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DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS

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BATTELLE MEMORIAL INSTITUTE
COLUMBUS LABORATORIES

INTERIM ENGINEERING PROGRESS REPORT IR-8-198 (VIII)

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ABSTRACT

Development of the Manufacturing Capabilities of the Hydrostatic Extrusion Process

R. J. Fiorentino
et al.
Battelle Memorial Institute

The purpose of the present program is to develop the manufacturing capabilities of the hydrostatic extrusion process. Specific applications to be studied are fabrication of wire, tubing, and shapes from relatively difficult-to-work materials such as refractory-metal alloys, high-strength steels and aluminum alloys, titanium alloys, beryllium, and other selected materials.

Investigation of critical process variables for the cold hydrostatic extrusion of 7075-0 aluminum, AISI 4340 steel and Ti-6Al-4V titanium alloy was continued during this report period. Several experiments on wrought TZM molybdenum alloy were conducted in which the effects of extrusion ratio, billet lubricants and die design were evaluated. Further work on the extrusion of beryllium in billet and wire form is reported. Important developments in the program are given below.

(1) Stick-slip was eliminated in the extrusion of 7075-0 aluminum at ratios up to and including 40 : 1 and at ram speeds of 20 ipm. At 20 : 1, this was achieved by a new lubricant, 20 wt % MoS_2 in stearyl stearate (L53). At a ratio of 40 : 1, a special billet nose design was effective in eliminating stick-slip.

(2) Tandem extrusion of 7075-0 aluminum billets with a counterbored joint was achieved without separation or any discontinuity in the extrusion pressures.

(3) Several very effective lubricating systems have been developed for AISI 4340 steel.

(4) A 4-1/2-inch length of high-quality Ti-6Al-4V tubing 0.663 OD x 0.030 wall was produced from tube stock having a wall thickness of 0.069 inch.

(5) A simplified die-seal arrangement eliminated the need for a metal seal ring and was effective in containing fluid at high pressures.

(6) In several extrusions of a TZM molybdenum alloy, circumferential billet cracking was eliminated with a special die design. Only a few longitudinal cracks occurred on the extruded section.

(7) A 5-foot length of beryllium wire was produced by hydrostatic extrusion-drawing at a reduction of 25 percent.

PUBLICATION REVIEW

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Approved by: P. J. Rieppel

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FOREWORD

This Interim Engineering Progress Report covers the work performed under Contract No. AF 33(615)-1390 from 1 September 1966 through 30 November 1966. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with Battelle Memorial Institute of Columbus, Ohio, was initiated under Manufacturing Methods Project No. 8-198, "Development of the Manufacturing Capabilities of the Hydrostatic Extrusion Process". It is being administered under the direction of Mr. Gerald A. Gegel of the Metallurgical Processing Branch (MATB), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program is being conducted at Battelle by the Metalworking Research Division, with Mr. R. J. Fiorentino, Associate Chief, as project engineer. Others who have contributed to the program are Mr. B. D. Richardson, Research Metallurgical Engineer, Mr. George E. Meyer, Research Metallurgical Engineer, Mr. A. M. Sabroff, Chief, and Mr. F. W. Boulger, Senior Technical Advisor. Mr. R. L. Jentgen, Project Leader in the Experimental Physics Division, is assisting in the fluid and lubrication studies of the program. Dr. J. C. Gerdeen, Research Mechanical Engineer, Mr. E. C. Rodabaugh, Senior Mechanical Engineer, and Mr. T. J. Atterbury, Chief of the Applied Solid Mechanics Division are contributing to the high-pressure-container design study. Mr. R. E. Mesloh, Research Mechanical Engineer of the same division, is assisting in the design of an instrument for measuring fluid pressure at elevated temperatures. Data from which this report has been prepared are contained in Battelle Laboratory Record Books Nos. 21799, 21990, 23055, 23287, 23585, 23791, and 23836.

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DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS

by

R. J. Fiorentino, B. D. Richardson, A. M. Sabroff,
and F. W. Boulger

INTRODUCTION

The purpose of the present research program is to develop the manufacturing capabilities of the hydrostatic extrusion process with the aim of extruding high-quality shapes from materials of interest to the Air Force. It is a continuation of the recently completed program on Contract No. AF 33(600)-43328. The current program is divided into two phases with the following general objectives:

Phase I. Process-Development Studies

Part 1. (a) To study the effect of critical process variables on pressure requirements and surface quality in hydrostatic extrusion of AISI 4340 steel, Ti-6Al-4V titanium alloy, and 7075 aluminum alloy.

(b) To correlate all available hydrostatic-extrusion-pressure data with material properties wherever possible in order to assist direction of the experimental effort and maximize the information developed in the present program.

Part 2. To explore the hydrostatic extrudability of TZM molybdenum alloy (cast and wrought), beryllium, Cb-752 columbium alloy, powder compacts, and other materials to be selected later in the program.

Part 3. To conduct a design study for high-temperature, high-pressure hydrostatic extrusion tooling based on (1) estimated pressure requirements for high-ratio extrusion of materials of interest to the the Air Force, (2) latest high-pressure-vessel technology, and (3) latest tooling materials available.

Part 4. To conduct a process economic study on the construction, installation, and operation of equipment with the same operational and size requirements as the tooling developed in the previous program on Contract No. AF 33(600)-43328.

Phase II. Process-Application Studies

Part 1. To evaluate the application of the hydrostatic extrusion process for sizing and finishing conventionally hot-extruded (or rolled) structural shapes by various combinations of drawing and extruding. Primary emphasis will be on AISI 4340 steel, although some effort will be devoted to Ti-6Al-4V, 7075-0 aluminum, and selected refractory metals.

Part 2. To determine the feasibility of producing wire and filaments from beryllium and TZM molybdenum alloy by combinations of hydrostatic extrusion and drawing.

Part 3. To develop tooling and define process parameters necessary for the reduction of tube blanks to finish tubing from AISI 4340 and a selected columbium alloy.

The study of critical process variables for hydrostatic extrusion was continued during this report period. Room-temperature extrusion trials were made with 7075-0 aluminum in which the variables investigated were

(1) Lubricants and fluids
(2) Billet nose design
(3) Tandem extrusion
(4) T-sections
(5) Dies with tungsten carbide surfaces
(6) Extrusion ratio.

Lubricants and fluids were investigated with AISI 4340 steel rounds and Ti-6Al-4V titanium alloy rounds and tubing.

Special die designs to eliminate cracking were evaluated during the hydrostatic extrusion of wrought TZM molybdenum alloy.

Experiments on the extrusion of beryllium rounds and extrusion-drawing of beryllium wire were continued in this period.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

Extrusion Tooling

The major components of the hydrostatic-extrusion tooling used during this report period were previously described.(1, 2, 3, 4, 6)* Minor modifications in die-orifice design are discussed in the appropriate section of this report.

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*References are listed at the end of the text.

An improvement in the die seal arrangement was made during this interim period. Figure 1 shows the present seal arrangement which consists of a beryllium-copper seal-ring and a rubber O-ring.

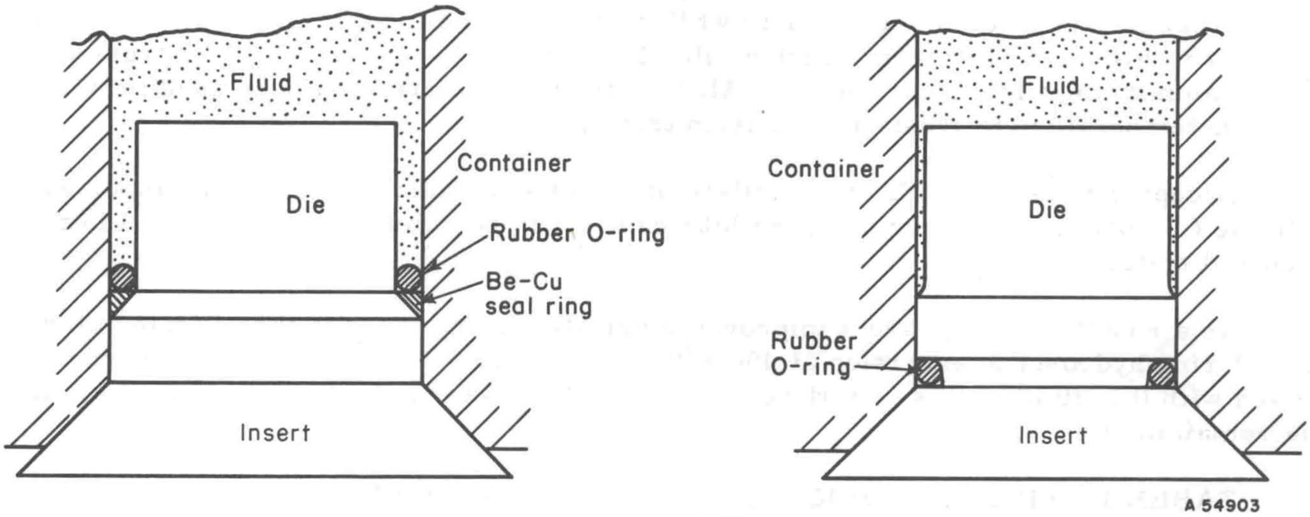

FIGURE 1. DIE SEAL ARRANGEMENTS EVALUATED IN HYDROSTATIC EXTRUSION

The new seal arrangement consists of a single rubber O-ring located at the base of the die. This arrangement is similar in principle to that used at the High Pressure Laboratory, ASEA, Sweden. The advancement is essentially an economic one since sealing was never a problem with the previous arrangement. The new arrangement eliminates need for a metallic seal ring and reduces the die machining costs somewhat. Sealing with this design was achieved in several trials up to about 180,000 psi, the maximum attempted thus far.

