AFML-TR-67-242
PART I

PROCESS VARIABLES IN METAL EXTRUSION

Part I: Liner Friction During Extrusion

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FOREWORD

This report was prepared by the Westinghouse Electric Corporation, Astronuclear Laboratory, Pittsburgh, Pennsylvania, under USAF Contract AF 33(615)5317. The contract was administered under the direction of the Air Force Materials Laboratory (MAMP), Research and Technology Division, with Mr. Vincent DePierre as Air Force Project Engineer.

The program was conducted under the technical direction of Mr. Daniel R. Carnahan, Westinghouse Lead Engineer and Mr. Vincent De Pierre, Air Force Project Engineer. Significant contributions have been made to this program by Messrs. T. E. Jones and R. A. Sweeney, of Westinghouse, and M. Meyers and G. Saul of the Air Force Materials Laboratory.

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This technical report has been reviewed and is approved.

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ABSTRACT

Three-inch diameter billets of 1018 steel, maraging steel (300 ksi), titanium alloy (6Al-4V), In - 100, and aluminum alloy (7075-0) were extruded on an instrumented 700-Ton Experimental Extrusion Press to obtain quantitative friction data under processing conditions. Friction data are presented; effect of processing variables on friction values are discussed.

Calculated interface shear stresses for glass-coated billets were significantly lower and more uniform than bare billets for comparable processing parameters and materials. For glass-coated billets, the nose and tail values are generally higher than the center values because of lower billet temperatures in these areas which results in an increase in viscosity or solidification of glass in these areas. The center friction values (K_2) represent the glass lubrication effectiveness under uniform temperature conditions. Friction stresses ranged from 2.7 to 5.8 ksi and consumed a large portion of the working pressure.

For bare billets, friction stresses in the absence of galling decreased with temperature and speed of testing. Galling increased with processing temperature.

Need for improved lubricants and lubrication systems for hot metal extrusion was demonstrated.

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I. INTRODUCTION

In metal deformation processes, friction forces are generated at the interface between the tools and deforming materials. These forces have the following effects:

1. The total deformation loads are increased.
2. The internal structure and surface characteristics (surface finish and surface cracks) of the product are influenced.
3. Wear is produced on the tooling material.
4. Tool die life is reduced.
5. Dimensional variations are produced in the processed material.

Because of its effects, friction is considered a major variable in metalworking operations and must be controlled to optimize processing procedures for economically producing products with desired external geometry and internal structure. For effective friction control, quantitative data on the effects of other processing variables on friction are essential.

Studies have been made by both laboratory tests and metalworking operations to obtain quantitative data on friction. Although laboratory tests furnish valuable measurements on friction behavior under controlled conditions, it is difficult to simulate processing conditions (such as temperature, speed of deformation, state of stress, lubrication system and pressure) in these tests. For obtaining the desired quantitative process friction data, the metalworking process itself with proper instrumentation to separately measure deformation and friction forces is considered more useful than laboratory tests. The extrusion process has been shown (1) amenable to instrumentation for quantitative friction studies under metalworking conditions.

This report describes metal extrusions made on the Air Force Materials Laboratory 700-ton instrumented extrusion press to obtain quantitative friction data under processing conditions. Friction data are presented; effects of processing variables on friction values are discussed. Available methods and development work for minimizing friction forces during extrusion are recommended.

II. THEORY

In the forward extrusion process (Figure 1) used in this investigation, the total force necessary to produce deformation is the sum of several forces as illustrated in Figure 2 and expressed in the following equation:

$$F_t = F_d + F_{f_b} + F_{f_f} \qquad (1)$$

where F_t = total force for extrusion

F_d = force applied on the die (metal deformation force plus friction force between die and billet material during deformation)

F_{f_b} = friction force between the container and billet material

F_{f_f} = friction force between the container and follower material

Pierce (2) has derived the following relationship between container liner friction forces and other forces:

$$P_i = P_d + \frac{4KLi}{D} \qquad (2)$$

where P_i = total pressure exerted on the billet at any instant i (F_{t_i} - F_{f_f} divided by cross-section area A_o of the container liner)

P_d = die pressure (F_d/A_o)

L_i = length of the upset billet in the container liner at any instant i

D = inside diameter of container

K = average unit shear strength of the interface between the container and billet material

Equation 2 with measurements of P_i, P_d, L_i, and D during extrusion provides quantitative values of the interface friction shear stresses (K) and a basis for studying friction variations under different processing conditions.

III. EXTRUSION EQUIPMENT

The 700-ton experimental extrusion press shown in Figure 3 was used for studying friction forces generated during extrusion at the interface between the container and billet material. A detailed description of the equipment is furnished in Reference 1. The following press characteristics are pertinent to the subject container friction studies:

1. Water plus soluble oil hydraulic system with a 3000 psi accumulator.
2. Ram speed, 20 to 900 inches per minute.
3. Ram stroke, 30 inches
4. Peak capacity, 700 tons
5. Container liner (H12 Die Tool Steel, Rockwell C 46-50) I.D., 3.062 inches at room temperature and 3.072 inches at 800° F.
6. Container temperature, room temperature to 800°F.
7. Instrumentation for continuously recording on a Model 1508 Visicorder (30-millisecond response) force on the stem, force the die, and position of the stem during extrusion. A representative trace identifying data points and their identification terminology appears in Figure 4.

IV. EXTRUSION PROCEDURES

A. Billet Preparation

A 0.5 inch long 30° or 45° bevel was machined on the front or "nose" of the billets and the sharp nose edges were rounded. Both bare and glass-coated billets were extruded. Bare billets required no further preparation; the others were sandblasted, cleaned with acetone, and warmed from 170° to 190° F. before glass lubricants were applied. These billets were removed from the oven, and while hot coated by brushing with a glass suspension made in accordance with the recipe in Table VIII, Reference 1.

The heat of the billet caused the water in the suspension to evaporate leaving a glass residual coating 0.020 to 0.030 inches thick on the billet. The bottom of the billet was left uncoated. After being coated, the billet was allowed to dry at least 10 minutes prior to being transferred to the heating furnace. At the extrusion temperature the glass became liquid and the surface roughness prevented the liquid glass from flowing off the billet. The liquid film had a thickness of about 0.010 to 0.015 inches.

B. Billet Heating

Billets were heated in electric resistance furnaces in argon atmospheres and held at temperature for 60 minutes.

C. Press Calibration

All load cells and the press were calibrated. This was accomplished by utilizing the hydraulic pressure gauge as the standard and then setting the voltage on the stem to enable agreement with the hydraulic gage at maximum tonnage. After verification of the linearity and agreement between the hydraulic system and the stem, the stem became the standard and was employed as such for load cell calibrations. Further discussion on press calibration may be found in Reference 2.

D. Extrusion Practice

Billet transfer to the container was accomplished manually with tongs in six to ten seconds. A graphite block was inserted immediately behind the billet; this was followed by a tool steel block. Then the press ram was moved forward at 1 to 4 inches per second and the ram stem pushed the tool steel block and graphite billet through the container liner to the insert die in the exit end. The billet was extruded through the die opening and the back end of the extrusion was forced through by the graphite which was partially extruded. The extrusion traveled through the die and press backup tooling into a runout tube. The extrusions were removed from the runout tube and were permitted to cool in air, or if necessary, in Sil-O-Cel which enabled a slow cooling rate to be maintained concomitant with oxidation protection.

