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THE COLD EXTRUSION OF TITANIUM

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FOREWORD

This report was prepared by the Battelle Memorial Institute under USAF Contract No. AF 33(616)-2446. This contract was initiated under Project No. 7351, "Metallic Materials", Task No. 73510, "Titanium Metal and Alloys", formerly RDO No. 615-11, "Titanium Metal and Alloys", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with 1 Lt J. W. Seeger acting as Project Engineer.

This report covers a period of work from June 1954 to July 1955.

In addition to the authors, other Battelle personnel who contributed to this project were W. M. Parris, O. J. Huber, J. H. Jackson, and C. H. Lorig. Acknowledgment is also given to J. F. Meyer and D. C. Vollmer, who ably assisted in conducting the extrusion experiments.

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ABSTRACT

Cold-extrusion studies were conducted on two grades of unalloyed titanium — AMS 4900 and AMS 4921 — to evaluate the effects of die design and extrusion reduction. By utilizing a fluoride coating and a conventional oil-graphite-molybdenum disulfide lubricant, forward extrusions with reductions of 40, 50, and 60 per cent were successfully accomplished on 1-1/2-inch-diameter by 3-inch billets. Conical dies with included angles of 90, 120, and 150 degrees were used for each reduction. Working pressures were comparable to those required for cold extruding steel. For a given die angle, the extrusion pressure and average work of extrusion increased in an approximately linear relationship with the percentage reduction.

Metal-flow studies were conducted on split billets inscribed with grids. Deformation by compression and elongation was uniform over the cross sections of the bars, with maximum shear deformation occurring in the outer fibers. The amount of shear deformation increased as the die angle and per cent reduction increased.

Work hardening during extrusion was nearly uniform within the bars, the over-all hardness variation from center to surface being within 20 Bhn. Increases in strength varying from about 25 to 60 per cent were produced under the various extrusion conditions. However, adequate ductility (elongation greater than 10 per cent in 1 inch) was maintained.

The extruded bars had a smooth surface finish, with few traces of galling. No measurable die wear occurred, indicating the fluoride coating functioned satisfactorily. Dimensional tolerances on the extruded bars were maintained within 0.001 inch.

PUBLICATION REVIEW

This report has been reviewed and is approved:

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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THE COLD EXTRUSION OF TITANIUM

by

Alvin M. Sabroff and Paul D. Frost

INTRODUCTION

The cold shaping of metals, particularly steel, by compression has become a well-established and important manufacturing process. Generally, the process is termed cold extrusion, but it actually consists of a combination of various cold-forming methods, including forward and backward extrusion, drawing, coining, ironing, compacting, and expanding. Ordinarily, these operations are performed in conventional hydraulic or mechanical presses equipped with cylindrical punches and circular dies.

The principal application of the process had been in the production of ordnance items, such as mortar and artillery shells and cartridge cases. More recently, however, other concentric shapes have been cold extruded that have integral studs, various types and combinations of offsets, multiple flanges, flutes, or integral webs. Some of the advantages that are gained by cold extrusion are:

(1) Conversion of low-strength alloys to high-strength finished products because of the work-hardening effect

(2) Saving of time and material because of fewer operations and smaller machining losses.

(3) Production of an uninterrupted fiber flow, resulting in a greater load-carrying capacity

(4) Good surface finish and maintenance of tolerances within close limits.

These advantages were expected to be equally applicable to titanium and its alloys.

At present, there is an increasing demand for titanium parts in aircraft construction. The ability to form intricate parts in a few simple operations with small machining losses would be of particular advantage in view of the high cost of titanium mill products. However, the process has never been applied to titanium in commercial practice. This was true mainly because of a lack of a suitable surface coating, which is the principal requirement for successful cold extrusion.

In research at Battelle on surface coatings for titanium to prevent galling and seizing, a surface treatment was developed that produced excellent results in wire and tube drawing and reciprocating and rotary wear tests(1)*. The treatment, which consists of immersion in a fluoride-phosphate bath at room temperature, produces an adherent, continuous coating on titanium that performs as a lubricant retainer and gliding agent. In view of the outstanding performance of this coating in preventing galling and seizing, it appeared that the cold extrusion of titanium could be accomplished successfully. Consequently, this research program was initiated at Battelle by the Air Force to determine the feasibility of applying the process to titanium.

SUMMARY

This report describes the experimental work conducted during the period June 1, 1954, to July 31, 1955, under USAF Contract No. AF 33(616)-2446.

Cold-extrusion studies were conducted on two grades of unalloyed titanium – AMS 4900 and AMS 4921 – to evaluate the effects of extrusion reduction and die design on (1) extrusion pressure, (2) metal flow, and (3) mechanical properties. Forward extrusions with reductions in cross-sectional area of 40, 50, and 60 per cent were successfully accomplished, with 90-, 120-, and 150-degree conical dies, on billets 1-1/2 inches in diameter by 3 inches long. A fluoride coating for titanium, in combination with an oil-graphite-molybdenum disulfide lubricant, was satisfactory in preventing seizing between the workpiece and the die and in producing a good surface finish.

Working pressures were comparable to those encountered in the cold extrusion of steel under similar conditions. Maximum pressure during extrusion was required to initiate flow, after which the pressure dropped as much as 30 per cent for the higher reductions. The extrusion pressure and the average work of extrusion increased in an approximately linear relationship with the extrusion reduction. For a given reduction, the extrusion pressure increased as the die angle increased. The maximum pressure during extrusion varied from 105,000 psi for a 40 per cent reduction with a 90-degree die to 282,000 psi for a 60 per cent reduction with a 150-degree die.

Studies on split billets, extruded after grids had been inscribed on the dividing surfaces, indicated that deformation by compression and elongation was uniform throughout the extruded bar for a given combination of reduction

*References are listed at the end of the report.

was uniform throughout the extruded bar for a given combination of reduction and die angle. Total deformation was greatest in the surface layers of the bar, which had undergone the maximum shear deformation. As the die angle decreased, the amount of shear deformation decreased and the grain and fiber structure became more uniform throughout the bar.

Considerable work hardening occurred during cold extrusion. The hardness of Grade AMS 4900 increased from 145 Bhn to values in the range 185 to 225 Bhn. Similarly, the strength increased from 60,000 psi to strengths in the range 87,000 to 97,000 psi. Grade AMS 4921 increased in hardness from 195 Bhn to 250 to 295 Bhn, with the strength increasing correspondingly from 83,000 psi to strengths in the range 109,000 to 119,000 psi. The hardness measurements indicated that work hardening was nearly uniform over the cross section of the bar, the maximum hardness variation being within 20 Bhn. With each material, adequate ductility (minimum elongation greater than 10 per cent in 1 inch) was maintained in the strengthened conditions.

Although the experimental work conducted in this research was of a preliminary nature, it has demonstrated that cold extrusion of titanium can be successfully accomplished. Further, the process offers a means whereby unalloyed titanium can be shaped, without machining, and simultaneously strengthened to make it suitable for applications in which it might otherwise not be usable.

EXPERIMENTAL PROCEDURES

The initial approach to the problem of cold extruding titanium was based on information obtained from published literature on the cold extrusion of steel. The literature was reviewed for data on die design and construction, die materials, working pressures, lubricants, and other design criteria that might be of importance in cold extruding titanium. The bibliography compiled during this work is presented in Appendix I.

A series of experiments, similar to those in the early work on steel by Pessl and Hauttman(2) and Feldman(3), was conducted to determine the influence of basic variables in the cold-extrusion process. These consisted of forward extruding round billets of unalloyed titanium to bars of smaller diameter to study the effects of die design and extrusion reduction on extrusion pressure and mechanical properties. In addition, studies on the flow of metal during cold extrusion were conducted on split billets with grids inscribed on the dividing surfaces.

The billets used in these studies were 1-1/2 inches in diameter by 3 inches long. The billets were extruded with reductions of 40, 50, 60, and

70 per cent of the cross-sectional area. The size of the extruded bars and the extrusion ratios corresponding to these reductions are as follows:

Reduction in Area, per cent	Area of Cross Section, in.^{2}	Diameter, in.	Extrusion Ratio
Initial billet	1.767	1.50	--
40	1.060	1.16	1.66:1
50	0.884	1.06	2:1
60	0.707	0.95	2.5:1
70	0.530	0.82	3.33:1

To study the effects of die design, conical-shaped dies having included angles of 90, 120, and 150 degrees were used for each reduction.

Description of Extrusion Equipment

The extrusion tests described in this report were performed on a 700-ton hydraulic press at Battelle. The press, similar to those in use for cold extruding steel, is equipped with a die cushion that has a 100-ton stripping capacity. The extrusion tools for conducting the tests were designed and constructed by the Lake Erie Engineering Corporation, Buffalo, New York. The tools consist of a punch, container, interchangeable dies, and ejector. A schematic drawing of the complete tool assembly is shown in Figure 1.

The die design adopted was one that had been applied successfully in cold extruding steel. A detail drawing of a typical die is shown in Figure 2. The first die land is the bearing surface of the die; the lower lands are larger in diameter and act as guides to prevent buckling during ejection of the extruded bar. A sharp corner at the edge of the die opening was employed, since this design was reported to require the lowest extrusion pressure.

The die and container are supported by double shrink rings into which they are press fitted on a 1-degree taper with a force of 150 tons. This design permits easy replacement of the container and die and, at the same time, provides adequate support. Sealing force between the container, die, backing plate, and die holder is provided by the clamp ring, which is connected to the die holder by eight heavy-duty bolts.

The ejector is operated by the die cushion located below the bolster plate of the press. With the ejector pin in its lowered position, a bar 6 inches in length could be extruded.

To minimize the number of parts required for the various die sizes, interchangeable bushings are mounted in the backing plate and die holder.

