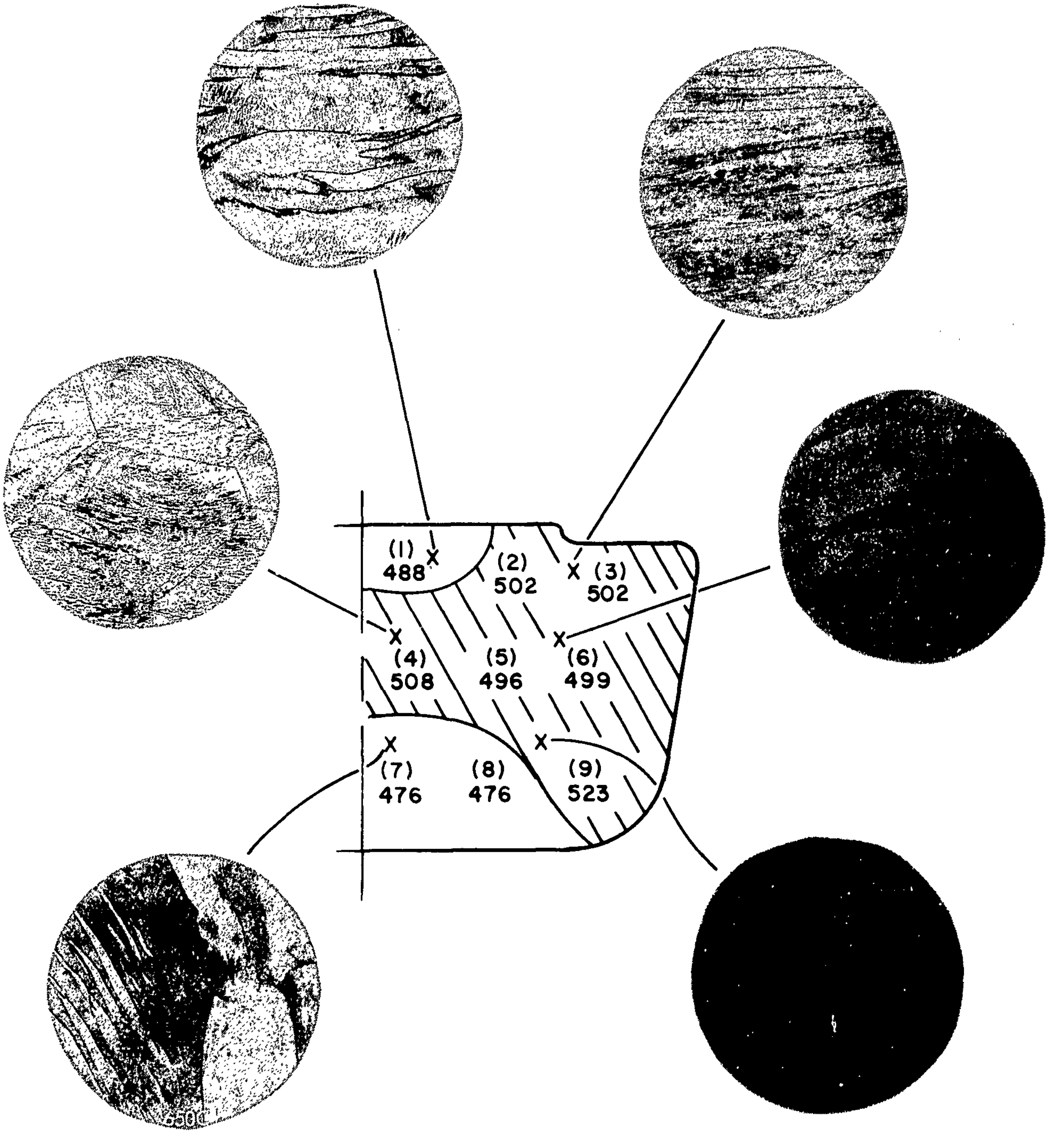
The as-forged microstructures of the semi-coined forgings, except for No. 6-4C, exhibited cold worked structures throughout. Representative as-forged microstructures and DPH hardness determinations are shown in Figure 27. The shaded area comprises the depth to which the punch effectively worked the forging sidewall. The degree of punch effectiveness was further demonstrated in coined forging No. 6-4C (billet recrystallized prior to forging), in which the outer diameter sidewall region still retains the partially recrystallized structure seen in Figure 28. The cold working observed in the outer sidewalls of all the other forgings is, then, principally supplied by the extrusion and upsetting operations.

G. Recrystallization

The forgings previously discussed under Microstructure were further sectioned to provide additional samples for study of the response of as-forged properties to heat treatment. The sections were heated for one hour within the temperature range 2500°F to 3100°F.

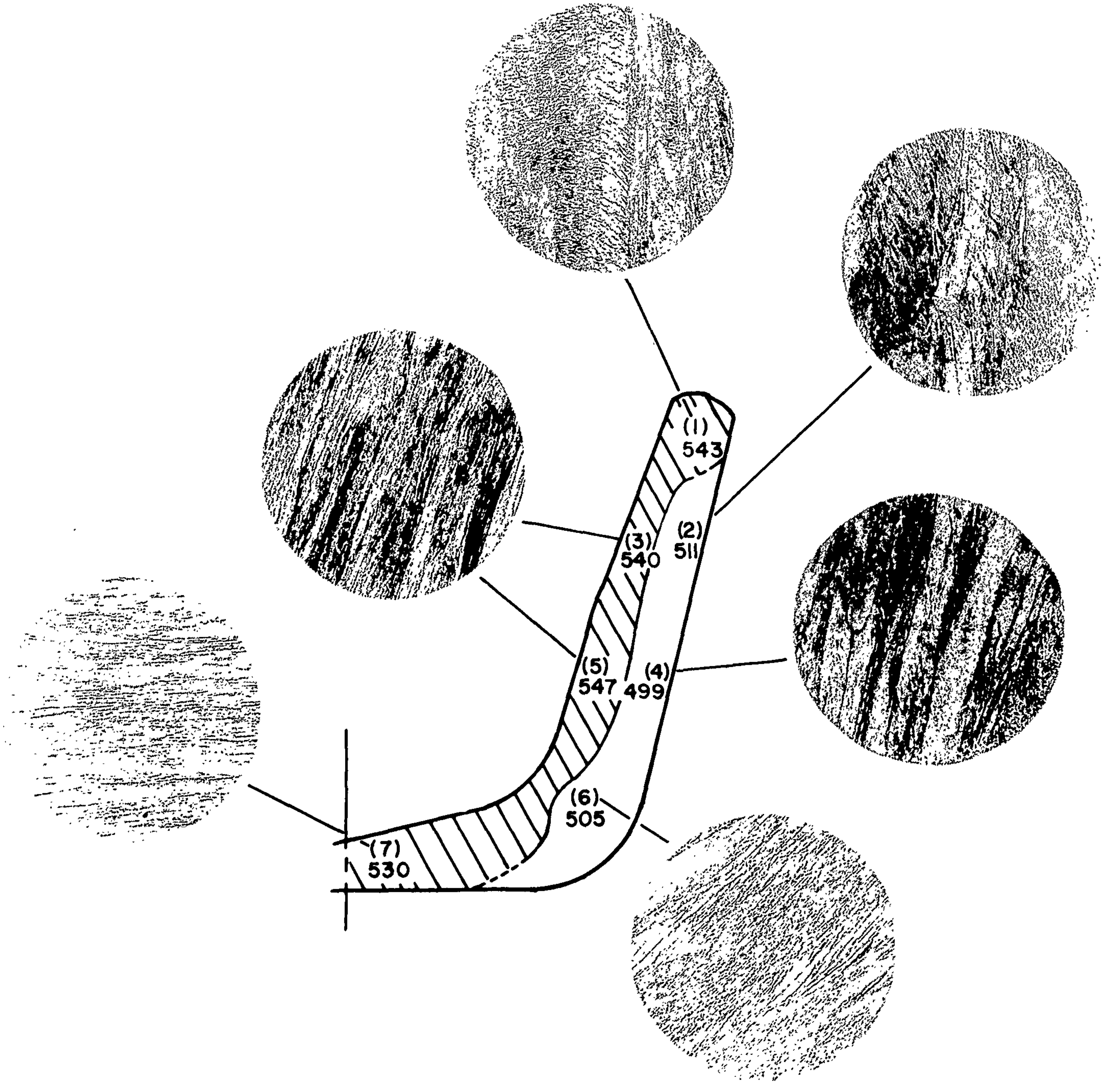
The effect of the heat treatment on the hardness values for the upset No. 2 sections are recorded in Table X. The average hardness values within the shaded area and the average values in the clear areas (see Figure 26) are plotted as a function of temperature in Figure 29. Within the shaded area the initiation of one hour recrystallization occurs at approximately 2700°F, and full recrystallization is apparent at 3000°F. The areas outside the shaded area respond to the heat treatments in the same manner as the as-extruded stock; i.e., initiation of recrystallization above 2700°F and full recrystallization at 3100°F.