V. BILLET MATERIALS

The following materials were used for liner friction studies:

1. 1018 Steel (As Rolled Condition)
2. Maraging Steel (300 ksi) (Rolled and Annealed Condition)
3. Titanium Alloy Ti-6Al-4V (Rolled and Annealed Condition)
4. IN - 100 Nickel Base Superalloy (As Cast Condition)
5. Aluminum Alloy 7075-O.

The chemical compositions and description of the machined materials are given in Tables I and II respectively.

VI. EXTRUSION TESTS AND RESULTS

Extrusions were made of glass-coated billets to furnish quantitative data on liner friction. Processing parameters for these tests are shown in Table III. Load and billet length measurements are furnished in Table IV. Equation 2 and Table IV values were used to calculate liner friction values in Table V.

For further information and comparison with glass-coated billets, several bare billets were extruded. Processing parameters for these extrusions are given in Table VI. Test results and calculated liner friction values for bare billets are furnished in Tables VII and VIII respectively.

VII. DISCUSSION OF RESULTS

For purposes of discussion the interface shear stresses for glass-coated and bare billets are summarized in Table IX. It is evident from the listed results that glass coating of billets results in significantly lower and more uniform liner friction values than bare billets for the given processing parameters and materials. For glass-coated billets, the nose and tail friction values are generally higher than the center values. This is attributed to temperature losses at the nose and tail of the billet and a resulting increase in viscosity or solidification of the glass lubricant at these locations. To provide uniform lubrication conditions with glass, heated nose blocks and follower blocks have shown promise in reducing temperature losses at the billet nose and tail. Quantitative measurements of the effectiveness of this method will be made in future liner friction studies. The center friction values (K_2) represent the glass lubrication effectiveness under uniform temperature conditions. These values range from 2.7 to 5.8 ksi and indicate a large portion ($4KL/D$) of the working pressure in extrusion will be consumed in overcoming liner friction even under desired controlled temperature conditions. Although glass lubrication is a major step forward in reducing liner friction, more reduction in liner friction is desired to utilize a greater percentage of the working forces for useful deformation of billet materials. For this purpose better lubricants and lubrication techniques must be developed for extrusion processes.

Bare billet extrusion tests furnished the following information:

1. In the absence of galling, friction shear values decrease with increasing temperature, e.g. maraging steels and aluminum alloy 7075-0.
2. In the absence of galling, friction shear values decrease with speed, e. g. 7075-0.
3. Galling increases with temperature and varies with different materials. Galling was observed in extrusion at the following working temperatures:
   a. With 1018 steel at 1800°F, 2000°F and 2200°F.
   b. With maraging steel at 1800°F.
   c. With Ti-6Al-4V at 1550°F, 1750°F, 1850°F and 2150°F.
   d. With 7075-0 at 900°F.

Friction shear values obtained for bare billets as well as glass-coated billets can serve as a quantitative base line for evaluating effectiveness of lubricants for reducing liner friction in extrusion.

VIII. CONCLUSIONS

1. The AFML instrumented extrusion press is an effective means for testing lubricants under extrusion processing conditions.

2. Although glass lubricating techniques furnish lower interface friction shear values than those obtained with bare billets, better lubricants than glass can provide significant advances in extrusion processing.

IX. RECOMMENDATIONS

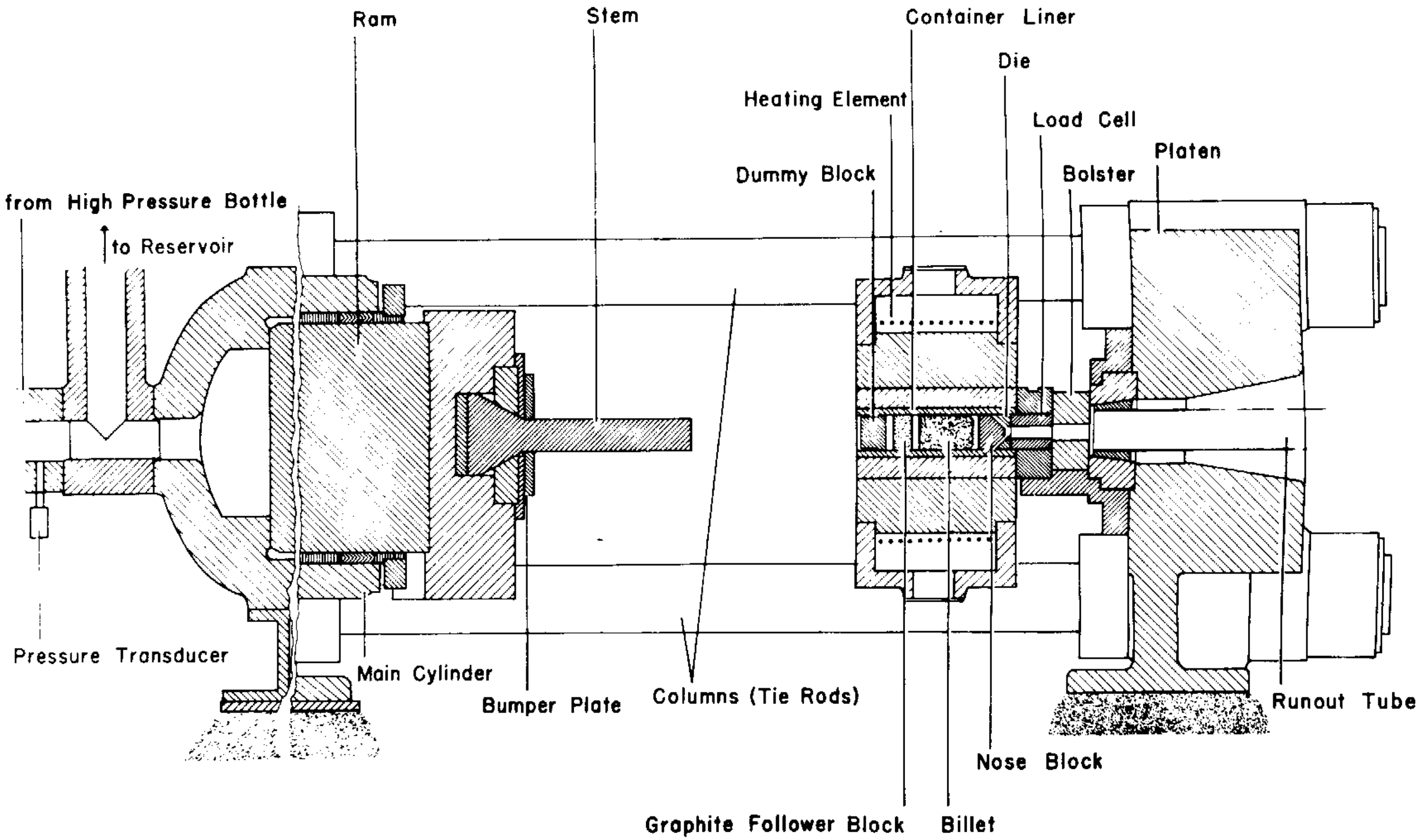
1. Development work to produce better lubricants and lubrication systems for extrusion should be continued.

