SECTION 2

PRODUCTION ASPECTS OF HYDROSTATIC EXTRUSION

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XIV

SUMMARY OF SECTION 2

The aim of this portion of the program was to apply the technology of hydrostatic extrusion to products other than round bars and to consider some of the problems involved in high rates of production using the hydrostatic extrusion process. Products selected for study were tubing, T-sections, and round wire.

High-quality thin-walled tubing was produced from 7075-O Al, AISI 4340, and Ti-6Al-4V alloy. In the case of the 7075-O Al and steel, two sequential reductions with in-process anneals were required to achieve 98 and 91 percent reductions, respectively. A single pass reduction of 60 percent was achieved with the Ti-6Al-4V alloy tubing. It reduced the wall thickness of the tubing from 0.069 to 0.030 inch.

T-sections were produced from round billets of 7075-O Al and AISI 4340 and from previously extruded T-sections of 7075-O Al, Ti-6Al-4V, and Cb 752 alloy. The die designs used for those operations are considered significant developments.

The HYDRAW operation, which is described in detail, was used for extruding T-shaped billets of the 7075-O aluminum alloy.

The HYDRAW process was applied to the reduction of wire from beryllium, Ti-6Al-4V, and TZM alloy with which single-pass area reductions of up to 60 percent were achieved.

Consideration was given to tandem hydrostatic extrusion (extrusion of two billets in sequence). A successful joint design for use with this technique is described.

The economics of hydrostatic extrusion were analyzed on the basis of producing rounds from or variety of materials and tubing from Ti-6Al-4V alloy. The results of the analysis show that the hydrostatic extrustion process can be very competitive with conventional techniques.

XV

HYDROSTATIC EXTRUSION OF TUBING

Tooling

The arrangement of the mandrel tooling used for extruding tubular billets to reduce their wall thickness is shown in Figure 27. A floating rather than fixed-type mandrel was used. It was anchored at the top end by a guide which rested on the top of the billet and had a sliding fit in the container bore. The fluid was free to flow past the mandrel guide to surround the billet but the flat interface between the billet and the mandrel guide acted as a seal to prevent fluid leaking past the mandrel. As the billet extruded, the mandrel and guide moved with it. The mandrel was slightly tapered to reduce frictional drag on the tubing as it was extruded over the mandrel.

Effect of Floating-Mandrel Arrangement

It can be seen in Figure 27 that in addition to the effect of fluid pressure, the billet also supports the fluid pressure acting on the mandrel so that the pressure on the billet-end exceeds the fluid pressure, P, by

$$\frac{PA_m}{A},$$

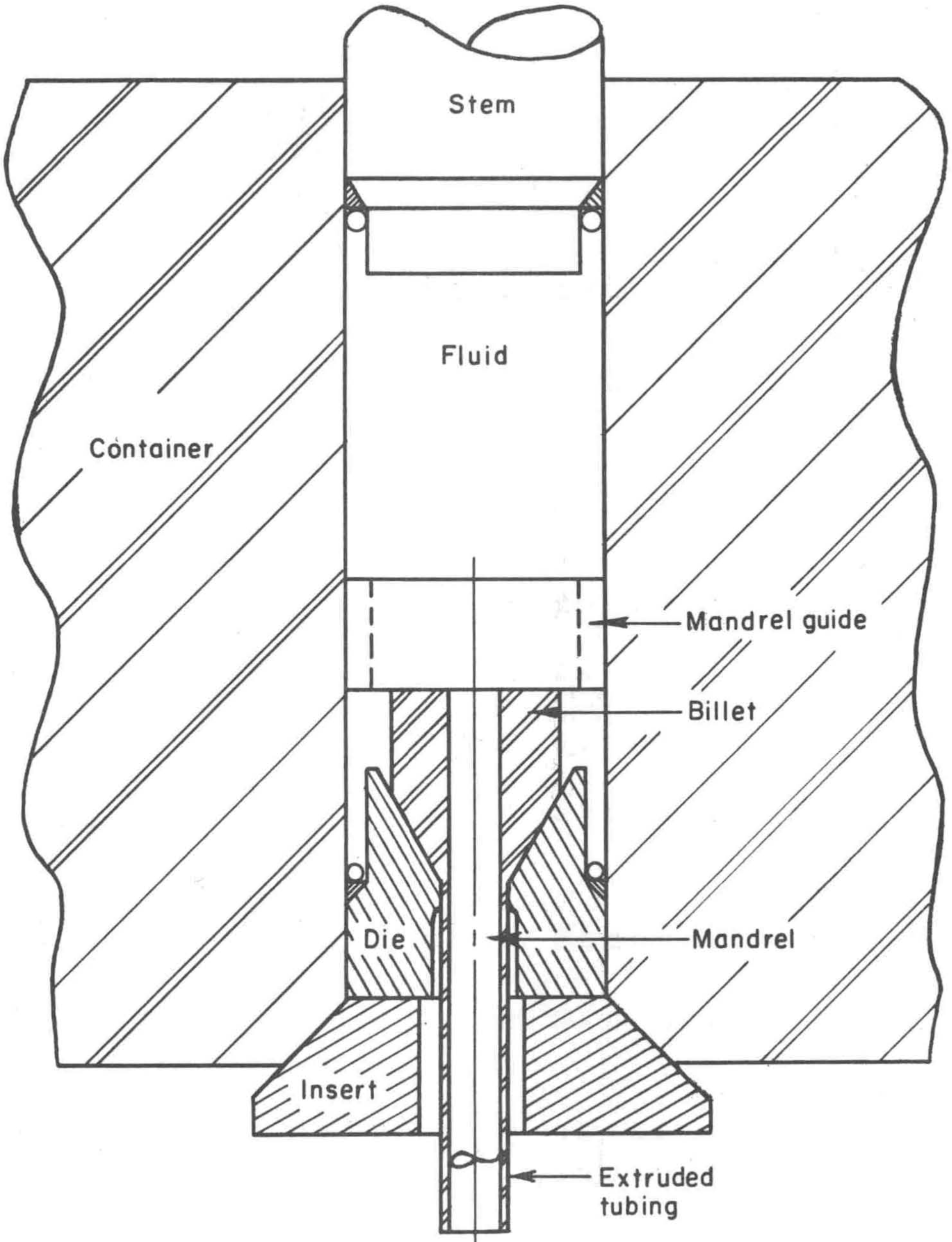
where

A_m = mandrel cross-sectional area

A = billet cross-sectional area.

It is the magnitude of the billet-end pressure, $P + \frac{PA_m}{A}$, that effects extrusion and consequently, this value is presented with the experimental data for evaluation purposes. Table XXIX gives the data obtained in the extrusion of tubes of 7075-O aluminum, AISI 4340 steel, and Ti-6Al-4V alloy. With each of these alloys, good quality thin-walled tubing was obtained at ratios close to the maximum ratios reported in Section 1 for solid rounds of the same materials. If the mandrel friction coefficient is high, then the billet end pressure may be further increased. The frictional drag of the extruded tube over the mandrel will exert an axial force on the mandrel which is borne by the tube billet.

It is difficult to predict the maximum extrusion ratios achievable in the hydrostatic extrusion of tubing using the floating-mandrel arrangement because of the possibility of billet upsetting due to the effect of the additional or "unbalanced" billet-end-pressure. The magnitude of this pressure, $\frac{PA_m}{A}$, is clearly dependent on the dimensions of the tube blank to be extruded. However, the extra billet-end-pressure produced by the mandrel enables extrusion to take place at a lower fluid pressure level than would be required for a solid billet at a given ratio. This is particularly significant for thin-walled tubing where the end pressure might be several times higher than the fluid



$$\text{Total pressure on end of billet} = \frac{p(A + A_m)}{A} = p + \frac{p A_m}{A}$$

where
p = fluid pressure
A_m = area of mandrel
A = area of billet

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FIGURE 27. FLOATING MANDREL ARRANGEMENT FOR HYDROSTATIC EXTRUSION OF TUBING

Analysis Is Given Showing Difference Between Fluid Pressure and Billet End Pressure

TABLE XXIX. EXPERIMENTAL DATA FOR 80 F HYDROSTATIC EXTRUSION OF TUBING FROM 7075-O Al, AISI 4340, AND Ti-6Al-4V

Die Angle - 45 degrees (included)   Fluid - Castor oil   Billet surface finish - 60 to 120 microinches

ial	Nominal Extrusion Ratio	Outside Diameter, inches		Mandrel Dimensions		Stem Speed, ipm	Billet Lubricant (Listed in Table 3)	Extrusion Pressure, 1000 psi				Billet-End Pressure(b), 1000 psi	Type of Curve (Fig. 26)	Length of Extrusion, inches	Comments
				Diameter, inch (max)	Taper, inch/inch on diameter(a)			Breakthrough		Runout					
		Billet	Extrusion					Stem	Fluid	Stem	Fluid				
							7075-O Aluminum								
3	1.86	1.107	0.959	0.749	0.0011	20	L17	20	19	20	19	35	A1	4.5	
5(c)	3.2	1.104	0.782	0.749	0.0011	20	L17	33	30	32	29	53	D1	7.0	
1	3.8	1.750	1.107	0.749	0.0003	20	L17	50	49	48	47	58	A4	9.0	
3	3.8	1.750	1.107	0.749	0.0003	20	L17	48	49	48	48	59	A1	14.0	
1	3.8	1.750	1.107	0.749	0.0011	20	L17	49	51	48	50	61	A1	13.0	
8	3.8	1.750	1.107	0.749	0.0011	20	L48	49	48	50	48	59	A1	13.0	
5	3.8	1.750	1.107	0.749	0.0011	20	L52	51	49	48	47	58	A1	11.0	
9	7.0	1.750	0.959	0.749	0.0011	20	L17	78	75	73	71	86	D1	18.0	
5	12.2	1.750	0.875	0.749	0.0003	1	L17	135	127	99	93	114	D1	48.0	
2	12.2	1.750	0.875	0.749	0.0003	6	L17	121	115	98	87	106	D4	42.0	
4	12.2	1.750	0.875	0.749	0.0003	20	L17	118	109	100	89	109	D1	36.0	
0	12.2	1.750	0.875	0.749	0.0011	80	L17	112	107	96	97	119	D2	28.0	
4(c)	12.9	1.107	0.782	0.749	0.0011	20	L17	178	161	--	--	297	--	4.0	Billet upsetti occurred at breakthroug
							AISI 4340								
2	2.6	1.750	1.240	0.749	0.0011	6	L17	112	109	105	105	128	B1	8.0	
6	3.8	1.750	1.107	0.749	0.0003	6	L17	174	158	179	155	190	B4	9.5	
3	3.8	1.750	1.107	0.749	0.0011	6	L17	166	159	162	154	189	B3	7.0	
4	3.8	1.750	1.107	0.749	0.0011	6	L48	170	160	164	154	189	B1	10.0	
5	3.8	1.750	1.107	0.749	0.0011	20	L48	169	160	165	154	189	B1	11.0	
9	3.8	1.750	1.107	0.749	0.0011	20	L48	162	150	160	147	180	B1	13.0	
1	5.7	1.750	1.001	0.749	0.0011	6	L48	240	209	232	202	247	D3	6.0	
7	7.0	1.750	0.959	0.749	0.0011	6	L48	280	249	--	--	--	--	--	P_b not achie

386(d)	3.2	1.107	0.875	0.749	0.0011	6	L48	125	116	120	112	206	C4	1.5	Nose only extruded
390(d)	3.2	1.107	0.875	0.749	0.0011	20	L48	164	149	146	129	238	C4	5.0	
							Ti-6Al-4V								
437	2.9(e)	0.750	0.663	0.613	0.0012	6	C3-L17	85	79.5	85	77	234	C4	5.0	
438	2.9	0.750	0.663	0.613	0.0012	6	L33 only	103	95	--	--	--	--	--	P_b not achieved
439	2.9	0.750	0.663	0.613	0.0012	6	C3-L33	104	99	--	--	--	--	--	P_b not achieved
485	2.9	0.750	0.663	0.613	0.002	20	C2-L17	84	79	81	78	237	C4	10.0	
506	2.7	0.750	0.663	0.606	0.0008	20	C3-L17	85	75	84	74	212	C4	6.5	
517(f)	1.8	0.663	0.635	0.606	0.0008	20	C3-L17	37	39	--	--	237	--	--	P_b not achieved Tube billet split

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(a) Mandrel was 8 inches long.

(b) Billet-end pressure calculated from fluid runout pressure except when billet upsetting occurs; here the maximum fluid pressure is used.

(c) Reextrusion of tubing produced in Trial 351 annealed to 65 BHN.

(d) Reextrusion of tubing produced in Trial 355 and 354 without an intermediate anneal.

(e) For thin-wall tubing, ratio is nominal; ratio varied slightly over tube length because mandrel was tapered.

(f) Reextrusion of tube from Trial 485 without anneal.

pressure itself. This was the case with the Ti-6Al-4V tubing where only a 75,000 psi **fluid pressure** was required to extrude at a ratio of 2.7:1, whereas about 200,000 psi **is** required for solid rounds at the same ratio.

7075-O Aluminum Tubing

Extrusion Ratio

The fluid pressures, at runout, for hydrostatic extrusion of 7075-O Al tubing at various ratios and two tube blank sizes are plotted in Figure 28. The chart also shows (1) billet end-pressures (determined from $P + PA_m/A$) developed at corresponding fluid runout pressures and (2) fluid runout pressure for extrusion of solid rounds of 7075-O Al. It is interesting that the points plotted for billet-end-pressure almost fall on the line representing runout pressure requirements for solid rounds. The fact that the pressure requirements are quite similar for rounds and tubing indicates that the mandrel friction was low for this material under the conditions employed. It is well to point out that with the floating mandrel arrangement, relative motion (and hence friction) between the billet and mandrel only occurs in the billet deformation zone and beyond. In a fixed-mandrel arrangement, friction would occur over the entire length of mandrel, unless it were possible to provide relief on the mandrel.

The advantage of using the floating-mandrel arrangement is seen by the fluid pressure requirements for tubing on the two lower curves in Figure 28. These curves are specifically for the tube blank sizes indicated. The difference in pressure between the fluid pressure curve for tubing and the diverging billet-end-pressure curve, represents the additional end-pressure due to the 3/4-inch-diameter floating mandrel. For a given tube blank size, as extrusion ratio is increased, so does the additional end-pressure simply because of the greater fluid pressures required at the higher ratios.

At a ratio of about 13:1 (Trial 384), the unbalanced pressure was sufficiently high to cause billet upsetting due to the high axial compressive stress, rather than to effect extrusion. Nevertheless, about 4 inches of thin-walled high-quality tubing was produced. The additional end-pressure is estimated to be about 55,000 psi based on the measured difference between the appropriate curves in Figure 28. The yield strength in compression of 7075-O aluminum is approximately 18,000 psi. Because a short length of tube was produced before upsetting occurred, a ratio of 13:1 is believed to be close to the threshold condition where billet upsetting will commence. (For other billet and extrusion dimensions, the critical ratio will be different.) Whereas billet upsetting would not occur with a fixed mandrel arrangement, such as one connected directly to the ram, the pressure requirements would be higher.

Lubrication

Except for two trials, billet Lubricant L17 was applied to the OD and bore of all the 7075-O aluminum tube blanks. Data in Table XXIX indicates that, at extrusion ratios below 4:1, the lubricant worked well and tubing of excellent surface quality was produced. Above this ratio, stick-slip occurred and the finish was good only on the portions of product produced during the slip portions of the stem stroke. In the two trials where lubrication was varied (Trials 388 and 425), neither pressures nor finishes were better than those obtained using L17.