Materials

Except for the TZM Molybdenum alloy, the billet materials used during this report are described in Interim Report Numbers I and VI$^{(1,5)}$. Wrought TZM bar stock was obtained in the following conditions:

Condition	Heat Treatment	Hardness, DPH
Stress relieved	1 hr at 2350 F	276
Recrystallized	1 hr at 2900 F	196

The chemical composition of the stock was reported to be:

Ti - 0.42

Zr - 0.10

C - 0.023

Others - 0.007

Mo - balance

Lubricants, Coatings, and Fluids

Table 1 lists billet lubricants used during the last quarterly period. Lubricant 52 was modified to L53 by adding 20 wt % molybdenum disulphide. This in turn was modified further to L54 by the addition of 10 wt % graphite. The modifications were made in an effort to produce a lubricant which would eliminate stick-slip during the extrusion of 7075-0 aluminum at low stem speeds. All the other lubricants have been used previously in room-temperature hydrostatic extrusion trials.

Except for one billet all of the billets of Ti-6Al-4V titanium alloy were anodized with the C3 coating before applying the lubricant. The remaining billet was used in the uncoated state.

As a result of the apparent improved lubrication achieved with the silicate ester fluid during hydrostatic extrusion at 400 F(6), some room-temperature trials were conducted with this fluid in this report period. Castor oil was used as the fluid medium in the remaining trials.

TABLE 1. BILLET LUBRICANTS USED FOR HYDROSTATIC EXTRUSION DURING THIS INTERIM REPORT PERIOD

Lubricant	Source	Description	Billet Material Treated
L17	Battelle	20 wt % MoS_2 in Castor Wax	7075-0 Al, Ti-6Al-4V, TZM, 4340
L31	Commercial	Fluorocarbon Telomer	7075-0 Al, 4340, Ti-6Al-4V
L33	Battelle	55 wt % MoS_2 and 6 wt % graphite in sodium silicate	7075-0 Al, Ti-6Al-4V
L38	Commercial	PTFE lacquer	7075-0 Al, 4340, Ti-6Al-4V, TZM, Be
L52	Commercial	Stearyl stearate	7075-0 Al
L53	Commercial & Battelle	20 wt % MoS_2 in stearyl stearate	7075-0 Al, 4340
L54	Commercial & Battelle	20 wt % MoS_2 and 10 wt % graphite in stearyl stearate	7075-0 Al

CHARACTERISTICS OF PRESSURE-DISPLACEMENT CURVES

In reporting the results of trials conducted so far, a written description of the characteristics of the pressure-displacement curve obtained during extrusion has been used. To simplify matters, the types of curves obtained will now be described by using typical representative diagrams of the curves. It has been found that the extrusion pressure-displacement curves can be classified into families as shown in Figure 2, page 25. The figure is placed at the end of the text on a foldout page for ready reference when the extrusion data are being examined. Each family of curves is designated by a letter, and the number following it classifies the typical runout characteristics within each family.

Curves Types A, B, C, and D represent quality of lubrication in decreasing order of effectiveness. These curve types have been numerically classified further according to the following characteristics during runout:

No.	General Runout Characteristics
1	Constant
2	Decreasing
3	Increasing
4	Special

Type A Curves. One of the aims of the experiments in lubrication systems in the current program is to obtain conditions giving a curve of Type A 1 which represents completely effective lubrication throughout the extrusion stroke. Experience has shown that once this type of curve is achieved, for a given material and extrusion ratio other lubrication systems may not lower the value of P_r (runout pressure) markedly and therefore the curve very likely represents near-optimum lubrication conditions. There is no breakthrough pressure (P_b) peak above the runout pressure which suggests that the static friction, μ_s, is about the same as the kinetic friction coefficient, μ_k, developed once the billet starts to move.

The runout characteristics in the other Type A curves may represent partial lubrication breakdown due to pressure-temperature effects at the billet-die interface or changes in flow strength due to adiabatic heating of the billet.

Type B Curves. All the curves in this category are generally characterized by a rounded breakthrough pressure peak (P_b) followed by a smooth runout curve at a lower pressure (P_r). The occurrence of a rounded pressure peak has been attributed to the fact that μ_s is somewhat higher than μ_k(1), but not sufficiently to cause a sharp stick-slip peak. In some cases, the breakthrough pressure peak is sharp, indicating a stick-slip situation at breakthrough only.

Type C Curves. These curves are similar to Type B curves except that one or a few cycles of stick-slip follow the breakthrough pressure peak. Here stick-slip is generally not severe, its amplitude decreasing to give a smooth runout curve.

Stick-slip in hydrostatic extrusion is caused by the energy stored in the fluid at P_b being sufficient to overcome μ_s but much more than necessary for μ_k. Consequently extrusion occurs very rapidly and is accompanied by a sharp drop in pressure(1). The μ_s achieved at the P_r level apparently is not sufficiently greater than μ_k to cause stick-slip of the same magnitude to occur again.

Type D Curves. In these curves stick-slip is generally severe and continues throughout the stroke. Extrusion takes place at extremely rapid rates after each pressurizing stroke. The lower pressure level reached after each "slip" tends to occur at the same level during each cycle of stick-slip. Experimental results have indicated that this level represents fairly well the value of P_r if stick-slip had not occurred.

For this reason, the level is designated as "P_r" to indicate that this is the apparent runout pressure. Often the amplitude of stick-slip (P_b-"P_r") is about 30 percent greater than "P_r".

It is of interest to note that, because of the decreasing stick-slip in curve D2, a smooth runout might eventually be obtained if extrusion were continued further. In curve D3, a constant amplitude of stick-slip is superimposed on an increasing "P_r". As a contrast, however, the amplitude of stick-slip has also been observed to increase over an apparently constant "P_r" value as in Curve D4.

COLD HYDROSTATIC EXTRUSION OF 7075-0 ALUMINUM ALLOY ROUNDS AND T-SECTIONS

In the trials with 7075-0 aluminum alloy, the main points of the study were:

(1) Lubricants and fluids
(2) Special billet nose designs
(3) Tandem extrusion
(4) Extrusion and re-extrusion of T-sections
(5) Extrusion at low ratios
(6) Flame-plated dies.

Extrusion data for trials made to produce 7075-0 aluminum rounds are given in Table 2.

Lubricants and Fluids

A significant advance in lubrication systems for 7075-0 aluminum has been achieved during this report period. It was mentioned in the last interim report(6) that stearyl stearate (L52) was to be modified with additions of MoS_2 and graphite. This was because it showed promise as a base lubricant at a 40 : 1 extrusion ratio.

At a ratio of 20 : 1 and a stem speed of 20 ipm, Lubricant 53 (20 wt % MoS_2 in stearyl stearate) produced exceptionally good results (Trial 454). To illustrate the improvements gained, Figure 3 shows the extrusion pressure-displacement curves obtained with L53 and another good lubricant (L38, PTFE lacquer) in comparison with the curve obtained in Trial 347 with the previous "best" lubricant, L17 (20 wt % MoS_2 in castor wax). Also shown is the further improvement gained when castor oil is replaced by silicate ester (Trial 464). It can be seen that L53 reduced the breakthrough pressure obtained with L17 by 12 percent and completely eliminated stick-slip during runout. L38 was almost equally effective.

Furthermore, silicate ester lowered the runout pressures obtained with castor oil by a further 4000 psi. Billet Lubricant 53 was used in both cases.

Under the same extrusion conditions as those in Figure 3 Lubricant 52 (stearyl stearate) did not show any improvement over L17 while L31 (fluorocarbon telomer)

TABLE 2. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION OF 7075-0 ALUMINUM ALLOY ROUNDS

Die Angle - 45 degrees (included) Billet surface finish - 60-100 microinches, rms
Fluid - Castor oil

Item	Trial	Extrusion Ratio	Stem Speed, ipm	Billet Lubricant	Extrusion Pressure, 1000 psi				Type of Curve (see p 25)	Length of Extrusion, inches	Comments
					Breakthrough		Runout				
					Stem	Fluid	Stem	Fluid			
1	347	20	20	L17	162	152	144	130	C1	65	Reference trial(4)
	431	20	20	L52	188	169	142	119	D2	74	--
	432	20	20	L53	164	150	144	123	C2	79	Insufficient lubricant on nose
	453	20	20	L53	155	138	142	122	B2	108	Pressure for first billet in tandem
		20	20	L53	--	177	--	122	C2	20	Restarting pressure
	454(a)	20	20	L53	150	134	136	122	B2	108	Leading billet only
	463	20	20	L53	152	137	138	123	B2	66	Stepped billet nose, A = 1.25 in.
	464(b)	20	20	L53	149	135	133	119	B2	68	--
	433	20	20	L54	169	154	143	127	C2	57	Insufficient lubricant on nose
	436	20	20	L38	156	140	140	122	B2	39	--
	440	20	20	L33	169	150	159	138	B3	40	--
	447	20	20	L31	168	148	136	125	C2	65	--
	449(a)	20	20	L31	176	153	141	128	C2	65	--
2	435	40	20	L53	254	221	165	142	D2	58	--
	468(b)	40	20	L53	204	164	144	135	D3	137	--
	446	40	20	L38	204	179	146	135	D1	119	--
	470	40	20	L53	168	150	154	137	C2	140	Compound-angle billet nose, A = 0.75 in.
3	434	20	80	L53	170	148	144	126	B2	88	--
	448	20	80	L54	168	150	144	126	B2	50	--
	467	20	80	L31	174	158	144	133	B2	44	--
4	457	2.5	20	L17	48	46	48	46	A1	8	--
	456	7	20	L17	99	94	96	89	A2	18	--

(a) Flame coated die used.