2. Methods for improving present lubrication techniques should be investigated to provide more uniform lubrication conditions.

REFERENCES

1. D. R. Carnahan, D. S. Michlin, and V. DePierre. Extrusion of Refractory Metals and Superalloys. AFML-TR-66-344, December 1966.

2. C. M. Pierce, Forces Involved in the Axisymmetric Extrusion of Metals through Conical Dies. AFML-TR-67-83, May 1967.



FORWARD EXTRUSION WITH LOAD CELL

Figure 1 Schematic Illustration of the AFML Extrusion Press

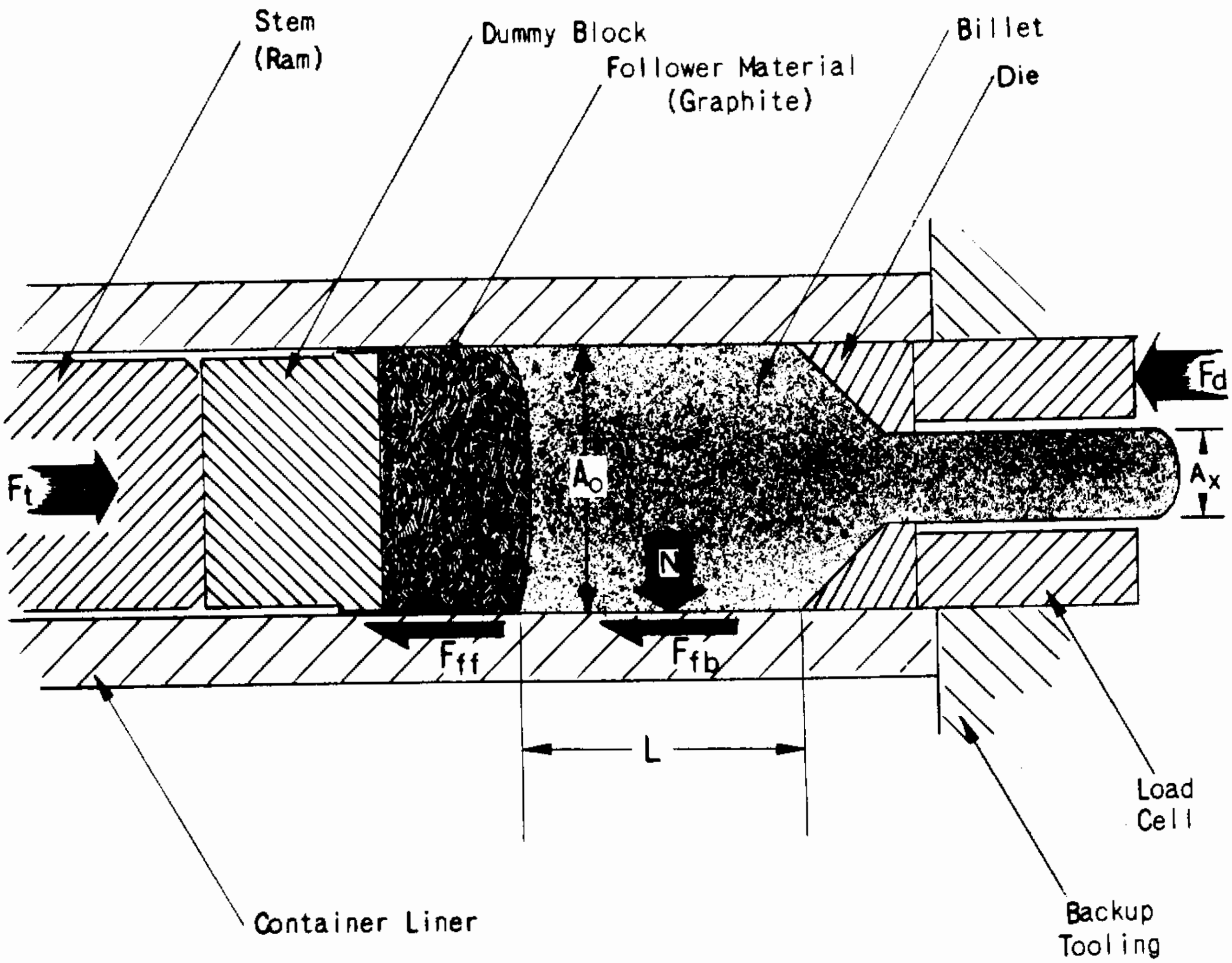


Figure 2 Schematic Illustration of Forces During Forward Extrusion

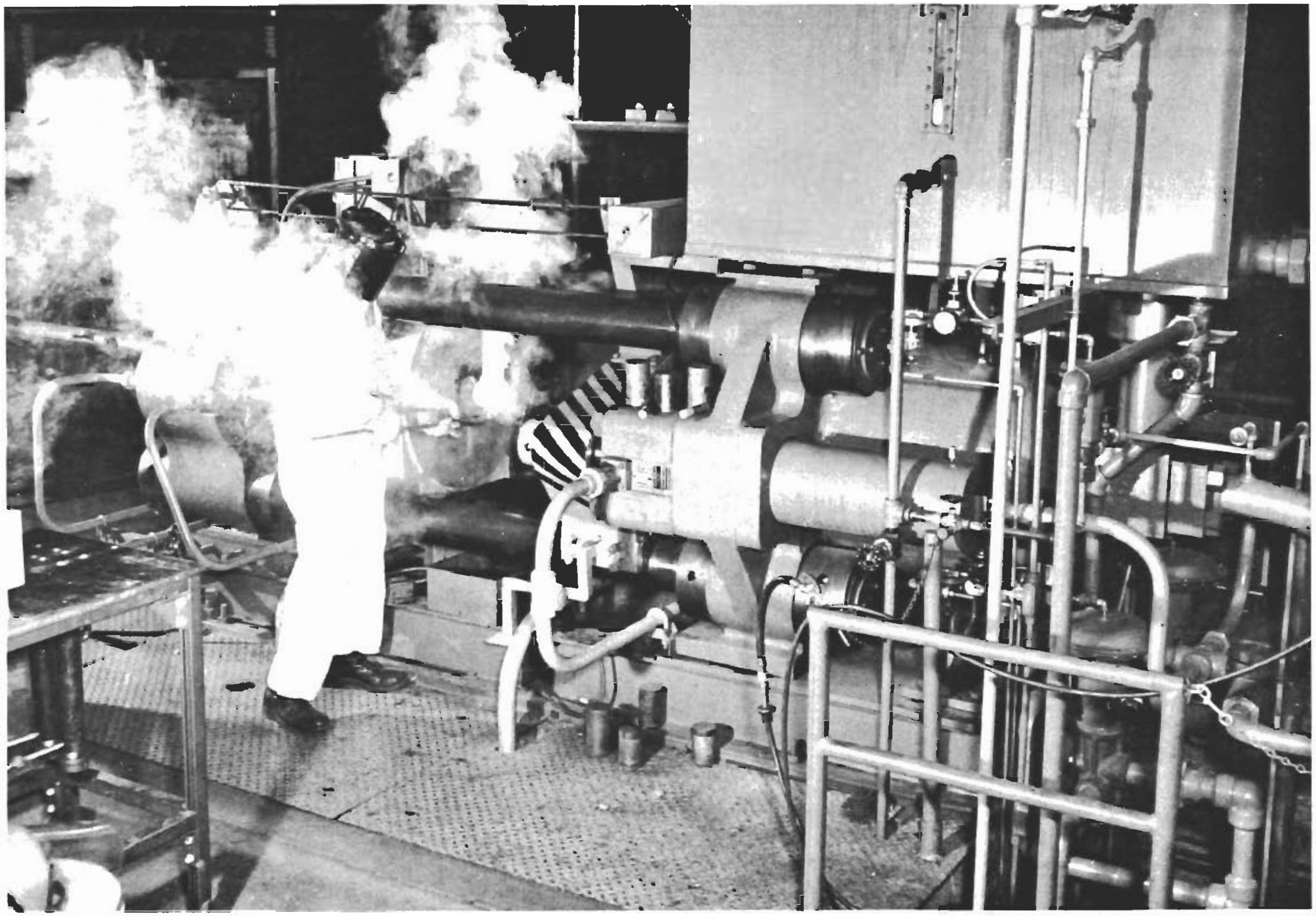


Figure 3.

AFML 700 Ton Extrusion Press

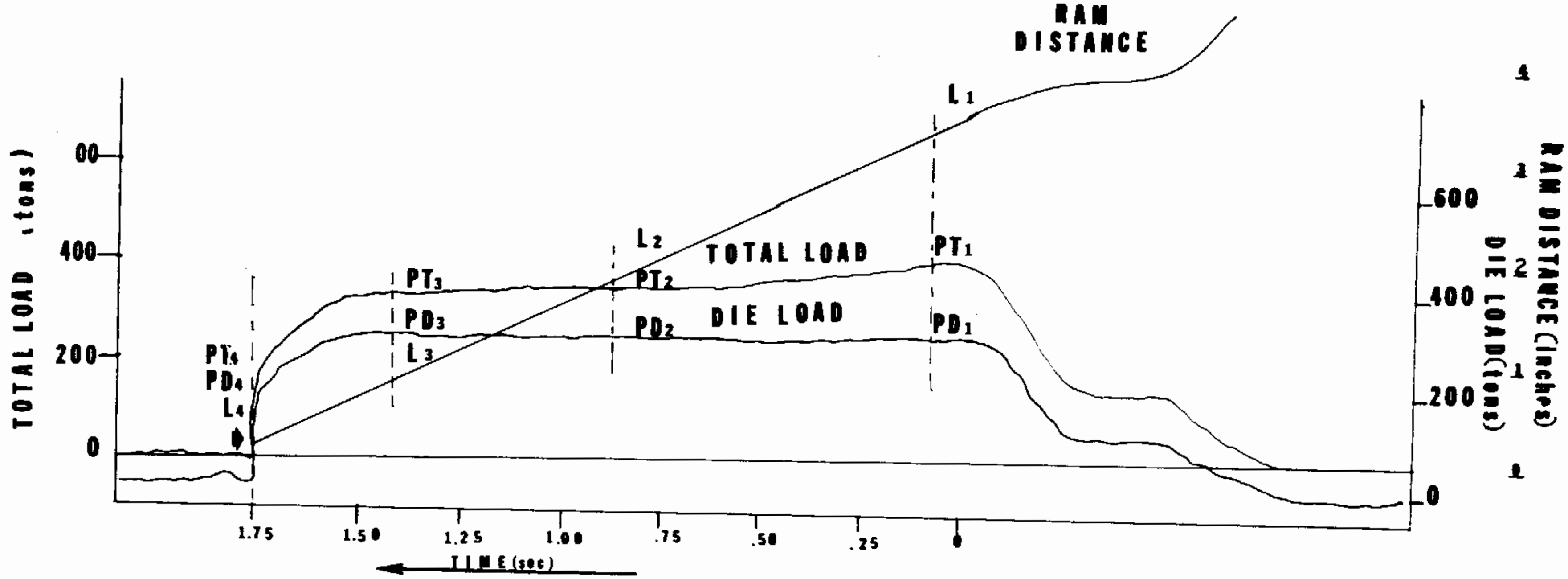


FIGURE 4

Representative Trace of Loads, Ram Velocity and Ram Travel Recorded During Extrusion..

TABLE I

CHEMICAL COMPOSITION OF MATERIALS USED FOR STUDY OF LINER FRICTION DURING EXTRUSION (1)

	1018 Steel (Actual)	Maraging Steel (Actual)	Ti-6Al-4V (Actual)	IN - 100 (Nominal)	Aluminum 7075-0 (Nominal)
C	.19	.02	.02	.18	
S	.22	.09			.50
Mn	.90	.05			.30
S	.026	.005			
P	.010				
Ni		18.12			
Mo		5.05		3.0	
Co		9.01		14.0	
Ti		.73	Bal.	5.0	
Al		.08	6.4	5.7	
Fe	Bal.	Bal.	.05		.70
Mg					2.1/2.9
Cu					1.2/2.0
V			4.3	1.0	
Zn					5.1/6.1
Cr				10.0	.18/.40
Zr				.06	
B				.015	
N			.009		
O			.189/.192		
