IR-8-198 (VI)

DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS

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BATTELLE MEMORIAL INSTITUTE
COLUMBUS LABORATORIES

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

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FOREWORD

This Interim Engineering Progress Report covers the work performed under Contract No. AF 33(615)-1390 from 28 February 1966 through 31 May 1966. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

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

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

ABSTRACT

Development of the Manufacturing
Capabilities of the
Hydrostatic Extrusion Process

R. J. Fiorentino
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Battelle Memorial Institute

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

During this interim report period, investigation of critical process variables was continued for cold hydrostatic extrusion of AISI 4340 steel, 7075-0 Al, and Ti-6Al-4V. Also, initial attempts were made to extrude beryllium at room temperature. In addition, a pressure transducer, designed and fabricated under this program, for use at high pressures and elevated temperatures was calibrated. Some of the important cold hydrostatic extrusion results include

(1) extrusion of Ti-6Al-4V alloy rounds at a ratio of 3.33:1 with surface finishes in the order of 25 microinches, rms, made possible by an improved lubrication system
(2) extrusion of AISI 4340 steel tubing at a ratio of 3.77:1 (74 percent area reduction) with excellent surface finishes
(3) extrusion of beryllium at a ratio of 2.5:1 (60 percent area reduction) with partial success, indicating that die design modifications may help to overcome surface-cracking problems.

Another phase of the program initiated during this report period was the fabrication of beryllium wire by the hydrostatic process; the major effort in this area included tooling design and material procurement. It is expected that extrusion and drawing of beryllium wire will be started during the next interim report period.

PUBLICATION REVIEW

Approved by: ______________________
A. M. Sabroff, Chief
Metalworking Research Division

Approved by: ______________________
P. J. Rieppel, Manager
Department of Process and Physical Metallurgy

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INTRODUCTION

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

<u>Phase I. Process-Development Studies</u>

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

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

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

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

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

Phase II. Process-Application Studies

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

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

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

Experimental trials to study the critical process variables for hydrostatic extrusion (Part 1 of Phase I) and fabrication of tubing (Part 3 of Phase II) were continued during this report period. Also, initial attempts to extrude beryllium (Part 2 of Phase I) were made. In addition, preparations for hydrostatic extrusion at elevated temperatures were completed. Important variables investigated included lubrication, stem speed, extrusion ratio, die design, and billet surface finish. Information for certain of the variables was obtained for AISI 4340 steel, 7075-0 aluminum, and Ti-6Al-4V titanium alloy.

In addition to extrusion trials, extrusions produced during the fifth interim report period were evaluated. Also, tool design and material procurement preparatory to experiments designed to fabricate wire (Part 2 of Phase II) were initiated.

EQUIPMENT AND EXPERIMENTAL PROCEDURE

Extrusion Tooling

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

Materials

Except for beryllium, billet materials used during this report period were described in Interim Report No. 1[3]. The beryllium billets were made from Brush Beryllium S-200-C powder grade containing 98.9 percent Be and 1.54 percent BeO. The mechanical properties of the as-received beryllium were reported to be:

51,200 psi ultimate strength
36,900 psi yield strength (0.2 percent offset)
2.5 percent elongation

Lubricants and Coatings

Billet lubricants and coatings used during this report period are listed in Table 1. In addition to lubricants applied directly to the billet surface, some billets were first pretreated with special coatings before the lubricants were applied. One coating, C2, is a fluoride-phosphate chemical-conversion coating and was previously described[1]. Coating C3 is a special anodized coating developed at the Watervliet Arsenal[5]. Coating C4 is a diffused nickel plating produced at Battelle by using conventional plating procedures followed by vacuum annealing to diffuse the nickel into the billet material.

Fluids

Most of the trials were made with castor oil as the fluid media. However, water, polyethylene glycol, and a polyphenyl ether were used in a few trials. Both castor oil and polyethylene glycol were previously used[3]. The polyphenyl ether (a mixed, isomeric, five-ring type) is a commercial product developed for use in high-temperature hydraulic, heat-transfer, and lubricant applications, and is one of the fluids which will be evaluated for use at elevated temperatures. However, the fluid was used at room temperature for extrusion of Ti-6Al-4V for reasons discussed later. The kinematic viscosity of the fluid is 363 cs at 100 F.