(b) Fluid used was silicate ester (SE).

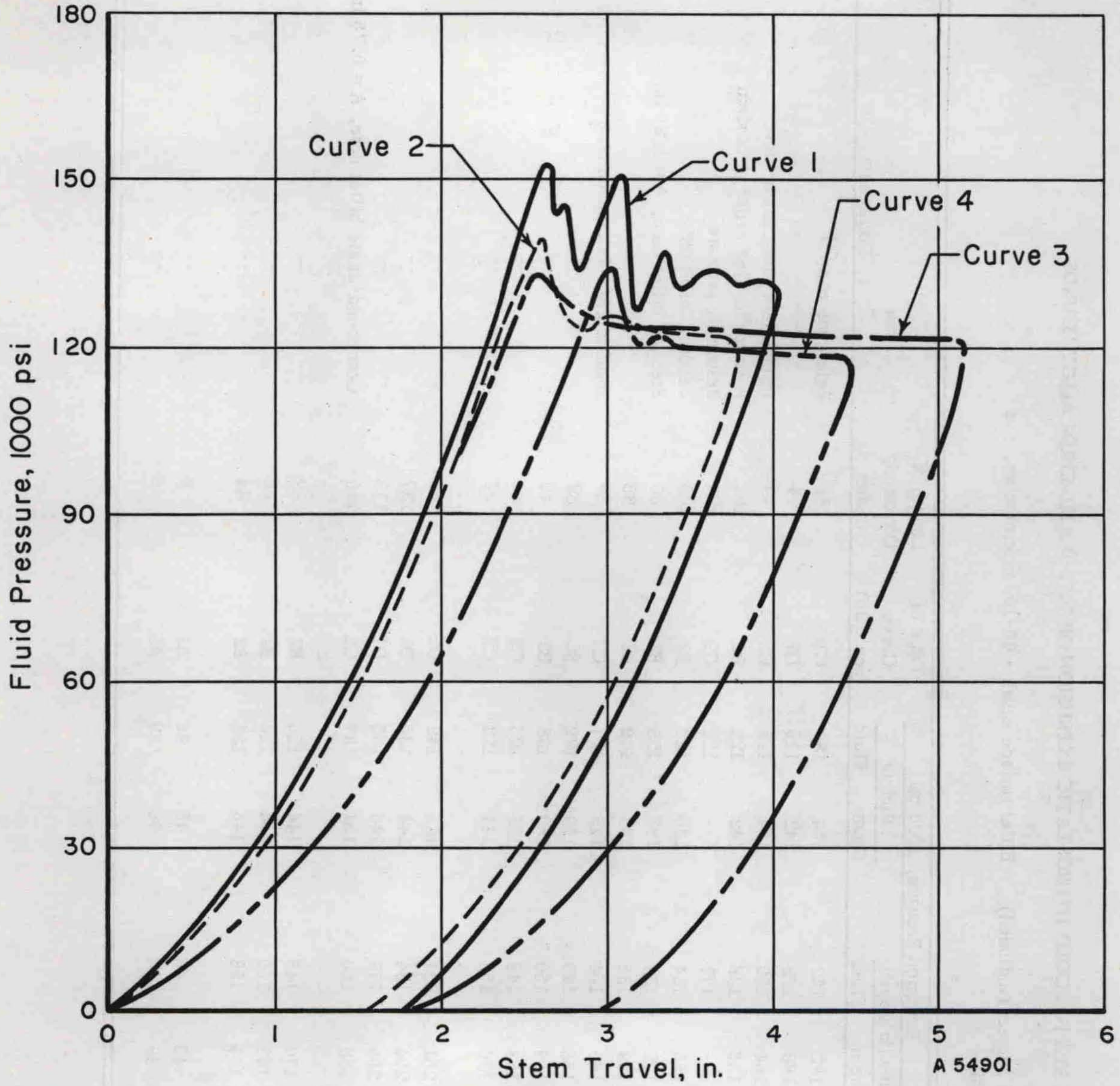

FIGURE 3. EFFECT OF FLUID AND BILLET LUBRICANT ON PRESSURE-DISPLACEMENT CURVES OBTAINED IN THE HYDROSTATIC EXTRUSION OF 7075-0 ALUMINUM AT A RATIO OF 20:1

Extrusion Conditions:	Stem speed	20 ipm
	Die angle	45 degrees included

Curve	Trial	Fluid	Billet Lubricant
1	347	Castor oil	20 wt. % MoS_2 in castor wax (L17)
2	436	Castor oil	PTFE (L38)
3	454	Castor oil	20 wt. % MoS_2 in stearyl stearate (L53)
4	464	Silicate ester	20 wt. % MoS_2 in stearyl stearate (L53)

and L33 (55 wt % MoS_2 and 6 wt % graphite in sodium silicate) provided only marginal reductions in extrusion pressures. In Trials 432, the lubricant (L53) was not applied properly on the nose causing stick-slip to occur. Further trials with L53, in which stick-slip did not occur, demonstrated the importance of careful billet lubrication. Also in Trial 433, inadequate billet nose lubrication with Lubricant 54 (20 wt % MoS_2 and 10 wt % graphite in stearyl stearate) is believed to have caused the stick-slip observed.

At a stem speed of 80 ipm, stick-slip occurs at breakthrough only and is completely eliminated during runout by all of the lubricants evaluated to date including the new Lubricants 31, 53 and 54. Stick-slip during runout is prevented because the high stem speeds do not allow the billet to stop at the end of fluid decompression during slip after breakthrough, thus maintaining kinetic friction conditions. The surface of the products here were not cracked and had a good finish in all cases. The product exit speed was almost 250 fpm whereas in conventional commercial extrusion of 7075-0 aluminum exit speeds are kept roughly to below 2-3 fpm to avoid product cracking.

All lubricants evaluated thus far at 80 ipm have given extrusion curves of Type B2 with a sharp fluid P_b peak of about 150,000 psi and a P_r of about 125,000 psi. These pressure levels were obtained with L17, L53 and L54, whereas L31 gave readings about 5 percent higher.

At an extrusion ratio of 40 : 1 and a stem speed of 20 ipm, severe stick-slip always occurred in previous trials in the program. Lubricants L53 and L38 failed to eliminate it though L38 showed some lowering of pressure levels. In spite of the stick-slip, however, the extruded surface finish obtained with these lubricants was very good. Again, silicate ester resulted in marked reductions in pressure obtained with castor oil as shown by comparison of Curves 1 and 2 in Figure 4.

Billet Nose Design

In an attempt to reduce breakthrough pressure peaks, two special billet nose designs were evaluated; they are shown in Figure 5 below with the standard nose.

Trials with these special billet nose designs were conducted with 7075 aluminum at a stem speed of 20 ipm and L53 as the billet lubricant. At an extrusion ratio of 20 : 1 (Trial 463), the stepped-nose design did not reduce the P_b peak but appeared to have effected a multi-stepped, more gradual transition from the maximum pressure to the runout pressure.

This observation led to the design of the compound-angle nose which was evaluated at the higher ratio of 40 : 1 (Trial 467), where the likelihood of stick-slip is even greater. The lubricant used was again L53. In Figure 4, Curve 3 shows the extrusion curve obtained with this design compared with the standard nose design. Clearly the compound-angle design not only reduced the P_b peak by about 70,000 psi but the severe stick-slip, which is normally present at this extrusion ratio, was completely eliminated. These results are explained as follows:

(1) The second or upper angle on the compound-angle nose provides for more efficient "thick-film" lubrication at breakthrough, thereby reducing the coefficient of static friction, μ_s, and thus, the P_b peak.