Tables XI and XII record the DPH hardness values determined for the semi-coined forging and the coined forgings respectively after one hour heat treatments. The hardness values reported for the coined forging, together with the microstructural response to heat treatments



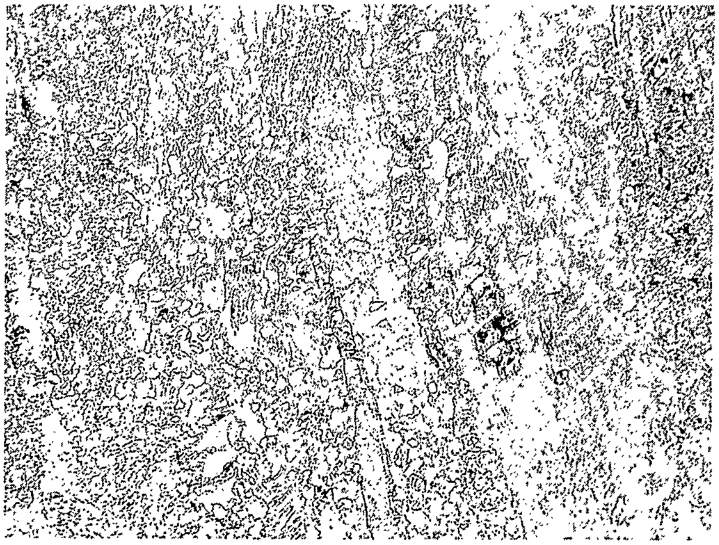
AS FORGED MICROSTRUCTURES AND DPH HARDNESS AT POSITIONS INDICATED FOR UPSET NO. 2 (No. 6-10) - 50X
Nos. 1 through 9 Refer to Hardness Measurement Locations

FIGURE 26

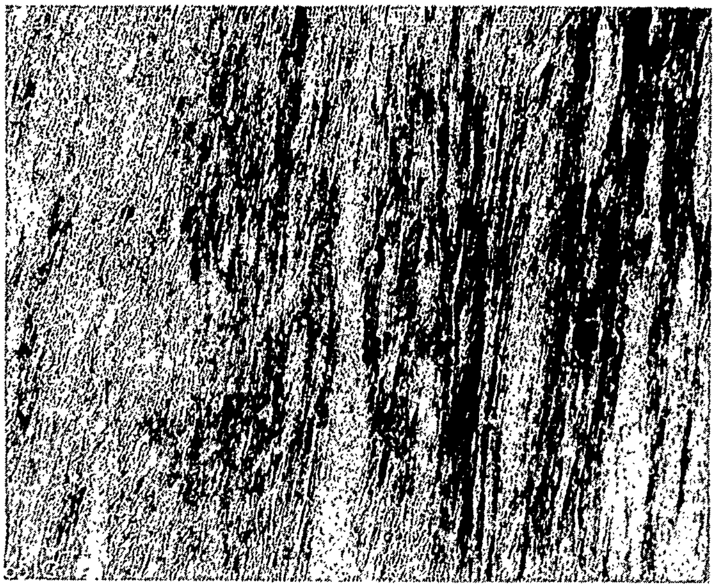


REPRESENTATIVE AS FORGED MICROSTRUCTURES AND DPH HARDNESSES AT LOCATIONS NUMBERED 1 THROUGH 7 AS INDICATED FOR SEMI-COINED AND COINED FORGINGS - 50X

FIGURE 27



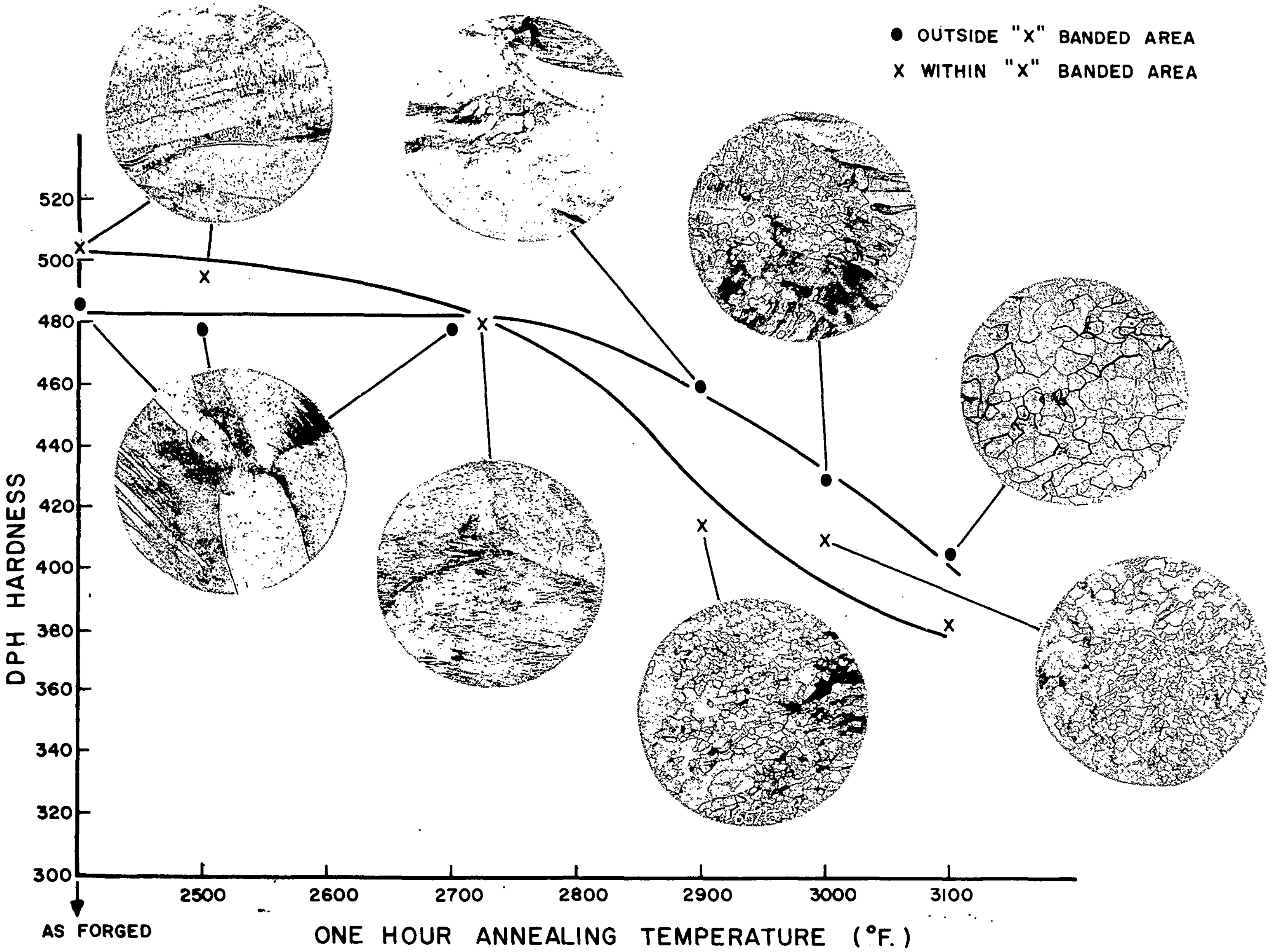
O.D. (Die Sidewall)



I.D. (Punch Sidewall)

AS FORGED MICROSTRUCTURES OF FORGING NO. 6-4C
(Recrystallized Starting Billet) - 50X

FIGURE 28



RECRYSTALLIZATION OF UPSET NO. 2

FIGURE 29

TABLE X

Hardness of W-2%Mo After Upset No. 2 and One Hour Heat Treatments at Various Temperatures

Condition	DPH Hardness at Positions*									Average DPH Hardness	
	1	2	3	4	5	6	7	8	9	1, 7, 8	2, 3, 4, 5, 6, 9
As-Forged	488	502	502	508	496	499	476	476	523	485	505
2500°F	488	487	496	484	496	481	470	476	533	478	496
2700°F	481	493	490	490	484	487	470	480	436	477	480
2900°F	462	422	420	402	422	415	473	432	420	459	417
3000°F	436	427	415	410	415	413	434	415	409	428	415
3100°F	379	383	383	381	373	373	429	406	391	405	381

* See Figure 26

TABLE XI

Hardness of W-2%Mo After Semi-Coin and One Hour Heat Treatments at Various Temperatures

Condition	DPH Hardness at Positions*							Average DPH Hardness	
	1	2	3	4	5	6	7	1, 3, 5, 7	2, 4, 6
As-Forged	537	511	537	517	550	520	528	538	516
2500°F	523	514	543	502	523	520	528	529	512
2700°F	517	505	523	493	505	496	499	511	498
2900°F	502	490	476	481	457	478	467	475	483
3000°F	434	429	404	476	400	499	402	410	468

* See Figure 27

TABLE XII

Hardness of W-2%Mo After Coin and One Hour Heat Treatments at Various Temperatures

Condition	DPH Hardness at Positions*							Average DPH Hardness	
	1	2	3	4	5	6	7	1, 3, 5, 7,	2, 4, 6
As Forged	543	511	540	499	547	505	530	540	505
2500°F	537	496	505	490	530	505	527	525	497
2600°F	512	502	523	502	530	502	499	516	502
2700°F	470	493	478	481	493	481	481	481	488
2900°F	404	396	396	400	391	427	391	396	408
3000°F	396	385	381	387	379	375	389	386	382

* See Figure 27.

(Figure 30), are representative of all the coined forgings produced regardless of prior forging process conditions. This can be attributed, in part, to the broad cold working temperature range made possible by the relatively high recrystallization temperature of the as-extruded stock. Initiation of one hour recrystallization for the coined forgings, as shown in Figure 30, occurs for the more heavily worked areas adjacent to the punch above 2600°F, and the entire section is fully recrystallized at 3000°F.

H. Mechanical Properties

As-forged material was sectioned as illustrated in Figure 31 to provide specimens for the determination of mechanical properties. Ductile-brittle transition temperature and elevated temperature tensile properties were determined. The specimens utilized for the testing effort are shown in Figure 32.