COLD HYDROSTATIC EXTRUSION OF 7075.0 ALUMINUM ROUNDS

7075-0 aluminum alloy is known for its tendency to crack during conventional hot extrusion when excessive extruded surface temperatures are encountered. To prevent cracking, the exit extrusion speeds are kept as low as one or several feet per minute. However, as mentioned in the fifth interim report[4], sound extrusions can be produced at exit speeds of about 3000 ipm by hydrostatic extrusion.

An area which requires additional improvement in hydrostatic extrusion, however, is billet lubrication. Stick-slip occurs during momentary lubrication breakdown. This causes high breakthrough pressure peaks and sometimes causes surface cracking of the extrusion during the "slip" portion of stick-slip.

Lubrication Systems

The experimental data developed in the evaluation of several new lubrication systems (hydrostatic fluid + billet lubricant) are given in Table 2. Since castor oil and L17 billet lubricant was the most effective system found in the previous studies, Trial 347

TABLE 1. BILLET LUBRICANTS AND COATINGS EVALUATED IN CURRENT HYDROSTATIC EXTRUSION PROGRAM

Lubricant	Coating	Source	Description	Billet Material Treated
L8	--	Battelle	10 w/o graphite in commercial self-drying, semihydrogenated gum resin	7075Al and Ti-6Al-4V
L17	--	Battelle	20 w/o MoS_2 in castor wax	7075Al, AISI 4340, Ti-6Al-4V, Be
L22	--	Battelle	20 w/o MoS_2 in polyethylene glycol, m w 1000	7075Al
L26	--	Battelle	20 w/o I_2 in a chlorinated terphenyl (42% chlorine)	Ti-6Al-4V
L31	--	Commercial	Fluorocarbon telomer	Ti-6Al-4V
L34	--	Battelle	50 w/o MoS_2 in castor wax	Ti-6Al-4V
L35	--	Battelle	20 w/o graphite in castor wax	Ti-6Al-4V
L39	--	Battelle	20 w/o I_2 and 20 w/o MoS_2 in chlorinated terphenyl (42% chlorine)	Ti-6Al-4V
L45	--	Commercial	Microfine low-density polyethylene resin	Ti-6Al-4V
L46	--	Battelle	50 w/o MoS_2 in low melting castor wax	7075Al
L47	--	Battelle	50 w/o MoS_2 in carbowax	
L48	--	Battelle	20 w/o MoS_2 in castor wax plus metallic lead, copper flake, and graphite	AISI 4340
L49	--	Battelle	20 w/o graphite in fluorocarbon telomer	Ti-6Al-4V
L50	--	Battelle	20 w/o graphite in microfined low-density polyethylene resin	Ti-6Al-4V
L51	--	Commercial	Metallic lead, copper flake, and graphite	7075Al
--	C2	Battelle	Fluoride-phosphate coating	Ti-6Al-4V
--	C3	Watervliet Arsenal	Anodized coating	Ti-6Al-4V
--	C4	Battelle	Diffused nickel-plating	Ti-6Al-4V

was used as the base line for comparison with the other systems. A comparison of the data indicates that none of the new lubrication systems evaluated appeared to be better than castor oil and L17 lubricant. For five of the new lubricant systems the trials were stopped before extrusion breakthrough occurred. This was because either relatively excessive pressures were obtained or, in the case of Trial 346, because one pressure-recording instrument falsely indicated a high pressure. In Trials 345 and 365 extrusions were produced with pressures approximating those obtained with L17 lubricant (Trial 347). Although the extrusions produced in Trials 345 and 347 were of generally good quality, lubrication breakdown occurred as evidenced by stick-slip during runout and some areas of poor extruded surfaces. In the case of Trial 365, the combination of polyethylene glycol and L47 lubricant decreased the severity of stick-slip (as compared to castor oil in Trial 345), but did not eliminate it.

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

Die Angle	45 degrees	Stem Speed	20 ipm
Extrusion Ratio	20:1	Billet Surface Finish	60 to 100 microinches, rms