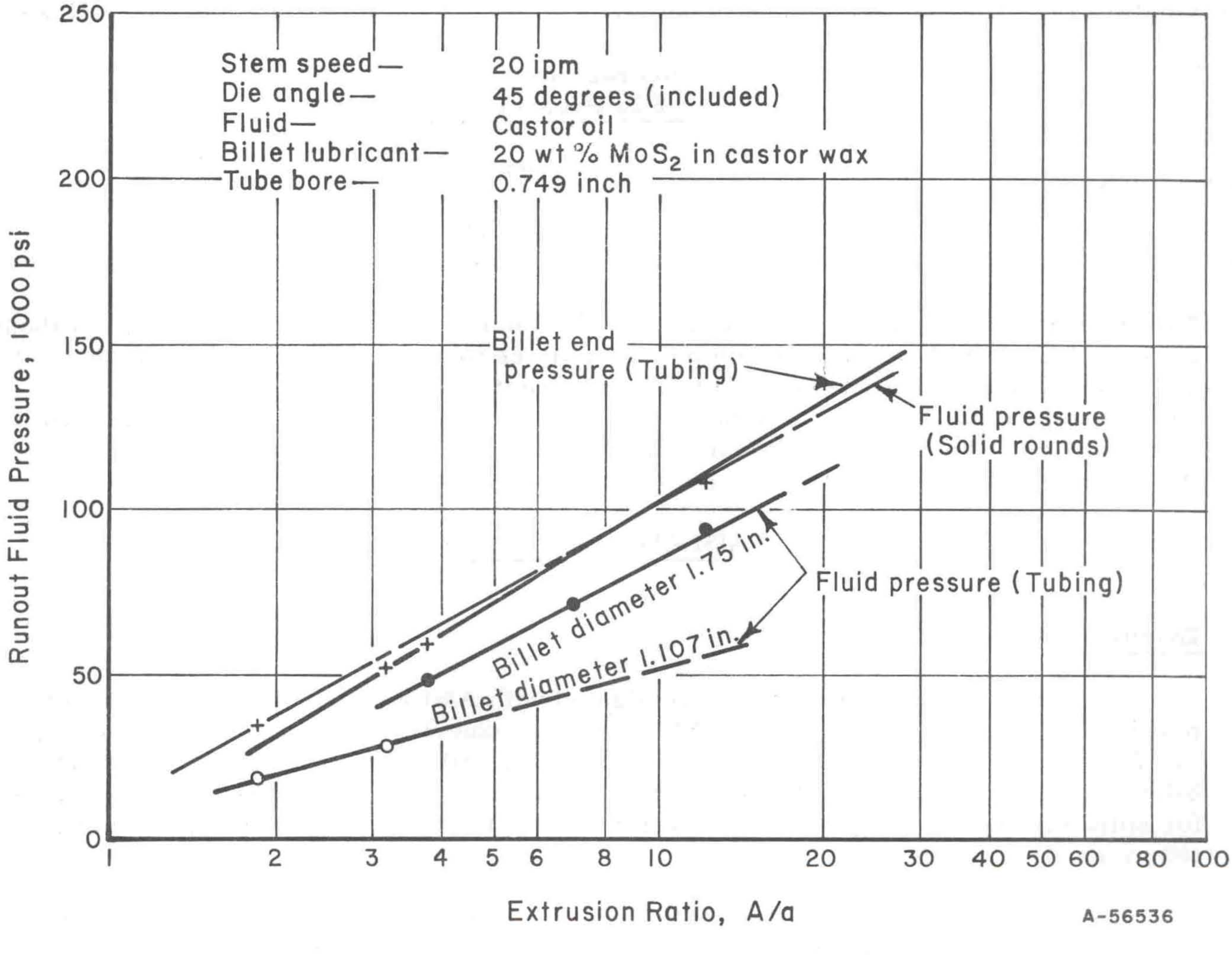


FIGURE 28. EFFECT OF EXTRUSION RATIO ON PRESSURE FOR COLD HYDROSTATIC EXTRUSION OF 7075-O ALUMINUM TUBING AND ROUNDS

Effect of Stem Speed

At a ratio of 12.2:1, where severe stick-slip was found to occur on runout, stem speeds over a range of 1-80 ipm were investigated with the aim of obtaining smooth runouts. In the extrusion of 7075-O solid rounds it was found that stick-slip on runout could be eliminated by increasing stem speed. The data in Table XXIX for Trials 332, 334, 335, and 350 indicate that stick-slip occurred even at the highest stem speed of 80 ipm. That stem speed produced an extrusion exit speed of 173 fpm. However, the amplitude of stick-slip was found to decrease with increases in stem speed as follows:

Stem Speed, ipm	Average Amplitude of Stick-Slip Pressure Cycles, psi
1	49,000
6	42,000
20	33,000
80	15,000

This indicated that a higher stem speed resulted in more efficient lubrication. Perhaps the techniques and lubricants developed later in the program, such as the compound angle nose and the stearyl-stearate based lubricants, which were so successful with 7075-O solid rounds, would eliminate the stick-slip tendency and perhaps even permit higher ratios to be achieved without billet upsetting.

AISI 4340 Steel Tubing

Extrusion Ratio

The range in extrusion ratio investigated with AISI 4340 steel tubing at room temperature was 2.6 to 5.7:1. Table XXIX gives the experimental data obtained and Figure 29 compares pressure requirements for tubing with those for solid rounds. The billet-end-pressures for tubing were about six percent higher than the fluid pressures for solid rounds. The higher pressure requirements for extruding tubing were attributed to mandrel friction.

Again, the advantage of the floating-mandrel arrangement is seen in the lower fluid pressures required for a given ratio compared with those required for solid rounds. Within the 250,000 fluid pressure capacity of the tooling, it is estimated from Figure 29 that a ratio of 8:1 should be possible, assuming adequate lubrication can be maintained. (This represents a single-pass tube wall reduction from 0.500 inch to 0.17 inch for a tube with a 3/4-inch bore tube.) In a single attempt to extrude tubing at a ratio of 7:1 (Trial 357), however, breakthrough was not achieved at a fluid pressure of 250,000 psi. Probably the billet lubrication broke down in this case since, even at the lower ratio of 5.7:1, some lubrication breakdown occurred on runout causing stick-slip to occur.

Lubrication

Two billet lubricants were evaluated for tubing, L17 and L48. Both lubricants provided good lubrication at a ratio of 3.8:1. The products obtained at this extrusion

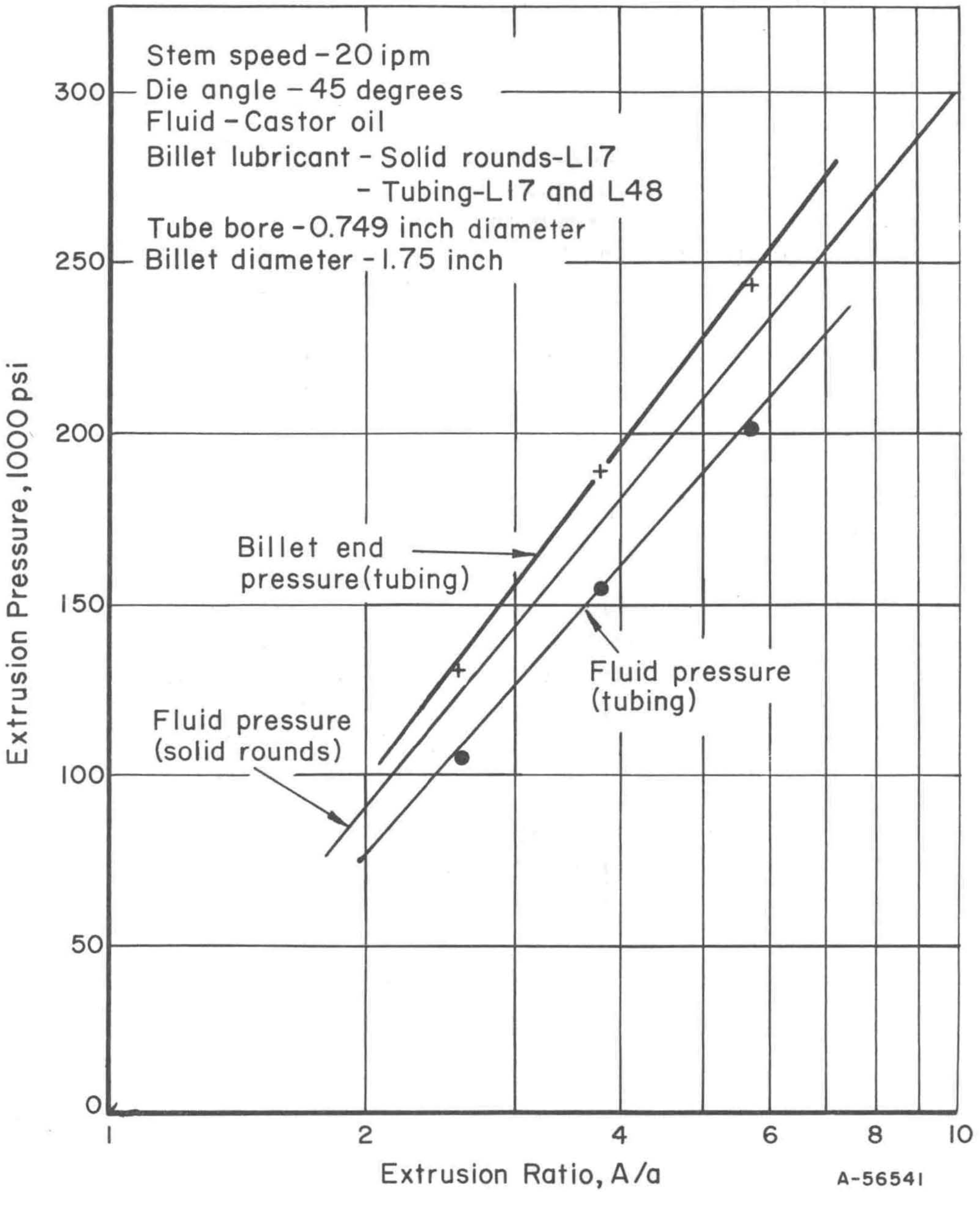


FIGURE 29. EFFECT OF EXTRUSION RATIO ON PRESSURE FOR COLD HYDROSTATIC EXTRUSION OF AISI 4340 TUBING AND ROUNDS

ratio had an excellent surface finish. Lubricant L48 was a modification of L17 (20 wt percent MoS_2 in castor wax), to which lead, copper, and graphite were added. These additions were intended to minimize friction on the billet and mandrel at the higher ratios. This modification did not, however, prevent momentary seizure at the ratios of 5.7 and 7:1 where lubrication breakdown apparently occurred. Despite this occurrence, at 5.7:1 the extruded product finish was quite good.

Effect of Mandrel Taper

In Trial 336, the runout pressure was uniform at first, indicating that lubrication was good. Towards the end of extrusion, the runout pressure began to rise continually without any evidence of stick-slip. Examination of the extrusion after disassembly revealed that the pressure rise was due to excessive frictional drag of the tubing over the mandrel. Consequently, the taper on the mandrel was increased for the remaining trials with AISI 4340 from 0.0003 in./in. to 0.0011 in./in. on diameter, to provide greater clearance between it and the extruded tubing. With this modification, no further problems arose.

Re-Extrusion of As-Extruded Tubing

In Trials 386 and 390, tubing which had been extruded previously by the hydrostatic process was further reduced in size without an intermediate anneal. The extrusion ratio was 3.2:1 which gave a total accumulative reduction of 92 percent and final wall thickness of 0.063 inch. In one trial at 6 ipm (Trial 386), only about 1-1/2 inches were extruded. However, at 20 ipm (Trial 390), a 4-3/4 inch length of tubing was produced. In both cases, lubrication breakdown occurred, which resulted in rapidly rising pressures and a scored product. It is possible that this problem may be overcome with further improvements in lubrication and perhaps mandrel design.

However, it is still quite significant that AISI 4340 tubing can be reduced 92 percent in just two passes without in-process anneals. The hardness levels obtained by hydrostatic extrusion are as follows:

	Tube Blank	Extruded Tubing	
Accumulative Reduction, percent	0	74	92
Hardness, R_C	11	31	39

Ti-6Al-4V Titanium Alloy Tubing

The experimental data given in Table XXIX describe the results obtained in reducing Ti-6Al-4V tube to extremely thin-walled tubing of excellent surface quality. The tube blank of 0.750-inch OD x 0.069-inch wall was produced by Wolverine Tube Company under Air Force Contract No. AF 33(615)-3089. It was hydrostatically extruded at a ratio of about 2.7:1 to a 0.663 OD x 0.030-inch wall tube.

In the reduction of this thin-walled tube, several interesting features were revealed. The extrusion conditions chosen happened to coincide with the threshold condition at which billet upsetting occurred. Consequently, it was possible to determine from these trials the parameters controlling extrusion of this alloy using the floating-mandrel arrangement.

Extrusion Ratio

Figure 30 summarizes the pressure data obtained at the nominal extrusion ratios of 2.7 and 2.5:1. Because the tubing billet was thin-walled, its area with respect to the mandrel cross-sectional area is small and therefore there is a large difference between billet-end-pressure and fluid pressure for tubing. It was not surprising that the fluid pressure required to produce solid rounds at a given extrusion ratio was more than twice that required for tubing. However, the billet-end pressure for tubing was higher than that for rounds by a larger factor than that for steel or aluminum. One possible explanation is that there might be a higher proportion of mandrel and die friction expended to extrude thin-walled tubing per unit volume of extrusion, than for the thick-walled tube blanks of 7075-O aluminum and AISI 4340 steel.

The low fluid pressures required to extrude tubing in comparison to those for solid rounds are indeed significant. However, the results indicated that, for the arrangement and tube dimensions used here, the maximum extrusion ratio was probably about 2.7:1. At this ratio (Trials 437 and 485), the unbalanced axial pressure of 157,000 psi on the billet was 25,000 psi in excess of the compressive yield strength of the material and billet upsetting occurred. Any higher extrusion ratios with the size tube blank would, of course, involve higher fluid pressures and hence billet upsetting.

Effect of Mandrel Taper

In the hydrostatic extrusion of thin-walled tubing, the mandrel taper is important because its magnitude causes appreciable variations in extrusion ratio along its length. In Trial 437, the mandrel taper used was 0.0012 in./in. which would cause variations in extrusion ratio of 2.6 to 2.9:1 over its 8-inch length. During extrusion runout, billet upsetting commenced at the point where the extrusion ratio was 2.7:1. Even though the mandrel taper was increased for Trial 485, billet upsetting again commenced when the ratio achieved during runout was 2.7:1. In both cases, the extrusion finish was excellent showing no signs of lubricant breakdown. Both the diameter of the mandrel and the mandrel taper were reduced in Trial 506 so that the maximum extrusion ratio was 2.7:1. However, the effectiveness of this procedure was not determined because some lubricant breakdown occurred at the commencement of extrusion and progressively became more severe, possibly resulting in premature billet upsetting. An extrusion ratio of only 2.5:1 was achieved which resulted in lower extrusion pressures than those obtained at 2.7:1. The data obtained at this ratio are plotted in Figure 30.

Lubrication

The best lubrication system for Ti-6Al-4V solid rounds, Coating 3 with Lubricant L17, also proved to be the most effective for tubing. Excellent surface finishes were obtained. However, Lubricant L33 both with and without the billet Coating C3 apparently was not as effective since a product was not obtained and billet upsetting occurred at high fluid pressure levels.