1. Ductile-Brittle Transition Temperature

Positions within the forging sidewall, when improperly selected for test specimens, can result in misleading data. The variation of transition temperature for a sintered and forged tungsten non-structural component is reproduced in Figure 33*. The data indicate a considerable drop in the ductile-brittle transition temperature as the test area approaches the more heavily worked forging inner sidewall. Since thermal stress failures in insert firings are associated with initial outer sidewall fracture, the specimen blank position sectioned from the W-2%Mo forging (Figure 31) will include the worst possible condition in the forging sidewall during mechanical testing.

Bend test data were obtained for the as-extruded W-2%Mo stock (Section No. 6-4D) from an area 0.4 in. from the extrusion O.D., the area predicted by the metal flow evaluation to be that which formed the specimen blank in the coined forging sidewall. Bend testing was accomplished on an Instron tensile tester using a crosshead speed of 0.020"/min. The bend angle values plotted in Figure 34 indicate the transition temperature of the extruded stock for the position selected to be approximately 475°F.

Two semi-coined and two coined forgings processed by the initial forging conditions were sectioned for ductile-brittle transition temperature bend test measurements. The forgings selected (Nos. 6-1A, 6-3A, 6-1C, and 6-2D) did not represent optimum forgings since the four sound production run forgings were withheld for a possible

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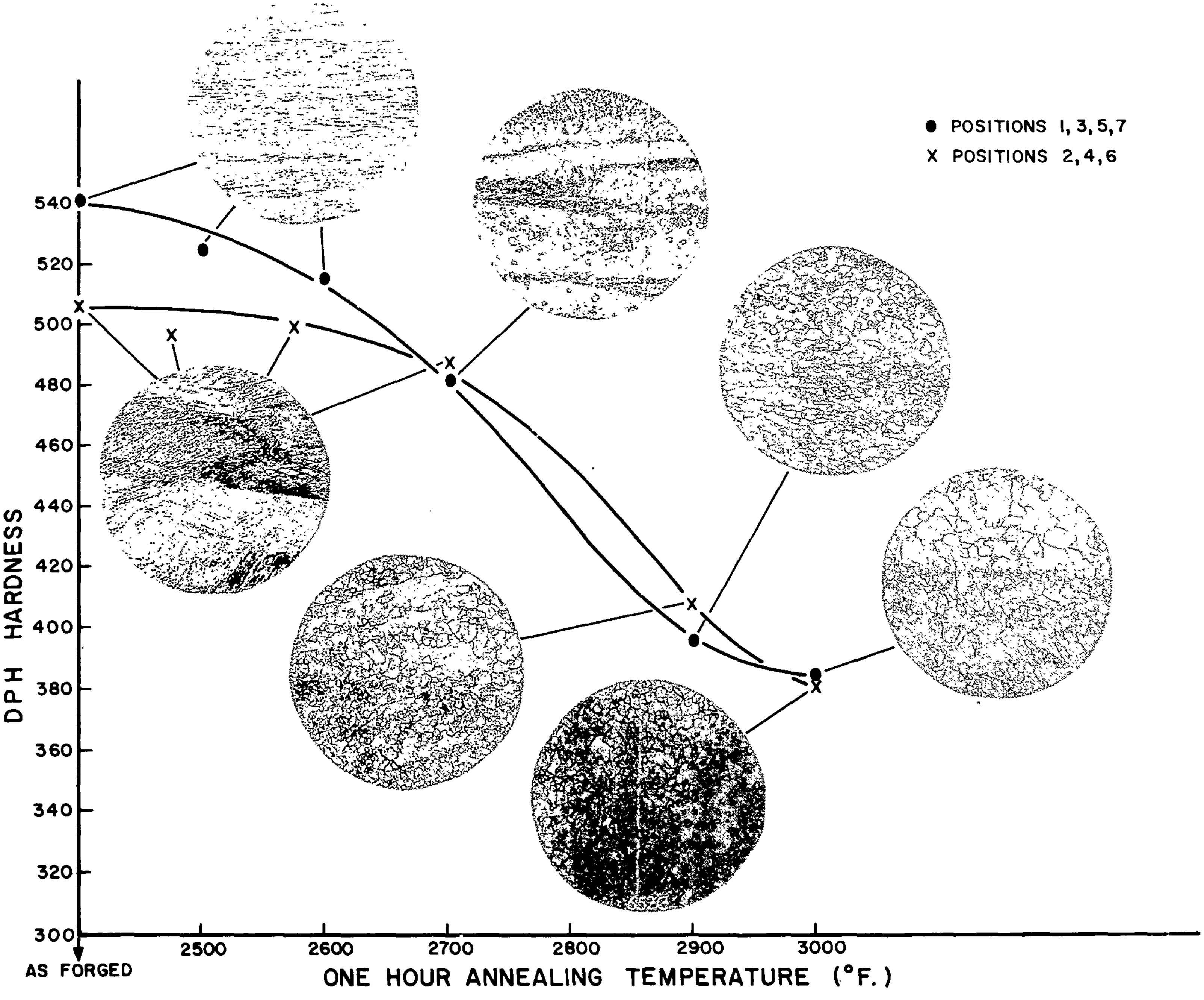
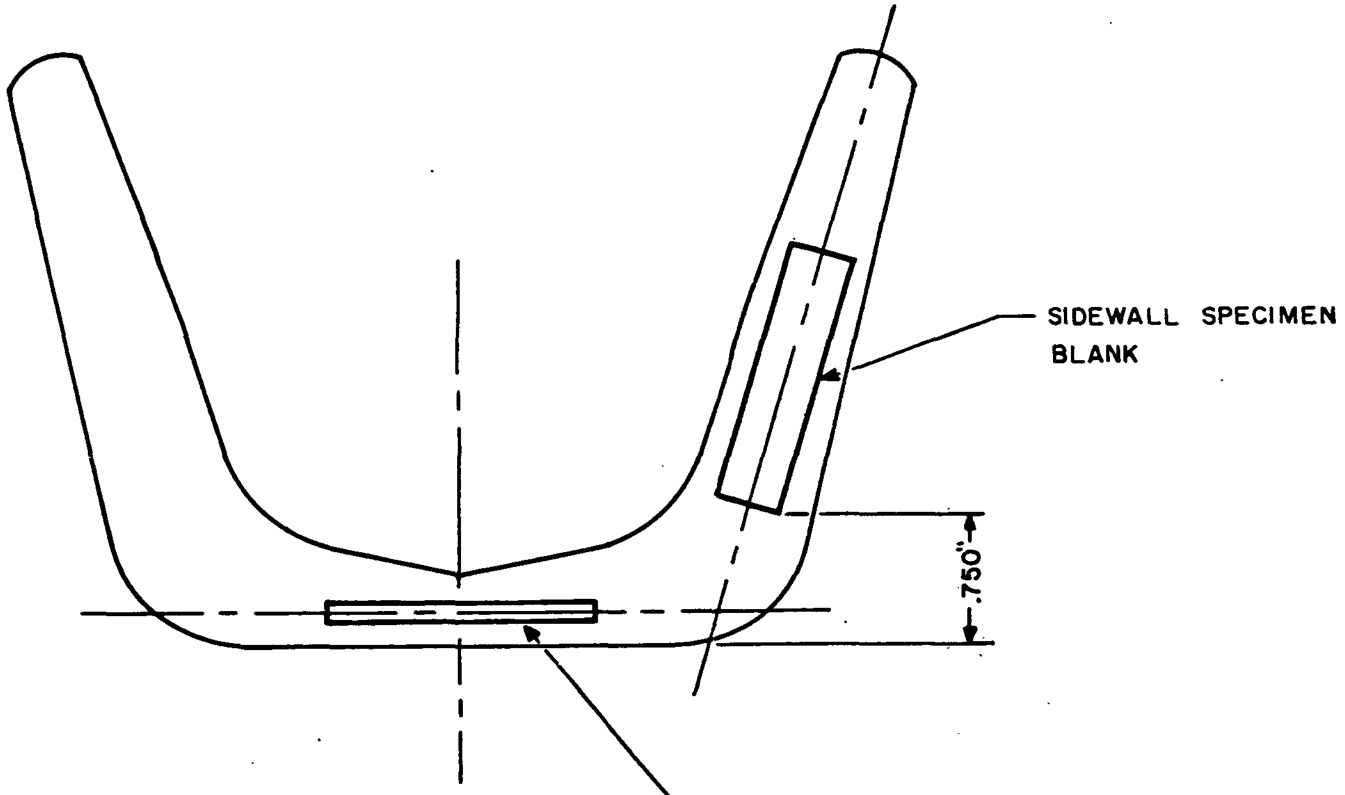
* Unpublished research, TAPCO (7).



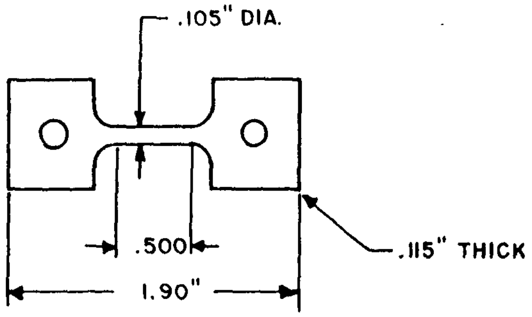
REPRESENTATIVE RECRYSTALLIZATION OF SEMI-COIN AND COIN FORGINGS

FIGURE 30

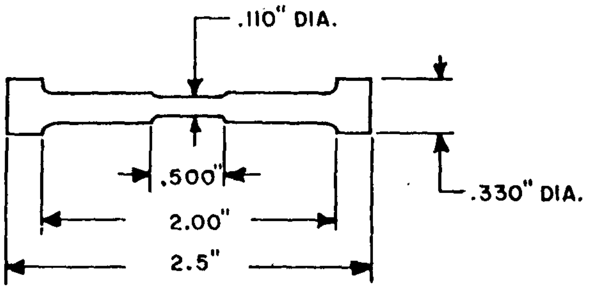


LOCATION OF TEST SPECIMENS TAKEN FROM FORGING SIDEWALL AND BOTTOM

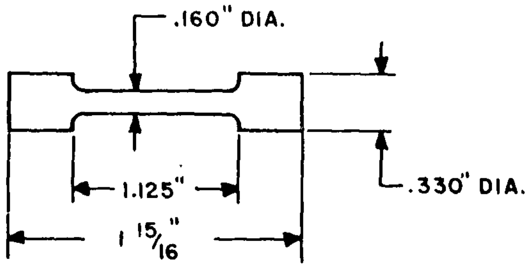
FIGURE 31



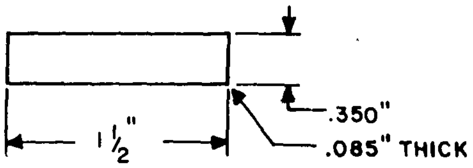
(a) High Temperature Tensile Specimen Radiant Heated - 3000-4000°F.