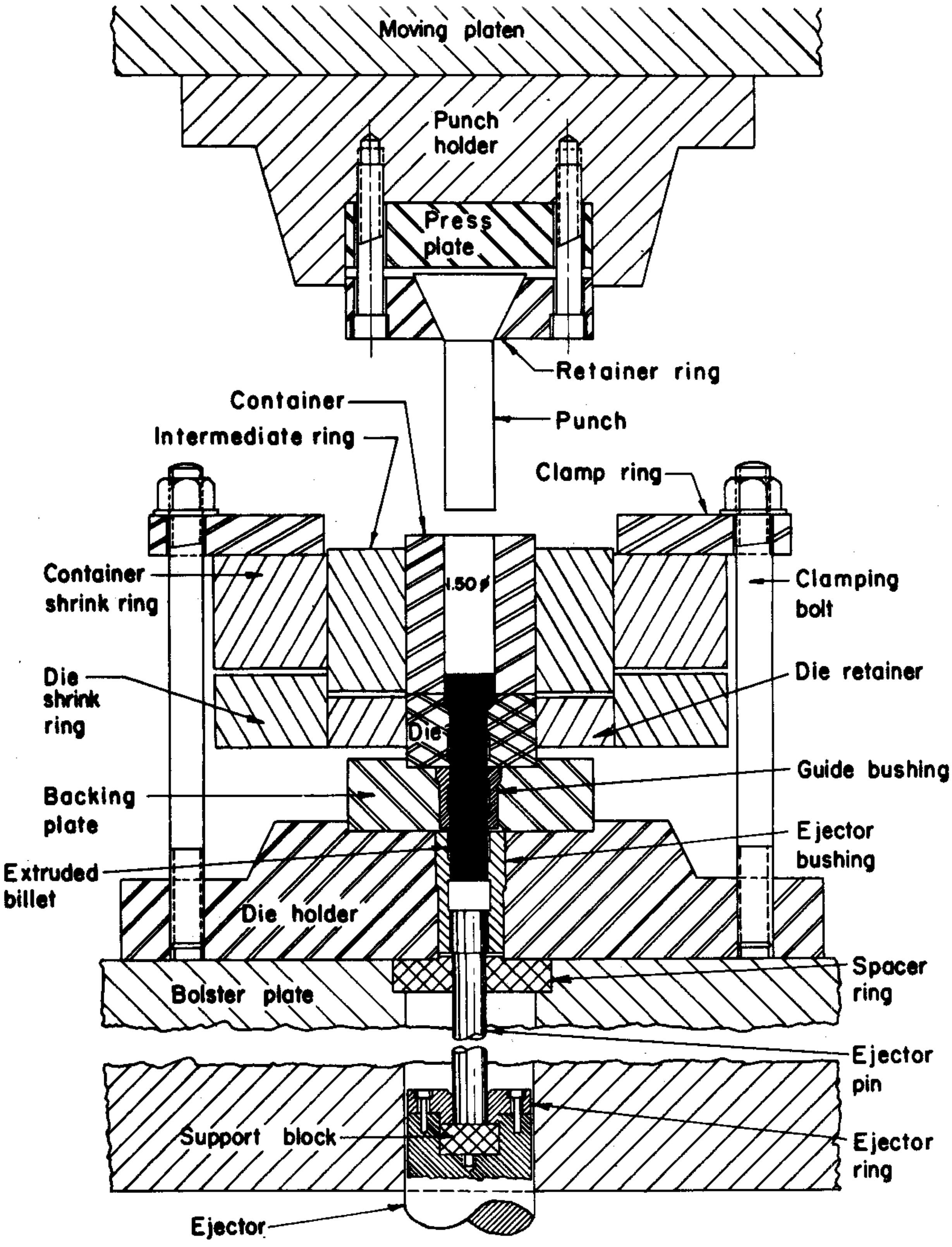

FIGURE 1. ASSEMBLY DRAWING OF THE EQUIPMENT FOR CONDUCTING THE COLD-EXTRUSION EXPERIMENTS

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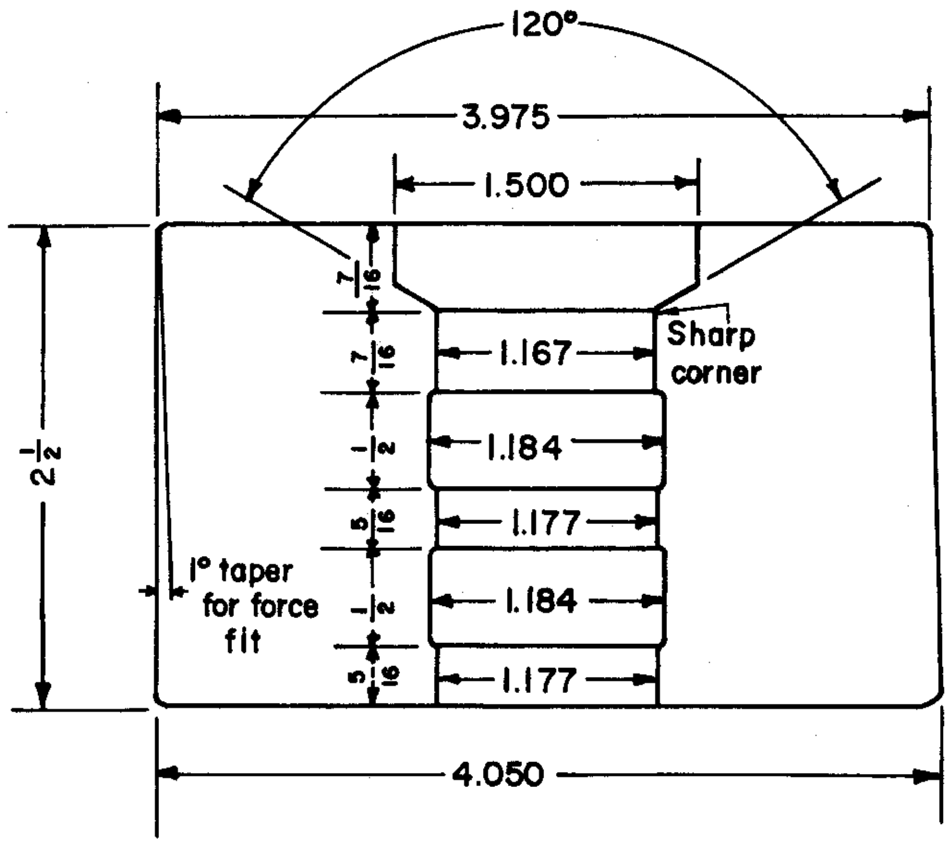

FIGURE 2. TYPICAL DESIGN OF DIES FOR COLD EXTRUSION OF SOLID ROUND BARS

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Similarly, the ejector assembly is designed so that only the floating ejector pin need conform with a given die size.

The design of the equipment is such that experiments other than those on forward extrusion of solid bars could be conducted. By inserting a blank die and a smaller diameter punch, backward extrusion could be accomplished. Also, by using a stepped punch with the existing dies, forward extrusion of hollow shapes could be accomplished.

The selection of materials for the various components of the tool assembly was governed by the load-carrying and abrasion-resistance requirements. Wherever possible, nondeforming tool steels were used for parts requiring a precision fit in order to maintain close dimensional tolerance during heat treatment. The materials used for the various parts of the assembly are as follows:

Part	Materials and Condition
Punch, ejector pin	Carpenter "Star Zenith" (0.72C, 0.25Mn, 0.20Si, 4.00Cr, 18.25W, 1.15V), 62-64 R_C
Container	Allegheny-Ludlum "Python" (0.95C, 0.26Mn, 0.22Si, 0.26V), 62-63 R_C
Die	Carpenter "Vega" (0.70C, 2.00Mn, 0.30Si, 1.00Cr, 1.35Mo), 60-63 R_C
Press plate, backing plate, support block	Allegheny-Ludlum "Deward" (0.90C, 1.55Mn, 0.25Si, 0.30Mo), 60-62 R_C
Spacer ring, ejector ring, bushings	Allegheny-Ludlum "Deward", 55-56 R_C
Die retainer, intermediate ring	SAE 6145, 47-49 R_C
Shrink rings	SAE 6145, unhardened
Punch holder, die holder, ejector, clamp ring	SAE 1035, unhardened.

The assembly is designed to operate at extrusion pressures up to 300,000 psi under normal extruding conditions. A photograph of the complete tool assembly installed in the 700-ton press is shown in Figure 3.

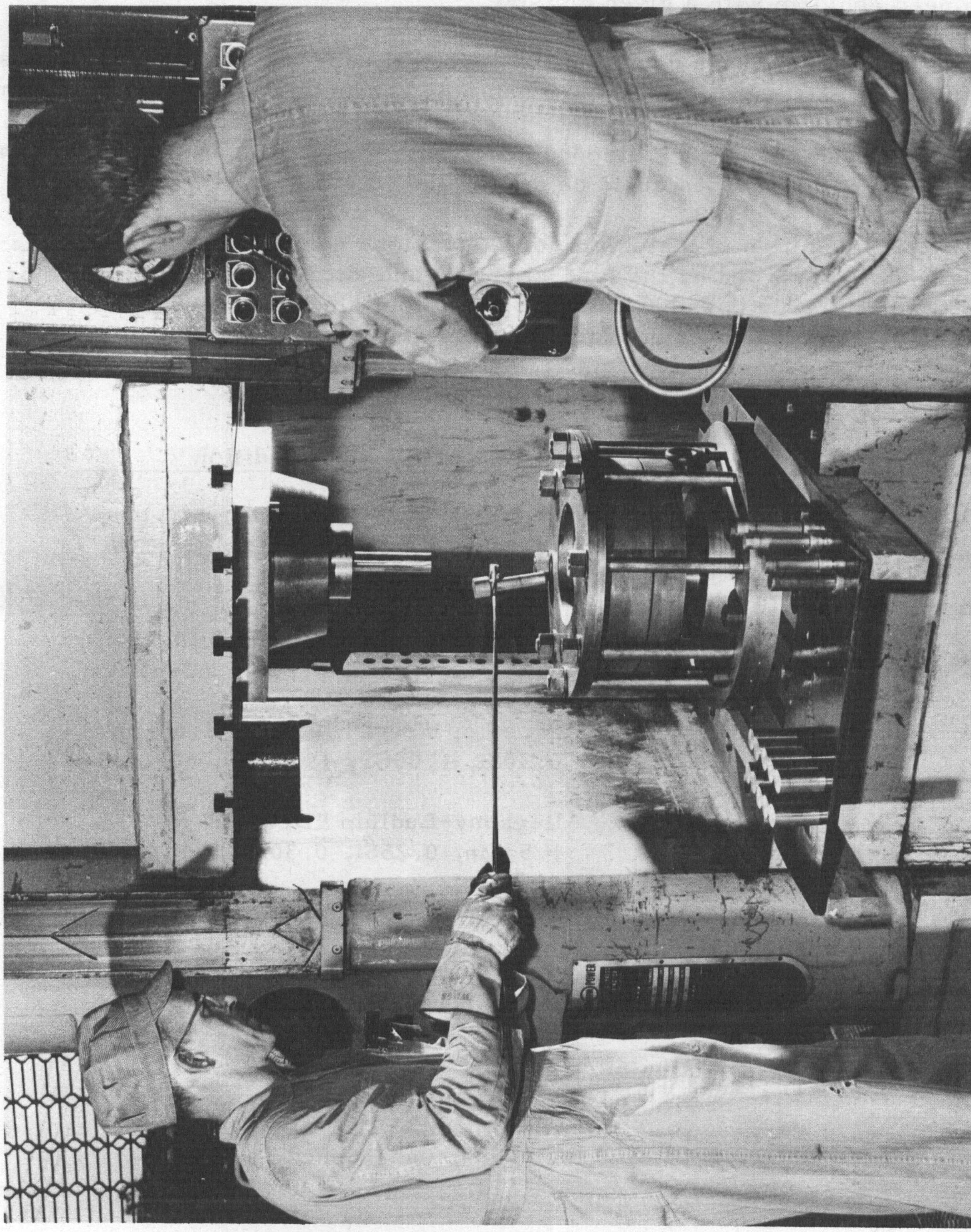

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FIGURE 3. EXPERIMENTAL COLD-EXTRUSION EQUIPMENT INSTALLED IN 700-TON HYDRAULIC PRESS AT BATTELLE

Preparation of Extrusion Billets

The extrusion billets used in this investigation were prepared from two grades of unalloyed titanium — AMS 4900 and AMS 4921. Billet stock was purchased from the Mallory-Sharon Titanium Corporation, Niles, Ohio, in the form of hot-rolled and annealed bars, centerless ground to 1.480 inches in diameter. The mechanical properties of the two grades were as follows:

	AMS 4900	AMS 4921
Ultimate Strength, psi	60,000	83,000
Yield Strength, 0.2% Offset, psi	47,000	70,000
Reduction in Area, %	65.0	42.0
Elongation, % in 1 inch	40.5	31.5
Hardness, Bhn	145	195

Split billets for the studies on metal flow were prepared only from Grade AMS 4900. The stock for these billets was purchased in the form of 2-inch-diameter as-rolled bar, which had the following mechanical properties:

Ultimate Strength, psi	73,000
Yield Strength, 0.2% offset, psi	58,000
Reduction in Area, %	49.7
Elongation, % in 1 inch	30
Hardness, Bhn	160

The bar was cut into 3-inch lengths, which were sectioned longitudinally. The dividing surfaces of each billet were ground flat, the billet sections were cemented together, and the billets were machined to 1.480 inches in diameter. Longitudinal and transverse grid lines 1/4 inch apart were inscribed on each dividing surface of the billets, as shown in Figure 4.

One end of both the solid and split billets was chamfered, either 15, 30, or 45 degrees, to correspond with the 90-, 120-, and 150-degree dies.

Surface Treatment

The fluoride coating for titanium developed by Battelle[1] was applied to the solid billets and each half of the split billets. The immersion coating bath, which operates at room temperature, had the following composition:

$$50\ g/l - Na_3PO_4 \cdot 12H_2O$$

$$20\ g/l - KF \cdot 2H_2O$$

$$23\ ml/l - HF\ (50.3\ wt\ \%).$$

Immersion time is a critical factor in obtaining a satisfactory coating, that is, one that is not powdery or easily rubbed off. The optimum immersion time varied from 2 minutes for the split-billet sections to 3 minutes for the solid billets. Under these conditions, a dark, metallic-gray, adherent coating was obtained on the billets, as shown in Figure 5.

The condition of the metal surface prior to immersion has a marked effect on the uniformity of the coating. Therefore, the billets were degreased and pickled to remove any surface films. The complete immersion-coating procedure was as follows:

(1) Degrease in acetone
(2) Rinse in cold water
(3) Pickle in 35% HNO_3-5% HF acid solution
(4) Rinse in cold water
(5) Immerse in fluoride-phosphate bath
(6) Rinse in cold water and dry.

Lubrication

A number of lubricants are suitable for use with the fluoride coating. In cold-drawing studies on fluoride-coated titanium wire, excellent results were obtained with a light grease containing molybdenum disulfide(1). Since higher unit pressures are encountered in cold extrusion, it was deemed advisable to use a lubricant containing colloidal graphite in addition to molybdenum disulfide to improve the extreme-pressure characteristics. A lubricant mixture consisting of petroleum oil, 10 per cent colloidal graphite, and 10 per cent molybdenum disulfide was selected for use in the tests.

DESCRIPTION OF EXTRUSION TESTS

Data for the extrusion tests conducted on the split and solid titanium billets are presented in Table 1. Originally, it was planned to extrude one split billet (for metal-flow studies) and one solid billet of each unalloyed grade through each combination of die angle and reduction. However, difficulties were encountered with the split billets for reductions greater than 50 per cent. The split billets could be extruded easily with a 60 per cent reduction, as indicated in Table 1, but the extruded bar could not be ejected from the die. Ejection difficulties were mainly a result of the type of die design used, wherein the die land is recessed to reduce friction. Where high ejection loads were required, the extruded bars upset into the recesses, preventing removal of the bars from the die.