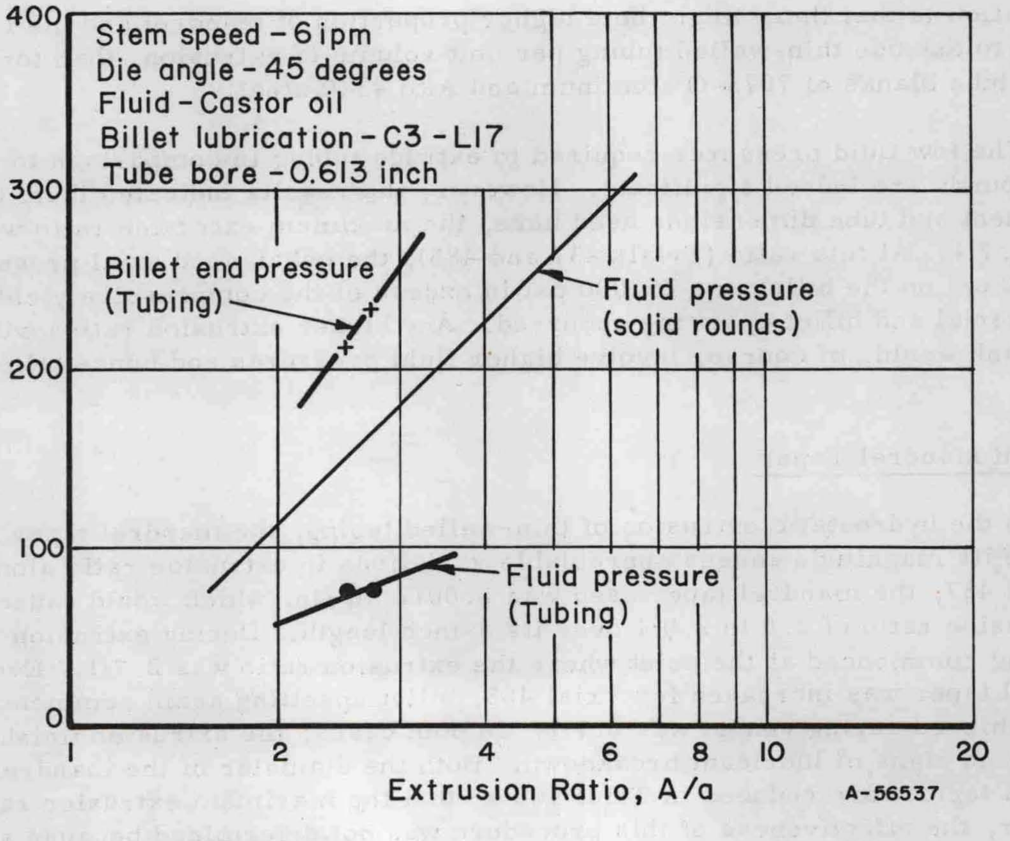


FIGURE 30. EFFECT OF EXTRUSION RATIO ON PRESSURE FOR COLD HYDROSTATIC EXTRUSION OF Ti-6Al-4V TUBING AND ROUNDS

Stem Speed

Based on work with Ti-6Al-4V alloy solid rounds, where higher stem speeds gave improvements in lubrication, stem speeds for tubing were increased from 6 ipm to 20 ipm with the aim of determining its effect on pressures and finish. Because of the large stem-to-extrusion area ratio, the tube exit speed was 150 fpm at a stem speed of 20 ipm. (As a contrast, Ti-6Al-4V alloy tube of similar dimensions is produced at about 1 fpm by conventional techniques.) The higher stem speed provided a product equally as good and did not change the pressure requirement compared with that obtained at the lower stem speed.

Re-Extrusion of As-Extruded Tube

A single trial (Trial 517) was conducted in which the extruded tube obtained in Trial 485 was to be reduced further to a wall thickness of 0.014 inch. This represented a low ratio of 1.8:1 which was selected to keep the pressure requirements relatively low. It was expected that the work-hardened material would require higher pressures than the starting material for a given ratio. At a fluid pressure of 39,000 psi, the tube billet buckled and split, rather than upset, under the resulting high unbalanced axial pressure of 200,000 psi. It is estimated from the pressure data plotted in Figure 30 that, if the tubing had been annealed before re-extrusion, a product might have been obtained under the above conditions. Extrusion might have taken place at about 20,700 psi. The unbalanced axial pressure at this level is estimated at about 120,000 psi – lower than the critical pressure of about 135,000 psi that would cause upsetting.

XVI

HYDROSTATIC EXTRUSION OF SHAPES

The extrusion of shapes from round billets and re-extrusion of shapes to smaller dimensions was explored for four materials in this program. Efforts were mainly directed toward investigating the process variables for the production of T-sections. The production of a re-entrant channel section from a round billet was investigated near the end of the program.

Die Design for the Extrusion of Shapes

Die Design for the Extrusion of Shapes From Round Billets

The dies used for the extrusion of solid rounds to T-section were of two basic designs shown in Figure 31. The first to be evaluated was the single-angle die (Figure 31a) with an intersecting T-shaped orifice. The compound-angle die (Figure 31b) design differs in that the conical entry is defined by a 45-degree conical surface leading into a 160-degree conical surface, the latter circumscribing the T-opening. This design offers the potential advantage of reducing die machining costs. Also, it permits the die bearing surface to be less irregular, which may be an advantage during extrusion. However, it was recognized that the relatively flat area near the T-opening would raise the extrusion pressure over that obtained with the "single-angle" die but the extent of this pressure rise had to be determined by experiment.

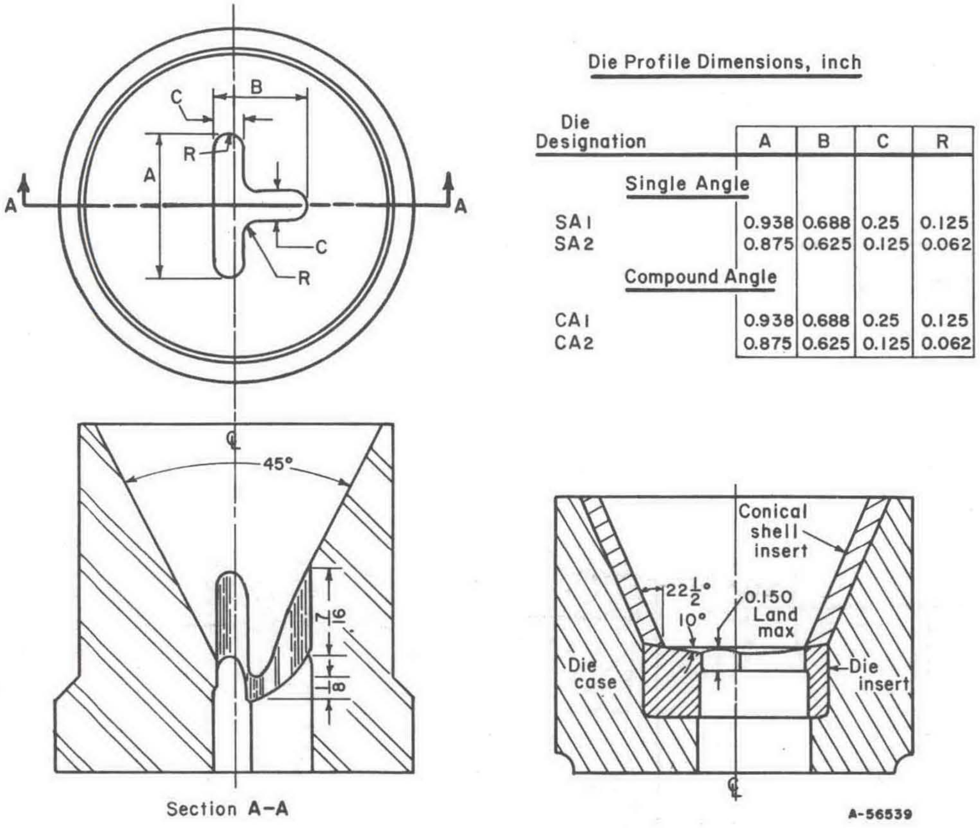
Early versions of the compound-angle die were made in one piece. However, cracking of the die occurred on occasion, and in an attempt to circumvent this problem, a three-piece design as shown in Figure 31b was used. The three-piece T-die design consists of a die insert, a conical shell insert, and a die case. The die insert was sized for a hand press-fit into the die case. The main advantage of this design is that a worn die insert or shell insert would be cheaper to replace than the whole die itself.

The die-orifice dimensions for two dies of each design are given in Figure 31. The dies are identified by a simple designation in the table for easy reference in the discussion.

The construction of the re-entrant channel die was similar in principle to the three-piece T-die design shown in Figure 31b. The insert and its orifice configuration are shown in Figure 32. Like the compound angle-T-die, the insert was supported by a die case having an orifice of the same profile.

Die Design for Re-extrusion of T-Sections

Several re-extrusion dies were constructed to enable the reduction of previously hydrostatically extruded T-sections. Figure 33 shows the geometry adopted. Here again a die insert is located in a die case. The die profiles were designed to take most of the reduction on the width of the T-legs and only sufficient reduction on the extremities of the



Die Profile Dimensions, inch

Die Designation	A	B	C	R
Single Angle				
SA1	0.938	0.688	0.25	0.125
SA2	0.875	0.625	0.125	0.062
Compound Angle				
CA1	0.938	0.688	0.25	0.125
CA2	0.875	0.625	0.125	0.062

a. Single–Angle Die

b. Compound–Angle Die

Orifice Profile Dimensions Same as for Single–Angle Die

FIGURE 31. TWO DIE DESIGNS USED IN THE HYDROSTATIC EXTRUSION OF T-SECTIONS FROM ROUND BILLETS

All dimensions given in inches.

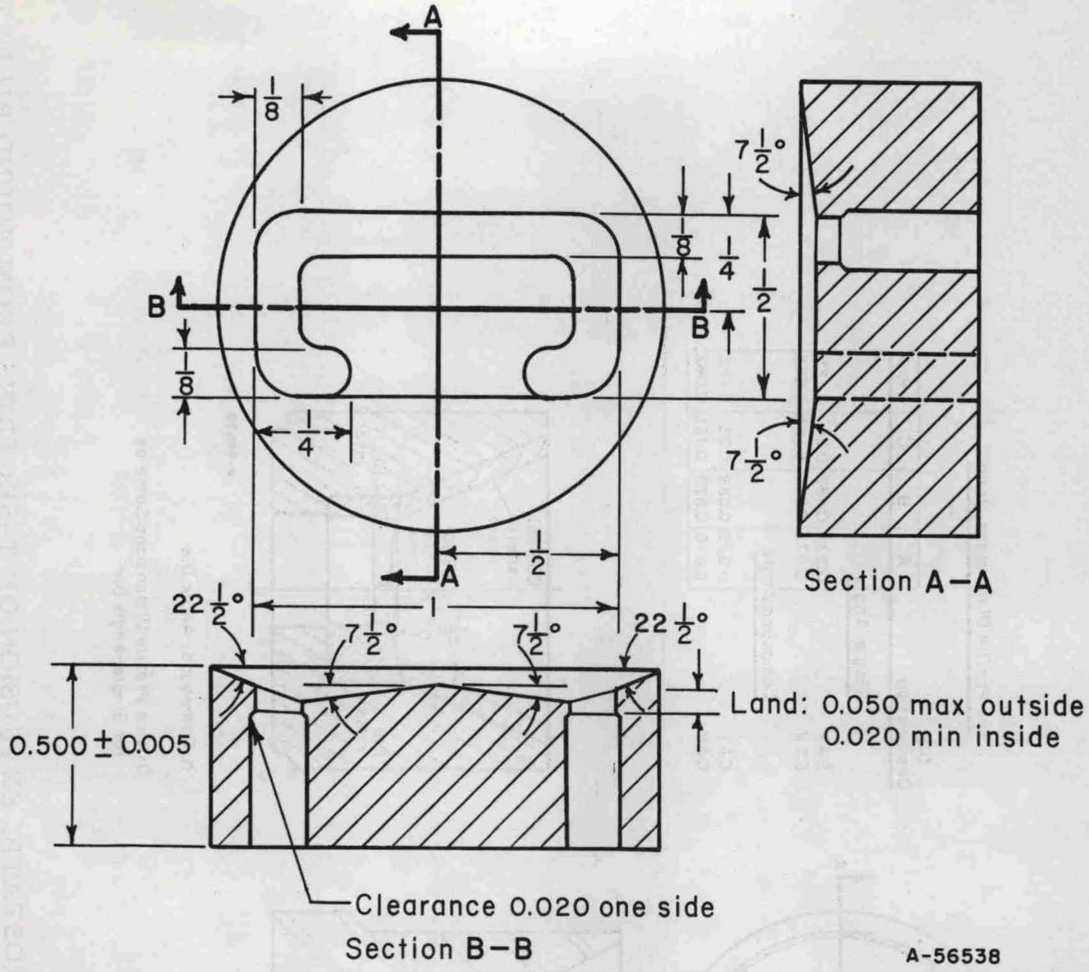
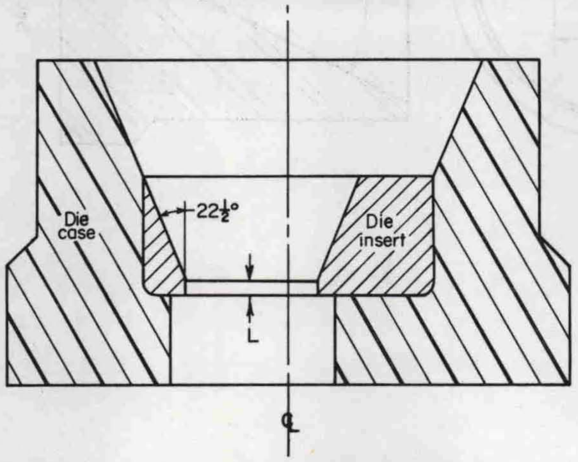


FIGURE 32. DIE INSERT AND ORIFICE DIMENSIONS FOR A RE-ENTRANT CHANNEL SECTION

All dimensions given in inches.



Die Designation	Nominal Web Dimension, in.	Die Dimension, in.				
		A	B	C	D	L
RD1	1/8	0.875	0.625	0.125	0.125	0.025
RD2	1/16	0.842	0.593	0.062	0.062	0.020
RD3	1/32	0.719	0.525	0.034	0.034	0.012

A-55831

FIGURE 33. DIE DESIGN FOR HYDROSTATIC EXTRUSION OF T-SECTION BILLETS

T-profile to make a good seal. In addition, the die entry angle for each leg of the T-shape was 45 degrees included. The die designations given in Figure 33 are for reference in later discussion.

Experimental Procedure

The experimental approach used in the hydrostatic extrusion of round billets through the T-dies was the same as that for the round-to-round trials except that for the compound angle dies, the billet had to be machined to conform to the dual-angle die profile. However, in the re-extrusion of T-sections, special techniques were required for sealing against fluid leaks.

Initially, attempts were made to machine the billet nose to conform closely with the die profile so that fluid leakage would not occur at the start of extrusion. This proved to be extremely difficult because of the complex shape of the die. In addition, the technique for mating the billet nose with the die contours was time consuming and therefore expensive. To simplify the technique, the nose was machined roughly to the die contour and a low-melting-point metal was cast into the orifice of the die with the billet standing in position. Lead, solder (50-50), and Wood's alloy were evaluated. Some limited success was achieved with the Wood's alloy and this material was adopted. This sealing procedure, however, presented an additional problem in that the hot metal tended to destroy the effectiveness of the billet lubricant in the nose area, generally resulting in high breakthrough pressures. However, it is believed that this problem is not insuperable. It is possible that other sealing materials, such as low-melting-point plastics, which exhibit good lubrication qualities in themselves, might be available. Also, it still might be possible to find a billet lubricant which would be unaffected by a molten metal contact. Alternatively, it might be possible to prepare a closely mating point fairly cheaply by such techniques as electrochemical machining.

Cold Hydrostatic Extrusion and Re-extrusion of 7075-0 Al Shapes

The data obtained in the study of critical process variables for the hydrostatic extrusion and re-extrusion of 7075-0 T-sections are given in Table XXX. Stem speed, billet surface finish, and die design were investigated.

Extrusion Pressure Requirements

Most of the trials were conducted at a ratio of 7.3:1 which represented a reduction of the 1-3/4-inch-diameter billet to a T-section having leg thickness of 1/4 inch and whose overall profile was circumscribed by a 1-inch-diameter circle. The pressures required to produce a T-section from a round billet at a ratio of 7.3:1 were about 105,000 psi, whereas about 92,000 psi is required to produce a round-to-round extrusion at the same ratio. This represents only about a 15 percent increase in pressures required to produce a T-section over those for rounds. However, stick-slip occurred at this ratio at stem speeds up to 20 ipm.