(b) High Temperature Tensile Specimen Resistance Heated - 5000°F.



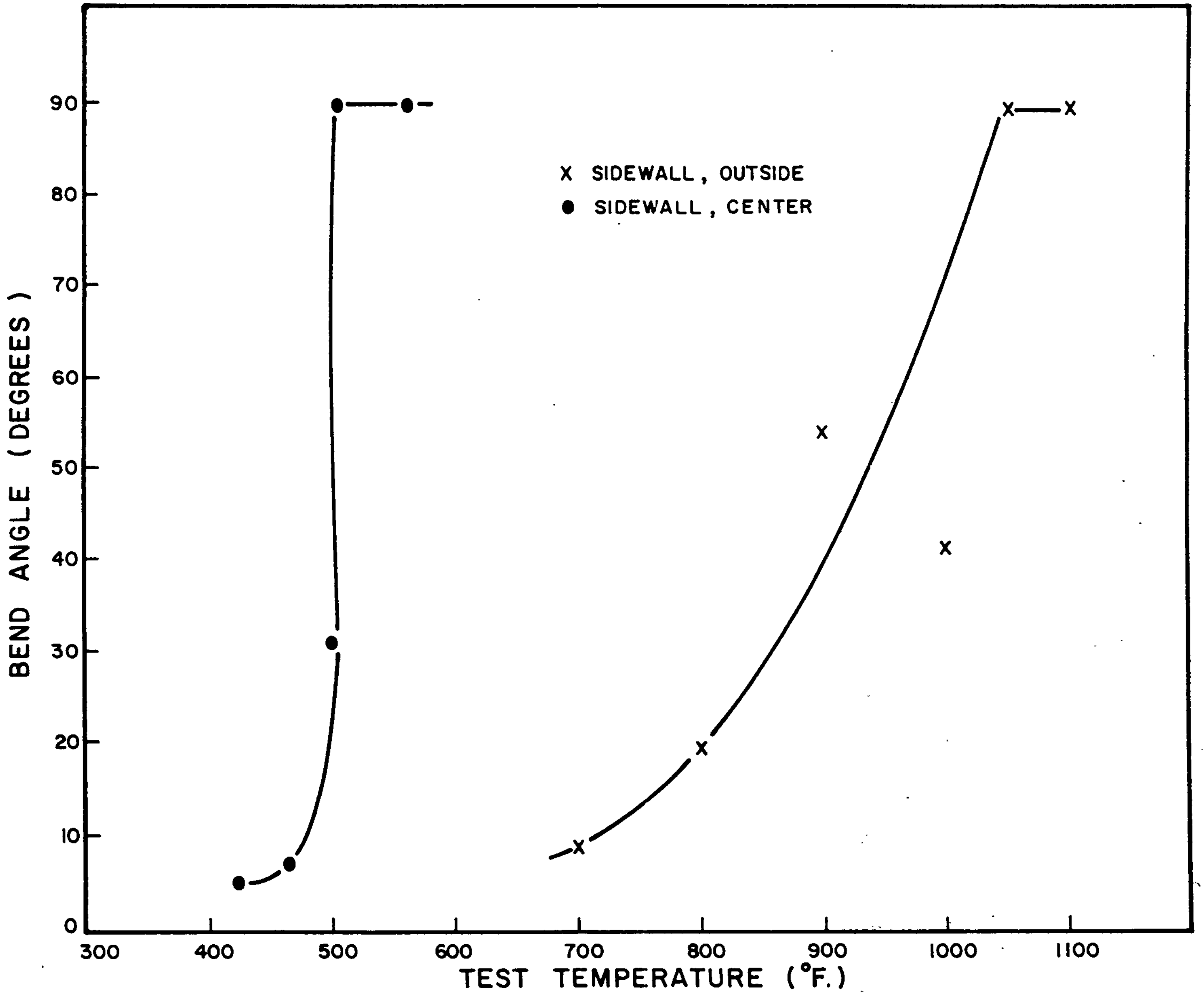
(c) Tensile Ductile-Brittle Transition Temperature Specimen.



(d) Bend Ductile-Brittle Transition Temperature Specimen.

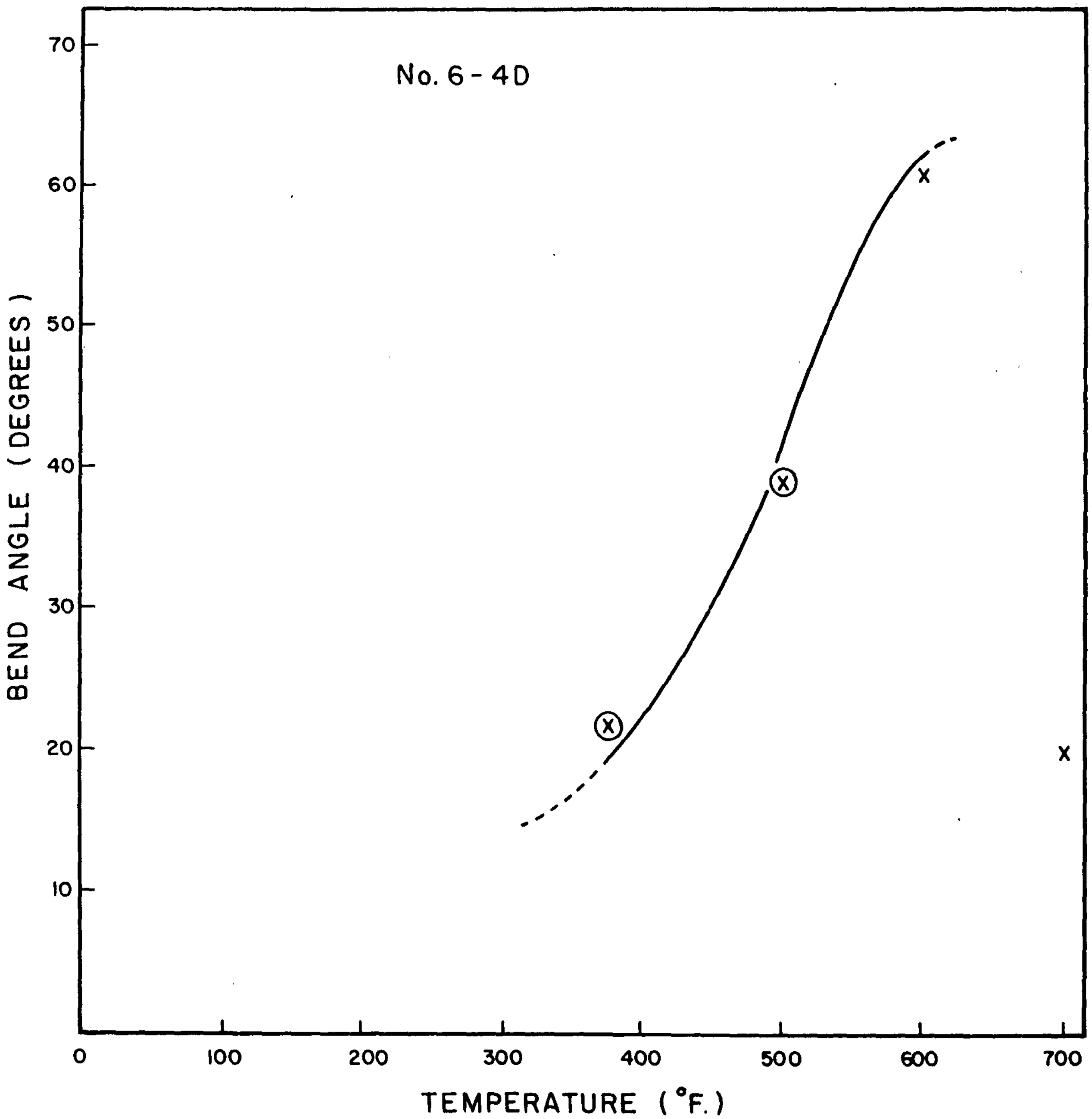
SPECIMENS USED FOR MECHANICAL PROPERTY DETERMINATIONS

FIGURE 32



EFFECT OF SIDEWALL TEST POSITION ON THE BEND DUCTILE-BRITTLE TRANSITION TEMPERATURE OF SINTERED AND FORGED UNALLOYED TUNGSTEN (7)

FIGURE 33



DUCTILE-BRITTLE BEND TRANSITION TEMPERATURE OF AS EXTRUDED W-2% Mo STOCK (SECTION NO. 6-4D)