H ppm			.39/.53		

(1) Weight Percent

TABLE II

BILLET DESCRIPTION

Extrusion Number	Overall Length (in.)	Diameter (in.)	End Shape	Weight (Lbs.)
		1018 STEEL		
2158	5.5	2.950	90° x .5"	10.4
2159	5.5	2.950	90° x .5"	10.4
2160	5.5	2.950	90° x .5"	10.4
2161	5.5	2.950	90° x .5"	10.4
2162	5.5	2.950	90° x .5"	10.4
2163	5.5	2.950	90° x .5"	10.4
2165	5.5	2.950	90° x .5"	10.4
2238	5.45	2.950	No Chamfer	10.1
2342	6.0	2.955	60° x .5"	11.6
2343	6.0	2.955	60° x .5"	11.6
2344	6.0	2.955	60° x .5"	11.6
2345	6.0	2.955	60° x .5"	11.6
2346	6.0	2.955	60° x .5"	11.6
2347	6.0	2.955	60° x .5"	11.6
2348	6.0	2.955	60° x .5"	11.6
2349	6.0	2.955	60° x .5"	11.6
2389	5.5	2.950	90° x .5"	10.3
2390	5.5	2.950	90° x .5"	10.3
2391	5.5	2.950	90° x .5"	10.3
		MARAGING STEEL (300 ksi)		
2094	5.5	2.950	60° x .5"	10.6
2114	5.626	2.950	60° x .5"	10.7
2115	5.5	2.950	60° x .5"	10.6
2126	5.625	2.950	60° x .5"	10.7
2127	5.625	2.950	60° x .5"	10.4
2133	5.625	2.950	60° x .5"	10.4
2135	5.625	2.950	60° x .5"	10.4
2197	5.625	2.950	No Chamfer	9.8
2231	6.189	2.940	60° x 2.44"	9.1
2232	6.125	2.941	60° x 2.44"	9.0
2233	4.189	2.938	No Chamfer	8.2
2250	4.125	2.941	90° x 1.06"	9.1
2252	4.75	2.942	120° x 1"	8.25
2253	4.75	2.939	120° x 1"	8.4
2254	4.75	2.937	120° x 1"	8.4
2368	6.0	2.951	90° x .5"	11.7
2369	6.0	2.950	90° x .5"	11.7
2370	6.0	2.950	90° x .5"	11.7