TABLE XXX. EXPERIMENTAL DATA FOR 80 F HYDROSTATIC EXTRUSION AND RE-EXTRUSION OF 7075-O ALUMINUM T-SECTIONS[a]

xtrusion Ratio	Die[b] Design	Stem Speed, ipm	Billet Surface Finish, microinches	Billet Lubricant (Listed in Table III)	Extrusion Pressure, 1000 psi: Breakthrough Stem	Breakthrough Fluid	Runout Stem	Runout Fluid	Type of Curve (Fig. 26)	Length of Extrusion, inches	Comments
				Hydrostatic Extrusion of 1-3/4-Inch-Diameter Billet to T-Section							
7.3	CA1	6	Grit[c]	L17	133	130	120	101	D2	17.0	
7.3	CA1	6	30-200	L17	133	121	119	100	D2	12.0	
7.3	CA1	20	Grit	L17	123	116	119	105	D1	15.0	
7.3	CA1	80	40-130	L17	130	124	112	108	B1	22.0	
7.3	SA1	6	300	L17	151	135	114	101	D1	20.0	
7.3	SA1	20	400	L17	154	142	116	103	D1	14.0	
7.3	SA1	80	Grit	L17	135	126	118	104	B1	11.0	
7.3	CA2	20	60-120	L53	120	105	108	99	D1	25.0	
14.5	SA2	6	60-120	L17	276	232	--	--	--	--	Pb not achieved
				Re-extrusion of 1/4-Inch-Thick T-Sections							
2.0	SA2	--	60-120	L53	--	--	--	--	--	--	Fluid leaked; Pb not ach
2.0	RD1	20	60-120	L17	30	34.5	--	--	--	1.5	Fluid leaked; Wood's al
2.0	RD1	6	60-120	L17	42	40.5	--	--	D1	14.0	Wood's alloy aided seali
4.0	RD2	20	60-120	L53	75	73.5	55	52.5	D2	24.0	Wood's alloy aided seali

astor oil.

es 31, 33 for die design details.

s grit blasted, then vapor blasted.

8, 509, and 510 were conducted under the same conditions except that sealing was attempted with lead, solder, and Wood's alloy, respectively; fluid lea on each occasion.

In a single attempt to reduce the 1-3/4-inch-diameter billet to a 1/8-inch-thick T-section at a ratio of 14.3:1 and a stem speed of 6 ipm (Trial 459), breakthrough was not achieved. This was probably due at least in part to lubricant breakdown. As with solid rounds, it is apparent that a limit in extrusion ratio set by the efficiency of the lubrication system exists, and this limit can be extended by further development of improved lubrication systems. Considering only pressure requirements, it is felt that much higher ratios than 7.3:1 are possible within the 250,000 psi pressure capacity of the tooling, provided adequate lubrication can be achieved.

Die Design

The data in Table XXX permit a comparison between the single-angle die and the single-piece compound-angle die (Trials 321 through 383). Without exception, breakthrough pressures for the compound-angle die were in the order of 10 percent lower than those for the single-angle design. The runout pressure requirements, however, were about the same for each die. The reductions in breakthrough pressure were particularly significant since the compound-angle design is less expensive to make and presents fewer machining problems than the single-angle design.

Stem Speed and Billet Surface Finish

In the study of stem speed, it was found that, with both single and compound-angle die designs, a stem speed of 80 ipm eliminated the stick-slip during runout experienced at the lower speeds. Further, the results in Table XXX, coupled with previous observations made with solid round extrusions, suggest that the range of billet-surface finishes evaluated had no appreciable effect on pressure requirements.

Billet Lubrication

Most of the trials were conducted with billet Lubricant L17. However, Trial 488 permitted a comparison of the effects of Lubricant L53 with L17 in the extrusion of a T-section from a round billet. It is believed that the slightly lower breakthrough pressure levels obtained with L53 were due more to improved billet lubrication than to differences in billet finish. The amplitude of stick-slip was reduced markedly with L53.

Extrusion of Re-entrant Channel Section

An attempt to produce the re-entrant channel section shown in Figure 32 from a 1.25-inch-diameter round billet was made in Trial 538. The extrusion ratio attempted was 7.5:1. At a fluid pressure of 40,000 psi, the die insert and support cracked across its weakest section and fluid leaked. It is apparent that this design requires greater support beyond the die than was found adequate for T-section dies.

Re-extrusion of 7075-0 Al T-Sections

T-sections having 1/4-inch-thick legs which were previously made by hydrostatic extrusion from round billets, were successfully re-extruded to T-sections having

1/8-inch- and 1/16-inch-thick legs. These reductions represented extrusion ratios of 2:1 and 4:1 respectively. Details of the trials are given in Table XXX and of the re-extrusion die-designs in Figure 33.

The techniques for preparing the billet nose for re-extrusion were explained in the introduction to this section. Several experiments with sealing compounds resulted in fluid leaks but in two cases, Trials 489 and 507, Wood's alloy permitted sealing and extrusions were obtained. In both trials, stick-slip occurred at breakthrough and on runout. This was due to the Wood's alloy which, when cast round the billet in situ, melted the billet lubricant.

The breakthrough pressures for the re-extrusion of T-sections were about 10 percent higher than for the extrusion of solid rounds, but this is attributed to lubricant breakdown rather than to a so-called "shape factor". It is of interest, in fact, that the runout pressure obtained in Trial 489 was actually about 17 percent lower than that for solid rounds.

Further experiments in the reduction of 1/4-inch-thick 7075-0 aluminum T-sections using the HYDRAW technique are described later in this section.

AISI 4340 Steel T-Sections

Table XXXI gives data for several trials aimed at producing 1/4-inch-thick T-sections from round billets. In the previous program(1), steel T-sections were produced at an extrusion ratio of 2.5:1 using the single-angle die. In this program, two trials (Nos. 316 and 387) with the single-angle die and two (Nos. 341 and 347) with the single-piece compound-angle die were conducted at an extrusion ratio of 3:1. In both trials with the single-angle die, the die cracked at high pressures, but in Trial 316 breakthrough was not achieved, the pressure required apparently being beyond the capacity of the tooling. In a single trial at a ratio of 2.5:1 (Trial 497), the compound-angle die cracked and leaked fluid at a relatively low pressure before breakthrough was achieved. For this to have occurred at such a low pressure, the die crack may have been initiated in a previous trial but it was not detected.

The data given in Table XXXI for Trial 147, conducted in the previous program(1), indicates that breakthrough pressure for the 2.5:1 ratio and a stem speed of 1 ipm was 214,000 psi. In Trial 316 where the extrusion ratio was 3:1, the breakthrough pressure was 210,000 psi. It is believed that the lower breakthrough pressure obtained at the higher ratio was partially due to the higher stem speed of 6 ipm. However, in both trials stick-slip occurred, and it was particularly severe at the higher ratio. In view of the breakthrough pressure reductions achieved by the compound-angle design with 7075-0 aluminum, a ratio of 3:1 was attempted in two trials with this design (Nos. 341 and 342). However, the pressure requirements again were too high. In view of these results, it may be that Coating Cl (zinc phosphate) applied in Trial 147 to the billet prior to lubrication but not applied in the other trials was an important factor in the successful T-section extrusion. This coating with L17 proved to be marginally more efficient than other systems in the hydrostatic extrusion of AISI 4340 solid rounds, reported in Section 1. It may be that, due to the particular severity of deformation in extruding from a round to a T-section, a coating such as Cl is necessary to provide adequate lubrication. More work would be required to settle this point.

TABLE XXXI. EXPERIMENTAL DATA FOR 80 F HYDROSTATIC EXTRUSION AND RE-EXTRUSION OF T-SECTIONS OF AISI 4340, Ti-6Al-4V, AND Cb 752 COLUMBIUM ALLOY

Fluid – Castor Oil

Trial	Extrusion Ratio	Die[a] Design	Stem Speed, ipm	Billet Surface Finish, Microinches	Billet Lubricant[b]	Extrusion Pressure, 1000 psi: Breakthrough Stem	Extrusion Pressure, 1000 psi: Breakthrough Fluid	Extrusion Pressure, 1000 psi: Runout Stem	Extrusion Pressure, 1000 psi: Runout Fluid	Type of Curve (Fig. 26)	Length of Extrusion, inches	Comments
					AISI 4340 Round-to-T-Section							
147[c]	2.5	SA1	1	--	C1-L11	245	214	228	196	D1	12	
316	3.0	SA1	6	50-100	L17	232	210	--	--	C4	2-1/4	Die broke at breakthrough
387	3.0	SA1	6	60-120	L48	283	244	--	--	--	--	Die cracked
341	3.0	CA1	6	Grit	L17	256	236	--	--	--	--	P_b not reached
342	3.0	CA1	6	Grit	L17	274	246	--	--	--	--	P_b not reached
497	2.5	CA1	6	60-120	L31	192	186	--	--	--	--	Die cracked and leaked before breakthrough
					Re-extrusion of 1/4-Inch-Thick Ti-6Al-4V T-Section[d]							
511	2.0	RD1	6	60-120	C3-L17	--	--	--	--	--	--	Woods metal failed to seal
531	2.0	RD1	6	60-120	C3-L17	165	144	--	--	--	--	Fluid leak past extrusion just after breakthrough; Woods' metal seal
516	4.0	RD2	20	60-120	C3-L17	300	261	--	--	--	1/2	P_b not achieved; Woods' metal seal
					Re-extrusion of 1/16-Inch-Thick Cb 752 Columbium Alloy T-Section							
530	2.0	RD3	6	50	L38	116	105	--	--	--	--	Seal leaked at onset of extrusion
533	2.0	RD3	6	50	L38	115	105	--	--	B1	12	Extruded too rapidly to record runout conditions

(a) See Figures 31 and 33 for die design details.

(b) Billet lubricants listed in Table III, coatings in Table IV.

(c) Trial conducted in earlier program; billet coating was zinc phosphate.

(d) Thickness given refers to nominal leg thickness of T-profile.

Re-extrusion of Ti-6Al-4V Alloy T-Sections

Three trials detailed in Table XXXI were conducted to evaluate the reduction by hydrostatic extrusion of 1/4-inch-thick Ti-6Al-4V alloy T-sections previously produced by conventional hot extrusion. As with the re-extrusion of 7075-0 aluminum T-sections, Wood's alloy was used to seal against leaks between the machined T-billet nose and the re-extrusion die. At an extrusion ratio of 2:1, a successful seal was achieved (Trial 531) but, just after breakthrough, fluid leaking prevented further extrusion. An examination of the billet and extrusion after disassembly revealed that the T-billet had shifted laterally relative to the die during extrusion, and sufficiently to cause leaking. The shift was believed to be due to unbalanced lateral pressures exerted on the billet during extrusion into the die orifice. It appeared that a slightly longer leg of the T-billet would have ensured sealing during extrusion. The breakthrough pressure of 144,000 psi obtained in Trial 531 was about 22 percent higher than that required for solid rounds. The high pressure was most likely due to lubricant breakdown by the Wood's metal sealing operation.

At an extrusion ratio of 4:1, the Wood's alloy again ensured sealing, but the pressure requirements for this reduction were evidently too high. This was not unexpected in view of the high pressure requirements for solid rounds at that ratio.

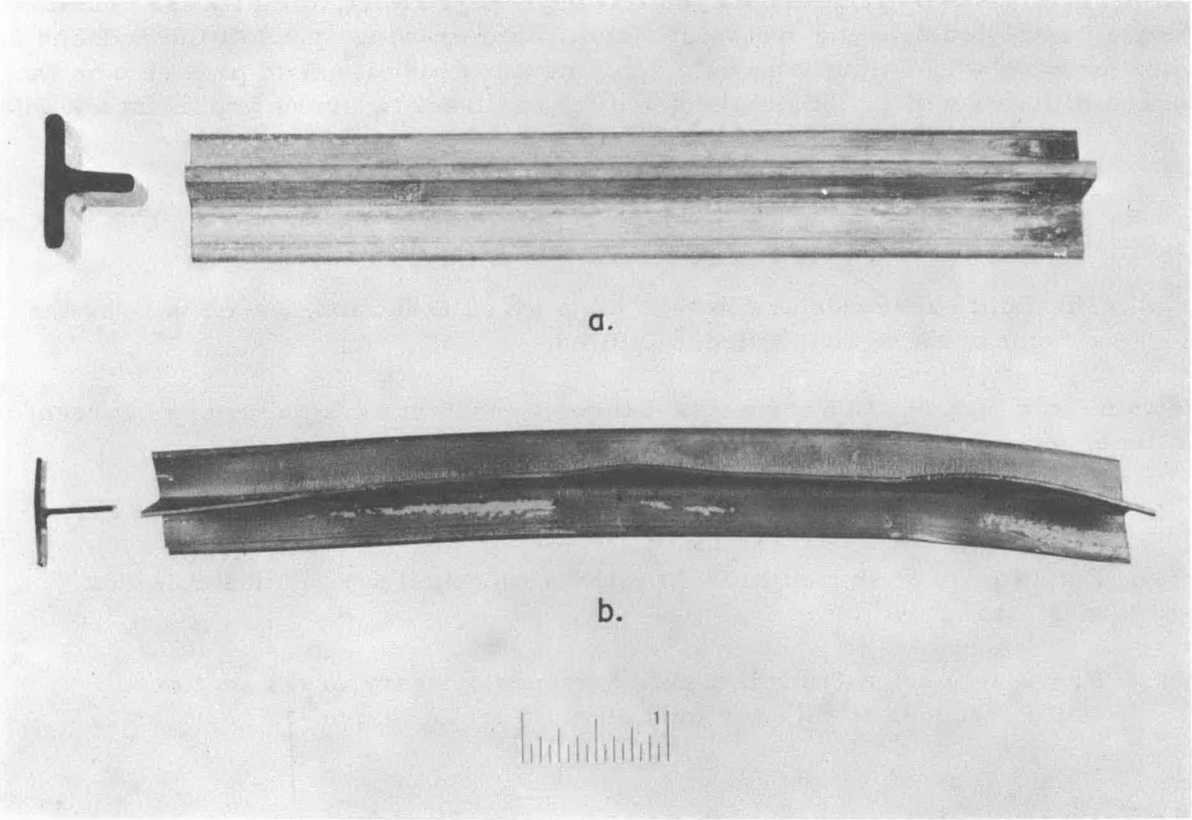
Re-extrusion of Cb-752 Columbium Alloy T-Section

Trials were conducted to establish the re-extrusion characteristics of T-sections of previously hot extruded and drawn by conventional techniques from Cb-752 columbium alloy. The experimental data for these trials are shown in Table XXXI. The columbium alloy was reduced from a 1/16-inch T-section to a 1/32-inch T-section. Figure 34b shows the resulting extrusion. The PTFE lubricant was removed during reduction; Wood's alloy was used to seal at the die-billet interface. In Trial 533, the sealing technique worked successfully yet in Trial 530 under identical conditions the seal leaked just after extrusion had started. No explanation could be found for this difference in behavior.

The pressure-displacement curve obtained in Trial 533 was unable to indicate the runout conditions because, due to the large ratio of stem area-to-extrusion area, the stem displacement required for extrusion to take place was only 1/10 inch. It is seen in Figure 34b that the extrusion is not straight. Attempts were made to straighten the extrusion but it was apparent that the distortion was permanent and was most likely caused by "shimmying", or movement from side to side, on exit.

It is considered significant, particularly from the standpoint of a potential manufacturing process to produce thin-section structural shapes from aerospace materials, that this Cb alloy was reduced from a 1/16-inch T-section to a 1/32-inch T-section in a single pass at a ratio of 2:1 (Trial 533).