FIGURE 34

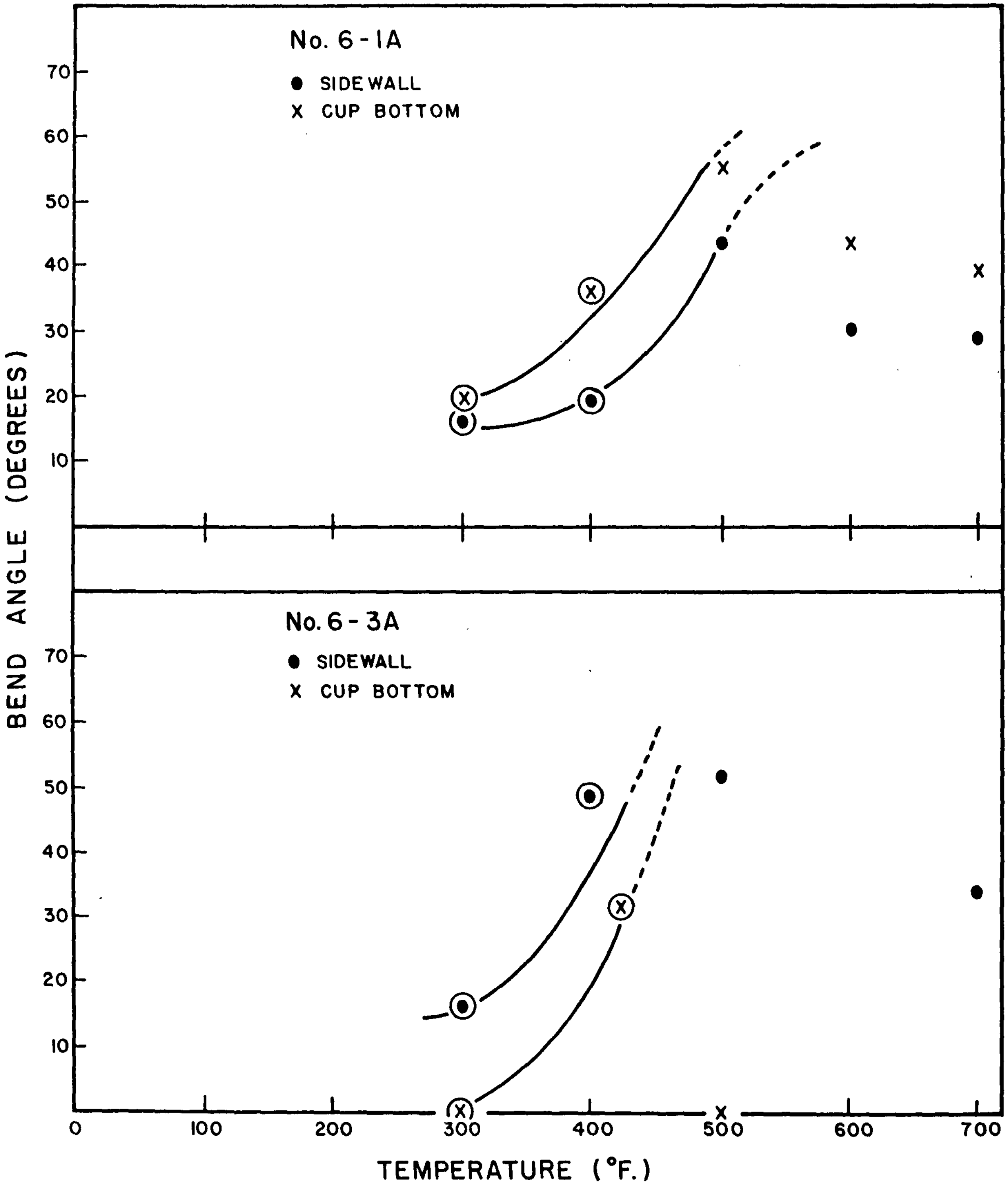
future firing analysis. Specimens were also machined from the forging bottoms (Figure 31). This was done to study the possible correlation between the properties of forging bottom and sidewall, thus possibly providing a quality control procedure from testing of coupons trepanned from the bottoms during insert machining. The data obtained from the bend tests are plotted in Figure 35 and 36. The anomalous results observed during the testing at 600°F and 700°F were attributed to poor specimen surface preparation prior to electropolishing. The effects of specimen preparation and surface conditioning on the ductile-brittle transition temperature have been thoroughly evaluated (9, 11). The circled points on the plots represent specimens which were reground, electropolished, and inspected. The data indicate the ductile-brittle transition temperature of both the semi-coined and coined forging sidewalls and cup bottoms to be approximately 450°F to 475°F.

To confirm the bend transition temperature test data, tensile specimens were prepared from sidewall blanks of forging Nos. 6-1A and 6-1C and were tested within the same temperature range. An Instron tensile tester with a crosshead speed of 0.020"/min. was again utilized. The results of this effort are tabulated in Table XIII. Reduction of area and elongation values are plotted in Figure 37. The tensile data indicate the transition temperature of the center sidewall section of both semi-coined and coined forgings to be approximately 400°F.

The transition temperature data indicate that the cold working imparted to the cast W-2%Mo billet during extrusion was not significantly increased during forging in the outer area of the workpiece. This has been demonstrated by the microstructures and hardness measurements presented. More significantly, the ductile-brittle transition temperature observed for the extruded stock was not appreciably lowered by the forging process. It would thus appear desireable to extrude larger diameter billets at greater reduction ratios (5.5/1 to 6/1) to achieve a lower transition temperature in the subsequently forged components.

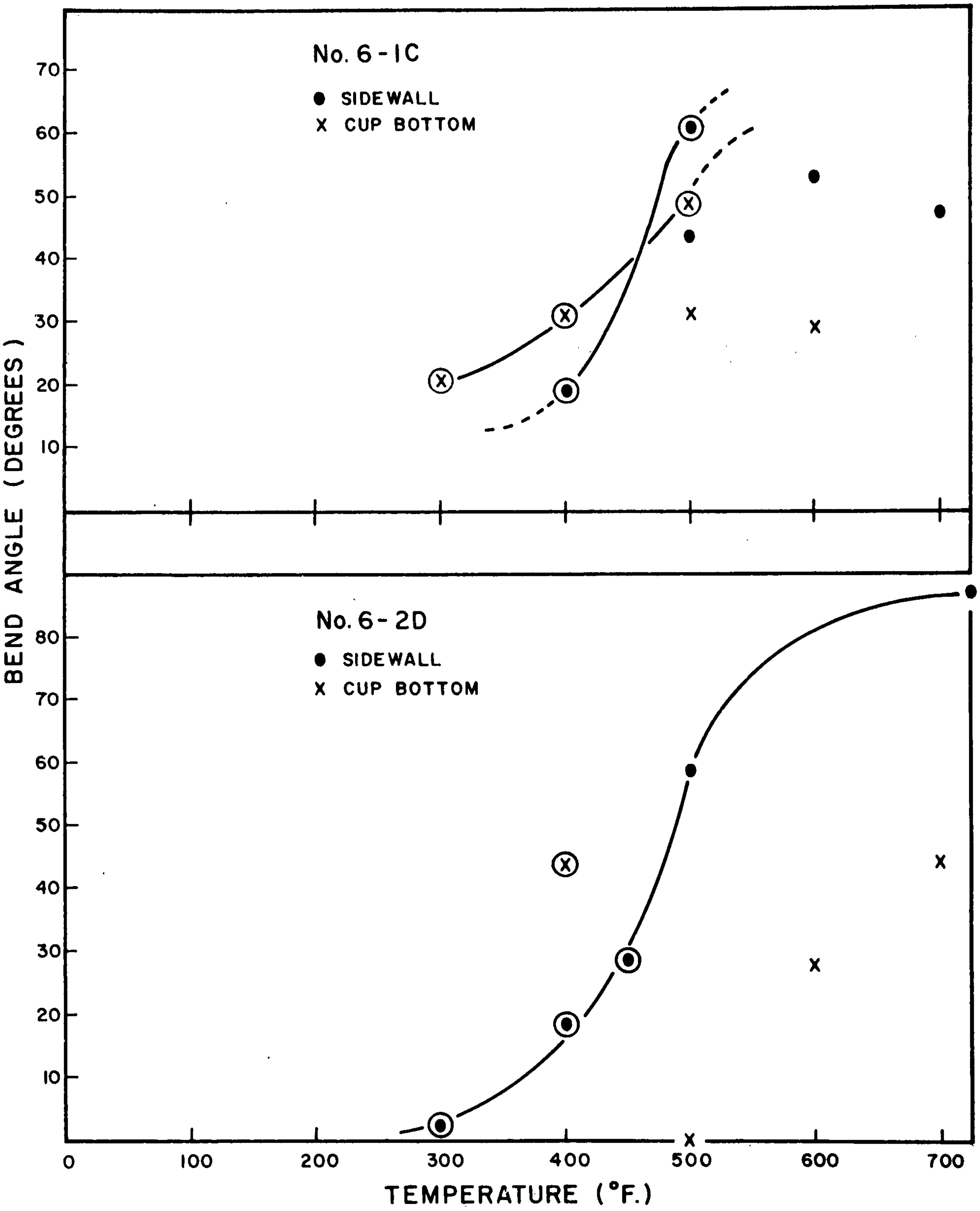
2. High Temperature Tensile Properties

Test specimens were machined from the sidewall blanks of both a semi-coined and a coined forging (Nos. 6-1A and 6-1C respectively). Testing procedures for the radiant heated specimens at 3000°F and 4000°F have been previously outlined (5). The procedures followed for the 5000°F tests were similar except the specimens were self-resistance heated. A current was passed directly through the specimen and the temperature measurements were taken using a calibrated pyrometer (9). The results of testing are summarized in Table XIV.