TABLE II - BILLET DESCRIPTION (cont'd)

Extrusion Number	Overall Length (in.)	Diameter (in.)	End Shape	Weight (Lbs.)
		TITANIUM ALLOY (6Al-4V)		
2267	6.0	2.940	60° x .5"	6.3
2268	6.0	2.940	60° x .5"	6.3
2269	6.0	2.940	60° x .5"	6.3
2270	6.0	2.940	60° x .5"	6.3
2271	5.5	2.925	60° x .5"	5.7
2316	6.0	2.940	60° x .5"	6.3
2317	6.0	2.940	60° x .5"	6.3
2318	6.0	2.940	60° x .5"	6.3
2319	6.0	2.940	90° x .5"	6.3
2320	6.0	2.940	90° x .5"	6.3
2321	6.0	2.940	90° x .5"	6.3
2323	6.0	2.940	90° x .5"	6.3
2324	6.0	2.940	90° x .5"	6.3
2325	6.0	2.940	90° x .5"	6.3
2326	6.0	2.940	90° x .5"	6.3
2362	6.063	2.947	60° x .5"	6.5
2366	6.00	2.947	60° x .5"	6.49
2384	6.00	2.940	90° x .5"	6.3
2386	6.00	2.940	60° x .5"	6.45
2387	5.75	2.946	60° x .5"	6.2
2388	5.9	2.955	90° x .5"	6.25
		IN - 100		
2021	5.1	2.937	60° x .5"	9.4
2124	5.1	2.933	60° x .5"	9.3
2125	5.1	2.938	60° x .5"	9.4
2131	5.06	2.933	60° x .5"	9.3
2132	5.06	2.938	60° x .5"	9.4
2216	5.0	2.930	60° x .5"	9.3
2217	5.0	2.934	60° x .5"	9.4
2218	4.3	2.935	60° x .5"	7.9
2219	5.0	2.935	60° x .5"	9.4
2220	5.0	2.932	60° x .5"	9.3
2221	5.0	2.935	60° x .5"	9.4
2223	5.0	2.930	60° x .5"	9.4
2224	5.0	2.930	60° x .5"	9.3
2225	4.88	2.930	60° x .5"	9.1
		ALUMINUM ALLOY (7075-O)		
2355	5.0	3.000	60° x .5"	3.5
2356	5.0	3.001	60° x .5"	3.5
2357	5.0	2.999	60° x .5"	3.5
2358	5.0	2.999	60° x .5"	3.5
2359	5.0	2.998	60° x .5"	3.5
2367	4.125	3.002	60° x .5"	2.9

TABLE III

EXTRUSION PROCESSING PARAMETERS FOR GLASS COATED BILLETS

Extrusion Number	Billet Lubrication	Extrusion Temperature (°F.)	Extrusion Reduction	Extrusion Die Angle (Degrees)	Remarks (Surface & Others)
			1018 STEEL		
2158	0010	1600	6.6:1	60°	Good
2159	7052	1600	6.6:1	60°	Good
2160	0010	2000	6.6:1	60°	Good
2161	7052	2000	6.7:1	60°	Good
2162	0010	1800	6.6:1	60°	Good
2163	7052	1800	6.6:1	60°	Good
2165	7052	2200	6.6:1	60°	Good
2346	0010	1600	4.3:1	60°	Fair, glass retention entire length
2347	0010	1600	4:1	60°	Excellent, glass retention entire length
2348	0010	1600	4.4:1	90°	Good, glass retention entire length
2349	0010	1600	4:1	90°	Excellent, glass retention entire length
			MARAGING STEEL (300 ksi)		
2094	0010	2100	8.6:1	90°	Good
2114	0010	2200	8.6:1	60°	Good
2115	0010	2200	8.6:1	90°	Good
2126	0010	2200	3.9:1	60°	Good
2127	0010	2200	8.6:1	60°	Good
2133	0010	2200	12.5:1	60°	Good
2197	0010	1600	4:1	60°	Good
2206	0010	2000	8.6:1	60°	Good
2231	0010	1700	4:1	60°	Good
2232	0010	1700	4:1	90°	Good
2233	0010	1700	4:1	90°	Good
2252	0010	1800	6.6:1	90°	Good
2368	0010	2000	9.8:1	120°	Good
2369	0010	2200	9.8:1	120°	Good
2370	0010	1800	9.6:1	120°	Good

TABLE III (cont'd)

EXTRUSION PROCESSING PARAMETERS FOR GLASS COATED BILLETS

Extrusion Number	Billet Lubrication	Extrusion Temperature (°F.)	Extrusion Reduction	Extrusion Die Angle (Degrees)	Remarks (Surface and Others)
			TITANIUM ALLOY (6Al-4V)		
2267	0010	1750	4.1:1	60°	Excellent, no glass 3" from nose
2268	0010	1750	6.1:1	60°	Excellent, no glass 4.5" from nose
2269	0010	1750	7.6:1	60°	Excellent, no glass 5.5" from nose
2270	0010	1750	10.1:1	60°	Excellent, no glass 6.5" from nose
2271	0010	1750	10.1:1	60°	Excellent, no glass 7" from nose
2316	0010	1850	4.1:1	60°	Good, glass retention entire length
2317	0010	1850	8.2:1	60°	Good, glass retention entire length
2319	7052	2150	4.1:1	60°	Good, glass retention entire length
2320	7052	2150	8.2:1	60°	Good, glass retention entire length
2321	7052	2150	10.2:1	60°	Good, glass retention entire length
2323	7052	2150	17:1	60°	Excellent, glass retention entire length
2324	0010	1550	4.8:1	60°	Excellent, glass retention entire length
2325	0010	1550	6.8:1	60°	Excellent, nò glass retention in middle
2366	0010	1800	6:1	60°	Good, no glass 5" from nose
			IN - 100		
2021	7052	2050	5.6:1	60°	Good
2124	7052	2050	5.3:1	60°	Good
2125	7052	2050	5.3:1	60°	Godd
2131	7052	2050	3.9:1	60°	Good
2132	7052	2050	3.9:1	60°	Good
2216	7052	2050	3.8:1	60°	Excellent
2217	7052	2050	3.8:1	60°	Excellent
2218	7052	2050	3.8:1	60°	Excellent
2219	7052	2050	3.8:1	60°	Excellent
2220	7052	2050	3.9:1	60°	Excellent
2221	7052	2050	3.9:1	60°	Excellent
2223	7052	2050	3.6:1	60°	Poor
2224	7052	2050	3.9:1	60°	Poor
2225	7052	2050	3.9:1	60°	Poor