Item	Trial	Hydrostatic Fluid	Billet Lubricant	Extrusion Pressure, 1000 psi: Breakthrough Stem	Breakthrough Fluid	Runout Stem	Runout Fluid	Length of Extrusion, inches	Comments
1	347	Castor oil	L17	162.0	152.0	144.0	130.0	65-1/2	Severe stick-slip followed by uniform Pr
2	380	Castor oil	L8	180.0	172.5	--	--	0	P_b not reached; stopped at indicated pressure
3	343	Water	L22	234.0	213.0	--	--	6	P_b not reached; die broke
4	344	Water	L46	195.0	186.0	--	--	0	P_b not reached; stopped at indicated pressure
5	346	Castor oil	L46	168.0	144.0	--	--	0	P_b not reached; stopped at indicated pressure prematurely because of false high pressure reading
6	365	Polyethylene glycol	L47	165.0	154.5	143.0	136.5	62-1/2	High P_b peak; moderate stick-slip
7	345	Castor oil	L47	165.0	156.5	141.0	130.5	44	High P_b peak; severe stick-slip
8	356	Castor oil	L51	202.0	187.5	--	--	0	P_b not reached; stopped at indicated pressure

It is expected that additional lubricants will be investigated during the next report period.

Extrusion Evaluation

Several of the 7075-0 aluminum extrusions produced during the last interim report period were examined to evaluate extruded product quality. Surface roughness and hardness measurements were determined.

As indicated in Table 3, extruded surface quality of 7075-0 aluminum rounds showed little dependency on extrusion conditions when evaluated by surface roughness measurements. The spread in surface finish obtained over the entire range of extrusion conditions shown is small. Of particular significance is the large improvement in surface generally obtained as a result of hydrostatic extrusion. The fact that considerable variation in extrusion variables can be permitted without significantly affecting surface quality will be important in commercial application of the hydrostatic extrusion process.

TABLE 3. SURFACE ROUGHNESS OF 7075-0 ALUMINUM ROUNDS HYDROSTATICALLY EXTRUDED UNDER VARIOUS CONDITIONS

Die Angle 45 degrees
Fluid Castor oil

Trial	Extrusion Conditions: Extrusion Ratio	Stem Speed	Lubricant	Surface Roughness, microinches, rms: Before Extrusion	After Extrusion
249	20	20	L11	270	10-20
297	20	20	L11	300	40-90
283	20	20	L11	420-540(a)	70-120
281	20	20	L17	400-500(a)	40-70
319	40	20	L17	380-520(a)	30-60
322	60	20	L17	350-500(a)	30-60
309	20	20	L17	100-250	20-30
310	20	80	L17	100-120	20-40
318	40	20	L17	45-65	50-120
324	60	20	L17	60-100	30-50

(a) Surface grit-blasted followed by vapor-blasting.

Hardness measurements made for extrusions made at a constant extrusion ratio showed no variation in hardness regardless of lubricant, stem speed, or type of extrusion curve variations. The increase in hardness obtained with increased area reduction is shown below:

Material Condition	Reduction in Area, percent	Vickers Hardness Number
As-received	--	90
Extruded at 20:1	95.0	100
Extruded at 40:1	97.5	115
Extruded at 60:1	98.3	120

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

Effort is being continued toward improving lubrication for cold hydrostatic extrusion of Ti-6Al-4V titanium alloy. As discussed in Report V[4], the problems of stick slip and die wear have been encountered with the lubrication systems evaluated previously. The results obtained with new lubrication systems are given in the following section.

Lubrication Systems

The experimental data obtained in the evaluation of several new lubrication systems for Ti-6Al-4V are given in Table 4.

The most promising system developed so far centers around an anodized coating, C3, used in conjunction with Lubricant 17 and castor oil as the fluid medium. The anodized coating was developed by Watervliet Arsenal[5] primarily to improve wear resistance of titanium and has been designated as "titanium hardcoat" by the developers.

The results with C3 coating are given in Items 3 and 4 of Table 4. In Trials 368 and 374 (3.33:1 ratio, 6 ipm stem speed, L17 lubricant), Ti-6Al-4V was extruded with excellent surface finishes, and without any stick-slip during the runout stroke. Only moderate breakthrough pressure peaks (10,000 to 15,000 psi) were encountered at the outset as compared to 25,000 psi obtained with some other lubrication systems. The surface finish obtained was in the order of 25 and 20 to 40 microinches, rms, in the longitudinal and transverse directions, respectively. Furthermore, because no metal-to-metal contact occurred between the die and titanium, no measurable die wear or scoring was obtained. Figure 1 clearly shows the influence of coating C3 on extruded surface quality.

An excellent surface finish was also obtained under similar extrusion conditions but at a stem speed of 20 ipm (Trial 369).