DUCTILE-BRITTLE BEND TRANSITION TEMPERATURE OF TWO SEMI-COIN FORGINGS (NOS. 6-1A AND 6-3A)

FIGURE 35



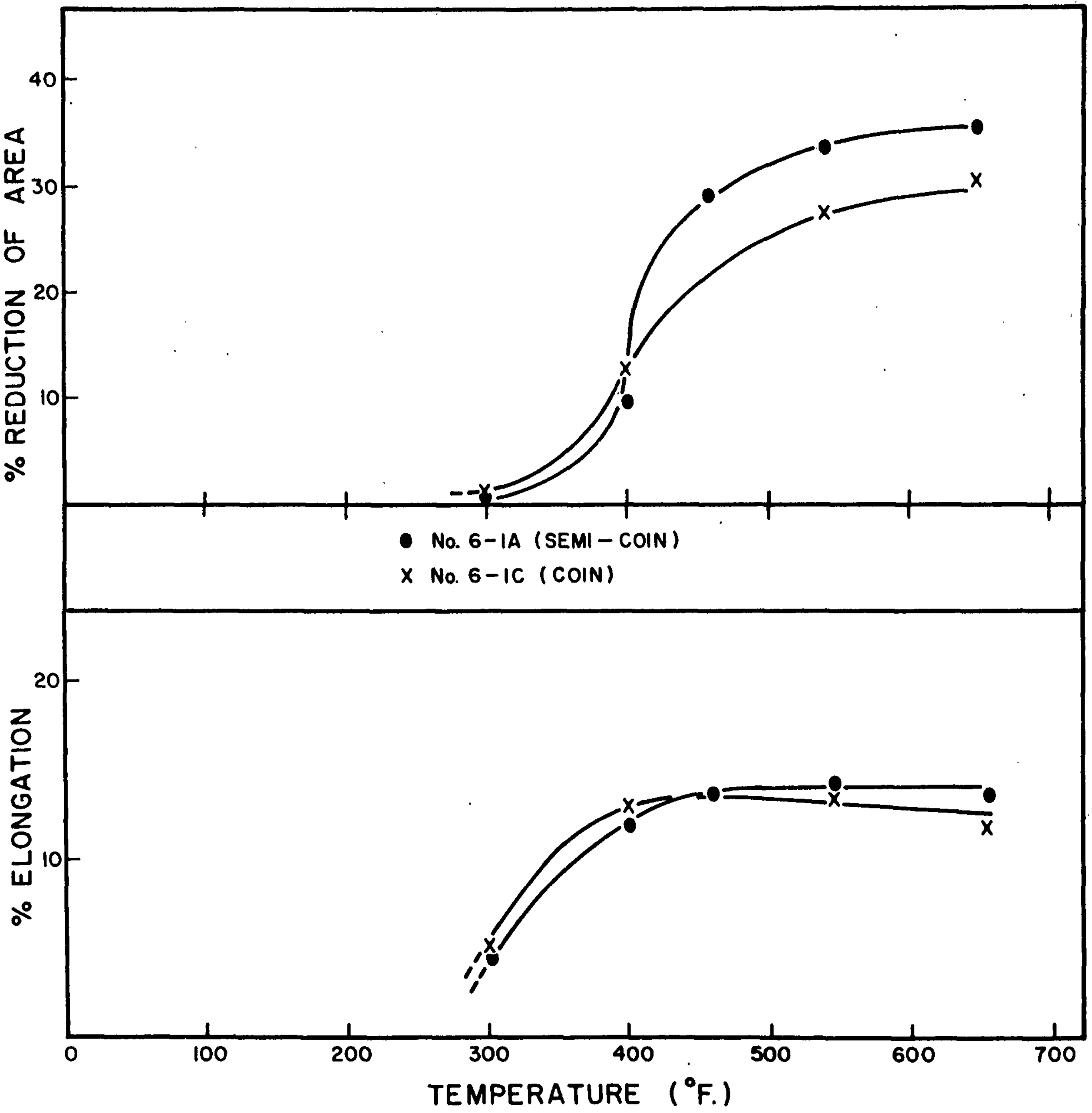
DUCTILE-BRITTLE BEND TRANSITION TEMPERATURE OF TWO COIN FORGINGS (NOS. 6-1C AND 6-2D)

FIGURE 36

TABLE XIII

Low Temperature Tensile Results for Universal Thin Section Forging at .020"/min. Crosshead Speed

Temp. °F	0.2% Y. S. (psi)	U.T.S. (psi)	% R. A.	% Elongation
Semi-Coin Forging (No. 6-1A)				
310	-	159,701	0	4.6
395	139,801	140,299	9.1	12.1
460	131,733	133,005	29.0	13.6
540	123,800	124,300	33.0	13.9
655	114,286	115,763	35.0	13.1
Coin Forging (No. 6-1C)				
310	160,448	161,194	1	4.8
400	143,283	144,279	11.9	15.1
540	121,300	121,800	27.4	13.8
655	116,915	117,413	29.9	10.6



TENSILE DUCTILE-BRITTLE TRANSITION PROPERTIES OF SEMI-COINED AND COINED FORGINGS

FIGURE 37

TABLE XIV

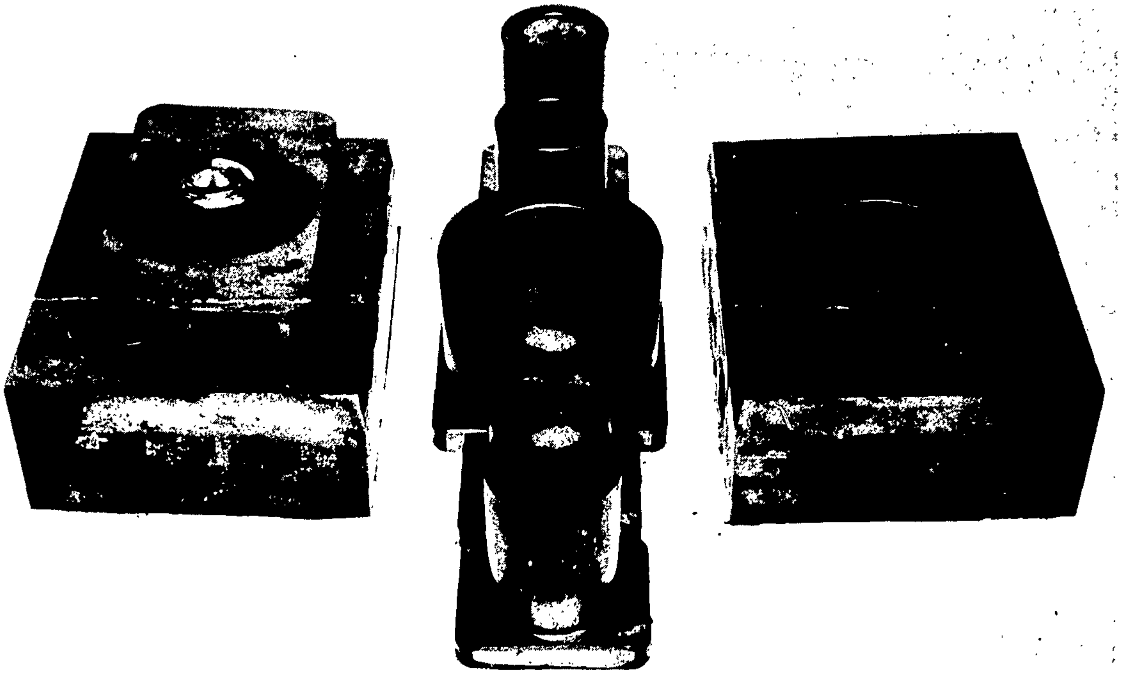
High Temperature Tensile Properties of Universal Thin Section Forging at .020"/min. Crosshead Speed

Temp. °F	0.2% Y. S. (psi)	U.T.S. (psi)	% R. A.	% Elongation
Semi-Coin Forging (No. 6-1A)				
2800	34,700	51,000	94.1	23.1
3000	44,700	52,300	91.8	25.6
3900	6,400	8,400	94.1	85.7
3900	6,300	8,800	96.5	96.8
5000	-	1,200	50.0	19.5
5000	1,500	1,800	58.6	22.2
Coin (No. 6-1C)				
3000	47,100	52,400	78.8	22.1
3900	6,200	8,300	99.1	91.0
5000	1,500	1,900	61.7	22.5
5000	-	1,600	52.8	23.0

The sidewall tensile values for the W-2%Mo semi-coined and coined forgings are comparable throughout the 3000°F to 5000°F test range. Comparison of the forged W-2%Mo ultimate tensile strengths to those of the previously forged W-15%Mo structural components (5) indicates that the W-2%Mo has 9000 psi to 14,000 psi greater strength at 3000°F. The previously reported strength values for W-15%Mo. W-0.52%Cb, and W-5%Mo (5) compared to W-2%Mo in the temperature range 3000°F to 4000°F further reveal the higher strength levels recorded for W-2%Mo. Because molybdenum acts as a solid solution strengthener in tungsten, it was anticipated that the high temperature strength of W-2%Mo would be inferior to those previously observed for W-5%Mo and W-15%Mo. That the reverse is true can possibly be attributed to strengthening mechanisms due to slight chemistry variations not detected by current analytical techniques. It should be noted that both the ingot source and the ingot melting practice were different from those utilized for the W-15%Mo structural forging development.

I. Analysis of Forging Tooling

The rapid single blow deformation inherent in mechanical press operations coupled with rapid workpiece handling during press loading and unloading operations minimizes tooling-to-workpiece contact time. This enabled the use of conventional tooling materials insulated with only commercial tooling lubricants in spite of forging temperatures as high as 2500°F. The punch and die inserts, shown in Figure 38 after the final forging run, were machined from AISI type H-12 tool steel hardened to R_c 50-52. A total of fifteen W-2%Mo forgings were produced by the tooling. Visual inspection, as well as the dimensional consistency of the last six coined forgings indicated no perceptable tooling damage or wear. Estimations of tooling life is currently precluded by the relatively few forgings processed.