Reductions up to 60 per cent were successfully accomplished with solid billets of both unalloyed grades. Photographs of the bars extruded with

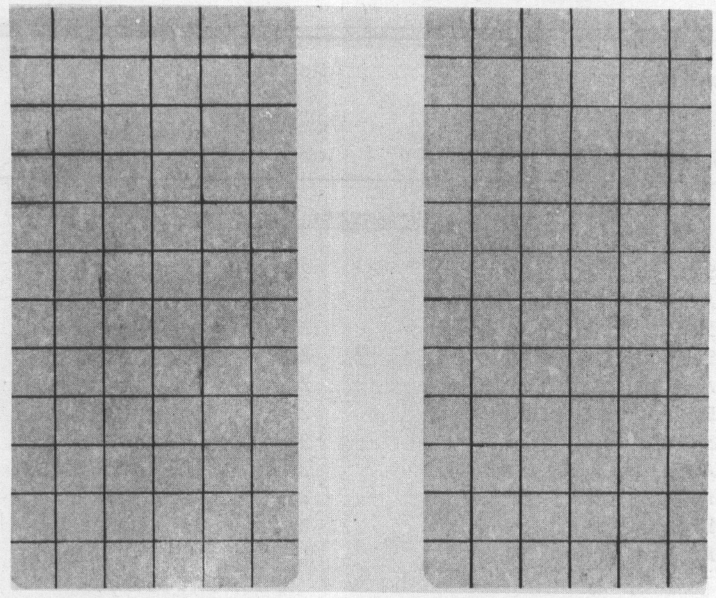

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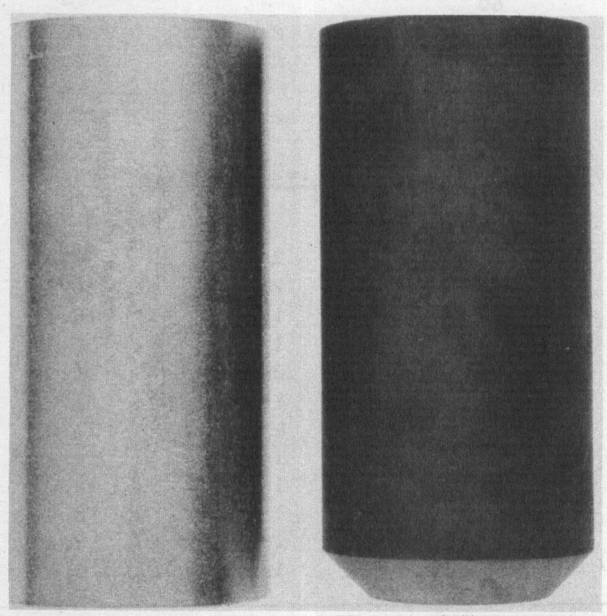
FIGURE 4. SPLIT BILLET OF UNALLOYED TITANIUM WITH GRIDS INSCRIBED ON DIVIDING SURFACES FOR STUDIES ON METAL FLOW



N22167

Left-Machined Billet as Prepared from Bar Stock
Right-Chamfered Billet With Fluoride Coating

FIGURE 5. UNALLOYED TITANIUM EXTRUSION BILLETS

TABLE 1. DATA ON EXTRUSION OF SOLID AND SPLIT BILLETS OF UNALLOYED TITANIUM UNDER THE VARIOUS TEST CONDITIONS

Test	Billet[(a)]	Extrusion Reduction, %	Length of Billet Extruded, inches	Extrusion Time, sec[(b)]	Extrusion Pressure, 1000 psi[(c)] Maximum	Minimum
			90-Degree Die Angle			
1	S-1	40	2	19.7	114.0	102.0
2	A-1	40	2	19.3	105.0	97.0
3	B-1	40	2	19.1	120.0	108.0
4	S-3	50	2	21.7	189.0	132.0
5	A-4	50	2	20.4	159.0	123.0
6	B-4	50	2	21.3	192.0	159.0
7	S-4[(d)]	60	2	21.5	249.0	192.0
8	A-5	60	2	19.8	197.5	126.0
9	A-6	60	2	19.6	204.0	120.0
10	B-5	60	2	20.3	216.0	159.0
11	A-9[(d)]	70	1-3/8	15.8	242.0	171.0
			120-Degree Die Angle			
12	S-2	40	2	19.9	144.0	117.0
13	A-2	40	2	19.7	128.0	114.0
14	B-2	40	2	20.0	150.0	120.0
15	S-5	50	2	21.0	210.0	135.0
16	A-3	50	2	20.5	180.0	128.0
17	B-3	50	2	20.8	216.0	138.0
18	S-6[(e)]	60	--	--	--	--
19	A-7	60	2	21.0	228.0	140.0
20	A-8	60	2	21.0	226.0	138.0
21	B-6[(e)]	60	--	--	--	--
22	B-7	60	2	21.4	273.0	168.0
			150-Degree Die Angle			
23	S-7	40	2	21.8	177.0	135.0
24	A-17	40	2	8.0	138.0	99.0
25	A-18	40	2	20.6	141.0	111.0
26	A-20	40	1-3/4	20.6	138.0	108.0
27	B-8	40	1-3/4	20.2	180.0	135.0
28	S-8	50	2	22.4	228.0	138.0
29	A-10	50	1-3/4	21.0	192.0	129.0
30	A-11	50	1-3/4	21.0	186.0	126.0
31	B-9	50	1-3/4	21.2	231.0	150.0
32	A-14	60	1-3/4	18.0	234.0	144.0
33	A-16	60	1-3/4	18.0	234.0	147.0
34	A-19	60	1-3/4	18.4	237.0	144.0
35	B-11[(d)]	60	1-3/4	18.6	282.0	186.0

(a) "S" designates split billet, Grade AMS 4900; "A" designates solid billet, Grade AMS 4900; "B" designates solid billet, Grade AMS 4921.

(b) Extrusion speed (measured as punch speed) was 6 inches per minute, except for Test 24, in which extrusion speed was 20 inches per minute.

(c) Maximum pressure occurred during initiation of flow; minimum pressure occurred at end of extrusion stroke.

(d) Extrusion could not be ejected from die.

(e) Incomplete extrusion; pressure exceeded maximum tolerable on tools.

reductions of 40, 50, and 60 per cent through 90-, 120-, and 150-degree dies after removal of the coating are shown in Figures 6, 7, and 8. Removal of the coating is easily accomplished in a light acid solution. A 70 per cent reduction was accomplished in Test 11 with a 90-degree die, but, as in the case of the split billets, the extruded bar could not be ejected from the die. The extrusion was machined out of the die and container, leaving only a thin shell, shown in Figure 9. Examination of the surface, which remained intact, indicated the bar had upset during ejection. Since complete redesigning of the dies would be required to eliminate this condition, no further tests were conducted on split billets for reductions greater than 50 per cent or solid billets for reductions greater than 60 per cent.

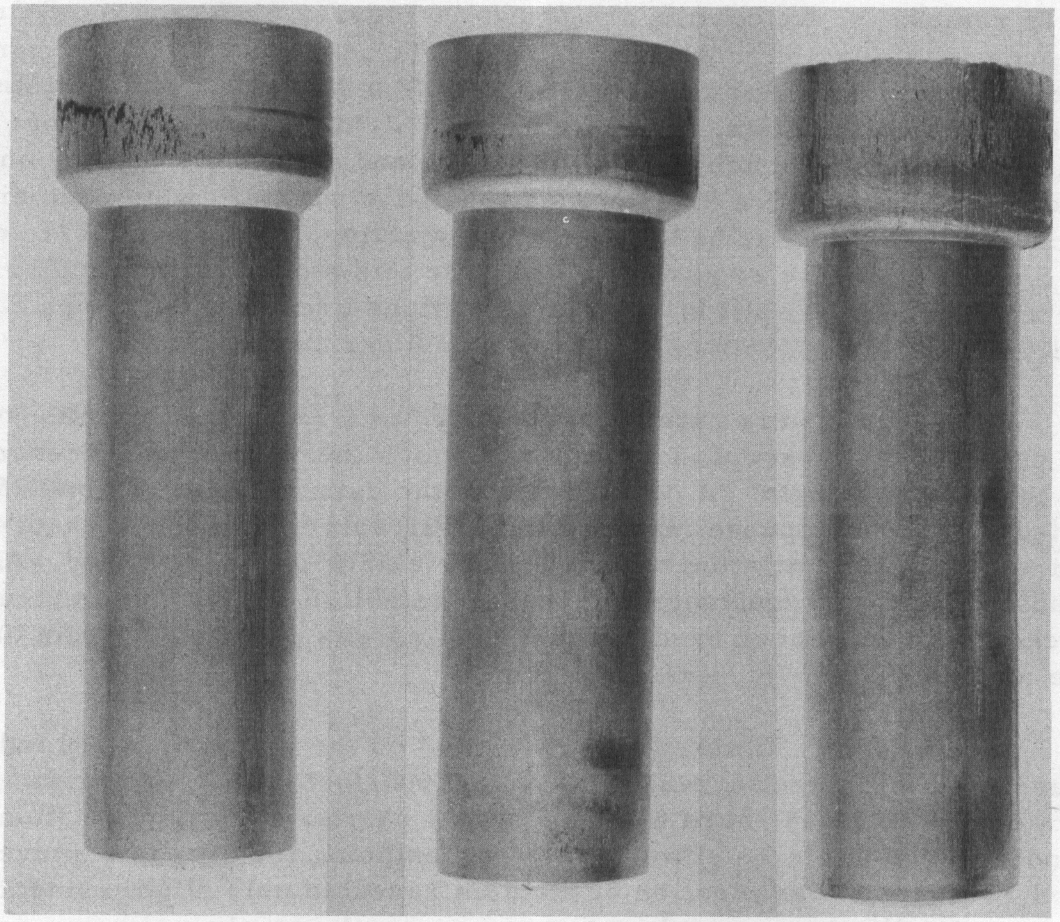
The billets were extruded at a speed of 6 inches per minute (measured as punch speed), except in Test 24, in which the speed was increased to 20 inches per minute. A comparison of the data for Tests 24 and 25 indicated that higher speeds may be more desirable in that the pressures required, both for initiation of flow and for extrusion, were lower. Additional studies would be required, however, to establish the optimum extrusion speed. The low speed used in these studies was selected to avoid damage to the tools.

Good surface finishes were obtained on the extruded bars, indicating that the fluoride coating was functioning satisfactorily. Any surface imperfections found on the bars were caused by chattering during ejection — a condition that could be eliminated by redesigning the dies to remove the die land recesses. Examination of the dies revealed only slight evidence of die wear and galling in several instances, particularly when ejection was difficult, but generally the dies were unaffected. Dimensional tolerances on the extruded bars were maintained to within 0.001 inch.

Metal Flow During Extrusion

Sections of the split bars extruded with 40 and 50 per cent reductions through the 90-, 120-, and 150-degree dies, showing the distortion of the inscribed grids, are presented in Figures 10 and 11. The flow patterns produced were of the same type as reported by Feldman(3) for similar experiments on steel.

During the initial stage of extrusion, the core of the billet advances into the die with practically no deformation taking place, whereas the peripheral fibers undergo severe axial compression. As the billet begins to extrude, the flow becomes markedly nonuniform because of the action of shear stresses on the outer fibers. Along the axis of the bar (central grid zones), deformation occurs principally as simple elongation (and compression) with a slight amount of shear. The outer grid zones undergo an equal amount of elongation, but are also subjected to additional shear deformations, which increase in magnitude toward the bar surface. Thus, the total deformation