It is believed that by imposing a controlled drawing stress and drawing speed on the extrusion as in the HYDRAW operation, the extrusion would be constrained to move axially. This would help prevent the axial distortion which apparently occurs in plain extrusion. The straight 7075-0 aluminum T-section shown in Figure 34a was produced by HYDRAW. The HYDRAW operation is described below.



39755

FIGURE 34. T-SECTIONS PRODUCED BY HYDRAW AND RE-EXTRUSION

a. HYDRAW of 7075-0 aluminum
b. Re-extrusion of Cb-752 columbium alloy.

XVII

THE HYDRAW OF WIRE AND SHAPES

The HYDRAW Process

The hydrostatic extrusion-drawing process, called HYDRAW, used in this experimental program is a Battelle-developed technique*. Briefly, the process consists of applying a controlled drawing stress at a controlled drawing speed to the reduced end of the billet or wire while simultaneously applying a hydrostatic fluid pressure on the unreduced billet or wire. This technique offers at least two very important advantages over plain hydrostatic extrusion of shapes or wire:

(1) The applied drawing stress permits close control over the exit speed of the reduced wire or shape

(2) The fluid pressures are lower, for a given reduction, essentially by the amount of the drawing stress applied.

In addition, this technique offers at least three important advantages over current fabrication techniques for making shapes and wire:

(1) Very high single-pass reductions are possible.

(2) Fabrication of shaped wire directly from round wire is possible in a single pass.

(3) Previously hot extruded or rolled shapes of heavy cross section can be reduced to thin sections at room temperature.

HYDRAW Tooling

General details of the tooling assembly for the HYDRAW of wire are shown in Figure 35. The main tooling is the same as that described in the beginning of this report. However, in the experiments with wire, provision is made for the product to exit at right angles to the container axis. This is achieved by aligning the container on a tapered insert which is backed up by a die holder. The die holder was designed to bridge the gap in the horseshoe below and give adequate support without distortion to the high loads imposed on the insert. The horseshoe block and horseshoe base plate were firmly bolted and doweled in position on the bottom base plate which was part of the press tooling.

Draw Control and Draw Load Measurement

A critical feature of the HYDRAW process is the ability to control drawing speed and drawing load independently. This minimizes problems of coiling, wire breakage, and uncontrollably fast wire exit speeds associated with stick-slip and/or with plain hydrostatic extrusion of wire.

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*U.S. Patent No. 3,328,998, "High Reduction Drawing", A. M. Sabroff and R. J. Fiorentino, Issued July 4, 1967.

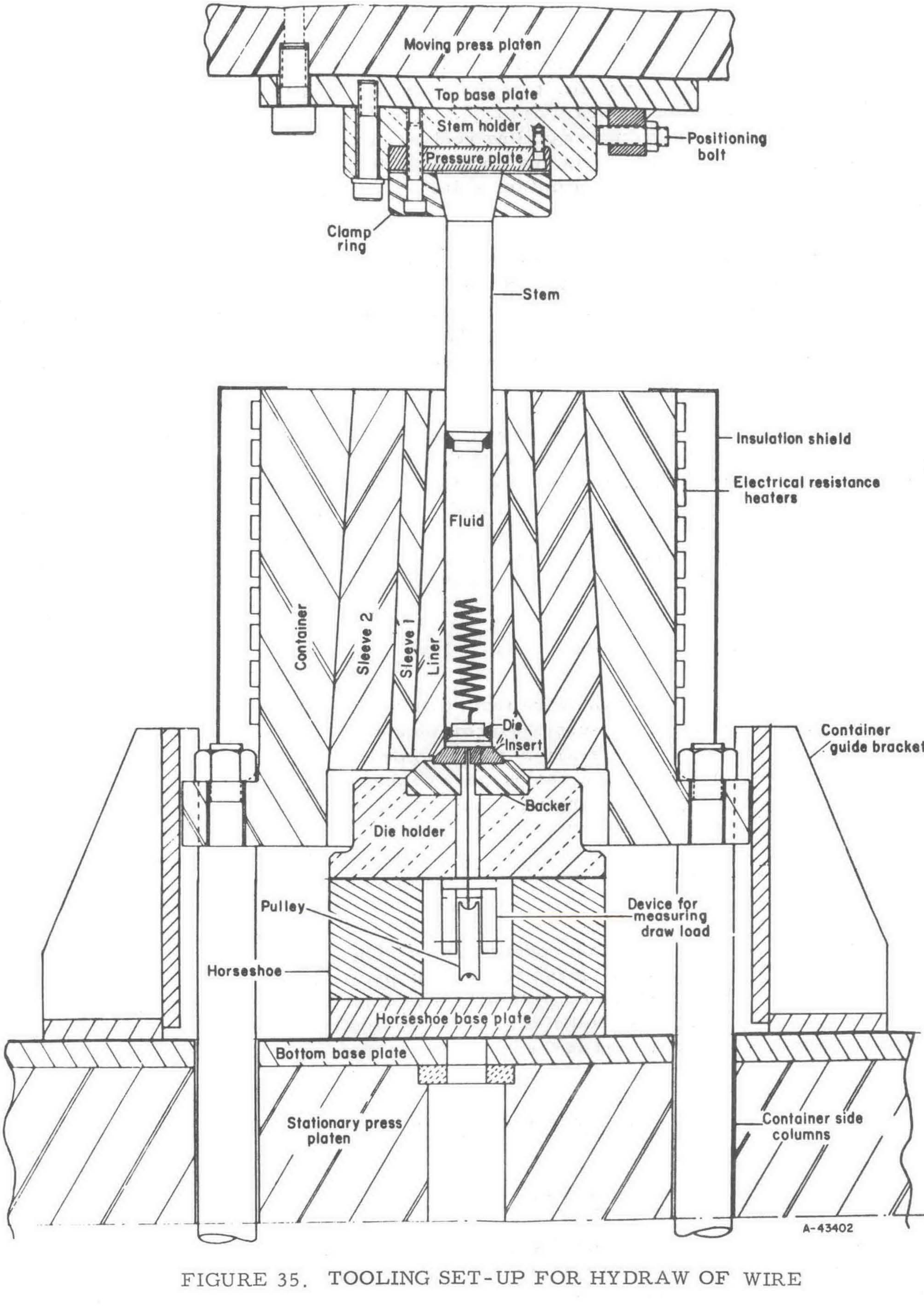

FIGURE 35. TOOLING SET-UP FOR HYDRAW OF WIRE

The drawing speed and drawing load were controlled by a unit which was capable of varying torque and speed independently. In the low draw load range for fine wire, a variable-speed motor (Zeromax Type El-S6M2) drove through one of two interchangeable electromagnetic variable-torque limiters (Vickers Magnaclutch, Model Nos. 1 MC 90B and 10 MC 90B) permitting a control of torque from 2 to 14 inch-pounds and 10 to 140 inch-pounds. A 2.8-inch-diameter coiling reel was mounted on the output shaft of the unit. The speed range of the output shaft was 0 to 50 rpm giving a draw speed range of 0 to 32 fpm. With the two torque limiters a draw-load range of 1.5 to 100 pounds was possible.

A draw-load measuring device was located in the gap of the horseshoe. The device consisted of a steel yoke which supported a pulley mounted in ball races. The purpose of the pulley was to allow the wire to exit normal to the die axis. Strain gages were mounted on the arms of the yoke to detect strains due to the application of a draw load applied to the wire or ribbon. Draw loads could be measured to within an accuracy of ±1 percent of the maximum drawing load capacity.

In the HYDRAW of shapes, the product exited axially and therefore provision was made for the draw load to be applied beneath the 700-ton press. This was achieved by attaching a steel cable to the reduced end of the shape, passing it round a pulley about 16 feet below the tooling and then around a pulley driven by the draw control unit. Here, draw control was accomplished by a unit whose output shaft speed could be varied between 0 and 120 rpm and draw load varied between 10 and 1000 lb. (Dynamatic Ajusto-Gear, Model No. AC MG-904F.) Draw load and speed were monitored on a control console.

Wire Coil Configurations

Two methods of uncoiling the wire from within the container were used. These are shown in Figure 36. The freely suspended coil on a vertical axis was used for most of the trials. The wire guide was necessary to assist in preventing tangling at the die entry. This technique was satisfactory for the purpose of these experiments, but in the handling of fine wire, such as beryllium, tangling occasionally occurred and therefore it was necessary to investigate the horizontal-axis reel. Neither technique provides for the accommodation of large quantities of wire. However, for the purposes of these experiments, the HYDRAW parameters were readily determined with relatively short lengths of wire.

Further refinements in accommodating and paying out large quantities of wire in small-bore containers were considered but their implementation were not possible within the scope of the program. These considerations will not be necessary when containers capable of handling production quantities of wire are available. The feasibility of such large bore containers is indicated in the container design study at the end of this report.

Experimental HYDRAW Procedure

Preparation of the Point on Wire and Shape

As with conventional wire and shape drawing, it is necessary to point the wire or shape in the HYDRAW process so that it may pass through the die in order to permit gripping and applying a drawing load. For wire, the point or lead was prepared by

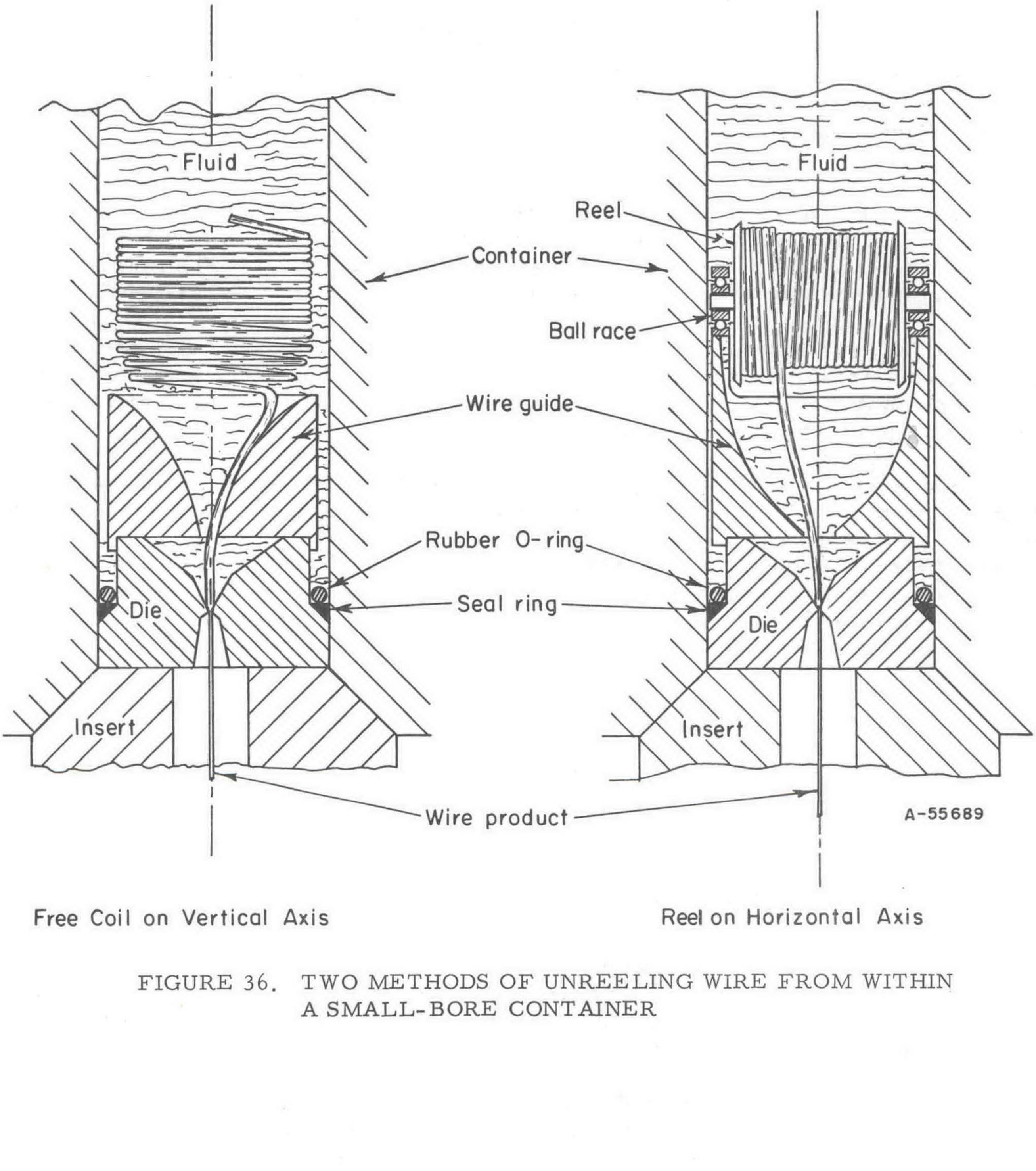

FIGURE 36. TWO METHODS OF UNREELING WIRE FROM WITHIN A SMALL-BORE CONTAINER

conventional wire-drawing techniques or by chemical etching. In the case of shapes, the point may be machined from the billet to be reduced by HYDRAW or a piece of similar material, suitable for attachment to the cable can be butt-welded to the billet.

Operational Sequence

At the start of a typical run, the die and the wire coil or billet would be seated in position on the insert. The container is lowered and seated on the insert with a hold-down force to assist in axial alignment of the container with the stem. The reduced section of the wire or billet is then connected to the take-up reel. A drawing load of about 80 percent of its breaking load is applied after the fluid is added to the container and the stem is lowered into the container ready to pressurize the fluid.

As the stem is forced against the fluid, the resulting fluid pressure rise is monitored on an X-Y recorder. When extrusion-drawing commences, the fluid pressure is held constant at the level (P). Like the hydrostatic extrusion of solid rounds when lubrication is not perfect, a breakthrough pressure peak is experienced. The runout draw stress on the draw stress/time chart is lower than the initial draw-stress setting.

The fluid pressure (P) + runout draw stress (D) requirement to cause extrusion is virtually constant for a given set of extrusion conditions. The value P + D is used in extrusion-drawing or HYDRAW for evaluation and comparison purposes in much the same way as fluid pressure is used in the hydrostatic extrusion of solid rounds.

During HYDRAW, the fluid pressure will gradually drop due to the volume of wire displaced from the container. For fine wire this is largely compensated for by the availability of an excess in draw-stress up to the set limit. If, as in the case of large-diameter wire or shapes, draw-stress compensation is inadequate to maintain the P + D value to cause extrusion drawing, then fluid pressure is increased. During a run, drawing speed may be occasionally varied to investigate the effect of exit speed on pressures and product quality. Intentional stopping of extrusion-drawing could be achieved by:

(1) Reducing the drawing stress when a known quantity of wire or shape was produced.

(2) Reducing the fluid pressure.

HYDRAW of Ti-6Al-4V Titanium Alloy Wire

HYDRAW trials were conducted with Ti-6Al-4V wire at reduction ratios of 1.35, 2, and 4:1 with the aim of determining the P + D requirements for this alloy. Data for these trials are given in Table XXXII. The wire was anodized with the C3 coating and was pointed by a combination of wire drawing and chemical etching.

Wire of good quality was produced at reductions in area of 1.35 and 2:1 at drawing speeds of 34 fpm. At the higher ratio of 4:1, however, breakthrough was not achieved. The data obtained at the two lower ratios indicate that the P + D requirements for the

TABLE XXXII. EXPERIMENTAL DATA FOR HYDRAW OF Ti-6Al-4V WIRE AT 80 AND 500 F

Die angle - 45 degrees (included)	Lubrication - Coating-C3	Starting-wire diameter - 0.045 inch
Fluid - Castor oil	Lubricant-L17	Temperature - 80 F, except(a)
	Draw speed - 34 fpm	Wire payed out from free vertical coil

Trial	Reduction Ratio	Area Reduction, percent	Pressure (P), 1000 psi		Draw, Stress, 1000 psi		P+D, 1000 psi (minimum)	Length of Wire, feet	Comments
			Stem	Fluid	Break through	Runout (D)			
513	1.35	26	43	55.5	60.0	35.0	90.5	7	
512	2.0	50	235	203.0	69.0	--	271.0	--	P_b not achieved
521	2.0	50	158	132.0	61.5	30.5	162.5	10	
534(a)	2.0	50	154	--(b)	61.2	--	--	2	Wire broke during extrusion-drawing
522, 523, 525	4.0	75	260	220.0	115.0	--	335.0	--	P_b not achieved
535(a)	4.0	75	210	--(b)	49.0	--	--	--	P_b not achieved

(a) Extrusion-drawing at 500 F; fluid - Acidless stearine; lubricant - L33.