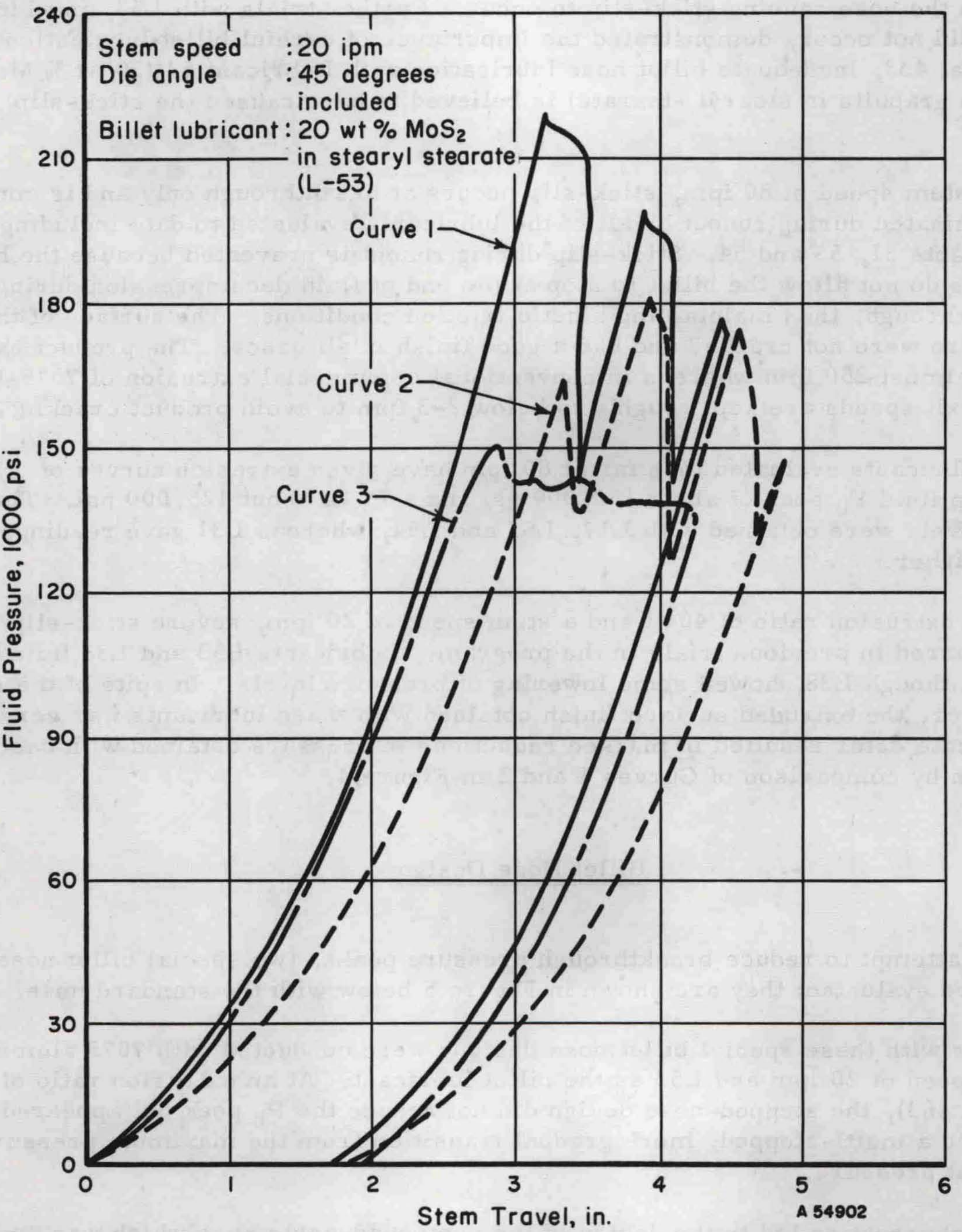

FIGURE 4. EFFECT OF BILLET NOSE SHAPE AND FLUID ON PRESSURE – DISPLACEMENT CURVES OBTAINED IN THE HYDROSTATIC EXTRUSION OF 7075-0 ALUMINUM AT A RATIO OF 40:1

Extrusion Conditions:

Curve	Trial	Fluid	Billet Shape
1	435	Castor oil	Standard
2	468	Silicate ester	Standard
3	470	Castor oil	Compound angle nose

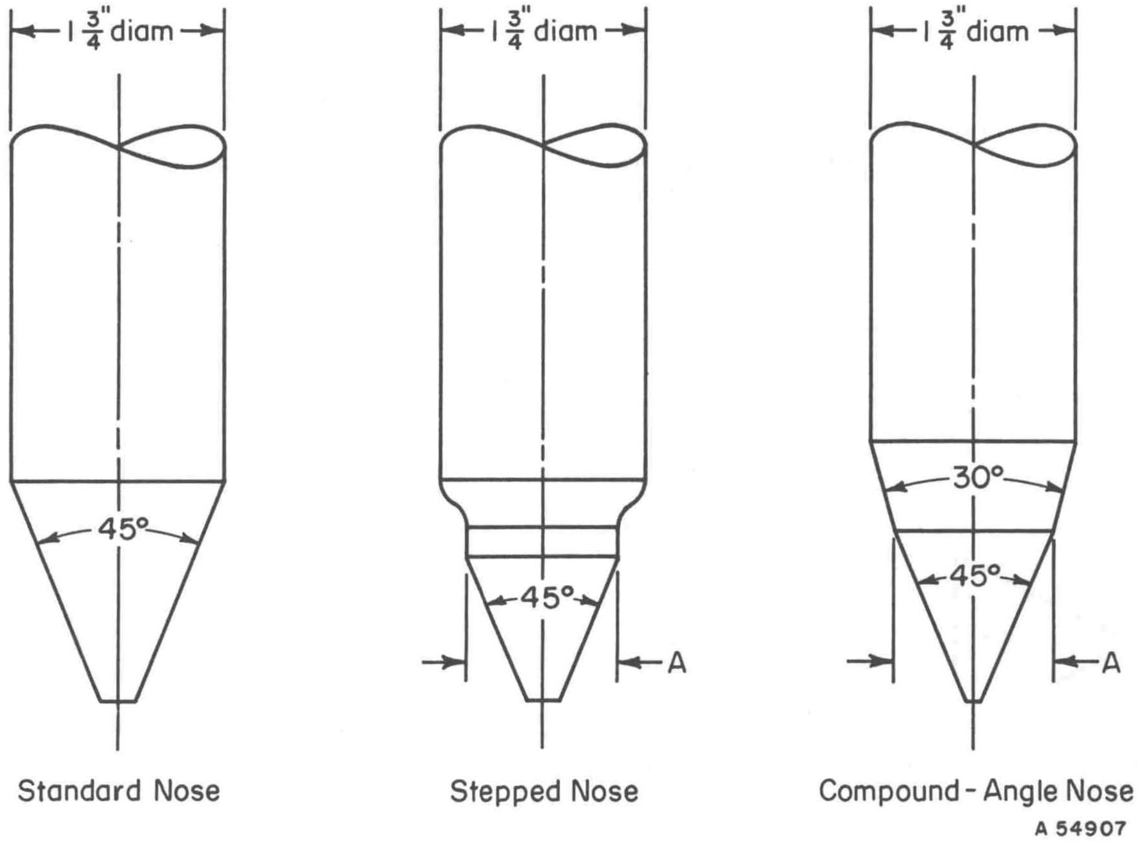

FIGURE 5. BILLET NOSE DESIGNS EVALUATED IN HYDROSTATIC EXTRUSION

(2) Elimination of a high P_b prevents the initiation of stick-slip during runout. Apparently, this is partly because "slip" from a high P_b peak occurs at such high speeds that some lubrication breakdown may occur during this time.

The compound-angle nose design will be incorporated in billets to be used in future extrusion trials where stick-slip is known to be a problem, e.g., in the extrusion of T-sections and at higher ratios with 7075 aluminum.

It is of interest to note that the compound-angle nose was evaluated in the last program(1) on 1100-0 aluminum at a ratio of 10 : 1. No pressure reduction was obtained, however, because the lubrication system used here was entirely adequate, the extrusion conditions being less severe.

Tandem Extrusion

Tandem hydrostatic extrusion (Trials 453 and 454) was carried out to determine the feasibility of stopping an extrusion, placing another billet on the back end of the first and commencing to extrude them in sequence. This technique would be desirable for a high-production operation.

The two methods of seating the second billet evaluated are shown in Figure 6. Design A is a counterbore fit and Design B is a taper connection. The extrusions were conducted at an extrusion ratio of 20:1 and stem speed of 20 ipm. Lubricant 53 and castor oil comprised the lubrication system, but the joint faces were not lubricated.