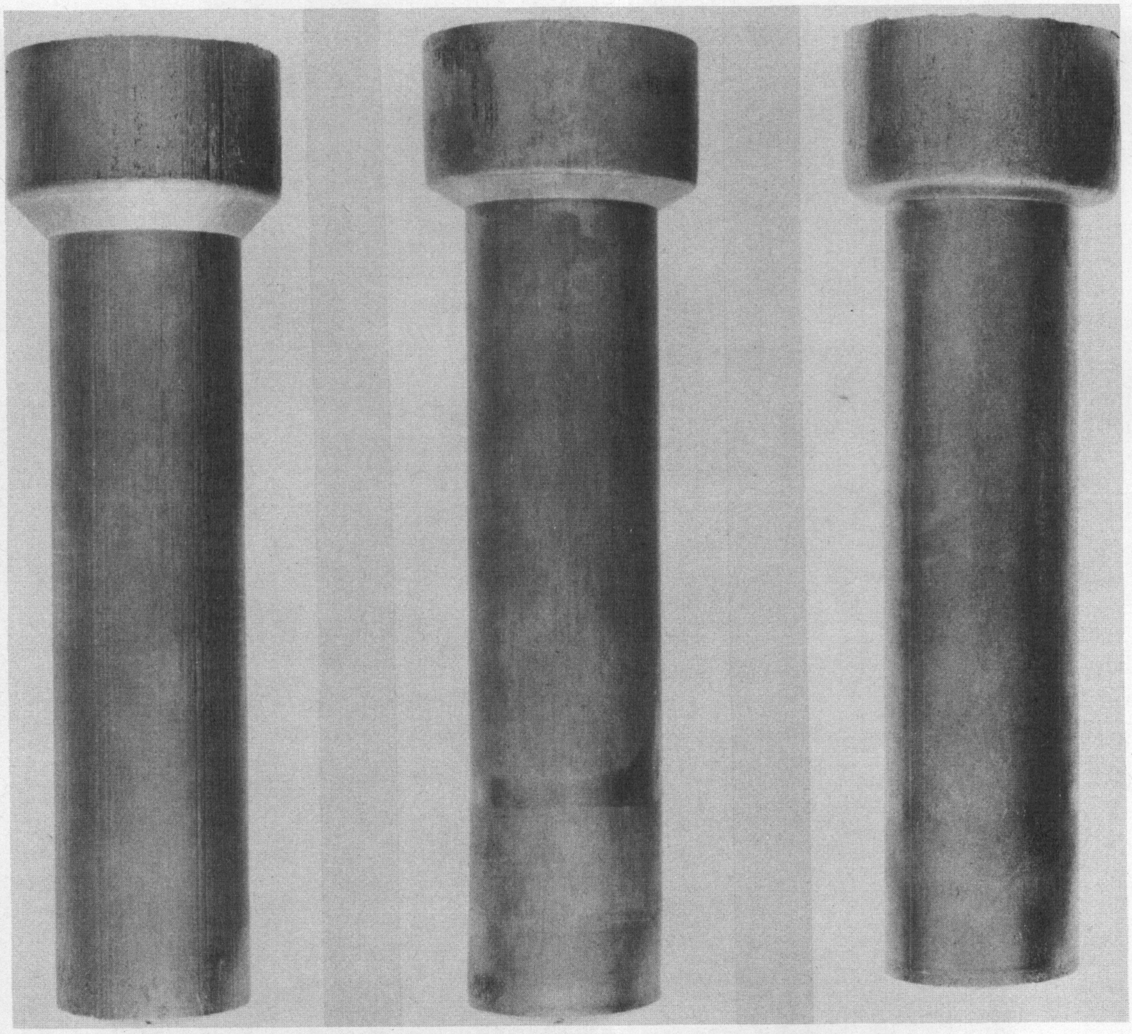


N22171
90-Degree Die

N22172
120-Degree Die

N22685
150-Degree Die

FIGURE 6. UNALLOYED TITANIUM BARS EXTRUDED WITH A 40 PER CENT REDUCTION THROUGH 90-, 120-, AND 150-DEGREE DIES



N22169

90-Degree Die

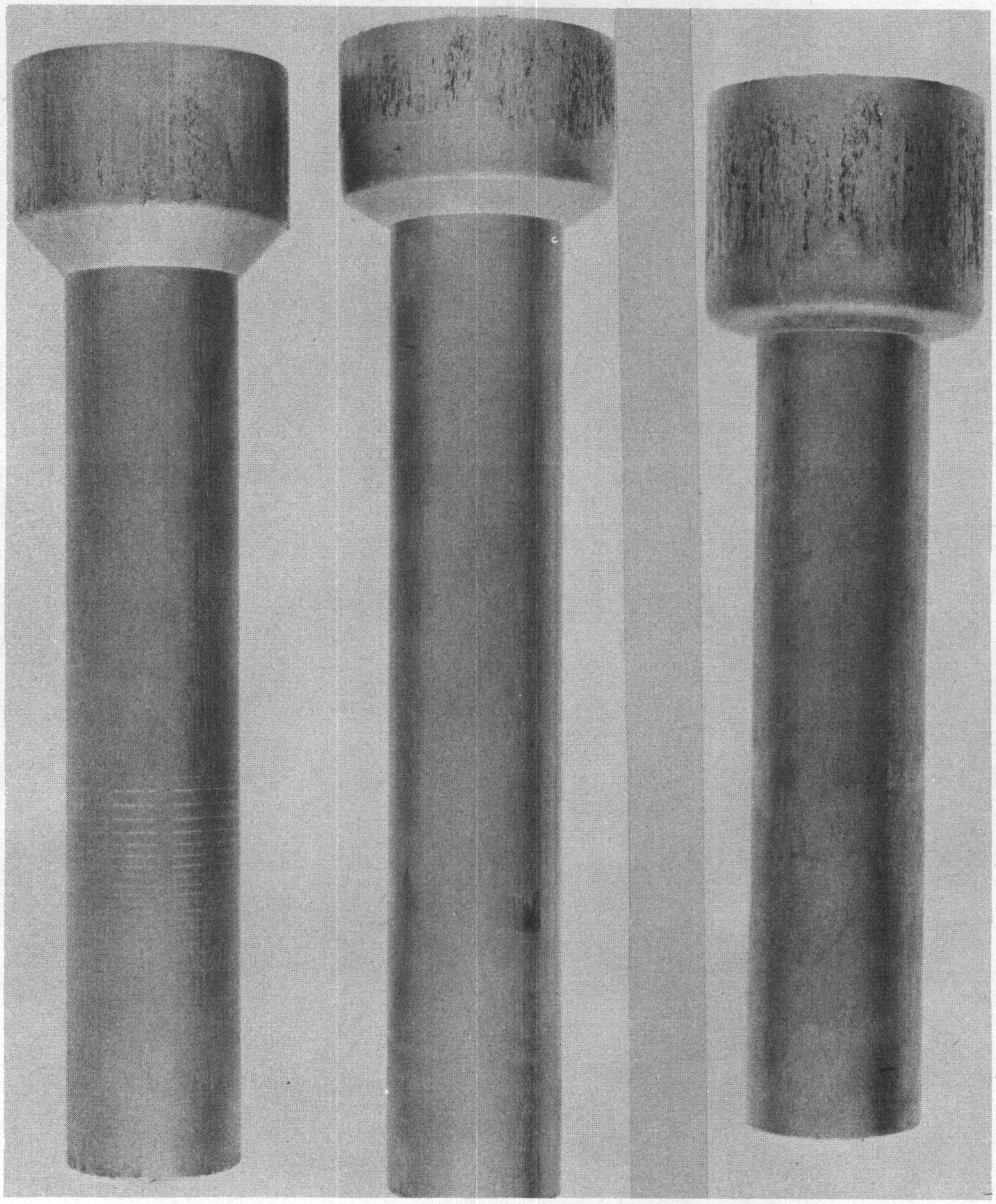
N22168

120-Degree Die

N22686

150-Degree Die

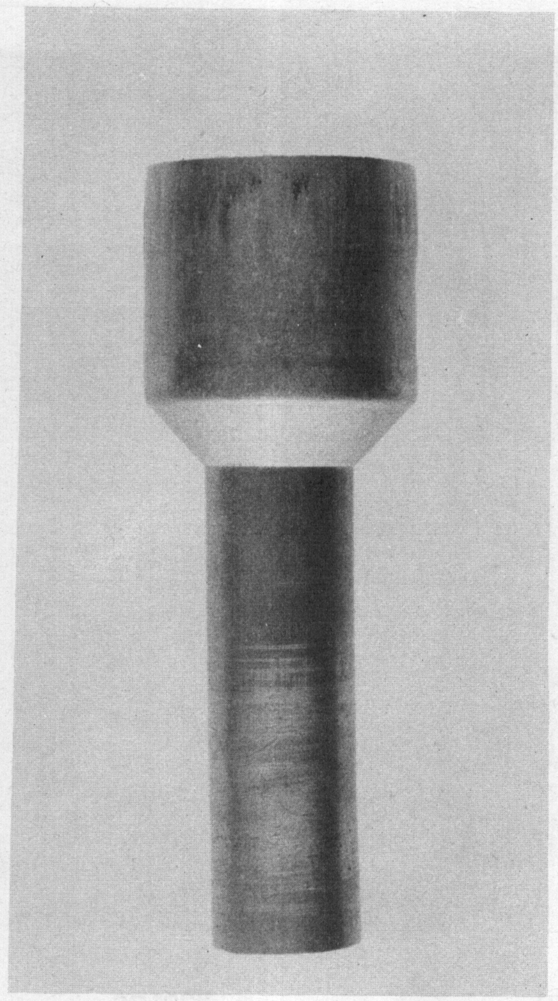
FIGURE 7. UNALLOYED TITANIUM BARS EXTRUDED WITH A 50 PER CENT REDUCTION THROUGH 90-, 120-, AND 150-DEGREE DIES



N22170 | N22170 | N22688
90-Degree Die | 120-Degree Die | 150-Degree Die

FIGURE 8. UNALLOYED TITANIUM BARS EXTRUDED WITH A 60 PER CENT REDUCTION THROUGH 90-, 120-, AND 150-DEGREE DIES

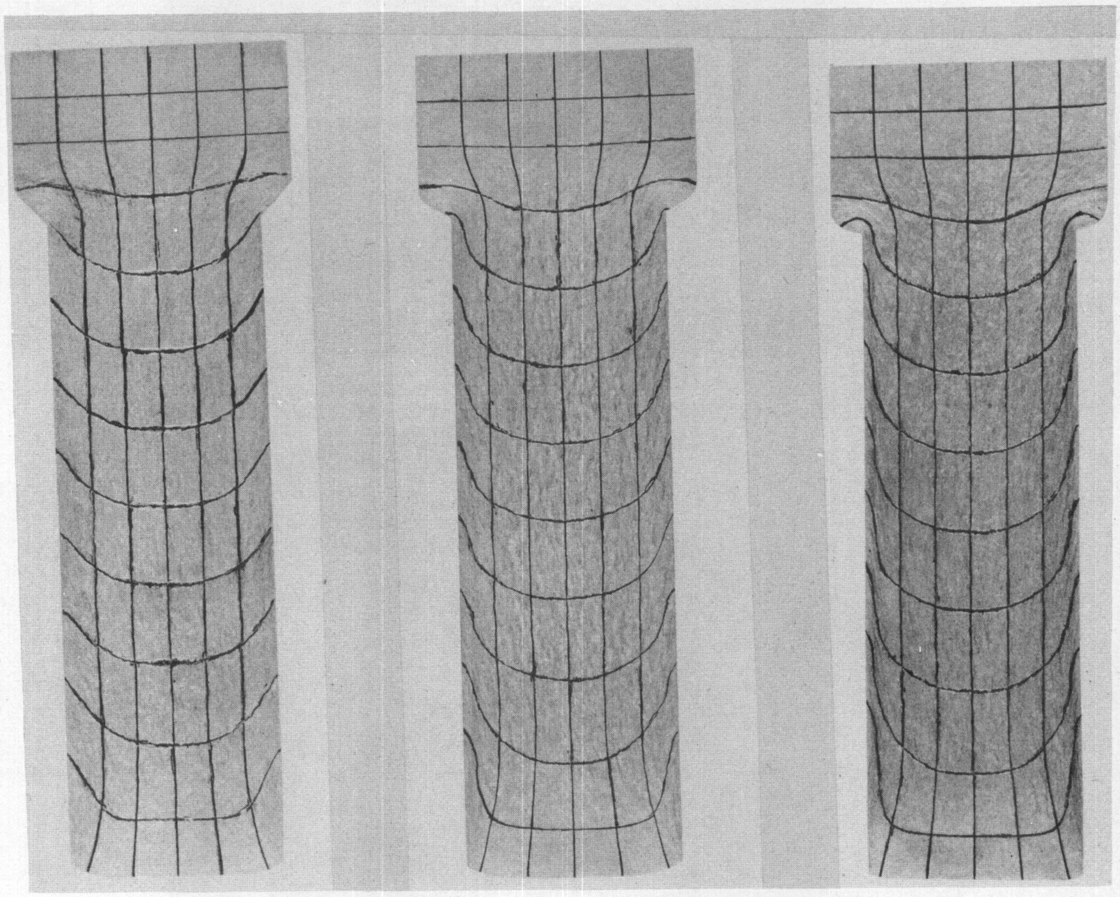
Markings on bar at left caused by chattering during ejection.



N22729

FIGURE 9. UNALLOYED TITANIUM BAR EXTRUDED WITH A 70 PER CENT REDUCTION THROUGH A 90-DEGREE DIE

Bar could not be ejected; removed from die after machining out core.



N22171 N22172 N22685

90-Degree Die 120-Degree Die 150-Degree Die

FIGURE 10. SECTIONS OF SPLIT BARS EXTRUDED WITH 40 PER CENT REDUCTION, SHOWING EFFECT OF DIE ANGLE ON GRID DISTORTION

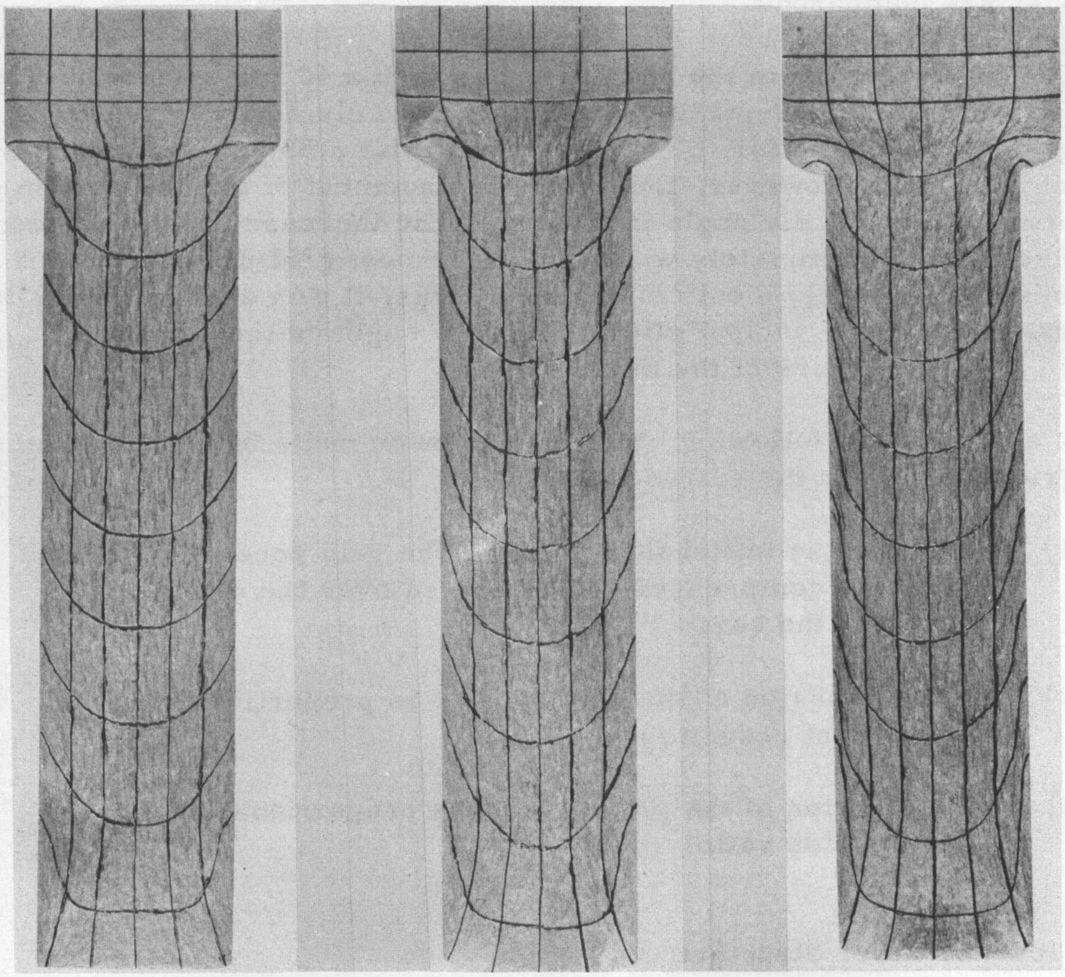


FIGURE 11. SECTIONS OF SPLIT BARS EXTRUDED WITH A 50 PER CENT REDUCTION, SHOWING EFFECT OF DIE ANGLE ON GRID DISTORTION

of the outer fibers is greater than at the axis. This fact is clearly apparent when the lengths of the transverse grid-line units in the outer and central grid zones are compared.

The grid spacings in the bars extruded with a 40 per cent reduction were the same for the 90-, 120-, and 150-degree die angles. Likewise, the spacings were the same for the bars extruded with a 50 per cent reduction. For each reduction, however, the shear displacement of the transverse grid lines increased as the die angle increased. The increase in displacement takes place almost completely within the outermost grid zones, the four central zones having nearly identical shapes. Thus, it was apparent that, for a given reduction, the principal effect of the die angle on the deformation process is in the outer fibers of the metal.