(b) High-temperature high-pressure gage and draw-load transducer out of order.

wire were about 19.0 percent higher than the runout pressures required to hydrostatically extrude solid rounds. These higher stress or energy requirements may be due to:

(1) The so-called "size effect" in which, at smaller "billet" sizes, there is a greater area of die/billet contact per unit volume of material being deformed. Therefore, the proportion of frictional losses is higher.

(2) Differences in the ratio of die bearing length/orifice diameter which will influence the amount of frictional losses expended. This ratio tends to be larger for wire dies than for extrusion dies.

(3) Differences in the condition of the starting material.

On the basis of the results at the two lower ratios, a projection of the P + D requirements for a ratio of 4:1 gives a value of 275,000 psi. In three attempts to reduce wire at this ratio a P + D up to 335,000 psi was achieved without breakthrough occurring. In a single trial (Trial 512) at 2:1, a P + D of 271,000 psi was achieved without breakthrough, yet Trial 521 shows that, in fact, 163,000 psi is all that should be required to effect extrusion-drawing at this ratio. Thus it appears that, in these trials where breakthrough was not achieved, lubrication breakdown may have occurred.

Trial 534 was conducted at 500 F and, comparing the results with those obtained at room temperature (Trial 521), it would appear that the higher temperature does not markedly affect P + D requirements (here comparison of stem pressure and breakthrough draw-stress data only is possible because of an instrument failure). This disagrees somewhat with the findings obtained in the hydrostatic extrusion of solid rounds, where pressures were reduced by about 12 percent when working at 500 F. More trials would be required to determine the contribution of temperature with more certainty.

In two tensile tests on the wire from Trial 521, the ultimate tensile strength was 166,000 psi and its elongation was 7 percent. The properties of the starting wire were 140,000 psi and 6 percent, respectively. The apparent increase in ductility achieved in reducing the wire is probably due to the 4-inch gage length which was used whereas the gage length for the as-received wire tensile tests was reported to be for 10 inches. A shorter gage length increases the effect of the necked area on the percent elongation. The data show, however, that the 50 percent single-pass reduction strengthened the wire without a sacrifice in ductility.

HYDRAW of Beryllium Wire

The aim of this portion of the program was to determine the technical feasiblity of producing beryllium wire down to a target diameter of 0.001 inch by hydrostatic extrusion-drawing. While time did not permit the target diameter to be attempted, the feasibility of producing sound beryllium wire of relatively high-strength was demonstrated.

After some exploratory trials under a variety of conditions including temperatures of 80 and 500 F, beryllium wire having a nominal diameter of 0.020 inch was reduced in one step by a 60 percent in area down to 0.0126 inch. The temperature required to achieve this reduction was 500 F. Table XXXIII gives the data obtained. The pressure

TABLE XXXIII. SELECTED EXPERIMENTAL DATA FOR HYDRAW OF BERYLLIUM WIRE

Die angle - 45 degrees (included)
Die material - Tungsten carbide
Fluid - Acidless stearine
Reduction ratio - 2.5:1
Area reduction - 60 percent
O-Ring seal arrangement - 1 PTFE + 1 Rubber

Beryllium wire starting diameter - 0.0196 inch
Wire lubricant - L38
Draw speed - 34 fpm
All wire payed out from free vertical coil
Wire points prepared by chemical etching

Trial	Temperature, F	Stem Pressure (P'), 1000 psi(a)	Draw Stress, 1000 psi Breakthrough	Draw Stress, 1000 psi Runout (D)	P' + D, 1000 psi	Length of Wire, feet	Comments
			Beryllium - Ingot Origin				
1021(b, c)	500	156	13.6	13.6	170.0	1	Wire exited at very slow speed
1022(c)	500	108	14.5	14.5	122.5	1	Wire exited at very slow speed
1027	500	128	16.8	16.8	144.8	1	Wire exited at very slow speed
1028	500	134	10.4	2.5	136.5	11	
1032	550	131	10.4	2.5	133.5	22	
1035	530	135	13.3	1.6	136.6	2	Wire tangled in container
			Beryllium - Powder Metallurgy Origin				
1033	550	126	10.4	10.4	136.4	25	Wire exited at very slow speed; after producing 2 ft, P' + D was increased to 237, at which time the remainder of the wire was freely extruded
1034	530	126	10.4	10.4	136.4	2	Wire exited at very slow speed

(a) Fluid pressure gage was out of order.
(b) HYDRAW trials for beryllium wire start at No. 1001.
(c) Fluid was polyphenyl ether; die and feeder were cold during loading.

requirements for a 60 percent reduction indicated that reductions up to 80 percent were possible within the pressure capacity of the container. Should these predictions be correct, it is anticipated that a maximum of 4 successive reductions would be required to reduce wire from 0.020-inch diameter down to the target diameter of 0.001 inch.

The Starting Wire

Beryllium wire of a nominal starting diameter of 0.020 inch was evaluated. It originated from two sources, each having a different processing history:

(1) Ingot wire supplied by the Beryllium Corporation. This originated from a cast ingot which was hot extruded (at 1800 F in a steel jacket) to 3/8-inch rod and then drawn down to 0.020 inch in a nickel sheath at 700-800 F. The nickel sheath was removed and the wire was annealed at 1300 F for 1/2 hours.

(2) Powder-metallurgy wire supplied by the Brush Beryllium Company produced from hot-pressed powder block. In this case, the wire was drawn without a nickel sheath but still at 700-800 F. The powder-metallurgy wire was annealed at 1250 F for 1 hour.

Experimental Developments

Thirty-nine trials were conducted in the HYDRAW of beryllium wire, mainly with the ingot material. Some of these are not reported because they represented trials where experimental procedures were investigated. Initially, copper and Nichrome A wire were used to test the dies and HYDRAW equipment before any attempts were made with beryllium. In some of the trials with beryllium wire, failure to produce wire was due to one of several causes. In each case a better understanding of the techniques required for handling fine beryllium wire and the associated tooling was obtained. The areas where improvements in technique were obtained are:

(1) Method of pointing

(2) Method of coiling

(3) Wire lubrication

(4) Stem and die sealing for 500 F trials

(5) Die design and construction

(6) Handling the wire and hot die during loading in the hot containers.

Method of Pointing. Initially, pointed lengths of wire were prepared long enough to be wrapped round the coiling reel after being passed through the die. This was about 6 feet. Problems encountered here were mainly due to an uneven etching rate by an ammonium bifluoride (NH_4F_2H) solution over the 6-foot length. These were overcome by etching a much shorter point, about 1 foot long. After passing this short point through the die, it was mechanically attached to a copper wire by twisting the latter around the beryllium wire point. The copper wire was then wrapped round the coiling reel which applied the draw stress. This technique does, however, cause some time delay between threading the hot die and loading in the container.

Method of Coiling. The coiling technique used was the free vertical coil described in Figure 36. Most of the coils used were in the order of 6 feet long and presented no problem in loading in the container. However, when 60 feet coils were to be loaded, a warm-wrapping technique was required to prevent excessive tangling during loading and paying out. In this technique, wire is wrapped on to a hollow steel tube which is heated to about 600 F. In this way, the wire is given a permanent set so that it remains in a tight coil and single coils in excess of 100 feet can be contained in the pressure chamber bore without difficulty.

Wire Lubrication. Although PTFE proved best, several wire lubricants were evaluated and the techniques of application of these lubricants was necessarily different from those used on large-diameter billets. Essentially, the techniques were of a tactual nature due to the small-gage wire and its inherent brittleness. The wire was coiled before the lubricant was applied. Pre-coiling did not present any problems because the PTFE coating was applied by spraying and because it was easier to handle a coil of wire in the subsequent baking operation at 750 F.

Stem and Die Seals. Various stem and die seal arrangements were evaluated because in the HYDRAW of beryllium wire, it was necessary to hold at a set pressure level for several minutes while draw load and draw speed were varied. During this time, it was felt that distortion and deterioration of the O-ring materials might cause problems. Even so, the best arrangement was a PTFE + rubber O-ring in spite of the fact that rubber O-ring became hard after exposure to the high temperature and pressure conditions.

Die Design and Construction. The dies used initially were similar to those used in standard wire-drawing practice for diameters of 0.020 inch and less. The usual practice is to mount a diamond die in a sintered compound supported by a steel case. This construction held up to fluid pressures of 250,000 psi at 80 F, but at 500 F, the sintered compound softened and the diamond blew out under pressure due to lack of adequate support. Even at 80 F, the high pressure caused the sintered mount to loosen from the steel case, however, an epoxy cement was sufficient to prevent fluid leaks.

The thermal-softening problem encountered with diamond dies necessitated the use of carbide dies. Support of the carbide insert or nib is readily achieved and problems of leaking were not encountered. However, carbide dies below about 0.005-inch diameter apparently are not available. Thus, in future work at these small wire sizes, diamond dies with special support will be required.

Handling of the Wire and Hot Die During Loading. Special care was required during loading the hot die, wire guide, and wire coil in the container. To improve accessibility to the area beneath the container when it was in the raised position, the tie rods supporting the container were lengthened by nearly 3 inches. A wide pulley beneath the container was used so that the fine beryllium wire would not get entangled around the bearings in the yoke during wire threading.

In a production operation designed around the HYDRAW concept it is envisaged that these handling problems could be avoided.

HYDRAW of Beryllium Wire of Ingot Origin

Trials were initially conducted at room temperature to determine the properties of the cold-worked extrusion-drawn wire. The aim was to reduce the nominal 0.020-inch-diameter wire by 60 percent in area. In all trials conducted at this reduction, the pressure requirements were beyond the pressure capacity of the tooling. In the trials, a fluid pressure of 200,000 psi plus a draw stress of up to 20,000 psi was found to be inadequate for the 60 percent reduction, whereas 200,000 psi was required to extrude a 1-3/4-inch-diameter billet at a reduction of 75 percent. While it was believed that die angles smaller than those specified (the diamond dies used had a flared or trumpet shaped entry instead of a straight 45 degree entry) contributed to the high pressures needed, preliminary trials with soft copper wire and experience with other materials indicated that there is a "size effect" in extrusion. That is, the energy per unit volume required to reduce a billet or wire a given amount increases as the starting diameter decreases. This is believed to be associated with the greater surface-area to volume-ratio for a given reduction as the starting size decreases.

Thus, a trial (No. 1020) at the modest reduction of about 25 percent was successful in producing 5 feet of wire to 0.0165-inch diameter. The conditions were the same as those in Table XXXIII except that the trial was conducted at 80 F and the fluid was castor oil. The die was tungsten carbide. In spite of the low reduction in area, the pressures required were relatively high. The fluid pressure of 116,000 psi and draw stress of 2,350 psi gave a P+D requirement of 118,350 psi.

After only a short length of 0.0165-inch-diameter wire was produced, the wire broke on bending through 90 degrees round a 3-inch-diameter pulley. The remaining coil of wire in the container continued to 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.

In view of the results at the low reduction of 25 percent, consideration was given to warm extrusion-drawing at a higher reduction. This was considered especially promising since in two earlier trials, electrical resistance heating techniques had produced a short length of sound wire at a 60 percent reduction (Trials 1017 and 1018) and also, since in the extrusion of large beryllium rounds at a 75 percent reduction, fluid pressures were reduced from 200,000 to 133,000 by raising the temperature to 500 F.

The data obtained in producing beryllium wire by HYDRAW at a 60 percent reduction and at fluid temperatures between 500 and 550 F are given in Table XXXIII. It is seen that in three trials, wire was produced under controlled exit conditions and considerable lengths of wire were produced. The P'+D levels in obtaining this wire were close to 135,000 psi; the minor variations in temperature did not appear to markedly affect the P'+D values. (P', the stem pressure, is used here because in these trials at 500 F the fluid pressure gage was out of order.) In Trials 1028 and 1032, almost all of the wire within the container was reduced, resulting in a total length of 33 feet.

In the remaining three trials with the ingot wire, the wire exited at a very low speed and true runout conditions were not achieved. The reason for the low exit speed is not clear but in two of the trials, it appeared to be connected with tangling of the wire in the container.

HYDRAW of Beryllium Wire of Powder Metallurgy Origin

Data for two trials with powder-metallurgy beryllium wire are given in Table XXXIII. In both trials, true breakthrough conditions (where full control over the exit velocity is achieved) were not obtained. In both cases, at a value of P' + D of 136,400 psi, wire exited at a very low speed and raising pressure above this value did not affect the exit velocity of the wire. There was no apparent hold-up in the container. After producing 2 ft of wire in Trial 1033, the fluid pressure was slowly increased until, at P' + D = 237,000, the wire freely extruded at a rapid rate. More work will be required to investigate the causes of the failure to achieve sustained runout conditions. Apparently tangling in the container bore did not occur. It may have been due to lubrication breakdown or build-up of the PTFE lubricant in the die orifice.

Tensile Data on Beryllium Wire

The tensile data in Table XXXIV for the ingot-origin wire are the averages of several tests and for the powder-metallurgy material, one test.

TABLE XXXIV. AVERAGE TENSILE PROPERTIES OF BERYLLIUM WIRE BEFORE AND AFTER HYDROSTATIC EXTRUSION DRAWING AT 500 F

Wire Source Material	Condition	0.2 Percent Yield Strength, psi	UTS, psi	Elongation, percent in 2 inches
Ingot (Berylco)	As received	47,000	88,000	9.0
	60 percent reduction by HYDRAW	124,000	131,000	0.2-0.9
Powder (Brush)	As received	88,000	142,000	12.0
	60 percent reduction by HYDRAW	186,000	198,000	0.4

Both wire materials increased in tensile strength by close to 40 percent and the yield strength more than doubled as a result of the 60 percent single-pass reduction. The ductility of the wire produced was markedly lowered but was still high enough to permit continuous coiling round a 3-inch-diameter pulley while under the draw stress.

HYDRAW of TZM Molybdenum Alloy Wire

Data are given below for a single trial in which 0.10-inch-diameter TZM wire was reduced by 60 percent in area by the HYDRAW process. The 15 feet of wire produced was of excellent surface quality and no problem was experienced in handling the material. The extrusion conditions were identical to those used for beryllium wire and given in Table XXXIV. The fluid temperature was 500 F.

Trial	Stem Pressure, P', psi	Draw Stress, psi		P'+D, psi
		Breakthrough	Runout	
536	159,000	18,600	18,000	177,000

The pressure plus draw stress requirements were about 30 percent higher than the pressure requirements for the extrusion of solid rounds. These higher pressures may have been partly due to the "size effect" and other factors discussed earlier. However, the energy required to uncoil the stiff 2-inch-diameter coil of 0.1-inch wire must have constituted a large proportion of the excess pressure requirements.

The wire was pointed by chemical etching and in one case (Trial 524), uneven etching caused fluid leaks between the wire and die.

HYDRAW of 7075-0 Aluminum T-Sections

A 1/4-inch-thick T-section of 7075-0 aluminum was reduced to a 1/8-inch thick section, representing a ratio of 2:1, by the HYDRAW process (Trial 526). A photograph of a short length of the extrusion is given in Figure 34. The draw force was applied to the billet through a 7075-0 aluminum alloy tab which was fusion welded to the nose of the billet. The nose of the T-section billet had been machined to approximate the die entrance entrance contours. A seal between the billet and die was ensured by casting Wood's alloy around the billet in the die prior to extrusion-drawing. A two-piece die described in Figure 33 was used in these trials.