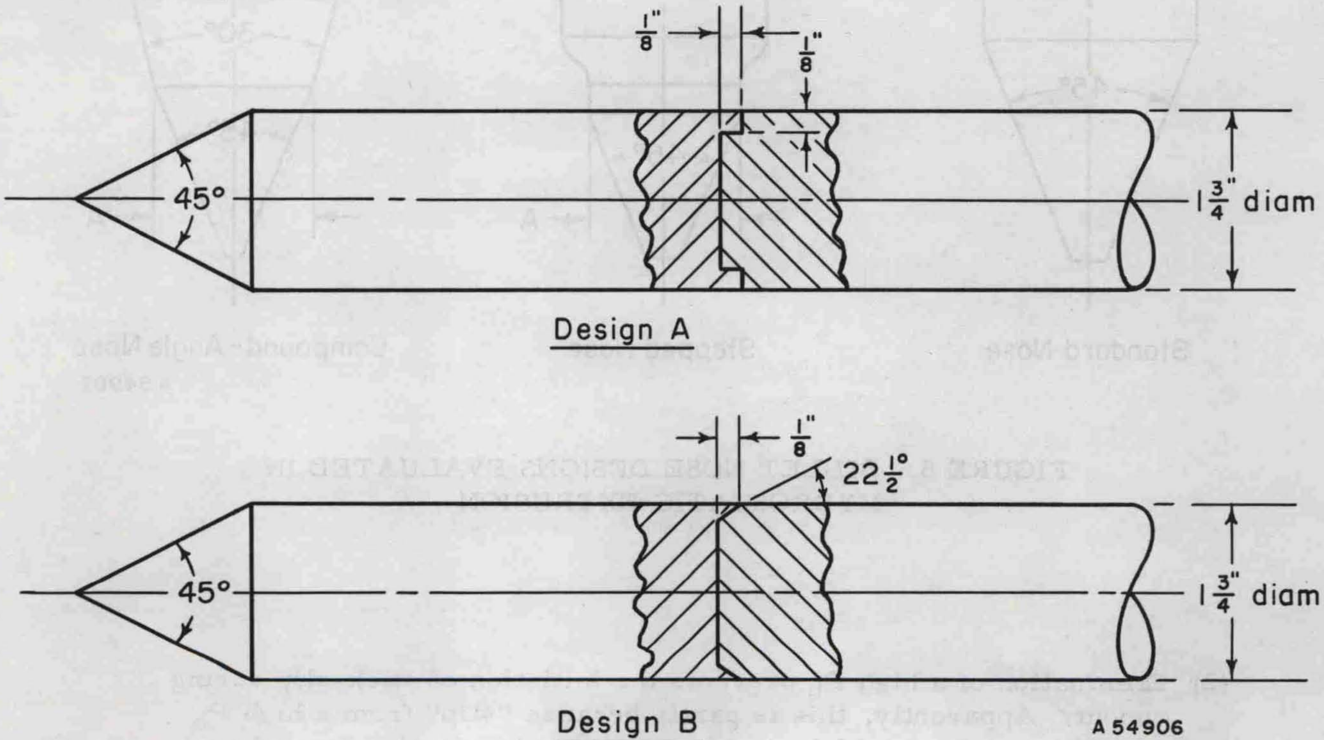

FIGURE 6. TANDEM BILLET JOINT DESIGNS EVALUATED IN HYDROSTATIC EXTRUSION

With Design A, the tandem joint extruded through the die satisfactorily without any discontinuity in the extrusion pressure curve. The shoulder in the female portion of Design A apparently gripped tightly around the mating surface and prevented the billets from separating. In contrast, with Design B, the second billet failed to extrude because of seizure in the die due to a lack of lubrication on the joint.

It is worthwhile to point out that the breakthrough pressure on restarting after stopping was, in both cases, about 43,000 psi or 32 percent higher than the pressure required for initial breakthrough. Also, it is significant that severe stick-slip occurred during runout, whereas no stick-slip occurred during runout of the first billet. In future trials, efforts will be directed toward minimizing these problems in restarting.

Other Trials

T-Sections

An attempt was made to extrude a 7075 aluminum T-section from a solid round billet at a ratio of 14.5:1 but the pressures required apparently were beyond the capacity of the tooling. The T-section die had the same configuration and overall dimensions as that used in previous trials except that the width of the arms and web of the T were reduced from 1/4 inch to 1/8 inch. This die was also used in an attempt to re-extrude T-sections obtained previously with the 1/4-inch-thick T-die but a seal was not achieved. The extrusion conditions used for the above (Trials 445 and 459) are given below:

Billet lubricant	L53
Fluid	Castor oil
Stem speed	6 ipm
Die angle	45 degrees (included)

A die specially designed for the re-extrusion of the 1/4-inch T-sections is being machined. Here, sealing of the billet is not expected to be a problem.

Low Extrusion Ratios

All previous work to date with 7075-0 aluminum solid rounds has been at ratios of 20, 40, and 60:1. The ratios at which tubing were extruded were much lower, ranging from about 4 to 12:1. Therefore, extrusions of solid rounds were made at ratios of 2.5 and 7:1 (Trials 456 and 457, Table 2) to provide data for comparison at the lower ratios. The results will be presented graphically in a later report.

Flame-Plated Dies

A die to be used at extrusion ratios of 20:1 with 7075 aluminum was "Flame-Plated"* on the billet contact surfaces with a 0.005-inch-thick coat of tungsten carbide containing 15-17 percent cobalt. The base material of the die was AISI M50 with a hardness of $55R_C$. The purpose of Flame-Plating was to provide a hard ($72R_C$), wear-resistant surface which reportedly reduces friction in some applications.

Table 2 provides the data for comparison with unplated dies for two lubricants. With Lubricant 53, Trials 453 and 454 indicate that the Flame-Plated die only marginally reduced the fluid breakthrough pressure (by 3 percent) and runout pressure was unaffected. However with L31, a relatively poorer lubricant than L53, the pressures with the Flame-Plated die (Trial 449) were marginally higher (compare with Trial 447). Thus, the Flame-Plated die does not appear to reduce friction, but may be useful for minimizing die wear in a commercial extrusion operation.

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*Flame-Plate is a proprietary process of the Union Carbide Corporation.

COLD HYDROSTATIC EXTRUSION OF AISI 4340 STEEL ROUNDS

Additional lubrication systems were evaluated for hydrostatic extrusion of AISI 4340 at a ratio of 5:1. Table 3 gives the extrusion data obtained with these systems along with that obtained with the previous "best" system to date, L17 (20 wt % MoS_2 in castor wax) and castor oil.

The three lubricants evaluated (L31, L38, and L53), gave low P_b peaks, and runout pressures were uniform at about 220,000 psi. These pressures are of the same order as those obtained with L17. Using L17 again but with silicate ester in place of castor oil, the P_b peak was eliminated completely.

A number of good lubrication systems are now available for AISI 4340. The choice of lubricant and fluid is clearly dependent upon their cost and availability.

In a single trial at an extrusion ratio of 6:1 with L17 as the billet lubricant, breakthrough was not achieved at a pressure of 246,000 psi. The purpose of this trial was to determine the feasibility of extruding at this ratio without a zinc phosphate coating (Cl) which had been used previously(1). With this coating, extrusion at a ratio of 6:1 was achieved at about 245,000 psi. However, more trials would be necessary to substantiate the necessity of the Cl coating at 6:1.

COLD HYDROSTATIC EXTRUSION OF Ti-6Al-4V TITANIUM ALLOY ROUNDS AND TUBING

The experimental data given in Table 4 describe the evaluation of several billet lubricants on both solid rounds and thin-walled tubing of Ti-6Al-4V titanium alloy.

The most notable result obtained was the production of a 4-1/2 inch length of high-quality tubing 0.663-inch OD x 0.030-inch wall (Trial 437). The tubing "billet", initially 0.069-inch wall, was extruded at a ratio of 2.4:1. The initial tube stock was produced by Wolverine Tube Company under Air Force Contract No. AF 33(615)-3089.

The lubrication used in the extrusion of the tube in this case was L17 (20 wt % MoS_2 in castor wax) on an anodized coating C3, a combination which was found to be the most successful with solid rounds(5).

During runout, increasing friction between the mandrel and the extruding tube prevented further extrusion and a continued increase in fluid pressure caused the billet to upset. It was shown in Interim Report VI(5) that the floating mandrel arrangement used here could cause billet upsetting when the billet end pressure exceeded the fluid pressure by roughly the billet's yield strength. In Trial 437, the fluid runout pressure was 77,000 psi which gave a billet end pressure of 234,000 psi. Thus, the unbalanced axial pressure on the billet end was 157,000 psi, 25,000 psi in excess of the compressive yield strength of the billet material.

With another billet Lubricant 33 (55 wt % MoS_2 and 6 wt % graphite in sodium silicate), tubing was not extruded at the same ratio and billet upsetting occurred.

TABLE 3. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION OF AISI 4340 STEEL ROUNDS

Die Angle - 45 degrees (included)
Fluid - Castor oil

Stem speed - 20 ipm

			Extrusion Pressure, 1000 psi						
			Breakthrough		Runout		Type of	Length of	
Trial	Extrusion Ratio	Billet Lubricant	Stem	Fluid	Stem	Fluid	Curve (see p 25)	Extrusion, inches	Comments
277	5	L17	240	224	240	217	B1	14	Reference Trial(4)
429	5	L38	267	230	264	218	B1	13	--
430	5	L31	266	230	262	217	B1	10	--
462	5	L53	260	225	255	221	B3	11	--
465[a]	5	L17	255	219	255	219	A1	14	--
451	6	L17	285	246	--	--	--	--	P_b not achieved

(a) Fluid used was silicate ester.

TABLE 4. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION Ti-6Al-4V ALLOY ROUNDS AND TUBING

Die Angle - 45 Degrees (included)
Fluid - Castor oil
Stem Speed - 6 ipm

Tube Dimensions
Billet - 0.750" O.D. x 0.069" wall
Extrusion - 0.663" O.D. x 0.030" wall

					Extrusion Pressure, 1000 psi						
			Billet Lubrication		Breakthrough		Runout		Type of	Length of	
Trial	Billet Type	Extrusion Ratio	Coating	Lubricant	Stem	Fluid	Stem	Fluid	Curve (see p 25)	Extrusion, inches	Comments
374	Solid Round	3.3	C3	L17	223	206	207	195	B1	9-3/4	Reference Trial(5)
450	Solid Round	3.3	C3	L31	250	222	220	196	C4	6-1/2	--
426	Solid Round	3.3	C3	L38	232	204	216	192	B4	6-1/2	--
427	Solid Round	4	C3	L33	291	245	--	--	--	--	P_b not achieved
466	Solid Round	4	C3	L31	285	250	--	--	--	--	P_b not achieved
437	Tube	2.5	C3	L17	85	79.5	85	77	B3	4-1/2	--
438	Tube	2.5	None	L33	103	94.5	--	--	--	1/2	P_b not achieved
439	Tube	2.5	C3	L33	104	98.5	--	--	--	5/8	P_b not achieved

In extrusion of solid rounds at an extrusion ratio of 3.3:1, products having good surface finishes were obtained with both L31 (fluorocarbon telomer) and L38 (PTFE). However, severe lubricant breakdown occurred after breakthrough in both cases. By comparison, L17 on C3 (see Trial 374) did not breakdown and gave a uniform pressure during runout.