In addition, the following observations were made from measurements of the grid spacings in the extruded bars:

(1) Except for the initial flow portion, the grid zones were uniformly compressed and elongated over the cross section of the bar.

(2) The compression of the grid zones was proportional to the per cent reduction.

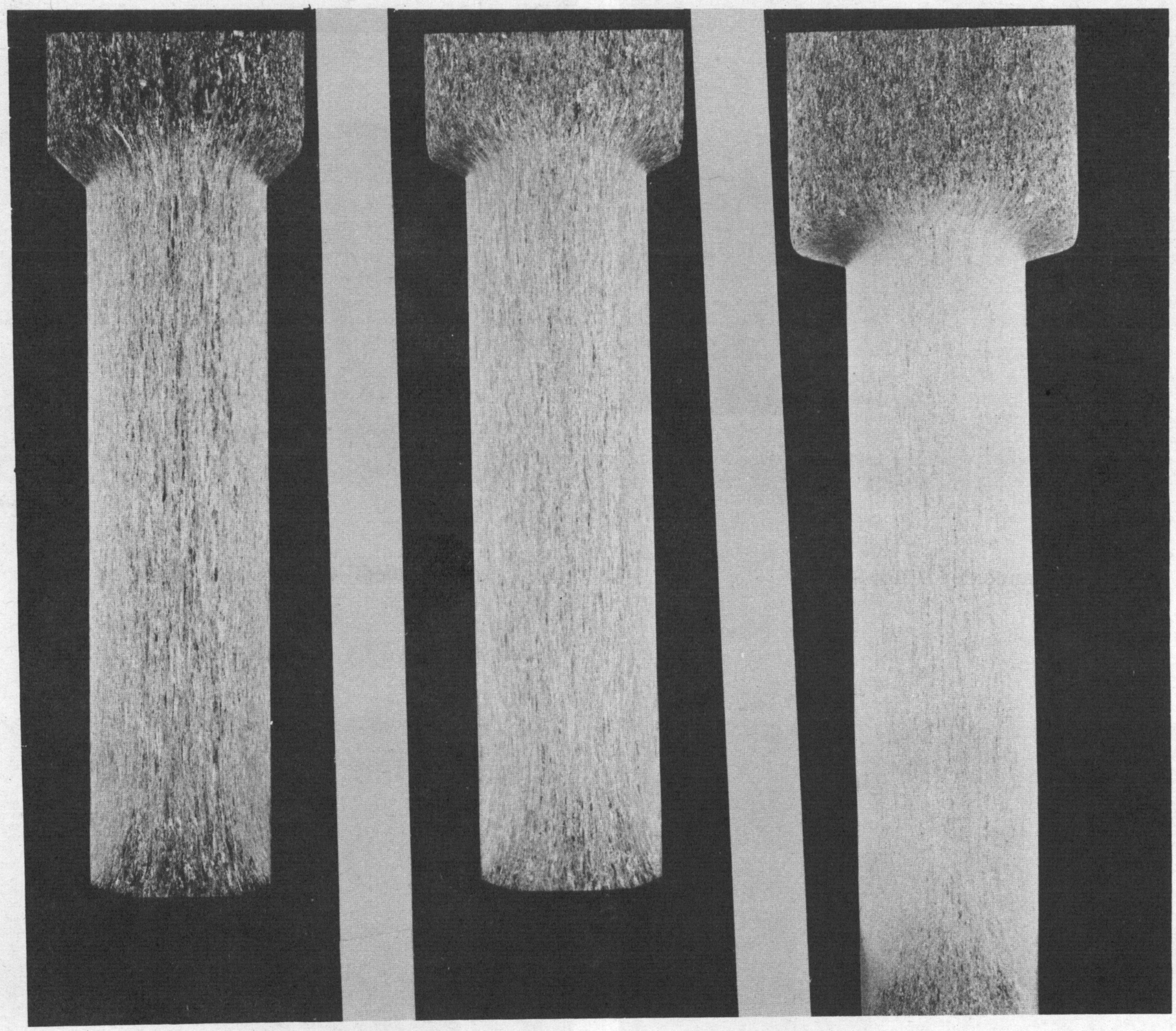
(3) The elongation of the grid zones was proportional to the extrusion ratio.

Grain Flow and Fiber Structure

The solid bars of Grade AMS 4900 titanium extruded with each reduction and die angle were sectioned longitudinally and macroetched to show the grain and fiber structure. The etched sections of the bars extruded with a 50 per cent reduction through the various dies, illustrating the typical structure, are shown in Figure 12. The structures corresponded very closely with the metal-flow patterns obtained with the split billets, being coarsest at the center of the bars, where the least amount of deformation occurred, and finest at the bar surface, where maximum deformation took place. As the die angle increased, the structure near the surface of the bar became finer, but the center was unaffected. For a given die angle, the over-all structure became increasingly finer as the per cent reduction increased. The structure at the front end of the bars, which underwent almost no deformation, was the same as that of the unextruded part of the billets.

Microstructures

The annealed billet stock and the extruded bars of both unalloyed grades were examined metallographically to determine the changes in microstructure

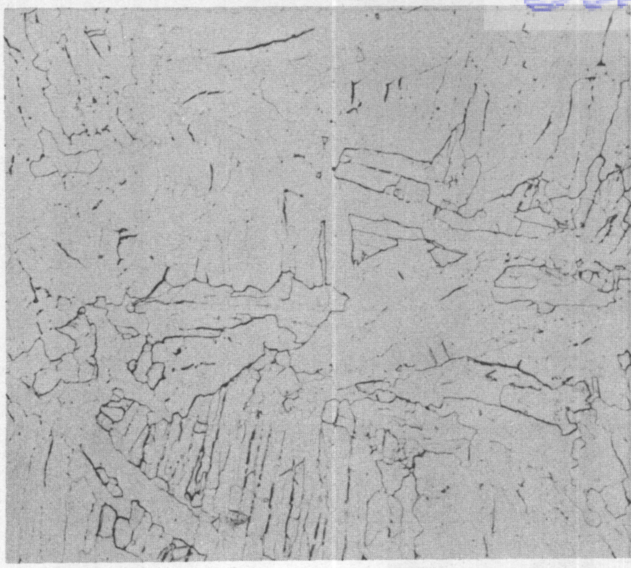


N22454
90- Degree Die

N22455
120- Degree Die

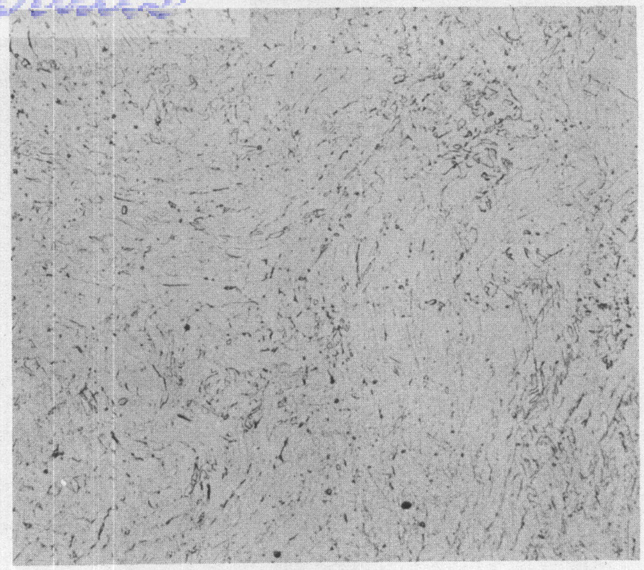
N23115
150- Degree Die

Figure 12. ETCHED SECTIONS OF UNALLOYED TITANIUM BARS EXTRUDED WITH A 50 PER CENT REDUCTION THROUGH 90-, 120-, and 150-DEGREE DIES, SHOWING TYPICAL FIBER STRUCTURE AND GRAIN FLOW



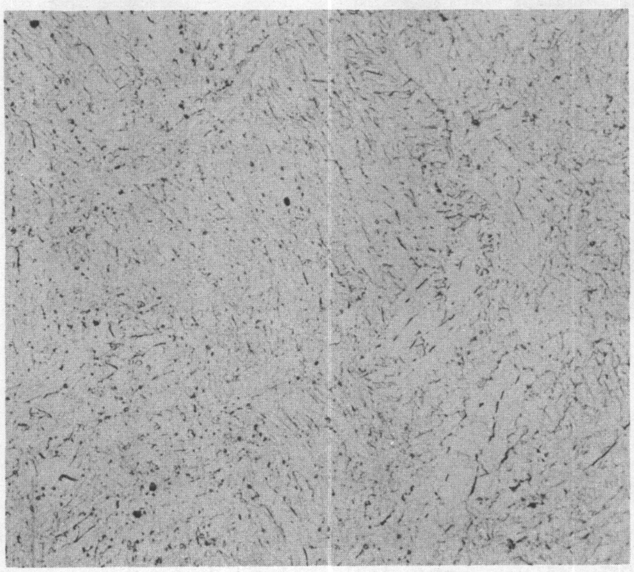
250X N22752

Annealed Billet Stock



250X N22749

As Extruded, 40 Per Cent Reduction



250X N22750

As Extruded, 50 Per Cent Reduction

250X N22751

As Extruded, 60 Per Cent Reduction

FIGURE 13. TYPICAL MICROSTRUCTURES OF EXTRUSION BILLETS AND BARS EXTRUDED WITH REDUCTIONS OF 40, 50, AND 60 PER CENT

resulting from cold extrusion. The typical structures are shown in Figure 13. The structure of the hot-rolled and annealed billets consisted of coarse, plate-like alpha grains that had been partially recrystallized. The microstructures of the extruded bars exhibited a severe distortion pattern with a much finer grain size. The grain size decreased as the per cent reduction increased, but was unaffected by the die angle. There were no significant differences in the appearance of the microstructures of the AMS 4900 and AMS 4921 grades for a given condition of extrusion.

Extrusion Pressure and Work of Extrusion

Pressure measurements during extrusion were made with a Bacharach hydraulic-pressure recorder. This instrument records the hydraulic pressure on the main ram as a function of punch travel. The pressure curves for Grade AMS 4900 (47,000-psi yield strength), showing the effect of extrusion reduction on the extrusion pressure required with 90-, 120-, and 150-degree dies, are presented in Figures 14, 15, and 16. Similarly, the pressure curves for Grade AMS 4921 (70,000-psi yield strength) are shown in Figures 17, 18, and 19.

The pressure curves are similar in shape to those obtained by Pessl and Hauttman[4] for cold forward extrusion of steel, exhibiting the characteristic maximum during initial flow and a gradual decrease to a constant value. The initial flow pressure for a given die angle varied with the extrusion reduction as a straight-line relationship for both grades of unalloyed titanium, as shown in Figure 20. Increasing the die angle shifted the relationship toward higher values of pressure, but the slopes of the lines were about the same.

The areas under the extrusion-pressure curves represent the total work of extrusion required for the various combinations of reduction and die angle. Using a polar planimeter, the areas under the curves (assuming the length of billet extruded to be 2 inches) were measured and the total work and average work per unit volume were determined. The calculated values for the total and average work for the various extrusion conditions are presented in Table 2. The effect of extrusion reduction on the average work per unit volume for the various die angles is shown graphically in Figure 21 for both unalloyed grades. The curves suggest that a straight-line relationship also exists between the average work and per cent reduction, as was observed between initial-flow pressure and per cent reduction (Figure 20). Additional tests would be required, however, to establish the exact relationship.

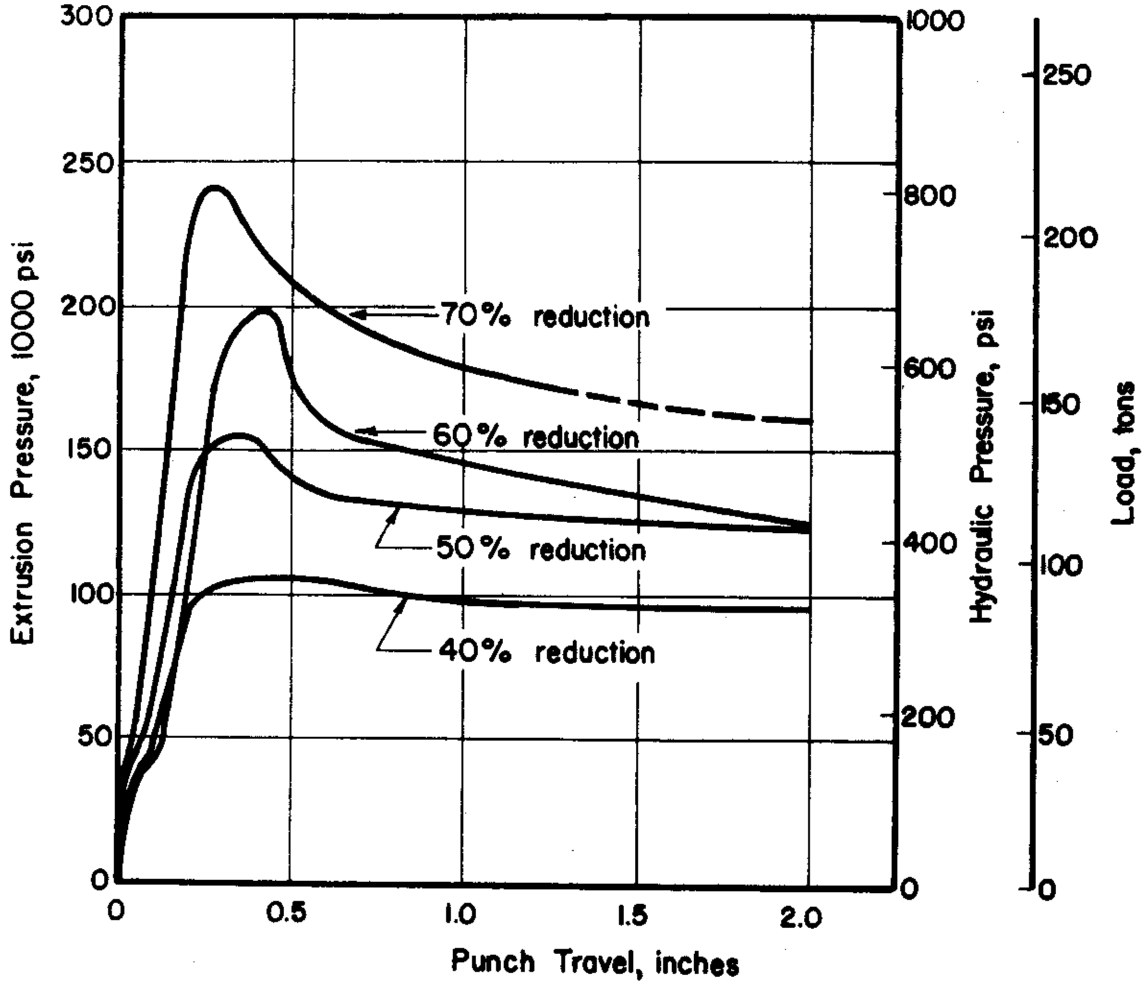


FIGURE 14. EXTRUSION–PRESSURE CURVES FOR GRADE AMS 4900 TITANIUM EXTRUDED THROUGH 90–DEGREE CONICAL DIES SHOWING EFFECT OF EXTRUSION REDUCTION