In Trial 376, the extrusion ratio was increased to 4:1. The titanium alloy was extruded with only moderate stick-slip during runout and without the need to preheat the fluid and die, which was the case in Trial 193 of the previous program[1]. However, the extruded surface contained score marks over the back half of the extrusion, indicating lubrication breakdown. The absence of score marks on the tapered surface of the billet, however, indicates that the lubrication system is breaking down only at or very near to the die land. Small transverse cracks were also observed at periodic points along the extruded surface. The crack spacings may be associated with the stick-slip cycles occurring during runout.

In Trial 372, the C3 coating was used in conjunction with L45 lubricant. Extrusion pressure and the shape of the extrusion curve were about the same as that obtained for L45 lubricant and C2 coating (Trial 360). However, the extruded surface quality was considerably better with the C3 than it was with the C2 coating. Also, although appreciable die wear occurred with the C2 coating, essentially no wear was noted with the C3 coating.

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

Die Angle 45 degrees Billet Surface Finish 60-100 microinches, rms
Fluid Castor oil

ial	Extrusion Ratio	Stem Speed, ipm	Billet Lubrication Coating	Billet Lubrication Lubricant	Extrusion Pressure, 1000 psi Breakthrough Stem	Breakthrough Fluid	Runout Stem	Runout Fluid	Length of Extrusion, inches	Comments
5	3.33	6	None[(a)]	L17	239.0	216.0	232.0	210.0	6-7/8	Slight P_b peak; increasing severity of stick-slip duri
7	3.33	6	C4	L17	257.0	230.0	230.0	207.0	5-1/2	High P_b peak; severe stick-slip; extrusion and die br
8	3.33	6	C3	L17	230.0	210.0	219.0	198.0	8-1/2	Moderate P_b peak; uniform P_r
4	3.33	6	C3	L17	223.0	206.0	207.0	195.0	9-3/4	Moderate P_b peak; uniform P_r
9	3.33	20	C3	L17	228.0	212.0	218.0	201.0	11-1/8	Moderate P_b peak; uniform P_r increasing slightly tov
6	4.0	6	C3	L17	271.0	242.0	242.0	222.0	9	High P_b peak; moderate stick-slip; small transverse
2	3.33	6	C3	L45	243.0	218.0	216.0	196.0	9-1/2	High P_b peak; slight stick-slip followed by uniform
9[(b)]	3.33	6	C3	L8	272.0	245.0	--	--	0	P_b peak not reached; stopped at indicated pressure
8	4.0	6	C3	L8	275.0	247.0	--	--	0	P_b peak not reached; stopped at indicated pressure
4[(c)]	3.33	6	None	L26	152.0	114.0	--	--	0	P_b peak not reached. Trial stopped at indicated pre where fluid apparently solidified.
2	3.33	6	C2	L31	248.0	225.0	226.0	205.0	9-1/8	High P_b peak; moderate stick-slip followed by unifo
3	3.33	20	C2	L31	250.0	226.0	224.0	203.0	11-3/8	High P_b peak; uniform P_r
8	3.33	6	C2	L34	242.0	220.0	232.0	211.0	5-1/2	Slight P_b peak; increasing severity of stick-slip duri
9	3.33	6	C2	L35	238.0	213.0	230.0	207.0	4-3/4	Slight P_b peak; moderate stick-slip
6	3.33	6	None	L39	268.0	240.0	--	--	0	P_b peak not reached; stopped at indicated pressure
1	3.33	6	None	L39	276.0	242.0	--	--	0	P_b peak not reached; stopped at indicated pressure
0	3.33	6	C2	L45	242.0	222.0	221.0	197.0	9-7/8	High P_b peak; P_r increased and then leveled off
1	3.33	20	C2	L45	241.0	219.0	219.0	198.0	10-3/4	High P_b peak; P_r increased and then leveled off
3	3.33	20	C2	L49	226.0	210.0	208.0	194.0	11-1/8	High P_b peak; P_r increased and then leveled off
)	3.33	20	C2	L50	249.0	225.0	223.0	200.0	10-1/8	High P_b peak; P_r increased and then leveled off

surface was roughened by grit blasting followed by vapor blasting.
from Trial 378 was used in Trial 379.
364 was made with polyphenyl ether fluid.