At an extrusion ratio of 4:1, Lubricants 31 and 33 were evaluated. However, breakthrough was not achieved in either case by fluid pressures in the range of 245,000-250,000 psi. It is worthwhile to point out, however, that L33 was a very effective lubricant in hydrostatic extrusion of Ti-6Al-4V at 400-500 F(6) even without C3 coating. This was also true for L38 which, as mentioned above, was not effective at 3.3:1 at room temperature.

COLD HYDROSTATIC EXTRUSION OF WROUGHT TZM MOLYBDENUM ALLOY AND BERYLLIUM ROUNDS

The results obtained in several hydrostatic extrusions of TZM molybdenum alloy rounds and a single extrusion of beryllium are presented in Table 5. Both materials are discussed together because each displayed similar cracking tendencies during cold hydrostatic extrusion. In fact, crack-free extrusions at extrusion ratios greater than 2:1 of both these materials are generally obtainable only when the product is hydrostatically extruded into a fluid back-pressure chamber(7, 8); this technique is sometimes referred to as differential-pressure hydrostatic extrusion or fluid-to-fluid extrusion. An alternative method is being investigated in the current program with the aim of eliminating the complexity and limitations of a second high-pressure fluid container. This method, described below, is based on novel die design concepts.

DIE DESIGN

Figure 7 shows two die designs intended for use with materials which exhibit circumferential ("rattlesnaking" or "fir-tree") cracking or longitudinal cracking. The standard die design used is also included. The controlled-relief die was designed to effect a gradual release of the elastic stresses present in the extrusion on exit from the die land. To determine the amount of taper relief required, the elastic strain on exit was calculated based on an estimated flow strength of the extruded product. Two dies of this type were made: one for use at a ratio of 2.5:1 where the controlled relief was 10' (minutes) x 1/4-inch long (β x L in Figure 7) and the other for use at a ratio of 3.3:1 where the controlled relief was 1' 35" x 2 inches long.

It was thought that cracking might also be prevented by applying a longitudinal compressive stress to the extruded product during exit from the die. This was achieved by using a double reduction die shown schematically in Figure 7. The die was made in two pieces with six radial ports at the side which could be opened or closed to the fluid pressure in the container. This enabled the die to apply an axial compressive stress to the extrusion under two conditions. One condition is where the extrusion is surrounded by a high fluid pressure which also assists in lubrication for the second reduction; the other is where the second reduction takes place "dry", i.e., without fluid pressure.

TABLE 5. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION OF WROUGHT TZM MOLYBDENUM ALLOY AND BERYLLIUM ROUNDS

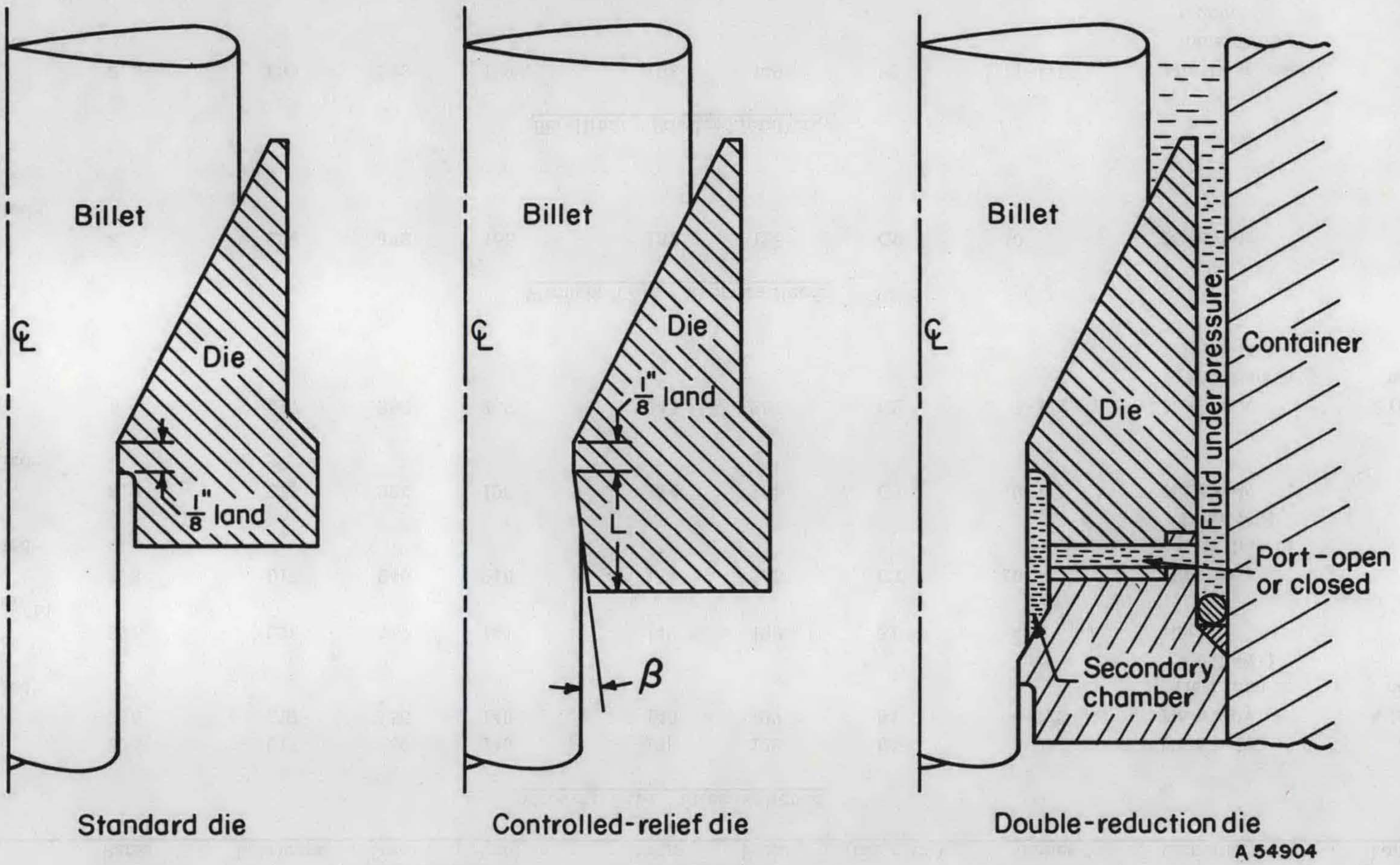
Die Angle - 45 degrees (included)
Fluid - Castor oil

Stem speed - 6 ipm

Trial	Die	Extrusion Ratio	Billet Lubricant	Extrusion Pressure, 1000 psi				Type of Curve (see p 25)	Length of Extrusion, inches	Cracks	
				Breakthrough		Runout					
				Stem	Fluid	Stem	Fluid			Circumferential	Longitudinal[a]
				Wrought TZM - Stress Relieved							
441	Standard	2.5	L17	156	140	136	122	B4	5	Nose only	3
442	Short controlled-relief	2.5	L17	156	140	140	127	B4	4-1/2	Nose only (less than in Trial 441)	4 (split open at nose)
469	Double reduction[b]	2.5	L38	157	141	142	129	B1	4	None	3
452	Long controlled-relief	3.3	L17	240	210	184	165	C1	10	Nose only (less than in Trial 442)	3
455	Long controlled-relief	3.3	L38	224	198	184	165	C2	10-1/2	Nose only	3
443	Standard	5	L17	280	237	240	207	C3	7-1/2	Nose only (less than in Trial 441)	2 (split open at nose)
				Wrought TZM - Recrystallized							
460	Long controlled-relief	3.3	L38	172	155	137	125	C2	10	Nose only	3
				Beryllium - Powder Metallurgy							
461	Long controlled-relief	3.3	L38	213	189	168	149	B2	11-1/2	Mostly at nose; some during runout	5

(a) Longitudinal cracks were generally a fine, hairline type which extended along most or all of the extruded length.

(b) Second reduction in area was 1.5 percent.