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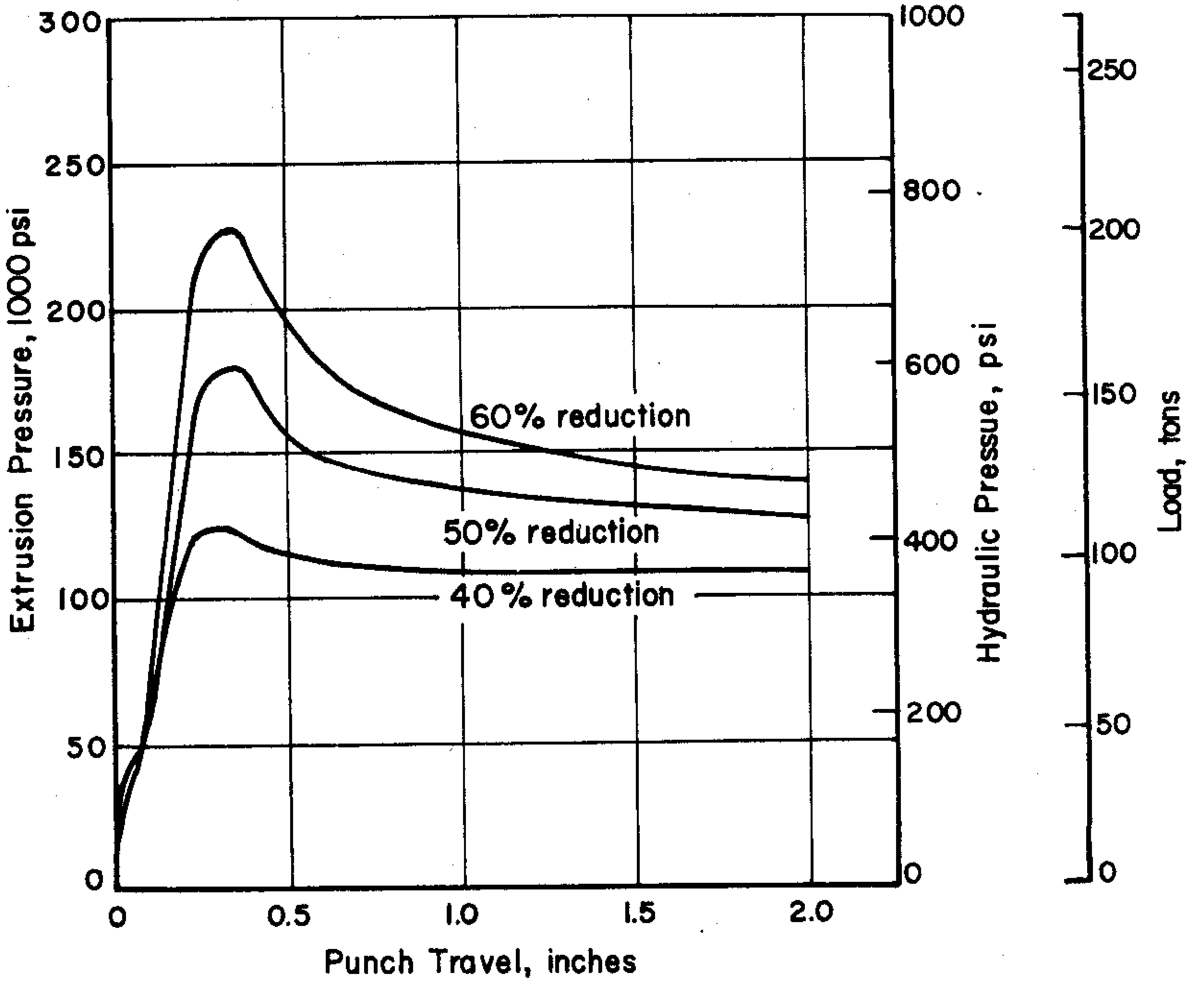

FIGURE 15. EXTRUSION-PRESSURE CURVES FOR GRADE AMS 4900 UNALLOYED TITANIUM EXTRUDED THROUGH 120-DEGREE CONICAL DIES, SHOWING EFFECT OF EXTRUSION REDUCTION

A-15809

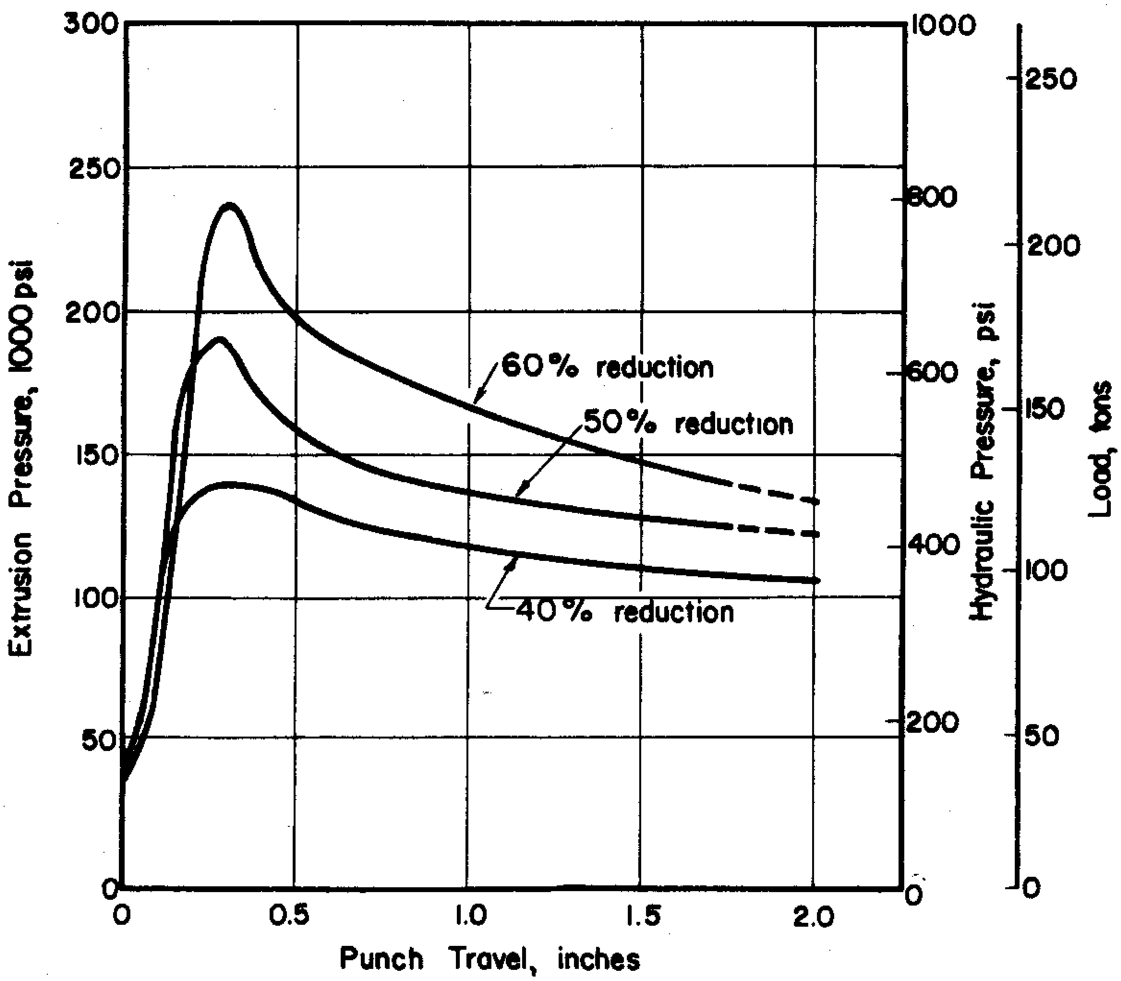

FIGURE 16. EXTRUSION-PRESSURE CURVES FOR GRADE AMS 4900 UNALLOYED TITANIUM EXTRUDED THROUGH 150-DEGREE CONICAL DIES, SHOWING EFFECTS OF EXTRUSION REDUCTION

A-15810

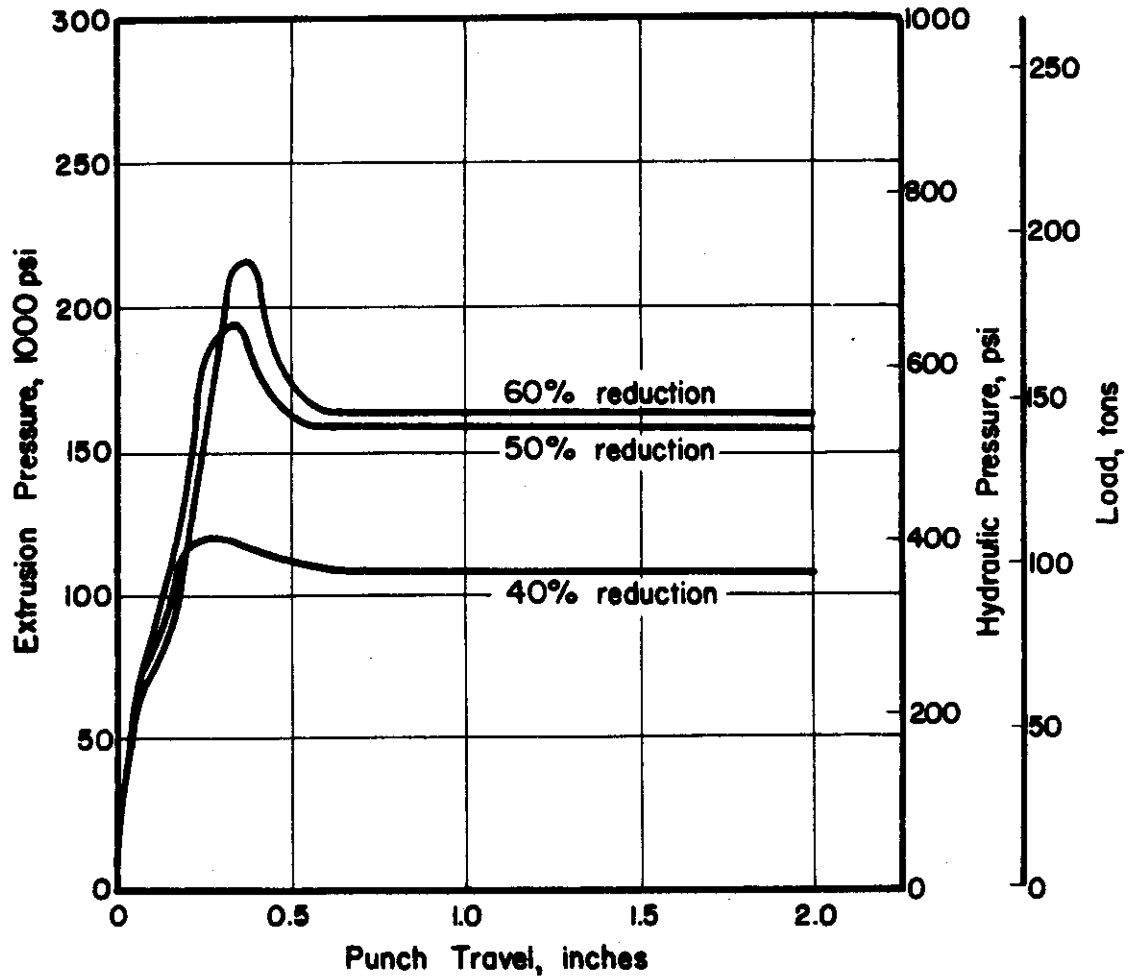

FIGURE 17. EXTRUSION-PRESSURE CURVES FOR GRADE AMS 4921 UN-ALLOYED TITANIUM EXTRUDED THROUGH 90-DEGREE CONICAL DIES, SHOWING EFFECT OF EXTRUSION REDUCTION