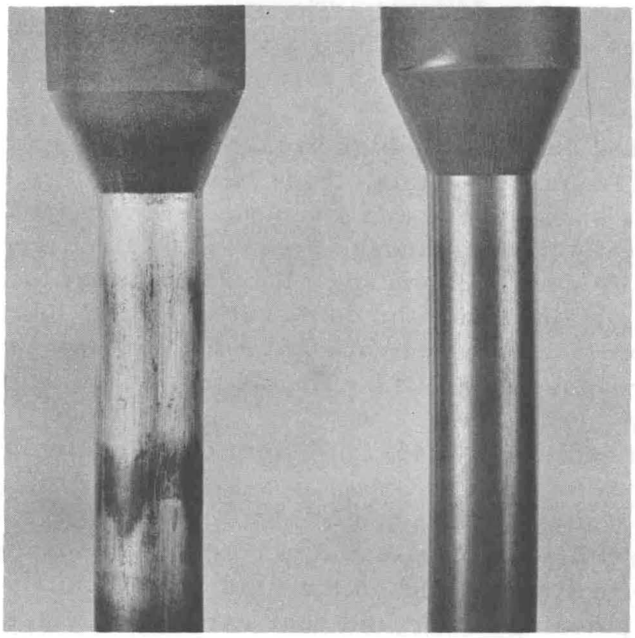

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FIGURE 1. COMPARISON OF SURFACE FINISHES ON COLD HYDROSTATIC EXTRUSIONS OF Ti-6Al-4V MADE AT A RATIO OF 3.33:1

	Trial 375	Trial 368
Lubrication System	(L17 lubricant alone)	(L17 lubricant + C3 anodized coating)
Surface Finish, microinches, rms (transverse)	120 - 150	20 - 40

By comparison, none of the other lubrication systems indicated in Table 4 performed as well as the combination of L17 lubricant and C3 coating. The diffused nickel-plate coating, C4, evaluated in Trial 367 did not perform satisfactorily, although Shapiro and Gisser(6) found this to reduce the friction coefficient and minimize stick-slip for commercial-purity titanium in a sliding friction-stick/slip type of test.

In previous studies(4), the fluoride-phosphate coating, C2, was found to be effective and it was considered worthwhile to evaluate this coating further in conjunction with several promising lubricants listed below:

Lubricant	Description
L31	Fluorocarbon telomer
L45	Low-density polyethylene
L49	20 wt percent graphite in L31
L50	20 wt percent graphite in L45
L34	50 wt percent MoS_2 in castor wax
L35	20 wt percent graphite in castor wax

Two trials were made with L31 lubricant. In one case, moderate stick-slip followed by uniform extrusion occurred during runout. The other trial with L31 gave a uniform runout. Somewhat similar results were obtained with L45 lubricant, although moderate stick-slip occurred during both trials, with uniform runout after the initial stick-slip.

For both L31 and L45 lubricants, high breakthrough pressures occurred at the beginning of extrusion. To minimize this, these lubricants were modified by adding 20 wt percent graphite as shown above and given the new designations L49 and L50. With L49 (Trial 373), the fluid breakthrough pressure was reduced by about 7 percent and the runout pressure by almost 5 percent. It turns out that these pressures are in the same order as those obtained with the combination of L17 lubricant on C3 coating. However, the extruded surface obtained with L49 + C2 was heavily scored whereas an excellent surface was produced using L17 + C3, as mentioned previously.

With L50 (graphite addition to L45), no effect on extrusion pressures was obtained (Trial 370).

The two remaining lubricants evaluated in conjunction with C2 coating (L34 and L35) were relatively ineffective. Although the fluid breakthrough pressure peaks were relatively low, stick-slip during runout and poor extruded surfaces were obtained, indicating lubrication breakdown.

Some of the iodine-containing lubricants evaluated previously[4] showed some promise of reducing stick-slip but were not effective in improving extruded-surface quality or in reducing the wear. The iodine addition was intended to react chemically with the bare billet surface to produce a compound which would offer less frictional resistance than the Ti-6Al-4V alloy itself. It was thought that such lubricants might be improved by adding a solid-film lubricant such as MoS_2 to assist in preventing metal-to-metal contact. In this connection L39 lubricant, which contained 20 wt percent MoS_2 and 20 wt percent iodine in chlorinated terphenyl carrier, was prepared and applied to the as-machined billet surface. In two attempts (Trials 366 and 371), extrusion breakthrough was not achieved although fluid pressures in the order of 240,000 psi were reached.