TOOLING USED FOR THE PRODUCTION OF "UNIVERSAL THIN SECTION" NON-STRUCTURAL FORGING

FIGURE 38

VI CONCLUSIONS

The basic objective of Phase V of this program was extension of the forging process developed for the structural tungsten forging to the production of non-structural thin section tungsten components. This objective was achieved and, further, the state-of-the-art of tungsten fabrication has been significantly advanced. The following conclusions can be drawn:

1. Six inch diameter centrifugally cast W-2%Mo billets can be reproducibly extruded to produce sound forging billet stock in which:
    a) Cold worked structures are produced throughout the temperature range utilized (3150°F to 3400°F).
    b) Superior extrusion surfaces are observed using a direct process scale up of extrusion procedures previously developed by this program.
2. A forging process has been developed for the production of thin section non-structural components. The parameters investigated indicate:
    a) A minimum five stage forging sequence is required.
    b) Optimum as-forged surfaces result from utilization of "bare" forging workpiece lubrication practice.
    c) Optimum temperature range for the forging sequence developed is 2350°F to 2200°F.
    d) More uniform microstructures and properties are obtained in the final forged W-2%Mo workpiece using forging billets in the as-extruded condition.
    e) Significant cold working imparted by the forging tooling is restricted in the W-2%Mo workpiece sidewall to a region from the inner sidewall to the sidewall center.
3. Ductile-brittle transition temperatures observed for the W-2%Mo forgings indicate a need for extruded billet stock of higher extrusion ratio.

VII REFERENCES

1. "Tungsten Forging Development Program", Sixth Interim Technical Progress Report, Contract AF 33(600)-41629, September 1962, F. N. Lake, Thompson Ramo Wooldridge Inc.
2. "Development of Wrought Tungsten Nozzle Inserts", Fourth Monthly Progress Report, Contract NOw 61-0874-c (FBM), July 1962, G. S. Doble, Thompson Ramo Wooldridge Inc.
3. "Tungsten Forging Development Program", Second Interim Technical Progress Report, Contract AF 33(600)-41629, December 1960, Materials Processing Department, Thompson Ramo Wooldridge Inc.
4. "Tungsten Forging Development Program", Third Interim Technical Progress Report, Contract AF 33(600)-41629, March 1961, F. N. Lake and E. J. Breznyak, Thompson Ramo Wooldridge Inc.
5. "Tungsten Forging Development Program", Fourth Interim Technical Progress Report, Contract AF 33(600)-41629, May 1961, F. N. Lake, E. J. Breznyak, and G. S. Doble, Thompson Ramo Wooldridge Inc.
6. "Discussion of the Special Projects Office Arc-Cast Tungsten Program", E. L. Olcott, Atlantic Research Corporation, Presented at the Aerojet Tungsten Program November 27, 1962, Sacramento, California.
7. "Tungsten Forging Program", C. R. Cook, Unpublished Research, Thompson Ramo Wooldridge Inc.
8. "Fabrication Study of Tungsten Nozzle Inserts", Final Report, Contract No. LMSD-18-02211 NORD 17017, April 1962, E. J. Breznyak, C. R. Cook, and R. W. Redlinger, Thompson Ramo Wooldridge Inc.
9. "Development of Fabricability and Property Data for Processing Tungsten Inserts", Final Report, Contract NOw 61-0874-c, November 1961, G. S. Doble, Thompson Ramo Wooldridge Inc.
10. "Development of Wrought Tungsten Nozzle Inserts", Contract NOw 61-0874-c (FBM), Mod. 3, Thompson Ramo Wooldridge Inc.
11. "Effect of Surface Condition on Ductile-to-Brittle Transition Temperature of Tungsten", Technical Note D-676, February 1961, J. R. Stephens, National Aeronautics and Space Administration.

VIII PROGRAM FOR NEXT PERIOD

The program for the next period is commencement of the Phase VI, Verification of Thin Section Forging. This effort will cover two major areas:

1. Demonstration of the complete universality of the tungsten forging process developed by scaling-up to a large thin section design.
2. Verification that the resultant mechanical properties can be controlled and maintained during the scale-up.

In addition, efforts during the next period will continue to attempt procurement of cast and extruded forging billets to a specification controlling chemistry, microstructure, soundness, dimensions, and surface finish. Prior forging development phases have, of necessity, included both procurement of ingots and responsibility for successful conversion to forging bar stock.

IX Appendix I

Modified Extrusion Work Statement

WORK STATEMENT NO. 2135-2
E. I. du Pont de Nemours & Co.
EXTRUSION OF TUNGSTEN - TAPCO PROCEDURE

A. BILLET DELIVERY

1. Each extrusion billet shall be suitably packaged by Thompson Ramo Wooldridge (TRW) and delivered to:

   E. I. du Pont de Nemours & Co.
   Metals Center
   Benhill Avenue
   Curtis Bay, Maryland
   Attention: W. K. Koopman

2. Each billet delivered shall be arc melted unalloyed tungsten or centrifugally cast W-2%Mo alloy.

3. Each billet delivered shall have been machined prior to delivery to a surface finish of 100 RMS or better all over.

4. Each billet delivered shall be a right circular cylinder 5.875" diameter ± 0.010" by 9.000" to 18.000" long.

5. Each billet delivered shall have been insepcted by TRW prior to delivery for surface and internal defects by:

   a) Super-Zyglo fluorescent penetrant inspection
   b) Red dye penetrant inspection
   c) Ultrasonic inspection

6. Each billet delivered shall have been machined by TRW prior to delivery on the lead (nose) end to a 1-1/2" radius and on the butt (rear) end to a 1" x 45° chamfer.

7. Each billet delivered shall be clearly identified by composition and billet number.

B. EXTRUSION TOOLING

1. Du Pont shall prepare all extrusion tooling including uncoated dies.

2. Extrusion dies shall be prepared per TAPCO blueprint No. 2135-A. Entrance angle shall be 60° (total included angle of 120°).

Orifice diameter shall be 3.033" ± 0.005". Die entrance and orifice surfaces shall be coated by TAPCO with a nominal thickness of 0.045" of plasma-arc sprayed coating.

3. A new extrusion die shall be utilized for each billet extruded.

C. EXTRUSION PROCESSING

1. One or more TRW representatives shall be present and shall be allowed to observe all heating, extrusion, and post extrusion operations for each billet.

2. Each billet shall be heated prior to extrusion in an argon atmosphere within a heating rate range of 100 to 200°F/min. to a temperature within the range 3100°F to 3500°F as specified by the observing TRW representative prior to heating.

3. Billet temperatures during heating shall be measured with an optical shawmeter and an optical pyrometer.

4. Target transfer time from initiation of billet removal from the furnace until the extrusion upsets in the liner shall be within the range 25 to 45 seconds.

5. Each billet shall be heated and extruded bare. Sejournet lubrication practices shall not be used. The interior surfaces of the liner shall be swabbed with the commercial molybdenum disulfide lubricant "Molydag" prior to extrusion. Liner lubricant shall be supplied by Du Pont.

6. No leader shall be employed during extrusion. A graphite follower preheated to 2400°F and a steel follower preheated to 2000°F shall be utilized. Necessary materials of the proper configurations shall be prepared by Du Pont.

7. Extrusion shall be accomplished by a press rated at 2500 tons. Maximum rated pressure shall be available for extrusion.

8. The press throttle valve shall be set at a minimum of 40% of its full open position during extrusion.

9. The press shall be operated such that a prefill stroke at 10 to 12"/second is utilized during the major portion of the ram movement prior to upsetting of the billet.

D. POST EXTRUSION OPERATIONS

1. Immediately after exit from the die, each extrusion shall be removed from the runout, placed in a suitable box filled with Silocel, transferred to an argon muffle furnace, held at 2400°F for one hour, and allowed to cool in the Silocel box.

2. After cooling each extrusion shall be grit blasted to remove residual lubricant.

E. METHOD OF SHIPMENT

1. Each extrusion shall be individually packaged by Du Pont by chocking in a solid wood box or crate in such a manner as to insure safe transmittal to TRW during shipment.

2. Each packaged extrusion shall be shipped to:

   Thompson Ramo Wooldridge Inc.
   23555 Euclid Avenue
   Cleveland 17, Ohio
   Attention:
   Materials Processing Department

3. Within one week after extrusion of each billet the following information and data shall be mailed to the address listed in Section E, Paragraph 2:

   a) Billet identification number
   b) Billet heating rate or rates
   c) Maximum billet temperature
   d) Total heating time
   e) Die temperature
   f) Container temperature
   g) Original or reproduced extrusion pressure trace
   h) Original or reproduced extrusion ram speed trace

F. EXCEPTIONS

1. Observing TRW representatives have the right to modify the requirements of this work statement as dictated by circumstances during processing, subject only to agreement by Du Pont

DISTRIBUTION LIST

ASD (ASRCTB)
Wright-Patterson AFB, Ohio (4)

ASD (ASRC, Dr. A. M. Lovelace)
Wright-Patterson AFB, Ohio

ASD (ASRCE, Mr. J. Teres)
Wright-Patterson AFB, Ohio

ASD (ASRCMC, Mr. W. C. Ramke)
Wright-Patterson AFB, Ohio

ASD (ASRCMP-4, Mr. S. Inouye)
Wright-Patterson AFB, Ohio

ASD (ASRCEM-1A, Mrs. N. Ragen
Wright-Patterson AFB, Ohio (2)

Aerojet-General Corporation
Attention: Dr. A. Levy
P. O. Box 1947
Sacramento, California

Aerospace Industries Association
610 Shoreham Building
Washington 5, D. C.