Standard die   Controlled-relief die   Double-reduction die

FIGURE 7. STANDARD-DIE PROFILE AND TWO DIES DESIGNED TO ELIMINATE CRACKING OF HYDROSTATIC EXTRUSIONS

EFFECT OF DIE DESIGN, EXTRUSION RATIO AND LUBRICANTS ON STRESS-RELIEVED TZM

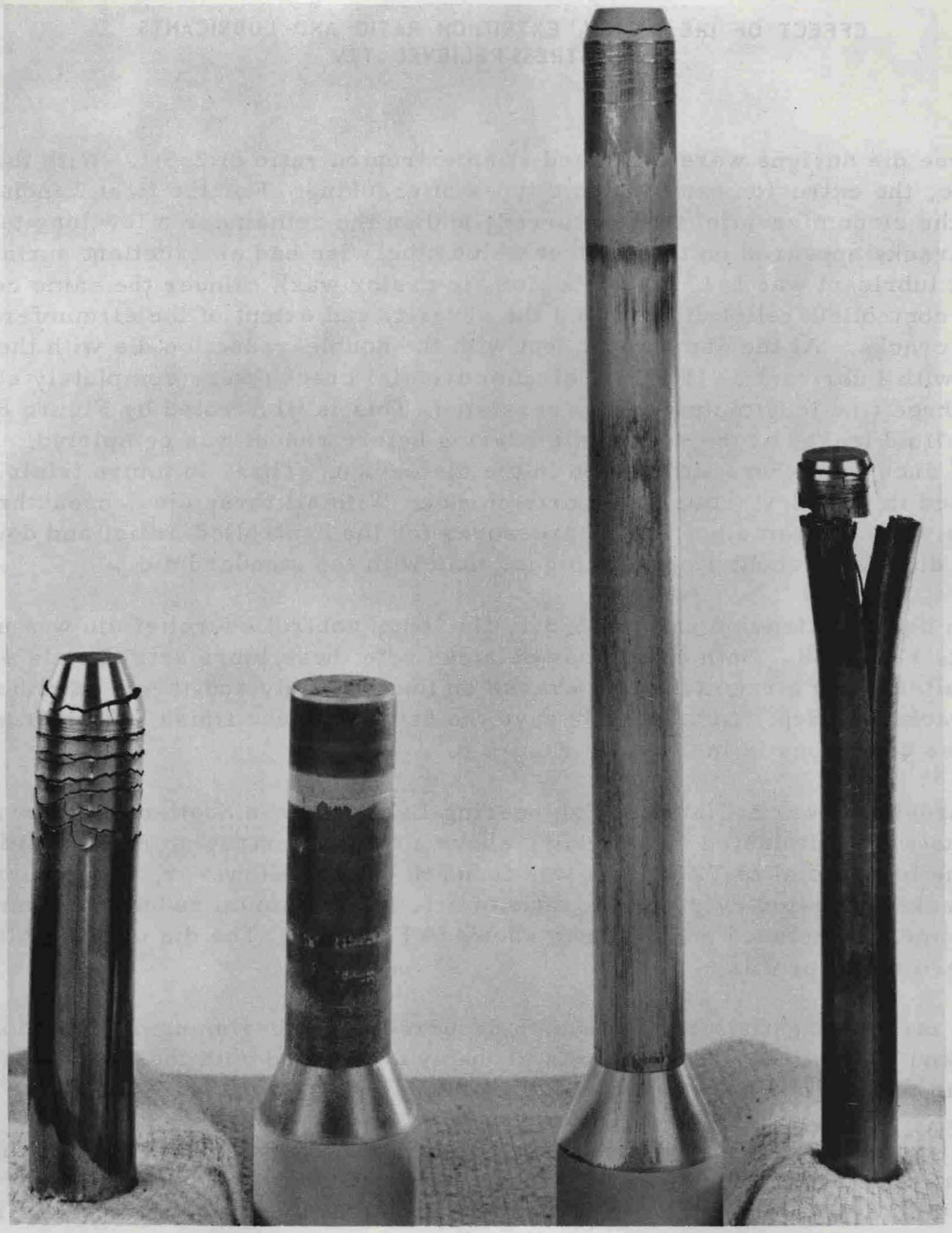
Three die designs were evaluated at an extrusion ratio of 2.5:1. With the standard profile die, the extrusion exhibited two types of cracking. For the first 2 inches of extrusion, the circumferential type occurred, and on the remainder a few longitudinal hairline cracks appeared on the product which otherwise had an excellent surface finish. The billet lubricant was L 17 (20 wt % MoS_2 in castor wax). Under the same conditions, the short controlled-relief die reduced the severity and extent of the circumferential and axial cracks. At the same ratio, but with the double-reduction die with the ports open and with Lubricant 38 (PTFE), circumferential cracks were completely eliminated although three fine longitudinal cracks persisted. This is illustrated by Figure 8. However, the fluid leaked at the second die bearing before runout was completed. The possibility of such a leak was anticipated in the die design. Thus, in future trials, the die will be used in the "dry" state with ports closed. With all three dies, breakthrough pressures were the same but runout pressures for the controlled-relief and double-reduction dies were about 4 percent higher than with the standard die.

At a higher extrusion ratio of 3.3:1, the long, controlled-relief die was used with Lubricants 17 and 38. Both extrusions obtained with these lubricants (Trials 452 and 455) exhibited a few circumferential cracks on the nose only and three hairline longitudinal cracks on each. Lubricant 38 gave the better surface finish. An extrusion made under these conditions is included in Figure 8.

In previous work at National Engineering Laboratory in Scotland(8), it was reported that cracks were eliminated by extruding above a critical extrusion ratio. With molybdenum, the base metal of TZM, this was found to be 3:1. However, in the current program, cracks persisted even up to a ratio of 5:1, the maximum reduction attempted. This specimen is included among those shown in Figure 8. The die used in this case had the standard relief profile.

The circumferential cracking which occurred at the beginning of extrusion with the standard and controlled-relief dies was probably associated with the lower extrusion ratio achieved in the tapered nose of the billet.

The extrusion pressure data obtained so far with the wrought TZM molybdenum alloy is presented in Figure 9. Even though conditions were varied somewhat, an approximate and tentative relationship can be drawn between extrusion ratio and fluid runout pressure. It is of interest to point out that the pressure requirements appear to be roughly the same as those for cold hydrostatic extrusion of AISI 4340 steel.



Trial	441	469	455	443
Extrusion Ratio	2.5	2.5	3.3	5
Billet Lubricant	L17	L38	L38	L17
Die	Standard	Double reduction	Long controlled-relief	Standard

FIGURE 8. INFLUENCE OF DIE DESIGN AND EXTRUSION RATIO ON CRACKING OF HYDROSTATIC EXTRUSIONS OF WROUGHT TZM MOLYBDENUM ALLOY

Specimens from Trials 455 and 469 are shown as extruded without the lubricant removed.

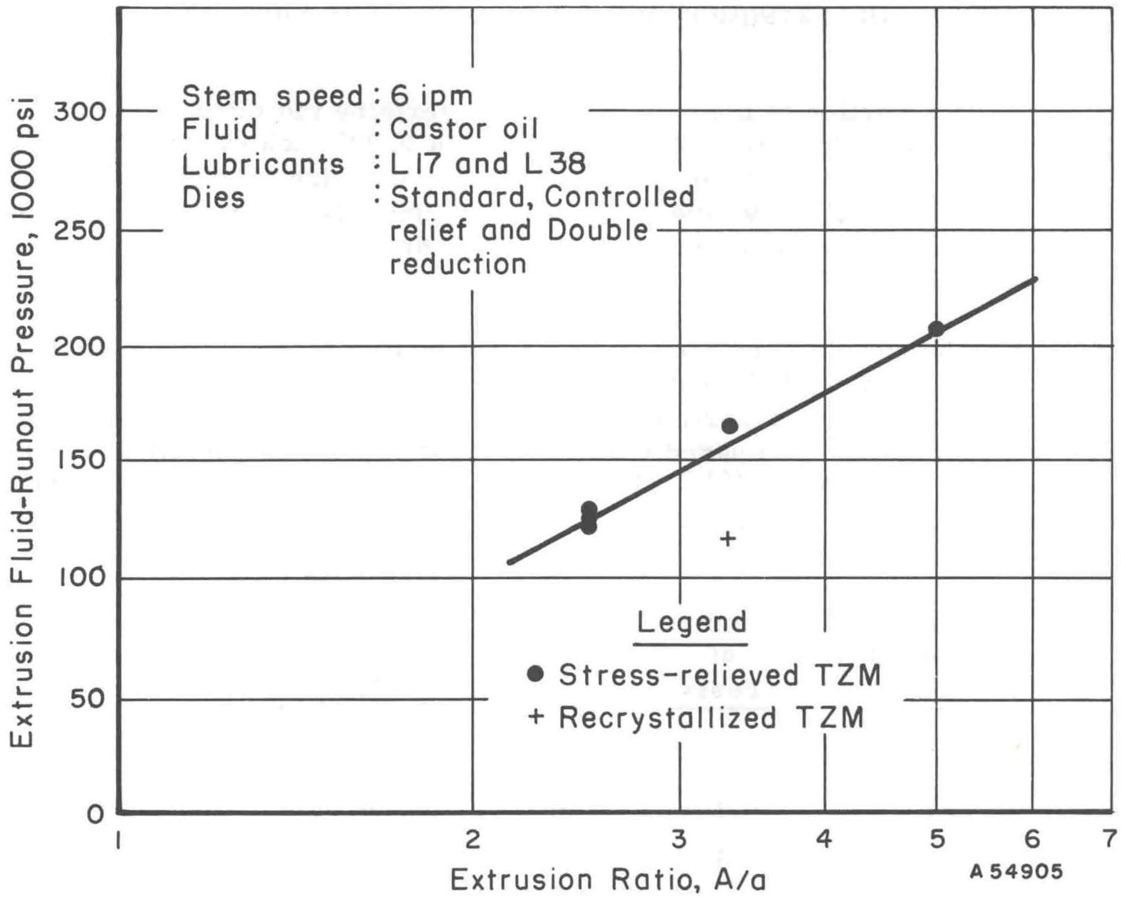


FIGURE 9. THE INFLUENCE OF EXTRUSION RATIO ON THE EXTRUSION FLUID-RUNOUT PRESSURE FOR WROUGHT TZM MOLYBDENUM ALLOY

EXTRUSION OF RECRYSTALLIZED TZM AND BERYLLIUM

Both recrystallized TZM molybdenum alloy and beryllium were extruded at an extrusion ratio of 3.3:1 with the long controlled-relief die (Trials 460 and 461). Lubricant 38 (PTFE) was applied to both billets. The data are given in Table 5.