The drawing force was applied to the end of the extrusion by a variable torque motor through a cable into a pinload fixture attached to the tab. During the application of the draw force, the cable tended to untwist. The untwisting torque caused the extrusion and die insert to turn slightly relative to the die case and the reduced T-section scraped the die case on exit. The scraping action caused the extrusion pressure + draw stress (P+D) requirements to be higher than the pressure requirements for straight hydrostatic re-extrusion under the same conditions (50,500 psi versus 40,500 psi).

In Trial 526, the draw stress applied to the extrusion cross section was limited by the strength of the tab or point to a value of 3,300 psi. However, even this low draw stress enabled some control over the exiting extrusion. In a production operation, it would be a relative simple matter to fusion weld a short length of section which had already been extrusion-drawn through the die to be used for applying a draw stress to the next extrusion. This would simplify the sealing problem and enable the application of a draw stress of about 30,000 psi, which would reduce the fluid pressure required to about 10,000 psi.

In a later attempt (No. 537) to HYDRAW a 1/4-inch-thick T-section to a 1/16-inch-thick T-section (a ratio of 4:1) the tab failed at the grip under a draw load of 500 lb before sufficient fluid pressure to cause extrusion-drawing was attained. The high draw load was intended to provide as high a draw stress (about 10,000 psi) as was reasonably possible with this arrangement, so that the fluid pressure requirements would be minimized. In the arrangement suggested previously, however, draw stresses even higher than 10,000 psi would be possible without point breakage. It is worthwhile noting that the tensile failure of the tab or point in Trial 537, occurred well away from the welded joint. Therefore, the technique of welding a lead or tab to the billet for HYDRAW seems to be sound.

XVIII

TANDEM EXTRUSION

Tandem hydrostatic extrusion was carried out to determine the feasibility of stopping an extrusion, placing another billet on the back end of the first, and extruding them in sequence. This technique would be one of the possible means of achieving a high production rate of operation with the minimum of waste. It might result in cost savings by eliminating the need for machining a nose on every billet; only the starting billet would require this. The 7075-0 aluminum was chosen to evalute two tandem joint designs, Trials 453 and 454, respectively. Table XXXV gives the experimental data obtained with the designs.

The two methods of seating the second billet evaluated are shown in Figures 37 and 38. 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.

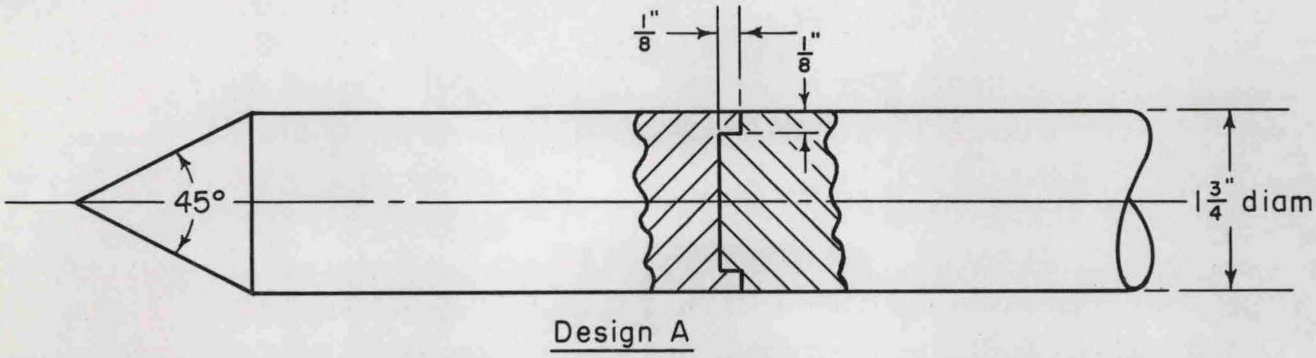

FIGURE 37. COUNTERBORED TANDEM BILLET JOINT DESIGN EVALUATED IN HYDROSTATIC EXTRUSION

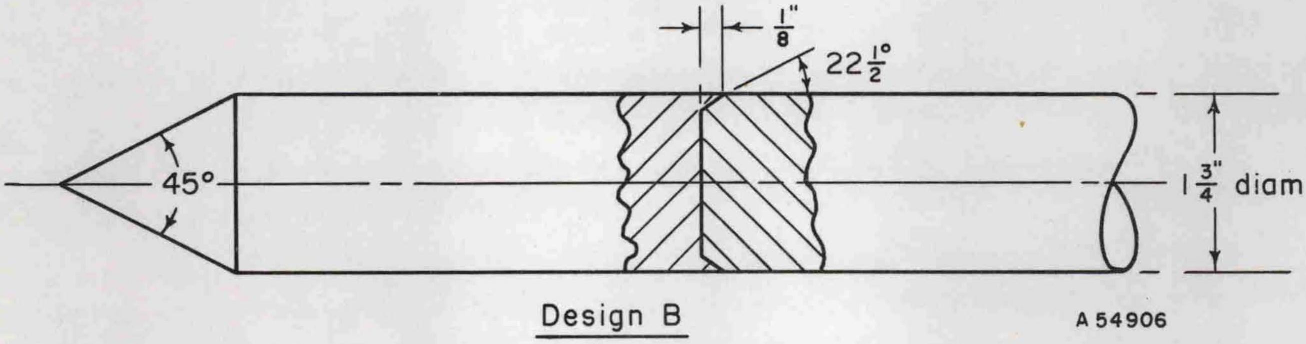

FIGURE 38. TAPERED TANDEM BILLET JOINT DESIGN EVALUATED IN HYDROSTATIC EXTRUSION

With Design A, Trial 453, 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, Trial 454, 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.

TABLE XXXV. EXPERIMENTAL DATA OBTAINED IN THE INVESTIGATION OF TANDEM EXTRUSION AT 80 F

Material - 7075-0 aluminum
Extrusion Ratio - 20:1
Stem Speed - 20 ipm
Billet Diameter - 1-3/4 inches
Fluid - Castor oil
Billet Lubricant - L53

Trial	Joint Design	Operation	Fluid Extrusion Pressure, 1000 psi		Type of Curve(a)	Length of Extrusion
			Breakthrough	Runout		
453	A	Extrusion stopped	138	122	B2	72
		Restarted after loading	177	122	C2	56
454	B	Extrusion stopped	134	122	B2	100
		Restarted after loading	179	120	D2	20
472	-	Extrusion stopped	135	121	B2	65
		Restarted after 10 sec.	172	122	D2	10

(a) See Figure 26.

This phenomenon was investigated further in Trial 472, which was conducted to determine the effect of stopping and restarting on pressure requirements during the extrusion of a single billet. Thus, on restarting 10 seconds after stopping, similar high breakthrough pressures and stick-slip occurred.

This behavior was probably due to lubrication breakdown although the precise mechanism is not clear. On depressurization of the fluid, the residual temperature at the die-billet interface (developed before stopping) may be high enough to cause a sharp viscosity drop and/or unfavorable chemical change in the lubricant system. Repressurization may not necessarily renew the same state of lubrication which existed during initial extrusion. Other factors may be that:

(1) The change in surface characteristics of the billet at the billet-die interface may have reduced the contribution of "squeeze" lubrication during re-extrusion.

(2) Sufficient work hardening of the billet nose occurred, in spite of adiabatic heating, that higher pressures were required for re-extrusion.

An alternative to the tandem technique which would eliminate waste of billet material would be to reduce the fluid pressure to the ambient pressure level at the point of final emergence of the extrusion from the die. This would be very difficult to achieve by press-control of the stem motion but may be achieved by a carefully designed plug which followed the billet. The plug design would vary with extrusion conditions and billet extrusion properties.

The tandem extrusion technique using the counterbore joint "A" was utilized in the extrusion of short billets of sintered aluminum product (SAP) which is described in Section 1. There was insufficient length of SAP billet on which to machine a 45 degree nose. The short billets were sandwiched between two billets of 7075-0 aluminum one of which formed the nose of the sandwich. Successful extrusions were obtained of the whole of the sandwiched billet at ratios of 10:1 and 20:1. The pressure-displacement curve indicated the position of the joint by a ripple in the runout pressure followed by a slightly lower runout pressure level. The interruption and lowering in the pressure curve was mainly due to a slight difference in mechanical properties of the two materials.

XIX

ECONOMIC ANALYSIS OF THE HYDROSTATIC EXTRUSION OF SOLID ROUNDS AND TUBING

The objective of this section is to evaluate the economics of the hydrostatic extrusion process and to relate the findings to conventional processes. During the course of the overall program a large number of process variables and materials were evaluated. To make use of this large amount of information, the economic analysis was directed toward establishing meaningful trends and relationships between hydrostatic extrusion and conventional processes rather than directing the analysis toward one product and one material. The cost figures used in this analysis were based on actual equipment costs whenever possible. No basic modifications of existing tooling were assumed in this study, although it was assumed that additional fluid and billet-handling equipment would be used. Thus, this analysis reflects the current state of the hydrostatic extrusion process and the costs obtained herein may be lowered still further as production refinements take place.

The procedure used in this analysis was to establish a press cost on a hourly basis and then to apply appropriate factors, such as production rates, die life, and billet weights, to determine a conversion cost per pound of extrusion. In the case of tubing a conversion cost was determined as a function of extruded length. The analysis was limited to determining conversion costs rather than selling cost and, therefore, items such as return on investment, inspection costs, and selling costs were not considered. These items would require additional assumptions and would tend to make the final cost figures less meaningful.

The press costs for hydrostatic extrusion were estimated as shown from the figures on Table XXXVI. The press and related equipment was assumed to have a 10-year life. Factors of 25 percent and 15 percent of equipment cost used to determine building, engineering, and contingencies costs may vary for different operations but are useful to establish the magnitude of these costs. Assuming the maintenance cost equal to the equipment cost over the life of the equipment is an accepted accounting procedure. In the normal life of industrial equipment, little or no maintenance may be required in the first few years of service, but in the remaining years maintenance costs mount and experience has shown this assumption to be reasonable.

The container used in this analysis was assumed to have a bore 2-3/8-inch diameter x 40 inches long. Since the most expensive component in hydrostatic extrusion tooling is the container, the hydrostatic extrusion tooling cost was estimated by doubling the cost of a 20-inch-long hydrostatic extrusion container constructed recently during this program. The container would have a 5-year service life based on a fatigue life of 10^5 cycles.

The assumed labor cost would allow for either a two-man operation, each with a high degree of skill, or a three-man operation with one skilled operator and two helpers. Overhead factors vary with accounting systems and type of industry. The value of 100 percent is frequently used in many heavy industries such as extrusion or forging plants.

Service costs were determined from the press used in this current study. A final press cost per hour was determined to be $46.96/hr. This value was determined from the following relationship.

TABLE XXXVI. THE ECONOMIC BASIS FOR DETERMINING PRESS COSTS

A. Capital Investment	
1. Cost of a 700-ton press	$150, 000
2. Material-handling equipment (such as fluid pumps, and mechanical devices to clear and clean dies).	12, 000
Total Cost of Equipment	$162, 000
3. Building costs (assumed 25 percent of equipment costs)	40, 500
4. Engineering costs (assumed 25 percent of equipment costs)	40, 500
5. Contingencies (assumed 15 percent of equipment costs)	24, 300
Total Capital Investment	$267, 300
B. Operating Costs	
1. Maintenance (equal to equipment cost over the life of the equipment)	162, 000
2. Hydrostatic extrusion tooling cost	30, 000
3. Labor ($10/hr x 100 percent overhead)	$20. 00/hr
4. Services (electric, water, etc.)	$2. 50/hr

$$\frac{\text{Capital Investment + Maintenance}}{10\text{ yr} \times 2000\text{ hr/yr}} + \frac{\text{Hydrostatic Tooling}}{5\text{ yr} \times 2000\text{ hr/yr}}$$

$$+ \text{ Labor + Service Costs = Press Cost per hour}$$

or

$$\frac{\$267,300 + \$162,000}{10 \times 2000} + \frac{\$30,000}{5 \times 2000} + \$20.00 + \$2.50 = \$46.96/\text{hr} \ .$$

The press operating cost per extrusion is, of course, directly related to the number of billets that could be extruded per hour. Using the tools developed in this program and assuming a relatively simple materials handling system, it was felt that the extrusion output could be up to 20 billets per hour for simple solid rounds extrusions or as low as 10 billets per hour for more complex extrusions. These production rates resulted in a press cost which varied from $4. 696 to $2. 348 per extrusion for production rates of 10 and 20 billets per hour, respectively. Additional costs would have to be added to these figures to cover the cost of dies, mandrels, fluids, and seals. These are considered on an individual basis in the following sections.

Conversion Costs to Produce Rounds by Hydrostatic Extrusion and by Conventional Hot Extrusion

It was assumed that essentially the same press facilities would be used for both the hydrostatic extrusion and hot extrusion operations. The labor costs were assumed to be equal in both operations.

Hydrostatic Extrusion of Rounds

The production output of the hydrostatic extrusion process measured in pounds per extrusion will depend on the extrusion rate, billet size, and on the density of the particular material extruded.

A production rate of 20 billets per hour was used to determine a press cost of \$2.35 per extrusion. (\$46.96/hr ÷ 20 extrusions/hr.) This rate reflects the use of only simple materials handling equipment and is certainly not a maximum value. Hydrostatic fluids and seals which are required in the hydrostatic extrusion process are generally reuseable, while lubricants are expendable. The life of the seals and the amount of fluid unrecovered from each extrusion cycle would have to be precisely determined to obtain an accurate cost for these items. A conservative estimate of these costs of \$0.50 per extrusion was used in this analysis, thereby obtaining net extrusion cost of \$2.85 per extrusion, exclusive of die costs.

A simple round production hydrostatic extrusion die would cost approximately \$100. It is apparent if a short die life is assumed, the die cost can exceed the press and fluid costs. The estimated die life is wholly dependent on the effectiveness of the lubrication system.

The hydrostatic extrusion chamber described in the previous section would accommodate a billet 2-inches in diameter x 30 inches long with allowance for fluid compression and tooling. The conversion costs were determined for five materials which are listed along with their billet weights in Table XXXVII.

The conversions costs per pound of extrusion were calculated to show the influence of both die life and billet material. Conversion costs were determined from the following formula:

$$\text{Conversion Cost Per lb} = \frac{(\text{Extrusion Costs}) + (\text{Die Costs})}{\text{Billet Weight}}$$

For example:

> Using a beryllium billet weighing 6.296 lb and a die life of five extrusions
>
> $$\frac{\$2.85 + (\$100 \div 5)}{6.296\ \text{lb}} = \$3.63/\text{lb}\ .$$

These conversion costs are shown on Table XXXVIII.