A-15811

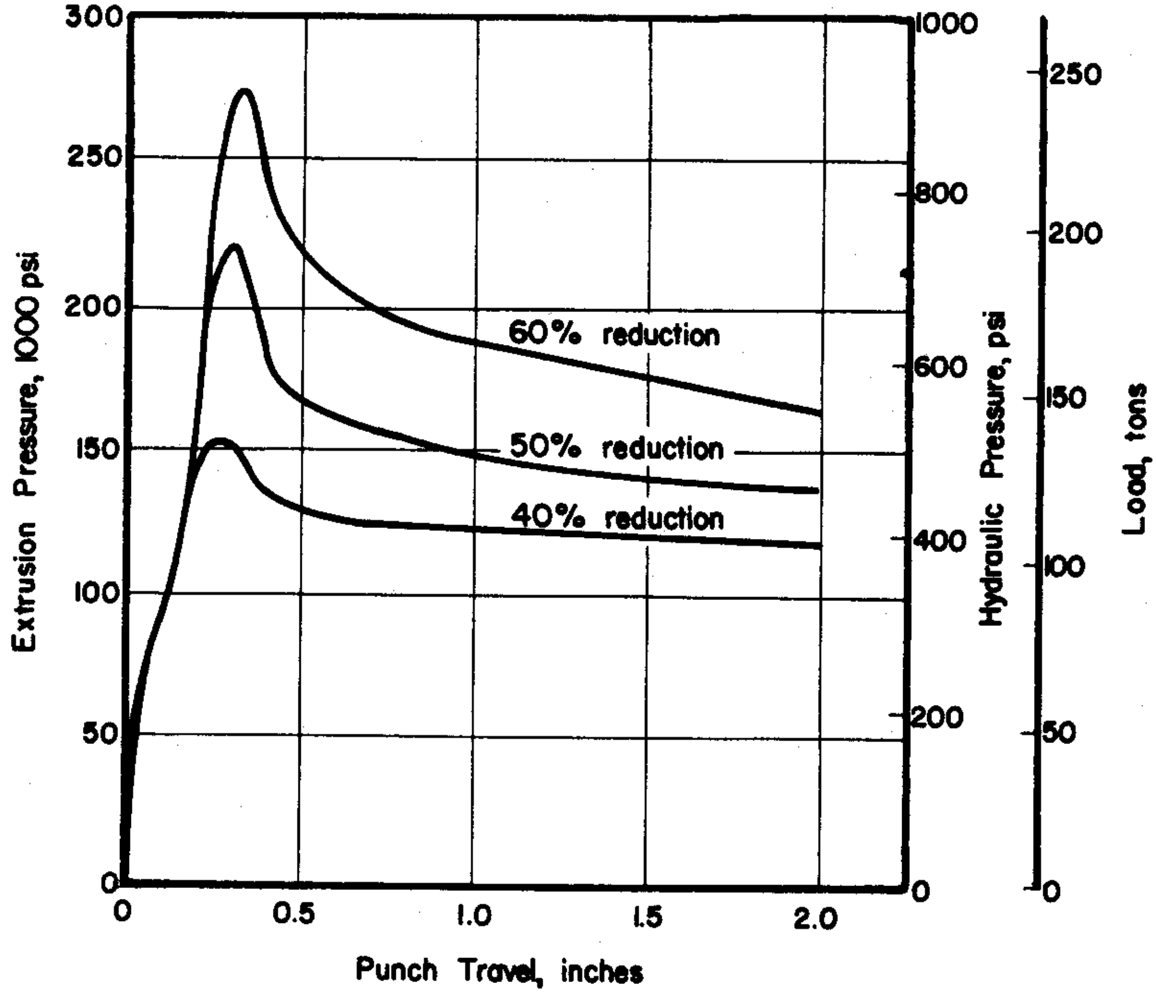

FIGURE 18. EXTRUSION—PRESSURE CURVES FOR GRADE AMS 4921 UN-ALLOYED TITANIUM EXTRUDED THROUGH 120—DEGREE CONICAL DIES, SHOWING EFFECT OF EXTRUSION REDUCTION

A-15612

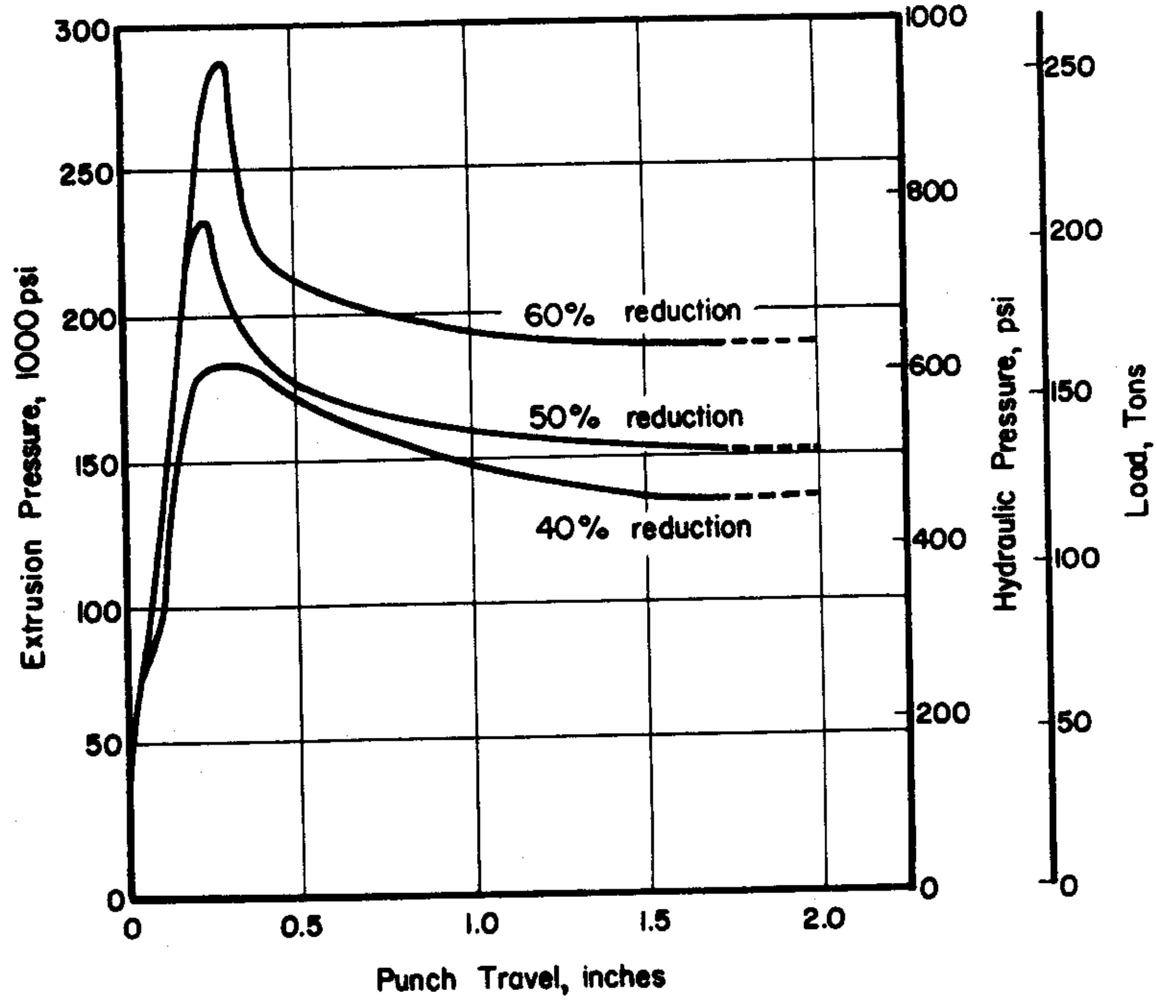

FIGURE 19. EXTRUSION–PRESSURE CURVES FOR GRADE AMS 4921 UNALLOYED TITANIUM EXTRUDED THROUGH 150–DEGREE CONICAL DIES, SHOWING EFFECT OF EXTRUSION REDUCTION

A-15813

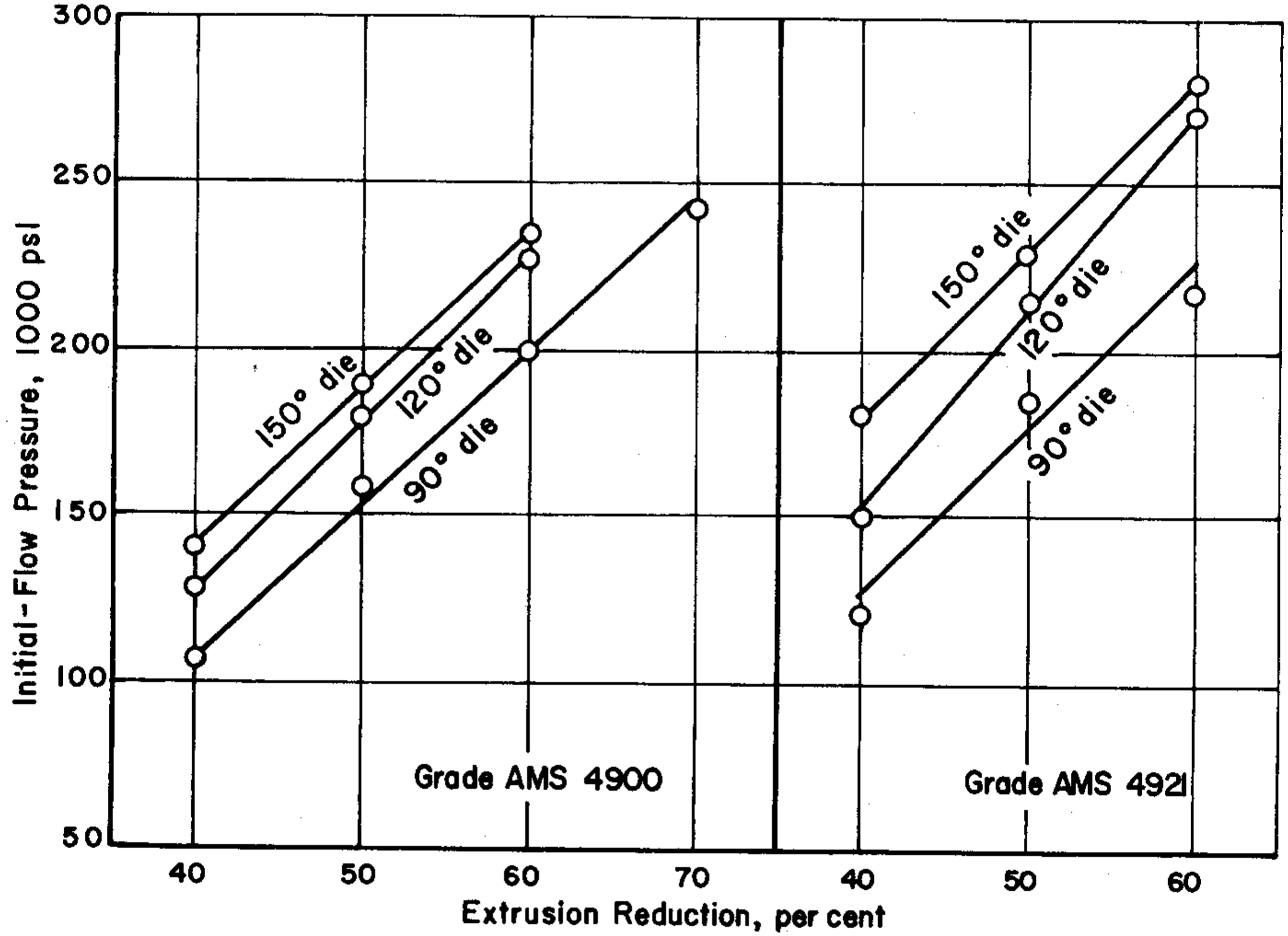

FIGURE 20. EFFECT OF EXTRUSION REDUCTION ON INITIAL-FLOW PRESSURE FOR COLD EXTRUSION OF UNALLOYED TITANIUM WITH 90-, 120-, AND 150-DEGREE DIES

A-15814

TABLE 2. CALCULATED VALUES OF TOTAL WORK AND AVERAGE WORK PER UNIT VOLUME FOR THE COLD EXTRUSION OF UNALLOYED TITANIUM WITH VARIOUS COMBINATIONS OF DIE ANGLE AND EXTRUSION REDUCTION

Extrusion Reduction, per cent	90° Die Angle: Area Under Curve, in.^{2}	90° Die Angle: Total Work, in-lb	90° Die Angle: Avg. Work per Unit Volume, in-lb/in.^{3}	120° Die Angle: Area Under Curve, in.^{2}	120° Die Angle: Total Work, in-lb	120° Die Angle: Avg. Work per Unit Volume, in-lb/in.^{3}	150° Die Angle: Area Under Curve, in.^{2}	150° Die Angle: Total Work, in-lb	150° Die Angle: Avg. Work per Unit Volume in-lb/in.^{3}
Grade AMS 4900									
40	1.08	344,000	97,500	1.20	382,000	108,000	1.26	400,000	113,000
50	1.38	439,000	124,500	1.51	480,000	136,000	1.55	493,000	140,000
60	1.53	487,000	138,000	1.72	547,000	155,000	1.80	572,000	162,000
70	1.96	624,000	176,500	--	--	--	--	--	--
Grade AMS 4921									
40	1.15	366,000	103,500	1.35	430,000	122,000	1.61	512,000	145,000
50	1.58	503,000	142,000	1.63	519,000	147,000	1.79	570,000	162,000
60	1.87	595,000	168,500	1.98	630,000	178,500	2.12	675,000	191,000