TABLE IV

EXTRUSION TEST RESULTS ON GLASS-COATED BILLETS

Extrusion Number	Billet Length In Container (In.)				Total Pressure (ksi)				Die Pressure (ksi)				Ram Speed (In./Sec.)			
	L_1	L_2	L_3	L_4	P_{t_1}	P_{t_2}	P_{t_3}	P_{t_4}	P_{d_1}	P_{d_2}	P_{d_3}	P_{d_4}	V_1	V_2	V_3	V_4
								1018 STEEL								
2158	4.25	3.60	1.95	0	128	100	92	54	81	78	76	54	1.00	1.75	1.50	1.75
2159	4.35	3.25	2.85	0	122	93	86	54	85	76	76	54	1.25	1.75	1.50	1.75
2160	4.55	3.40	2.05	0	70	58	58	14	45	43	43	14	2.00	2.00	1.75	2.00
2161	4.36	3.40	2.30	0	85	66	62	8	49	47	46	8	1.50	1.75	2.00	2.25
2162	4.50	3.40	2.45	0	95	73	70	11	54	54	54	11	2.25	2.00	1.75	1.75
2163	4.55	3.65	2.50	0	81	65	63	11	55	54	54	11	1.75	2.00	2.00	1.50
2165	4.55	3.60	2.35	0	70	51	46	8	38	32	32	5	2.00	2.00	1.50	1.25
2346	4.55	4.10	3.40	0	135	105	103	14	73	72	70	14	1.50	2.25	2.25	2.50
2347	4.40	3.45	2.75	0	144	100	97	16	86	76	76	16	1.00	2.00	2.00	2.50
2348	4.50	3.90	3.15	0	127	100	97	11	68	66	65	16	1.50	2.00	2.00	2.50
2349	4.60	4.00	3.40	0	127	103	100	14	74	73	70	14	2.00	2.50	2.50	3.00
								MARAGING STEEL (300 ksi)								
2094	2.45	2.10	1.40	0	119	108	92	22	73	72	70	22	2.25	2.25	2.25	1.25
2114	4.50	3.10	1.45	0	95	86	78	27	68	68	68	32	2.25	2.25	2.25	1.25
2115	4.20	3.40	1.75	0	124	108	105	16	72	72	78	27	2.00	1.75	1.75	1.25
2126	4.70	3.50	2.10	0	70	62	54	5	46	46	46	5	2.50	2.50	2.25	1.50
2127	4.60	3.60	2.20	0	96	86	81	8	74	73	72	8	2.25	2.25	2.00	1.25
2133	4.40	3.75	3.10	0	139	138	135	11	85	84	82	11	1.50	2.00	2.00	2.00
2197	3.40	2.75	.95	0	146	122	112	16	86	85	82	16	1.50	1.50	1.50	2.00
2231	3.55	2.65	2.05	0	97	97	92	0	84	88	86	0	3.00	2.00	2.25	2.50
2250	3.60	2.70	1.45	0	162	148	136	32	96	93	90	11	3.00	2.25	2.00	1.25
2368	4.75	4.30	1.45	0	144	134	140	5	111	107	113	5	2.00	2.00	1.75	3.00
2369	4.65	3.70	1.65	0	122	112	116	22	97	96	100	22	2.50	2.50	2.25	2.00
2370	4.70	4.30	1.10	0	163	144	142	5	135	127	130	5	1.50	2.00	1.75	2.50
								TITANIUM ALLOY (6Al-4V)								
2267	4.40	3.10	2.30	0	61	54	49	5	41	39	38	5	2.75	2.75	2.75	----
2268	4.80	3.55	2.25	0	81	65	59	11	58	54	53	11	3.00	2.25	2.50	1.75
2269	4.95	3.85	3.60	0	93	78	76	22	73	68	66	19	2.75	2.50	2.50	2.50
2270	4.35	3.80	2.90	0	97	86	81	35	76	74	73	35	2.50	2.50	2.50	3.50
2271	3.95	3.50	2.85	0	115	103	97	38	88	85	84	38	2.25	2.25	2.25	2.00
2316	4.25	3.15	1.75	0	57	43	42	11	28	27	26	11	2.50	2.75	2.75	2.00
2317	4.90	3.40	2.95	0	74	65	54	16	35	35	35	16	3.00	2.50	2.50	2.50
2319	5.30	4.30	2.70	0	42	41	39	11	19	22	24	11	3.50	1.75	2.50	2.00
2320	5.00	4.25	2.85	0	66	59	54	28	35	38	38	28	2.00	2.75	2.50	2.50
2321	5.15	4.40	3.95	0	68	62	59	32	35	38	39	33	2.00	2.75	2.75	3.00
2323	4.70	3.55	2.10	0	65	54	59	111	32	34	41	86	2.50	2.25	2.00	2.50
2324	4.80	3.35	1.75	0	154	109	105	11	88	86	81	11	1.50	2.25	2.00	2.50
2325	4.75	3.90	2.85	0	146	115	109	27	99	93	95	27	1.50	2.25	2.00	2.50
2366	4.30	3.60	2.10	0	51	49	46	16	43	39	36	16	2.75	2.50	2.00	1.50

TABLE IV (cont'd)

EXTRUSION TEST RESULTS ON GLASS-COATED BILLETS

Extrusion Number	Billet Length In Container (In.) L_1	L_2	L_3	L_4	Total Pressure (ksi) P_{t_1}	P_{t_2}	P_{t_3}	P_{t_4}	Die Pressure (ksi) P_{d_1}	P_{d_2}	P_{d_3}	P_{d_4}	Ram Speed (In./Sec.) V_1	V_2	V_3	V_4
								IN - 100								
2021	2.10	1.80	1.15	0	170	143	140	5	132	116	113	5	1.50	2.25	2.50	2.00
2124	3.65	2.45	1.15	0	177	140	130	5	135	130	127	5	1.00	2.25	2.00	2.50
2125	3.65	2.40	1.40	0	184	148	143	5	146	140	138	5	.50	2.00	1.50	2.00
2131	3.60	2.20	.65	0	151	130	124	11	131	119	119	11	.75	2.50	2.00	1.75
2132	3.50	2.55	1.10	0	184	140	138	38	134	126	124	38	.75	2.25	2.25	2.50
2216	3.70	2.55	1.50	0	162	122	116	5	123	112	111	5	1.00	2.25	2.25	4.00
2217	3.55	2.70	1.40	0	177	130	124	27	134	122	116	27	1.25	2.75	2.75	2.50
2218	3.05	2.30	1.50	0	167	130	122	5	130	119	117	5	1.25	2.75	2.50	3.00
2219	3.65	2.70	1.50	0	170	146	124	5	124	115	113	5	1.25	2.50	2.50	3.50
2220	3.60	2.55	1.35	0	173	124	115	16	127	116	113	16	1.25	3.00	2.75	2.50
2221	3.60	2.35	1.50	0	175	123	122	70	136	120	120	70	1.00	2.75	2.50	2.50
2223	3.80	2.95	1.80	0	167	135	130	38	122	115	115	49	1.50	2.75	2.50	3.00
2224	3.60	2.35	1.30	0	159	119	116	16	130	113	112	16	1.50	3.00	2.75	2.50
2225	3.60	3.20	2.85	0	165	124	122	5	130	113	108	5	1.25	3.25	3.00	3.00