TABLE XXXVII. BILLET WEIGHTS FOR HYDROSTATIC EXTRUSION AND HOT EXTRUSION AS A FUNCTION OF BILLET MATERIAL

Billet Material	Density, lb/in.^{3}	Hydrostatic Extrusion (Billet Size 2-inch diam x 30 inches) Billet Weight, pounds	Hot Extrusion (Billet Size 3-1/8 inch diam x 9-3/8 inches) Billet Weight, pounds
Beryllium	0.0668	6.296	4.80
7075 Aluminium	0.101	9.519	7.26
Titanium alloy	0.160	15.08	11.50
Steel	0.283	26.67	20.35
Molybdenum	0.369	34.78	26.53

TABLE XXXVIII. CONVERSION COSTS PER POUND OF EXTRUSION FOR HYDROSTATIC EXTRUSION AND HOT EXTRUSION AS A FUNCTION OF DIE LIFE AND A VARIETY OF MATERIALS

Die Life (Number of Extrusion per die)	Hydrostatic Extrusion						Hot Extrusion					
	Cost(a) per Extrusion, $	Conversion Cost(a) per Pound of Extrusion for Various Materials, $					Cost(a) per Extrusion, $	Conversion Cost(a) per Pound of Extrusion for Various Materials, $				
		Be	Al	Ti	Steel	Mo		Be	Al	Ti	Steel	Mo
1	102.85	16.33	10.80	6.82	3.85	2.95	100.59	20.96	13.85	8.75	4.94	3.79
2	52.85	8.39	5.55	3.50	1.98	1.52	50.59	10.54	6.97	4.40	2.49	1.91
3	36.18	5.75	3.80	2.40	1.36	1.04	33.92	7.07	4.67	2.95	1.67	1.28
4	27.85	4.42	2.93	1.85	1.04	0.80	25.59	5.33	3.52	2.23	1.26	0.96
5	22.85	3.63	2.40	1.52	0.86	0.66	20.59	4.29	2.84	1.79	1.01	0.78
10	12.85	2.04	1.35	0.85	0.48	0.37	10.59	2.21	1.46	0.92	0.52	0.40
15	9.52	1.51	1.00	0.63	0.36	0.37	7.26	1.51	1.00	0.63	0.36	0.27
20	7.85	1.25	0.82	0.52	0.29	0.23	5.59	1.16	0.77	0.49	0.27	0.21
25	6.85	1.09	0.72	0.45	0.26	0.20	4.59	0.96	0.63	0.40	0.23	0.17
50	4.85	0.77	0.51	0.32	0.18	0.14	2.59	0.54	0.36	0.23	0.13	0.10
100	3.85	0.61	0.40	0.26	0.14	0.11	1.59	0.33	0.22	0.14	0.08	0.06
200	3.35	0.53	0.35	0.22	0.13	0.10	1.09	0.23	0.15	0.09	0.05	0.04
500	3.05	0.48	0.32	0.20	0.11	0.09	0.79	0.16	0.14	0.07	0.04	0.03

(a) All values rounded off to the nearest $0.01.

Conventional Hot Extrusion

A rough comparison can be made using the preceding figures between conventional hot extrusion and hydrostatic extrusion. Conventional extrusion tooling would cost, perhaps, 1/3 the cost of the hydrostatic extrusion chamber. But, a conventional operation would generally require additional facilities to heat the tooling and billets. For simplicity, these additional heating costs can be assumed equal to the reduced tooling costs. If so, the press costs for the two processes are essentially the same.

The production rate for conventional hot extrusion should be significantly higher than in the hydrostatic extrusion process since both seal problems and the fluid handling systems are eliminated. A production rate of 80 billets per hour was used in this analysis. Although such a rate could be expected with good handling equipment for steel, titanium, molybdenum, and beryllium, it is doubtful for 7075 Al because of the problem of extrusion cracking at extrusion exit speeds much greater than about 5 fpm. Therefore, the conversion cost estimates for hot extrusion of 7075 Al are quite low, probably by a factor of about 10. At any rate, at a production rate of 80 billets/hour, the conversion cost per extrusion is \$0.59 (\$46.96/hr ÷ 80 billets/hr). No fluid or seals are required for hot extrusion and the lubrication costs were assumed negliglible. Because of its high L/D ratio, the billet dimensions used for the hydrostatic extrusion analysis could not be used in the hot extrusion process. The hot extrusion process is further differentiated from hydrostatic extrusion in that it is capable of making larger single-pass reductions than the hydrostatic extrusion process for many materials, except for perhaps the relatively softer nonferrous materials such as aluminum and copper. So that the hot extrusion process was not unduly restricted, the hot extrusion billet was assumed to be 3-1/8-inch diameter. This diameter corresponds to a unit stress on the billet of 180, 000 psi in a 700-ton press. This stress level is often used as the maximum practicable tooling stress in hot extrusion. Applying a L/D factor of 3 to the billet diameter results in a overall billet length of 9-3/8 inches. For billets of this size, billet weights for the materials considered are given in Table XXXVII.

As in hydrostatic extrusion, die life is critically important to the economics of conventional hot extrusion. Using the same formula and die cost used to evaluate hydrostatic extrusion, conversion costs for hot extrusion were determined for a range of extrusions per die and for five materials. The results are given in Table XXXVIII.

Comparison of Hydrostatic Extrusion and Hot Extrusion Conversion Costs

It may be seen from the data in Table XXXVIII, that die life is a very significant factor affecting conversion costs. If the tenuous assumption is made that the die life is equal for each process, it is apparent that the conversion costs for hydrostatic extrusion are lower up to a die life of 15 extrusions, equal at 15 extrusions, and higher for a die life above 15 extrusions. However, the assumption of equal die life for both processes is not realistic. A die life of one or two hot extrusions per die is not uncommon in commercial practice. Even when costly ceramic inserts are used in hot extrusion, the die life seldom extends above 25 extrusions. On the other hand, a die life of 250 to 500 extrusions can reasonably be predicted for hydrostatic extrusion. The predictions are made by comparing the hydrostatic extrusion process with the cold forging process. In cold forging the stem pressures are in the range of 300, 000 psi to 350, 000 psi and thus the die stresses in the two processes are comparable. In cold foring of steel, die lives of 50,000 pieces are common. Typically each forged piece may measure only 1-1/2 inches long, but after 50,000 pieces this is equivalent to extruding 75,000 inches of rod. The hydrostatic extrusion billet in this study was assumed 30 inches long. If this billet was reduced 10 to 1, 300 inches of extruded product would be produced per extrusion, or a die life of 250 extrusions would be equivalent to 75,000 inches of a forged product. If the billet was reduced only 5 to 1 a die life of 500 extrusions would be predicted. One could then realistically compare the cost for a die life of 200 extrusions in the hydrostatic extrusion process with the corresponding costs for hot extrusion for a die life of, say, 5 extrusions. From this view point, the hydrostatic extrusion process looks attractive over a wide range of die life and materials.

There are basic differences between hydrostatic extrusion and hot extrusion processes that could not be eliminated in this analysis. Foremost, the hydrostatic extrusion process produces a product with an excellent surface and good dimensional control. However, a hot extruded product often requires a sizing operation and for some materials the extrusion must be machined all over to produce a satisfactory surface.

Until pilot production runs are made using hydrostatic extrusion techniques to evaluate die life, seal life, and overall process yield, a more rigorous analysis of extrusion of rounds is not possible. It can be concluded, however, that the good possibility of much better die life in hydrostatic extrusion makes it potentially very economically attractive compared to conventional extrusion.

Conversion Costs to Produce Ti-6Al-4V Titanium Alloy Tubing by Hydrostatic Extrusion

Ti-6Al-4V titanium alloy tubing was selected for this part of the economic analysis because it was extruded by hydrostatic means during this contract and the assumptions made herein were based to some extent on the experimental work. Ti-6Al-4V alloy tubing is relatively difficult to fabricate, particularly for small-diameter (less than 1/2 inch), thin-walled tubing. It is, however, available commercially as a specialty item. Unalloyed titanium tubing, on the other hand, is easier to fabricate and is produced commercially. The selling prices for Ti-6Al-4V are quite high when compared to unalloyed titanium tubing. The cost figures for both materials are included in this analysis for comparison with cost estimates for producing tubing by hydrostatic extrusion.

This analysis is based on the experimental work performed on this contract, extrapolated to a production process. Therefore the diameters and lengths involved in this analysis have not been produced, but appear technically feasible. Three examples will be used to estimate the cost per foot to produce titanium tubing. One will be based on actual experimental results previously reported, i.e. 0.750-inch OD x 0.613-inch ID reduced approximately 3:1. The second will be based on the maximum extrusion ratio possible with a stationary mandrel, assumed to be 4:1 from Figure 30. The third example will be based on the use of a floating mandrel which adds extra pressure to the end of the tube. As previously discussed, this additional force is limited to the yield strength of the starting tube. Assuming the yield strength to be 135,000 psi for Ti-6Al-4V, the maximum reduction ratio achievable for a floating mandrel was estimated to be 8:1. This reduction requires a total billet-end pressure of 385,000 psi and was determined by extrapolating the plot of pressure versus reduction ratio on Figure 30. In the last two examples, the extrusion ratio cited are estimated to be the maximum possible within the 250,000 psi fluid pressure capacity of the present tooling.

The conversion cost of hydrostatic tube extrusions was estimated in the following manner. Since experimentally no die wear was observed from the hydrostatic extrusion of a properly lubricated Ti-6Al-4V titanium alloy tube, die and mandrel costs were estimated conservatively on a life of 25 extrusions each. It was assumed, using relatively unsophiticated tooling, that the mandrel manipulation might be time consuming and, therefore, a production rate of only 12 billets per hour was used to determine the press cost per extrusion. The final cost per extrusion and the breakdown of this cost are shown:

(1) Die costs: \$100/die ÷ 25 extrusions/die	= \$4.00/tube
(2) Mandrel costs: \$30/mandrel ÷ 25 extrusions/mandrel	= \$1.20/tube
(3) Seals, fluids, and lubricants	= \$0.50/tube
(4) Press cost: \$46.96/hr ÷ 12 tubes/hr	= \$3.91/tube
Total Tube Conversion Cost	\$9.61/tube

The conversion cost per unit length of tube produced by hydrostatic extrusion is a direct function of the length of tube produced per extrusion, which in turn depends on both the extrusion ratio and initial starting billet length. The relationships and resultant conversion costs are shown on Table XXXIX. To assist in establishing trends, containers capable of accommodating 3- and 6-foot-long tube blanks were assumed. The cost per extrusion of \$10.11 for starting lengths 4 to 6 feet was determined by doubling the cost of hydrostatic tooling (from \$30,000 to \$60,000) and keeping all other costs factors constant. The cost of pressure vessels generally vary linearly with length.

Two sources were used to obtain cost figures for comparison with hydrostatic extrusion. The first source was a published price list for standard Grade 2 titanium tube (commercially pure titanium). For the second source, oral quotations for Ti-6Al-4V tubing were obtained. Selected sizes of tubes representing reductions of 3:1, 4:1, and 8:1 were analyzed for both materials and are shown on Table XL. The dimensions of Tubes A, C, and D were chosen as typical sizes which could be made by both hydrostatic techniques and conventional processing. Dimensions for Tube B were selected to approximate the tube size produced in this program. The conversion costs for producing tubes by conventional techniques were estimated from selling prices and were determined as follows:

$$\frac{\left(\begin{array}{c}\text{Cost of the finished}\\ \text{tube, dollars/ft}\end{array} \times \begin{array}{c}\text{Amount of finished tube produced per}\\ \text{foot of starting tube, ft}\end{array}\right) - \begin{array}{c}\text{Cost of the starting tube}\\ \text{per foot, dollars}\end{array}}{\text{Amount of finished tube produced per foot of starting tube, ft}} = \begin{array}{c}\text{Conversion cost,}\\ \text{dollars/ft}\end{array}$$

The amount of finished tube produced per foot of starting tube was assumed equal to the reduction ratio.

TABLE XXXIX. ESTIMATED CONVERSION COSTS FOR PRODUCING Ti-6Al-4V TITANIUM ALLOY TUBING BY HYDROSTATIC EXTRUSION TECHNIQUES

Extrusion Ratio	Starting Length, ft	Finished Length, ft	Cost/Extrusion, dollars	Conversion Cost, dollars/ft
3:1	1	3	9.61	3.20
	2	6	9.61	1.60
	3	9	9.61	1.06
	4	12	10.11(a)	0.84
	5	15	10.11(a)	0.67
	6	18	10.11(a)	0.56
4:1	1	4	9.61	2.40
	2	8	9.61	1.20
	3	12	9.61	0.80
	4	16	10.11(a)	0.63
	5	20	10.11(a)	0.51
	6	24	10.11(a)	0.42
8:1	1	8	9.61	1.20
	2	16	9.61	0.60
	3	24	9.61	0.40
	4	32	10.11(a)	0.31
	5	40	10.11(a)	0.25
	6	48	10.11(a)	0.21

(a) This value was obtained by doubling the container length and cost and assuming all other costs factors remained constant.

A comparison of data in Tables XXXIX and XL, indicates that hydrostatic extrusion of Ti-6Al-4V titanium alloy tubes appears to offer cost advantages over conventional processing at the smallest reductions and shortest lengths considered. It should be emphasized that the figures for the hydrostatic extrusions are conversion costs only, whereas those conversion costs for conventionally produced tubes, as shown in Table XL reflect the influence of selling prices. The figures used for the cost of conventionally processed Ti-6Al-4V tubes are current and do not reflect potential cost reductions as the production becomes a production item. However, it can be shown that, even if substantial cost reductions are achieved in the conventional process, the hydrostatic extrusion process remains attractive. For example, considering Tube A in Table XL, the current selling price for the starting and finished tube sizes are $40.00 per pound and $150.00 per pound, respectively. (See footnotes b and c.) If it is assumed the starting cost of Ti-6Al-4V alloy tubing is $10.00/lb and the final cost is $20.00/lb, the conversion cost of Tube A is calculated to be $2.26/ft. However, the cost of producing the same size tubing by the hydrostatic extrusion process is estimated to be as low as $0.56/ft depending on the length produced (see Table XXXIX). The cost advantages of hydrostatic extrusion should be accentuated if very thin walled tubing was considered, since these items are particularly difficult to produce using conventional techniques. For example, Tube B, produced experimentally on this contract, could not be purchased commercially on fixed-price basis.

It is also of interest to point out that the analysis shows that under certain conditions, the hydrostatic extrusion technique could convert unalloyed titanium tubing at or below the estimated cost of conventionally produced unalloyed tubing. Generally, to

TABLE XL. ESTIMATED CONVERSION COSTS FOR PRODUCING TITANIUM AND Ti-6Al-4V TUBING BY CONVENTIONAL TECHNIQUES

	Tube A (3:1 Reduction)		Tube B (3:1 Reduction)		Tube C (4:1 Reduction)		Tube D (8:1 Reduction)	
	Starting Size	Finishing Size	Starting Size	Finishing Size	Starting Size	Finishing Size	Starting Size	Finishing Size
OD, in.	1.00	0.750	0.750	0.625	1.00	0.875	1.00	0.625
ID, in.	0.736	0.634	0.606	0.569	0.875	0.843	0.640	0.561
Wall, in.	0.132	0.058	0.072	0.028	0.062	0.016	0.180	0.032
Wt, lb/ft	0.69	0.24	0.294	0.098	0.346	0.0874	0.889	0.11
Material								
Commercially Pure Titanium								
Selling Price, dollars/ft	5.57(a)	2.08(a)	2.46(a)	1.25(a)	2.83(a)	1.32(a)	6.73(a)	1.31(a)
Conversion Cost, dollars/ft	0.22		0.43		0.61		0.47	
Ti-6Al-4V Titanium Alloy								
Selling Price, dollars/ft	27.60(b)	36.00(c)	47.04(d)	17.64(e)	13.87(b)	13.11(c)	35.50(b)	16.50(c)
Conversion Cost, dollars/ft	26.80		1.96		9.64		12.06	

(a) Based on published price list.
(b) Based on oral quote of $40.00/lb.
(c) Based on oral quote of $150.00/lb.
(d) Based on oral quote of $160.00/lb.
(e) Available only on a best-effort basis, therefore, the cost was based on an estimate of $180.00/lb.

compete with conventional processing it appears that the hydrostatic extrusion process must reduce the material at 4:1 in lengths approaching 6 feet long. Further, comparing the conversion costs for unalloyed tubing between Tubes A and B and between Tubes C and D, indicates that as the tube wall becomes thinner the costs of the conventional process increase significantly. The hydrostatic extrusion process costs should be relatively insensitive to the final wall thickness and thus should be able to compete even more favorably in the production of thin-walled tubing.

As pointed out previously, this analysis was not meant to be definitive, but certainly establishes a trend and indicates that the hydrostatic extrusion process should be further investigated as a tube-producing process. The process economics of hydrostatic extrusion will be further analyzed in a design study of a production hydrostatic extrusion press, a program currently in process at Battelle under Air Force Contract No. F 33615-67-C-1434.

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