Allegheny Ludlum Steel Corporation
Attention: Mr. Robb Hente
Brackenridge, Pennsylvania

Alloyd Research Corporation
Attention: Mr. Louis Mager
General Manager
202 Arsenal Street
Chicago 16, Illinois

Arcturus Manufacturing Corporation
Attention: Chief Engineer
4301 Lincoln Boulevard
Venice, California

Armour Research Foundation
Metals Research Department
10 West 35th Street
Chicago 16, Illinois

ASTIA
Arlington Hall Station
Arlington 12, Virginia (4)

Babcock & Wilcox Company
Attention: Chief Metallurgist
Beaver Falls, Pennsylvania

Baldwin-Lima-Hamilton
Attention: Mr. George Lessis
111 5th Avenue
New York 3, New York

6539 Test Group
Attention: DGSCH
Edwards AFB, California

Battelle Memorial Institute
Defense Metals Information Center
505 King Avenue
Columbus 1, Ohio

Bell Aerospace Corporation
Attention: Manager, Production Eng.
P. O. Box 482
Fort Worth 1, Texas

Bell Aerosystems Company
Attention: Manager, Production Eng.
Buffalo 5, New York

Bendix Products Division
Bendix Aviation Corporation
Attention: Chief Engineer
401 N. Bendix Drive
South Bend, Indiana

The Boeing Company
Materials Mechanical & Structures Branch
Systems Management Office
P. O. Box 3707
Seattle 24, Washington

Cameron Iron Works
Attention: Mr. J. W. Brougher
Vice President and Manager
Special Products Division
P. O. Box 1212
Houston 1, Texas

Canton Drop Forging & Manufacturing Co.
Attention: Quality Control Manager
2100 Wilett Avenue
Canton 2, Ohio

Chance Vought Corporation
Vought Aeronautics Division
Attention: Chief Librarian
P. O. Box 5907
Dallas, Texas

Climax Molybdenum Co. of Michigan
Attention: Mr. G. A. Timmons
Vice President
14410 Woodrow Wilson
Detroit 38, Michigan

Commander
Army Ballistic Missile Agency
Research Laboratory
Redstone Arsenal, Alabama

Crucible Steel Company of America
Midland Research Laboratory
P. O. Box 226
Midland, Pennsylvania

Crucible Steel Company of America
Central Research Laboratory
234 Atwood Street
Pittsburgh 13, Pennsylvania

Curtiss-Wright Corporation
Attention: Manager, Metallurgy
Wood Ridge, New Jersey

Douglas Aircraft Company, Inc.
827 Lapham Street
El Segundo, California

Douglas Aircraft Company, Inc.
Attention: Plant Eng. Supervisor
3855 Lakewood Boulevard
Long Beach 8, California

Douglas Aircraft Company, Inc.
Attention: Works Manager
3000 Ocean Park Boulevard
Santa Monica, California

Douglas Aircraft Company, Inc.
Production Design Engineering
2000 N. Memorial Drive
Tulsa, Oklahoma

E. I. du Pont de Nemours & Co., Inc.
Attention: Mr. E. M. Mahla
Experimental Station
Wilmington 98, Delaware

Fansteel Metallurgical Company
Attention: Chief
Metallurgical Division
2200 N. Sheridan Road
North Chicago, Illinois

Fansteel Metallurgical Company
Attention: Director of Research
North Chicago, Illinois

Firth Sterling, Inc.
Attention: Chief Metallurgist
3113 Forbes Avenue
Pittsburgh 30, Pennsylvania

Frankfort Arsenal
Philadelphia 37, Pennsylvania

General Dynamics Corporation/Convair
Attention: Director, Mfg. Development
General Office
San Diego 12, California

General Dynamics Corporation/Convair
Attention: Chief, Applied Manufacturing
Fort Worth, Texas

General Dynamics Corporation/Astronautics
Attention: Mr. A. Hurlich, Supervisor
Materials Research Group
Mail Zone 595-20, P. O. Box 1128
San Diego 12, California

General Electric Company
Alloy Studies Unit
Attention: Mr. E. S. Jones, Manager
Metallurgical Engineering-ARO
Building 200, FPLD
Cincinnati 15, Ohio

General Electric Company
Cleveland Wire Plant
Attention: Chief Metallurgist
21800 Tungsten Road
Cleveland, Ohio

Hercules Powder Company
Attention: Mr. D. E. Borgmeier
Head, Nozzle Design Group
Beehive Bank Building
Salt Lake City, Utah

Grumman Aircraft Engineering Corp.
Attention: Manufacturing Research Coordinator
Blant 12
Bethpage, Long Island, New York

Jet Propulsion Laboratory
California Institute of Technology
Attention: Mr. B. P. Kohorst
Pasadena, California

Kelsey Hayes Company
Attention: Director of Research
Metals Division
New Hartford, New York

Kropp Forge Company
Attention: Mr. Ray Kropp
5301 Roosevelt Road
Chicago 50, Illinois

Ladish Company
5481 Packard Avenue
Cudahy, Wisconsin

Lockheed Aircraft Corp.
Missile Systems Division
Palo Alto, California

Lockheed Aircraft Corp.
Missile Systems Division
Sunnyvale, California

Lockheed Aircraft Corp.
California Division
Attention: Director of Eng.
P. O. Box 511
Burbank, California

Lycoming Division
AVCO Manufacturing Corp.
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Stratford, Connecticut

The Marquardt Corporation
Attention: Mr. Gene Klein
Manufacturing Engineer
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Ogden, Utah

The Marquardt Corporation
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Van Nuys, California

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Attention: Manufacturing
Research & Development
Baltimore 3, Maryland

The Martin Company
Denver Division
Attention: Chief
Materials Eng.
Mail No. L-8
Denver 1, Colorado

Materials Advisory Board
Attention: Executive Director
2101 Constitution Avenue
Washington 25, D. C.

McDonnell Aircraft Corporation
Attention: Chief Engineer
Lambert-St. Louis Airport
P. O. Box 516
St. Louis 3, Missouri

NASA
Attention: Materials Research Division
1520 H Street, N. W.
Washington 25, D. C.

National Bureau of Standards
Attention: Mr. A. Brenner
Mr. W. E. Reid
Washington 25, D. C.

New York University
College of Engineering
Attention: Director
Research Division
New York 53, New York

North American Aviation, Inc.
Attention: Engineering Data Services
4300 East 5th Street
Columbus 16, Ohio

North American Aviation, Inc.
Los Angeles Division
Attention: Section Head
Materials
International Airport
Los Angeles 45, California

Department of the Navy
Bureau of Naval Weapons
Attention: Mr. H. E. Promisel
Washington 25, D. C.

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Norair Division
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Hawthorne, California

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President
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Albany, Oregon

Pratt & Whitney Aircraft Corp.
Attention: Metallurgical Eng. Dept.
East Hartford 8, Connecticut

Republic Aviation Corporation
Attention: Director,
Manufacturing Research
Farmingdale, Long Island, New York

Rocketdyne Division
North American Aviation Corp.
Attention: Department 574
6633 Canoga Avenue
Canoga Park, California

Rohr Aircraft Corporation
Attention: Vice President
Manufacturing
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Chula Vista, California

Ryan Aeronautical Company
2701 Harbor Drive
San Diego 12, California

Solar Aircraft Company
Attention: Director,
Advanced Research
2200 Pacific Highway
San Diego 12, California

Southern Research Institute
Attention: Mr. E. J. Wheelaham
2000 Ninth Avenue, South
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Stanford Research Institute
Attention: Director, Research
Menlo Park, California

Space Technology Laboratories
Attention: Dr. Robert P. Felger
Manager, Mechanics and Materials
P. O. Box 95001
Los Angeles 45, California

Special Metals, Inc.
Research Librarian
New Hartford, New York

Stauffer Metals Company
Division of Stauffer Chemical Co.
Attention: Mr. G. W. Bauer
Technical Sales Manager
1201 South 47th Street
Richmond 4, California

Steel Improvement & Forge Company
Attention: Works Manager
970 East 64th Street
Cleveland 3, Ohio

Sylvania Electric Products Corp.
Attention: Chief Engineer
Towanda, Pennsylvania

Taylor Forge & Pipe Works
Attention: Special Products Manager
P. O. Box 485
Chicago 90, Illinois

Thiokol Chemical Corporation
Attention: Mr. Patrick V. McAllister
Materials Department
Mail Stop 240
Wasatch Division
Brigham City, Utah

Transue & Williams Steel Forging Corp.
Attention: Mr. J. W. Ament
Sales Manager
Allience, Ohio

Union Carbide Metals Company
Division of Union Carbide Corporation
Technology Department
4625 Royal Avenue, P. O. Box 580
Niagara Falls, New York

U. S. Bureau of Mines
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Attention: Mr. Eugene Assi
Albany, Oregon

Universal Cyclops Steel Corp.
Refractomet Division
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Wah Chang Corporation
Attention: Mr. K. C. Li, Jr.
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100 Church Street
New York 7, New York

Waterton Arsenal Laboratory
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Watertown, Massachusetts

Western Gear Corporation
Attention: Mr. Martin Headman
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Lynwood, California

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32 North Main Street
Dayton 2, Ohio

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P. O. Box 228, AGT Division
Kansas City, Missouri

Westinghouse Electric Corp.
Attention: Director
Space Material Dept.
Churchill Borough
Pittsburgh 35, Pennsylvania

Wyman-Gordon Company
Attention: Works Manager
North Grafton, Massachusetts

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Thompson Ramo Wooldridge Inc.
Cleveland 17, Ohio
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30 November 1962 90 p. incl.
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