TABLE V

CALCULATED LINER FRICTION VALUES FOR GLASS-COATED BILLETS

EXTRUSION NUMBER	BILLET TEMPERATURE (°F)	BILLET LUBRICATION	PRESSURE RANGE (ksi) L_1	L_2	L_3	RAM SPEED (in/sec) V_1	V_2	V_3	LINER FRICTION (ksi) K_1	K_2	K_3
				1018 STEEL							
2158	1600	0010	128/81	100/78	92/76	1.00	1.75	1.50	6.1	4.6	6.4
2159	1600	7052	122/85	93/76	86/76	1.25	1.75	1.50	6.4	4.1	2.9
2160	2000	0010	70/45	58/43	58/43	2.00	2.00	1.75	4.3	3.4	5.6
2161	2000	7052	85/49	66/47	62/46	1.50	1.75	2.00	5.1	4.3	5.4
2162	1800	0010	95/54	73/54	70/54	2.25	2.00	1.75	6.8	4.3	5.1
2163	1800	7052	81/55	65/54	63/54	1.75	2.00	2.00	4.3	2.3	2.9
2165	2200	7052	70/38	51/32	46/32	2.00	2.00	1.50	5.5	4.0	4.4
2346	1600	0010	135/73	105/72	103/70	1.50	2.25	2.25	10.5	6.3	7.3
2347	1600	0010	144/86	100/76	97/76	1.00	2.00	2.00	10.1	5.4	6.1
2348	1600	0010	127/68	100/66	97/65	1.50	2.00	2.00	10.2	6.7	7.9
2349	1600	0010	127/74	103/73	100/70	2.00	2.50	3.00	8.8	5.7	6.7
				MARAGING STEEL (300 ksi)							
2114	2200	0010	95/68	86/68	78/68	2.25	2.25	2.25	9.6	9.7	5.7
2126	2200	0010	70/46	62/46	54/46	2.50	2.50	2.25	4.0	3.5	3.0
2127	2200	0010	96/74	86/73	81/72	2.25	2.25	2.00	3.6	2.9	3.3
2197	1600	0010	146/86	122/85	112/82	1.50	1.50	1.50	5.6	2.9	6.4
2231	1700	0010	97/84	97/88	92/86	3.00	2.00	2.25	2.9	2.7	2.0
2368	2000	0010	144/111	134/107	140/113	2.00	2.00	1.75	5.5	4.8	14.3
2369	2200	0010	122/97	112/96	116/100	2.50	2.50	2.25	4.0	3.4	7.5
2370	1800	0010	163/135	144/127	142/130	1.50	2.00	1.75	4.6	3.1	8.5
				TITANIUM ALLOY (6Al - 4V)							
2267	1750	0010	61/41	54/39	49/38	2.75	2.75	2.75	3.5	3.7	3.2
2268	1750	0010	81/58	65/54	59/53	3.00	2.25	2.50	3.7	2.3	2.6
2269	1750	0010	93/73	78/68	76/66	2.75	2.50	2.50	2.7	2.2	2.0
2270	1750	0010	97/76	86/74	81/73	2.50	2.50	3.50	3.8	2.5	2.1
2271	1750	0010	115/88	103/85	97/84	2.25	2.25	2.00	5.2	3.8	3.6
2316	1850	0010	57/28	43/27	42/26	2.50	2.75	2.75	5.1	3.9	7.1
2317	1850	0010	74/35	65/35	54/35	3.00	2.50	2.50	6.1	6.7	4.9
2319	2150	7052	42/19	41/22	39/24	3.50	1.75	2.50	3.3	3.4	3.1
2320	2150	7052	66/35	59/38	54/38	2.00	2.75	2.50	4.7	3.9	4.4
2321	2150	7052	68/35	62/38	59/39	2.00	2.75	2.75	4.8	4.2	3.9
2323	2150	7052	65/32	54/34	59/86	2.50	2.25	2.00	5.3	4.4	6.9
2324	1550	0010	154/188	109/86	105/81	1.50	2.25	2.00	10.6	5.25	10.7
2325	1550	0010	146/99	115/93	109/95	1.50	2.25	2.00	7.6	4.3	4.0
2366	1800	0010	51/43	49/39	46/36	2.75	2.00	1.50	1.4	2.0	3.5

TABLE V - CALCULATED LINER FRICTION VALUES FOR GLASS-COATED BILLETS (cont'd)

Extrusion Number	Billet Temperature (°F.)	Billet Lubrication	Pressure Range (ksi) L_1	L_2	L_3	Ram Speed (in./sec.) V_1	V_2	V_3	Liner Friction (ksi) K_1	K_2	K_3
				IN-100							
2124	2050	7052	177/135	140/130	130/127	1.50	2.25	2.00	8.8	3.4	1.8
2125	2050	7052	184/146	148/140	143/138	.50	2.00	1.50	8.2	2.6	3.0
2131	2050	7052	151/131	130/119	124/119	.75	2.50	2.00	4.3	3.8	6.4
2132	2050	7052	184/134	140/126	138/124	.75	2.25	2.25	11.0	4.5	9.4
2216	2050	7052	162/123	122/112	116/111	1.00	2.25	2.25	8.1	2.8	2.7
2217	2050	7052	177/134	130/122	124/116	1.25	2.75	2.75	9.6	2.3	9.4
2218	2050	7052	167/130	130/119	122/117	1.25	2.75	2.50	9.5	3.6	2.1
2219	2050	7052	170/124	146/115	124/113	1.25	2.50	2.50	9.7	8.8	5.5
2220	2050	7052	173/127	124/116	115/113	1.25	3.00	2.75	9.8	2.3	0.8
2221	2050	7052	175/136	123/120	122/120	1.00	2.75	2.50	8.4	0.4	0.7