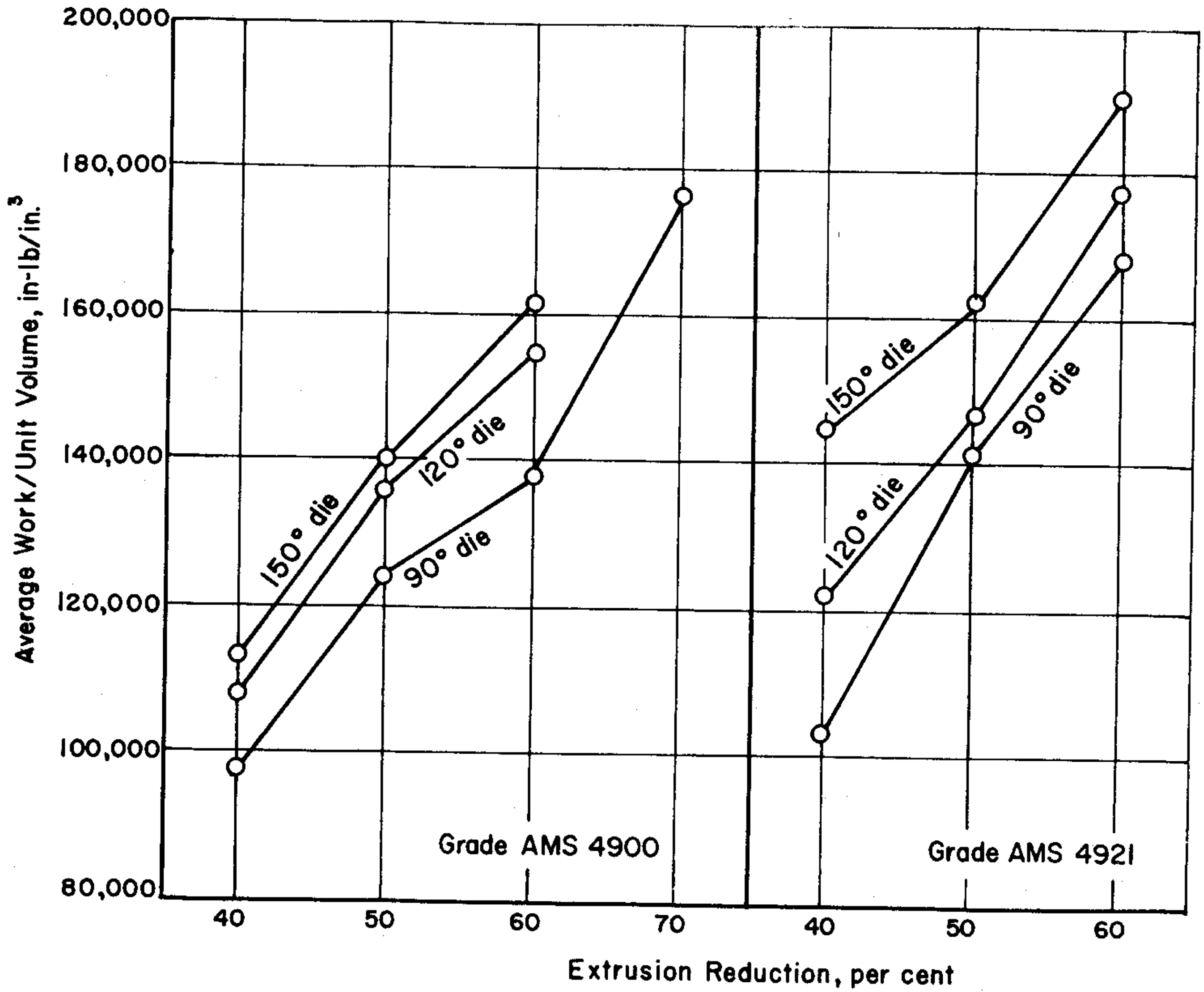

FIGURE 21. EFFECT OF EXTRUSION REDUCTION ON AVERAGE WORK REQUIRED TO COLD EXTRUDE 1 CUBIC INCH OF UNALLOYED TITANIUM WITH 90-,120-, AND 150-DEGREE DIES

A-15815

EFFECT OF COLD EXTRUSION ON MECHANICAL PROPERTIES

Hardness measurements were made on the longitudinal cross sections of each extrusion to determine the variation in work hardening occurring as a result of the differences in deformation between the center and the surface of the bars. To avoid the effects of micro-variations within the bars, the hardnesses were measured with a Rockwell tester, using the B scale for Grade AMS 4900 and the C scale for Grade AMS 4921. Five hardness measurements were made across the diameter at 1/2-inch intervals along the length of the bars. Except for the initial-flow zone, which underwent only slight deformation, the hardnesses, both at the center and the surface, were uniform along the length of the bars. A typical hardness traverse, showing the values at the center and surface, is presented in Figure 22.

The average hardnesses at the center and surface of the bars of both unalloyed grades are given in Table 3 in both Rockwell and Brinell units. The center of the bars was generally 10 to 20 Bhn softer than the surface metal, which had been more severely deformed during extrusion. The hardness increased as both the per cent reduction and die angle increase. The increase was small, however, the Grade AMS 4900 bars varying from 185 to 200 Bhn for a 40 per cent reduction with a 90-degree die to 208 to 222 Bhn for a 60 per cent reduction with a 150-degree die. Similarly, the Grade AMS 4921 bars increased from 250 to 264 Bhn to 271 to 286 Bhn.

The over-all hardening effect produced by cold extrusion was quite appreciable. The total hardness increase varied from 40 to 80 Bhn for Grade AMS 4900, and from 55 to 100 Bhn for Grade AMS 4921.

On completion of the hardness tests, the sections of each bar were machined into standard 0.250-inch-diameter tensile specimens. Tensile tests were conducted on a universal testing machine at a constant platen speed of 0.02 inch per minute. Yield strengths were determined from autographic data. The tensile properties of the bars in the various extruded conditions are presented in Tables 4 and 5.

The ultimate strength of Grade AMS 4900 increased from 60,000 psi, as annealed, to strengths in the range 87,000 to 97,000 psi, after cold extrusion, with a corresponding reduction in elongation from 40.5 to about 16 per cent in 1 inch. Similarly, Grade AMS 4921 increased in strength from 83,000 psi to values in the range 109,000 to 119,000 psi, with a decrease in elongation from 31.5 to about 14 per cent in 1 inch. The ultimate strength increased only slightly as the extrusion reduction increased - about 3000 psi for each 10 per cent increase. Increasing the die angle for a given reduction from 90 to 150 degrees had no significant effect on either strength or ductility.

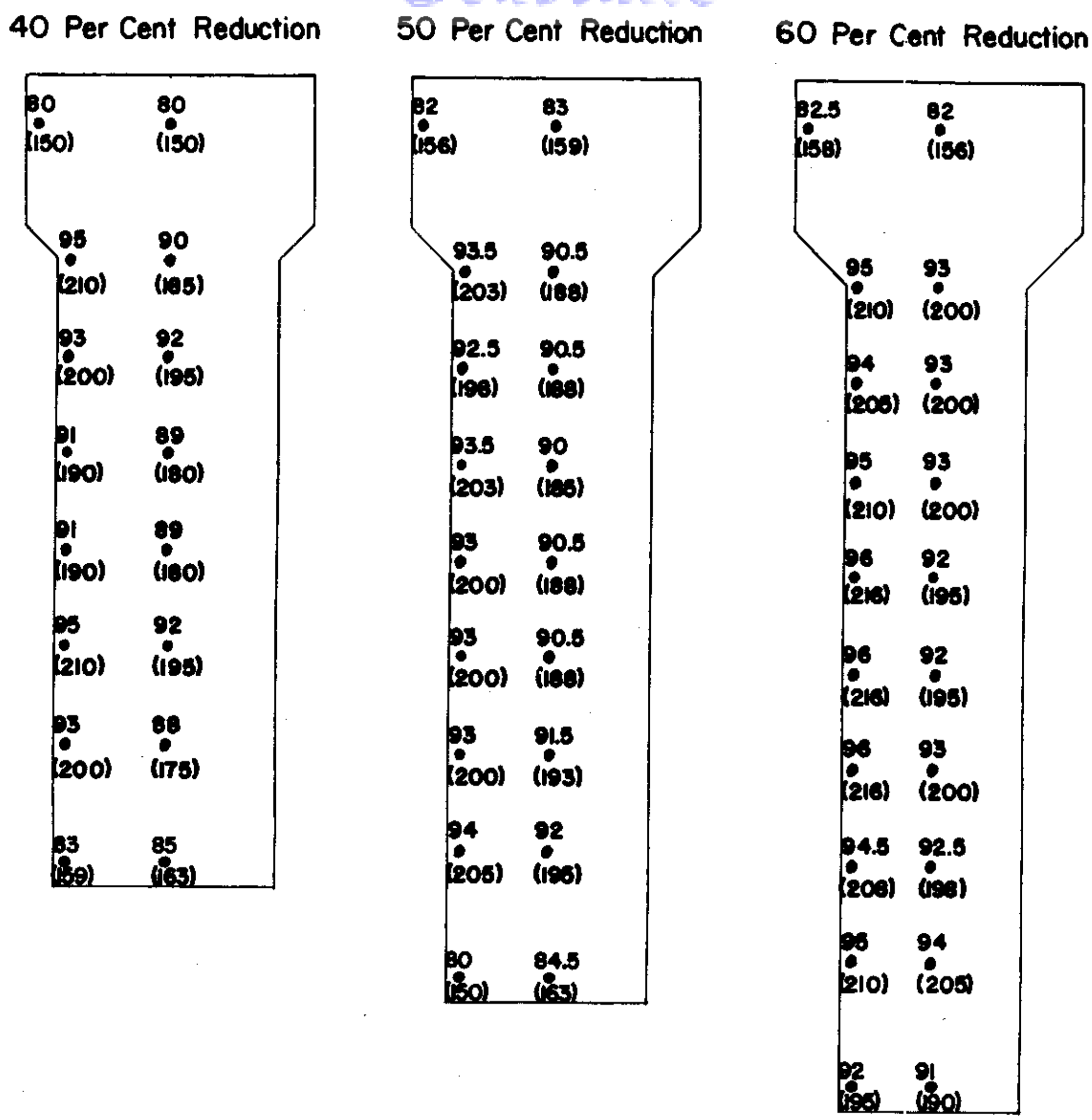

FIGURE 22. HARDNESS TRAVERSE FOR BARS OF GRADE AMS 4900 UNALLOYED TITANIUM EXTRUDED WITH 90-DEGREE DIES, SHOWING TYPICAL VARIATION FROM SURFACE TO CENTER

Actual hardness determined by Rockwell "B" measurements; corresponding Brinell hardness valves are shown in parentheses.

A-15816

TABLE 3. AVERAGE HARDNESS AT SURFACE AND CENTER OF COLD-EXTRUDED UNALLOYED TITANIUM BARS

Extrusion Reduction, per cent	Grade AMS 4900 Average Hardness[a] Surface[b] R_B	Grade AMS 4900 Surface[b] Bhn[c]	Grade AMS 4900 Center R_B	Grade AMS 4900 Center Bhn[c]	Grade AMS 4921 Average Hardness[a] Surface[b] R_C	Grade AMS 4921 Surface[b] Bhn[c]	Grade AMS 4921 Center R_C	Grade AMS 4921 Center Bhn[c]
				Annealed Billet				
--	--	145	--	145	--	195	--	195
				90° Die				
40	93	200	90	185	27	264	24.5	250
50	93.5	203	92	195	27	264	25	253
60	95	210	93	200	28.5	275	26.5	261
				120° Die				
40	92.5	198	90	185	27.5	268	25	253
50	93	200	91	190	28.5	275	25.5	256
60	97.5	225	93.5	203	30	286	27	264
				150° Die				
40	94	205	92	195	28.5	275	26	258
50	95.5	213	93.5	203	31	294	28	271
60	97	222	94.5	208	--	--	--	--

(a) Average of at least 5 readings.
(b) Hardness measured at depth of 1/16 inch from surface.
(c) Rockwell values converted to Bhn, 3000-kilogram load.

TABLE 4. MECHANICAL PROPERTIES[a] OF GRADE AMS 4900 UNALLOYED TITANIUM IN THE ANNEALED AND COLD-EXTRUDED CONDITIONS

Extrusion Reduction, per cent	Yield Strength, 0.2% Offset, psi	Ultimate Strength, psi	Reduction in Area, per cent	Elongation, % in 1 inch
		Annealed Billet Stock		
--	47,000	60,000	65.0	40.5
		Extruded Through 90° Die		
40	67,500	90,500	45.3	16.5
50	71,500	89,500	48.0	17.0
60	76,000	96,500	42.4	16.5
		Extruded Through 120° Die		
40	70,000	87,000	50.8	17.5
50	74,000	92,500	43.4	15.0
60	74,000	96,000	42.4	16.0
		Extruded Through 150° Die		
40	68,000	87,000	50.4	17.0
50	71,000	92,500	47.0	15.0
60	61,000	92,500	47.4	13.5

(a) Standard 0.250-inch-diameter tensile specimens. Tensile data are the average for two specimens.

TABLE 5. MECHANICAL PROPERTIES[a] OF GRADE AMS 4921 UNALLOYED TITANIUM IN THE ANNEALED AND COLD-EXTRUDED CONDITIONS

Extrusion Reduction, per cent	Yield Strength, 0.2% Offset, psi	Ultimate Strength, psi	Reduction in Area, per cent	Elongation, % in 1 inch
		Annealed Billet Stock		
--	70,000	83,000	42.0	31.5
		Extruded Through 90° Die		
40	82,000	112,000	30.8	13.5
50	82,500	114,500	27.5	16.0
60	90,500	119,000	24.8	13.5
		Extruded Through 120° Die		
40	91,500	110,500	27.5	14.0
50	95,500	115,000	24.0	12.5
60	83,500	117,000	17.7	12.0
		Extruded Through 150° Die		
40	82,500	109,000	31.6	14.5
50	82,500	112,000	28.6	15.0

(a) Standard 0.250-inch-diameter tensile specimens. Tensile data are the average for two specimens.

(Data from which this report was prepared are contained in Battelle Laboratory Record Book No. 9753.)

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APPENDIX I

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