Another attempt was made with an iodine-containing lubricant, L26, in Trial 364. In this case, the hydrostatic fluid used was a polyphenyl ether which was intended to assist in the lubrication process by acting as a charge-transfer medium to facilitate formation of titanium diiodide, the desired lubricating compound. However, the true effectiveness of this lubrication system was not determined because, at about 114,000 psi, the fluid apparently solidified. The system may be tried again but at elevated temperatures where the fluid would not be as viscous as it was at room temperature.

COLD HYDROSTATIC EXTRUSION OF TUBING

Efforts were continued in the cold hydrostatic extrusion of tubing from both AISI 4340 steel and 7075-0 aluminum. The mandrel tooling arrangement used was similar to that described previously[4] with some modifications. The mandrel taper was increased from 0.001 inch to 0.005 inch over the 8-inch tapered section; also, the lead end of the mandrel was rounded with a 1/8-inch radius. The increase in taper was intended to eliminate the problem of "sticking" which occurred previously during extrusion of AISI 4340 tubing. The extrusion data obtained with the modified mandrel are given in Table 5.

AISI 4340 steel tubing with excellent surface quality was extruded at reduction ratios of 2.58:1 and 3.77:1 (61 and 74 percent reduction in area, respectively). No tube sticking occurred on the mandrel during extrusion, indicating that the modified mandrel design was effective. Examples of tubing produced at the two extrusion ratios are shown in Figure 2.

An attempt (Trial 357) was made to extrude AISI 4340 tubing at the next highest extrusion ratio (7:1) as determined by the die sizes that were available. Prior to this, the highest ratio attempted and achieved with this material by hydrostatic means was 6:1 for extrusion of solid rounds. At 7:1, tubing was not extruded at a fluid pressure of about 250,000 psi, the point at which the trial was halted and the maximum design pressure of the container. A plot of pressure versus ln (extrusion ratio) for tubing indicates that the runout fluid pressure for a 7:1 ratio should be in the order of 230,000 psi. It appears that it will be possible, therefore, to extrude tubing at 7:1 with the present tooling provided the breakthrough fluid pressure can be lowered to 250,000 psi or less.

Some 7075-0 aluminum tubing was also extruded with the modified mandrel at ratios of 3.77, 7, and 12.2:1. The extent of stick-slip increased as the extrusion ratio was increased. Although a stem speed of 80 ipm eliminated stick-slip during runout in the extrusion of 7075-0 Al solid rounds at a ratio of 20:1, it apparently did not have the same effect with tubing, as seen from Trial 350.

Some transverse cracks were observed on the outer surface of the tubing extruded at ratios of 7 and 12.2:1. The location of the cracks along the tubing length suggests that they were associated with the periodicity of stick-slip. The cause of cracking may be due partly to inertial effects and partly to excessive surface temperatures developed during the slip portion of stick-slip.

DIE DESIGN

Some effort is being directed toward die design with the aim of reducing extrusion pressures. One important variable that already has been studied in the current program is die angle[3, 4]. Another factor which may have an effect on pressure is the configuration of the entry surface apart from the entry angle itself. One concept that has been investigated is the idea of a grooved entry surface. The thought here is that the groove would be occupied by the hydrostatic fluid during extrusion, thereby reducing the amount of billet-die contact area. In this case, the die is "roughened" with a groove to function in a manner similar to a roughened billet which drags fluid in at the die-billet interface. The grooved die evaluated in the program is shown in Figure 3. The groove is about 0.050 inch deep and has a 1/4-inch pitch. The peaks between the grooves are rounded to a 1/8-inch radius. The groove does not intersect the die bearing surface but stops at about 1/4 inch above it.

TABLE 5. EXPERIMENTAL DATA FOR COLD HYDROSTATIC EXTRUSION OF 4340 STEEL AND 7075 ALUMINUM TUBING

Die angle ------- 45 degrees
Fluid ------- Castor oil

Billet size ------- 1.750 OD x 0.750 ID
Mandrel ------- 0.7485 diameter at top; 0.7395 diameter at bottom