The extruded product of recrystallized TZM was similar to that obtained with stress-relieved TZM in that a few circumferential cracks at the very beginning were followed by three longitudinal hairline cracks. The extrusion runout pressure with the recrystallized material, however, was 12 percent lower.

In the extrusion of beryllium, a very considerable reduction in the number and severity of circumferential and longitudinal cracks was obtained in comparison with that obtained at a lower ratio with the short controlled-relief die. The improvement is believed to be attributed to both the longer-relief die design and the higher extrusion ratio.

The overall results obtained thus far with dies designed to minimize cracking are quite encouraging. Further die modifications and changes in extrusion conditions will be made with the aim of eliminating cracking completely.

HYDROSTATIC EXTRUSION AND DRAWING OF BERYLLIUM WIRE

The aim of this portion of the program is to determine the technical feasibility of producing beryllium wire down to a target diameter of 0.001 inch by hydrostatic extrusion and drawing. In this Battelle-developed process, the wire is subjected to hydrostatic fluid pressure on the entry side of the die and controlled draw stress on the exit side. The equipment for exerting and monitoring the draw stress on the wire was described in Interim Report VII(6).

The starting beryllium wire used in the initial trials originated from cast-ingot material. It was in the annealed condition and had a nominal diameter of 0.020 inch. A microscopic examination of a portion of the starting material revealed that it is relatively free from inclusions compared with other ingot or powder-metallurgy wire on hand to be drawn in this program(6). The lower inclusion content may have contributed to the ductility of the material. Average data from tensile trials are given below:

Distance Between Grips, inches	Extensometer Gage Length, inch	Number of Tests	Ultimate Strength, 1000 psi	0.2% Yield Strength, 1000 psi	Elong., %	Reduction in Area, %
2	1	4	88.6	49.5	6.8	6.7
2	(a)	4	88.2	47.3	9.0	7.7
10	(a)	5	80.6	47.3	5.5	7.8

(a) Extensometer not used.

As mentioned in the previous Interim Report(6), attempts to extrude and draw the annealed ingot wire indicated that pressure requirements were excessive for an area reduction of 60 percent. For the 0.020-inch-diameter wire, a 200,000 psi fluid pressure plus an external draw stress of up to 20,000 psi were found to be inadequate for 60 percent reduction, whereas only 150,000 psi fluid pressure alone was required to extrude 1-3/4-inch-diameter billet at a 70 percent reduction. While it was considered that die angles smaller than those specified contributed to the high pressures needed for wire, preliminary trials with soft copper wire and experience with other materials have indicated that there is a "size effect" in extrusion. That is, the total energy required to reduce a billet or wire a given amount increases as the starting billet or wire diameter decreases. This is believed to be associated with the greater surface area to volume ratio for a given reduction as the billet diameter decreases. In view of this, such factors as die bearing length, entry angle, and lubrication will play an even more important part in keeping the extrusion pressure plus draw stress (P + D) requirements to a minimum.

In subsequent trials, an attempt to extrude and draw beryllium wire at about 25 percent reduction was successful. Data for the production of a 5-foot length of wire is given below:

Wire diameter:	
Starting	0.019 inch
Finishing	0.0165 inch
Reduction	24.4 percent
Die angle	45 degrees (included)
Lubricant	L38 (PTFE)
Fluid	Castor oil
Fluid pressure	114,000 psi
Draw stress	2,350 psi

It is seen that the total fluid pressure plus draw stress (P + D) required for wire breakthrough was about 116,000 psi. However, after only a short length was produced, the wire broke on bending through 90 degrees round a three-inch-diameter pulley. The remaining coil of wire in the container continued to freely extrude at 114,000 psi for a short period. In subsequent handling of the extruded product, the wire was found to be extremely brittle (which perhaps explains why it broke initially on bending around the pulley). The wire surface was examined stereoscopically at low power and was found to contain short, periodic, circumferential cracks. The wire will be examined microscopically to obtain more information about the nature of these cracks.

In view of the results obtained at the low reduction of 25 percent, consideration was given to warm extrusion-drawing at a higher reduction. To avoid heating the container, fluid, and wire, a simple technique was utilized. This was to pass a current from a 12-volt battery through the wire and heat it on the exit side of the die by its electrical resistance. By this technique, it was believed that sufficient heat would be conducted to the wire in the area of deformation to reduce its flow strength and perhaps improve its ductility by introducing prismatic slip.

Using this technique a short length of wire produced at 55 percent reduction was obtained. The fluid pressure here was 150,000 psi and the draw stress 10,000 psi. Even after microscopic examination, no evidence of defects due to extrusion could be seen in the product. The temperature of the exit wire during extrusion was not determined because it was difficult to instrument satisfactorily. However, the technique showed promise as a method of heating the wire without heating the whole of the tooling. Other methods of applying heat to the wire will also be considered.

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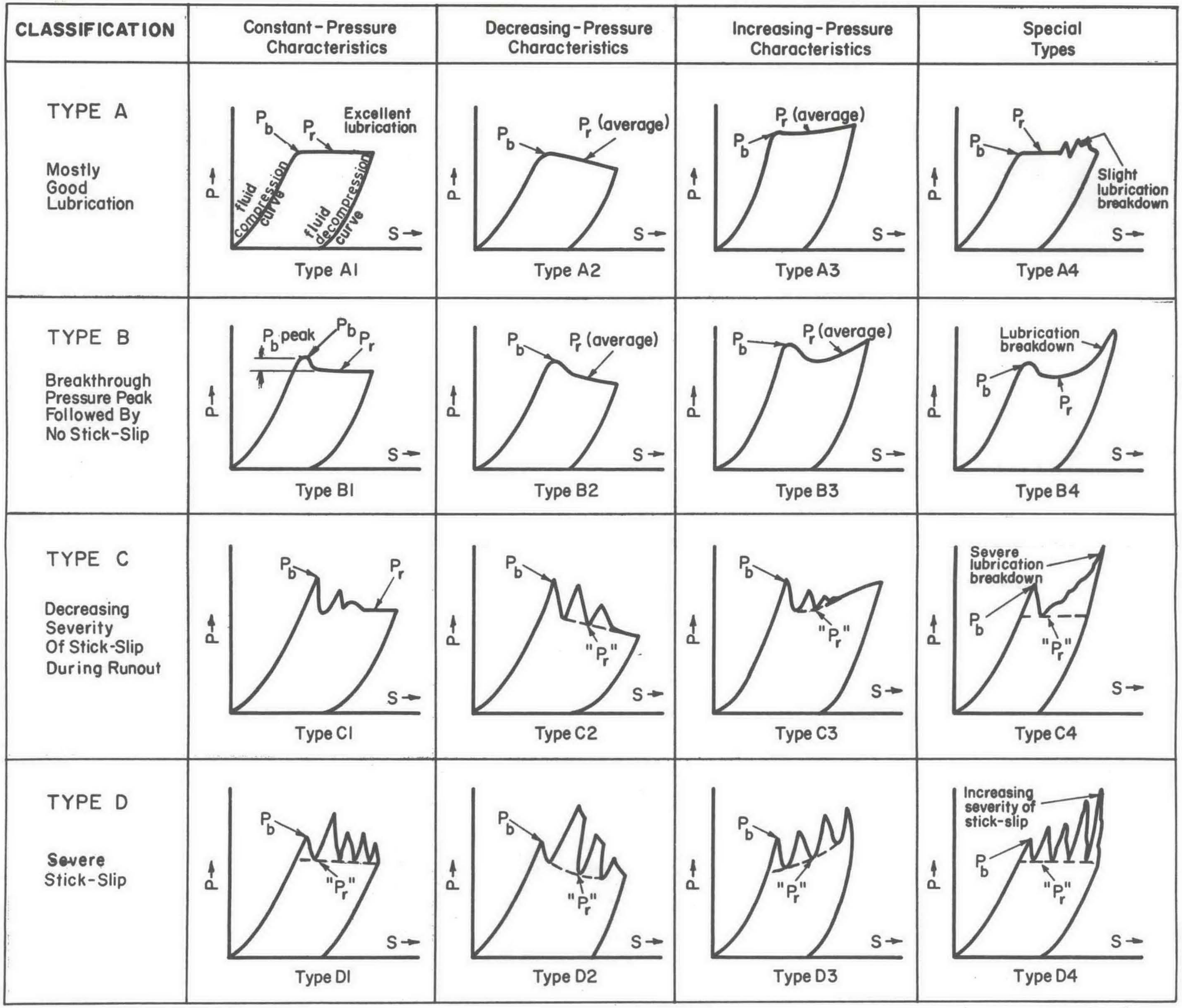

FIGURE 2. CLASSIFICATION OF PRESSURE – DISPLACEMENT CURVES OBTAINED IN HYDROSTATIC EXTRUSION

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