Die rifice, nches	Extrusion Ratio	Stem Speed, ipm	Billet Lubricant	Extrusion Pressure, 1000 psi: Breakthrough Stem	Breakthrough Fluid	Runout Stem	Runout Fluid	Length of Extrusion, inches	Comments
					4340 Steel				
1.237	2.58	6	L17	112.0	109.5	105.0	105.0	7 3/4	Slight P_b peak; unifo Pr
1.107	3.77	6	L17	166.5	158.0	162.0	153.5	6 7/8	Slight P_b peak; mode stick-slip
1.107	3.77	6	L48	170.0	159.0	164.0	153.0	10 1/8	Slight P_b peak; unifo Pr
1.107	3.77	20	L48	169.0	158.5	165.0	153.0	11	Slight P_b peak; unifo Pr with slight pres increase toward en
0.959	7.0	6	L48	280.0	249.0	--	--	0	P_b not reached; stop at indicated pressu
					7075 Aluminum				
1.107	3.77	20	L17	49.5	49.5	48.0	48.5	12 3/4	No P_b peak; uniform
0.959	7.0	20	L17	77.6	73.0	73.0	71.0	17 3/4	Slight P_b peak; mode stick-slip
0.875	12.2	80	L17	112.0	105.5	96.0	97.0	27 3/4	Slight P_b peak; seve stick-slip

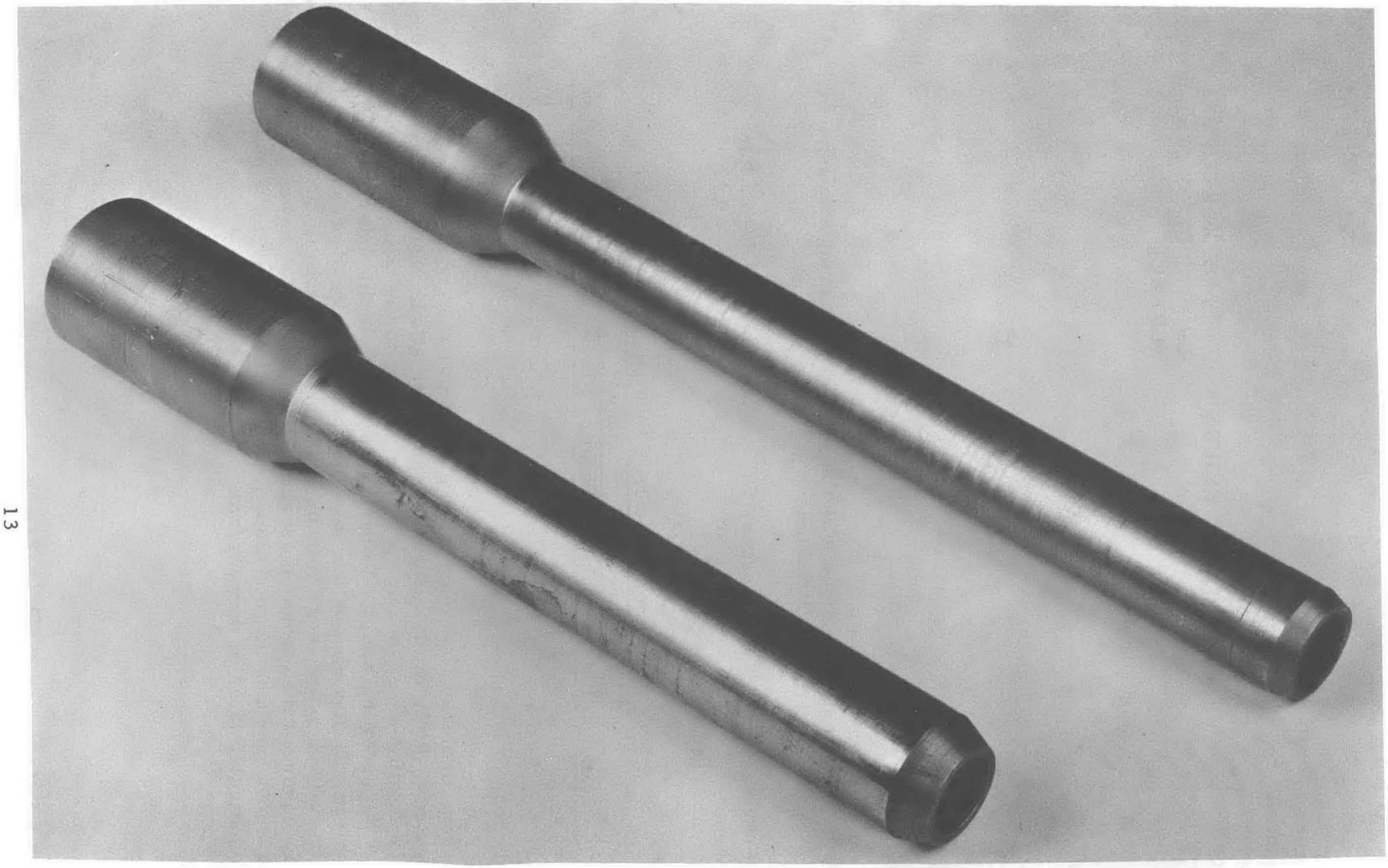

FIGURE 2. COLD HYDROSTATIC EXTRUSIONS OF AISI 4340 STEEL TUBING

Upper ---- 3.77 extrusion ratio (Trial 354).
Lower ---- 2.58 extrusion ratio (Trial 352).

FIGURE 3. DIE DESIGN WITH HELICAL GROOVE IN CONICAL-ENTRY SURFACE

The experimental results obtained with the grooved die during extrusion of AISI 4340 and 7075-0 Al are summarized below:

Die angle	45 degrees	Stem speed --- –	20 ipm
Fluid	Castor oil	Lubricant ---- –	L17
Extrusion ratio --- –	5:1		

		Extrusion Pressure, 1000 psi				
		Breakthrough		Runout		Length of
Trail	Material	Stem	Fluid	Stem	Fluid	Extrusion, inches
284	4340	244.0	220.5	--	--	3
348	7075	147.0	135.5	--	--	12-1/2

In both cases, the billet was found to have upset into the groove, only partially with the steel but completely in the case of the aluminum alloy. This indicates that the pressurized fluid itself does not provide adequate support to the billet to prevent upsetting. Part of the upsetting would, of course, be due to elastic compression of the fluid under pressure. It may also be due to some nonuniformity of pressure within the fluid itself as the fluid becomes more viscous and approaches solidification. The groove did not assist but hindered the extrusion operation. It is possible, however, that other groove configurations, perhaps more shallow in depth, might prove to be beneficial. This may be investigated later in the program.

COLD HYDROSTATIC EXTRUSION OF BERYLLIUM

Cold hydrostatic extrusion of beryllium rounds was initiated during this report period. A single attempt was made, thus far, to extrude beryllium under the following conditions:

Billet diameter	1-3/4 inches
Extrusion ratio	2.5:1
Area reduction	60 percent
Die angle	45 degrees (included)
Stem speed	6 ipm
Fluid	Castor oil
Billet lubricant	L17

	Extrusion Pressure, 1000 psi			
	Breakthrough		Runout	
Trial	Stem	Fluid	Stem	Fluid
377	142.5	137.5	134.0	129.0

Some stick-slip occurred during runout although the shape of the extrusion curve generally indicated good lubrication. Approximately 8 inches of extruded rod was obtained. Although the extrusion exhibited transverse surface cracks, the cracks were relatively small and the extrusion remained in one piece. The extrusion die used in this case was designed to effect a gradual release of the elastic stresses present in the extrusion on exiting from the die land. Additional trials will be made with dies with further modifications, and also under other extrusion conditions believed to reduce the tendency toward cracking.

In addition to this effort on extrusion of beryllium billets, work has been initiated on the fabrication of beryllium wire by hydrostatic extrusion-drawing. In this Battelle-developed process, hydrostatic pressure is exerted on the workpiece on the entry side of the die and draw stress is applied simultaneously to the workpiece on the exit side of the die.

The aim of this portion of the program is to determine the technical feasibility of producing beryllium wire down to a target diameter of 0.001 inch. The starting wire diameter will be 0.020 inch. Beryllium wire originating from both powder and cast ingot will be investigated in the study. The necessary dies and auxiliary equipment are being purchased or constructed. Brush Beryllium Company has been subcontracted to provide portions of the starting wire stock and to evaluate the fabricated wire from the standpoint of mechanical properties, dimensions, surface quality, microstructural characteristics, and deformational characteristics. Mr. H. Ll. D. Pugh, Visiting Professor at Case Institute of Technology is assisting in this portion of the program as a consultant.

FUTURE WORK

During the next interim report period it is expected that work will continue on development of lubricant systems for the cold hydrostatic extrusion of 7075 aluminum and

Ti-6Al-4V alloy. Also, work will continue on the hydrostatic extrusion of beryllium, shapes, and wire. Work will also begin on hydrostatic extrusion of selected refractory metals and alloys. In addition, it is expected that the design modifications of the elevated temperature-high pressure transducer will be completed and hot hydrostatic extrusion trials at 500 F will begin.

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