TABLE VI

EXTRUSION PROCESSING PARAMETERS FOR BARE BILLETS

Extrusion Number	Extrusion Temperature ($^oF.$)	Extrusion Reduction	Extrusion Die Angle (Degrees)	Remarks (Surface & Others)
		1018 STEEL		
2342	1600	3.9:1	60°	Fair
2343	1600	4.1:1	60°	Good
2344	1600	4.3:1	60°	Excellent, Front 9" Fair, remainder
2345	1600	4.0:1	60°	Excellent
2389	2200	7:1	60°	Good
2390	1800	6.9:1	60°	Good, long suck-in from die back to container
2391	2000	7:1	60°	Good, long suck-in from die back to container
		MARAGING STEEL (300 ksi)		
2252	1800	9.9:1	120°	Good
2253	2000	9.9:1	120°	Good
2254	2200	10.9:1	120°	Good
2385	1600	4:1	60°	Billet stuck
		TITANIUM ALLOY (6Al-4V)		
2362	1800	6.1:1	60°	Excellent, ¼"
2384	1550	4.1:1	60°	Good
2386	1750	10.2:1	60°	Good, entire carbon follow block surrounded by flashing
2387	1850	4.1:1	60°	Good, residual billet material left in container
2388	2150	7:1	60°	Good, entire carbon follow block surrounded by flashing
		ALUMINUM ALLOY (7075-O)		
2355	600	4:1	60°	Stuck
2356	900	4.1:1	60°	Good
2357	900	8.1:1	60°	Good
2358	900	2.1:1	90°	Good
2359	600	2.1:1	90°	Good
2367	600	3.8:1	60°	Good

TABLE VII

EXTRUSION TEST RESULTS ON BARE BILLETS

Extrusion Number	Billet Length In Container (In.)				Total Pressure (ksi)				Die Pressure (ksi)				Ram Speed (In./Sec.)			
	L_1	L_2	L_3	L_4	P_{t_1}	P_{t_2}	P_{t_3}	P_{t_4}	P_{d_1}	P_{d_2}	P_{d_3}	P_{d_4}	V_1	V_2	V_3	V_4
1018 STEEL																
2342	4.3	3.30	2.65	0	161	108	91	11	75	70	67	11	1.00	2.00	2.00	0
2343	4.3	3.65	3.30	0	172	143	132	8	90	86	83	8	.75	1.50	1.50	0
2344	4.4	3.55	2.50	0	167	116	97	5	83	81	75	5	.75	1.50	1.50	0
2345	4.4	3.75	3.20	0	178	121	110	5	81	70	70	5	.50	1.75	1.75	0
2389	4.55	1.50	0.40	0	108	75	109	81	24	24	44	51	2.00	1.50	1.25	0
2390	4.35	3.45	1.65	0	175	151	118	54	50	47	46	43	1.50	1.50	1.50	0
2391	4.55	3.45	1.85	0	145	118	106	78	39	36	38	48	1.25	1.50	1.00	0
MARAGING STEEL (300 ksi)																
2252	3.30	2.35	0.80	0	193	166	158	5	130	128	132	5	1.00	.75	1.00	0
2253	3.50	3.15	1.45	0	166	144	145	5	111	107	116	0	1.50	1.50	1.00	0
2254	3.60	3.15	1.20	0	129	113	106	5	86	83	86	0	2.50	2.00	1.50	0
2385	4.38	----	----	-	199	---	---	-	84	---	---	---	STUCK	----	----	-
TITANIUM ALLOY (6Al-4V)																
2362	4.80	3.85	3.10	0	125	100	89	54	59	56	55	54	1.75	2.25	2.25	0
2384	4.45	3.40	0.85	0	193	160	123	81	86	83	83	72	.75	1.75	1.50	0
2386	4.15	2.85	2.15	0	115	120	100	81	29	31	29	40	1.25	2.00	2.25	0
2387	3.80	2.85	1.05	0	102	100	135	189	25	27	32	54	2.25	2.00	2.50	0
2388	3.90	3.10	2.05	0	185	135	111	194	58	54	51	83	2.50	2.25	2.00	0
ALUMINUM ALLOY (7075-O)																
2355	4.13	----	----	-	210	---	---	-	54	---	---	---	STUCK	----	----	-
2356	4.10	2.80	1.10	0	140	98	65	48	52	47	42	40	1.00	1.25	1.25	0
2357	3.95	2.10	0.55	0	180	101	77	59	73	59	56	54	.75	1.50	1.50	0
2358	4.05	2.40	1.35	0	124	78	51	22	26	22	19	8	1.00	2.00	2.00	0
2359	3.75	3.00	2.50	0	200	161	135	40	54	48	48	46	1.00	1.00	1.00	0
2367	3.15	2.25	0.40	0	148	100	65	22	74	62	62	55	16.00	13.50	14.00	0

(1) L_1 Represents - Billet length at maximum break-thru pressure.

(2) L_4 Represents - Distance where sharp change in die load indicates zero billet length in container.

(3) Billet length measured after removal from container liner.

TABLE VIII

CALCULATED LINER FRICTION VALUES FOR BARE BILLETS

Extrusion Number	Billet Temperature (°F.)	Pressure Range (ksi)			Ram Speed (in/sec)			Liner Friction (ksi)		
		L_1	L_2	L_3	V_1	V_2	V_3	K_1	K_2	K_3
				1018 STEEL VERSUS H - 12 TOOL STEEL						
2342	1600	161/75	108/70	91/67	1.00	2.00	2.00	15.4	8.8	7.0
2343	1600	172/90	143/86	132/83	.75	1.50	1.50	14.7	11.8	11.3
2344	1600	167/83	116/81	97/75	.75	1.50	1.50	14.6	7.6	6.6
2345	1600	178/81	121/70	110/70	.50	1.75	1.75	17.0	10.5	9.7
2389	2200	108/24	75/24	109/44	2.00	1.50	1.25	15.5	26.2	72.5
2390	1800	175/50	151/47	118/46	1.50	1.50	1.50	22.2	23.1	33.9
2391	2000	145/39	118/36	106/38	1.25	1.50	1.00	18.5	18.0	24.1
				MARAGING STEEL (300 ksi) VERSUS H - 12 TOOL STEEL						
2252	1800	193/130	166/128	158/132	1.00	.75	1.00	15.1	12.3	24.4
2253	2000	166/111	144/107	145/116	1.50	1.50	1.00	11.7	7.3	14.3
2254	2200	129/86	113/83	106/86	2.50	2.00	1.50	8.1	5.9	9.5
2385	1600	199/84	------	------	----	----	----	20.2	----	----
				TITANIUM ALLOY (6Al - 4V) VERSUS H - 12 TOOL STEEL						
2362	1800	125/59	100/56	89/55	1.75	2.25	2.25	10.6	8.6	8.4
2384	1550	193/86	160/83	123/83	.75	1.75	1.50	19.3	17.4	35.4
2386	1850	115/29	120/31	100/29	1.25	2.00	2.25	22.6	20.0	22.2
2387	2150	102/25	100/27	135/32	2.25	2.00	2.50	15.8	24.7	25.5
2388	1750	185/58	135/54	110/51	2.50	2.25	2.00	15.5	20.0	75.2
				ALUMINUM ALLOY (7075-O) VERSUS H - 12 TOOL STEEL						
2355	600	210/54	------	------	----	----	----	30.0	----	----
2356	900	132/52	90/47	57/42	1.00	1.25	1.25	14.9	11.1	13.5
2357	900	175/73	95/59	71/56	0.75	1.50	1.50	19.9	13.45	18.85
2358	900	110/26	65/22	39/19	1.00	2.00	2.00	20.9	19.5	14.0
2359	600	184/54	145/48	119/46	1.00	1.00	1.00	27.1	24.8	22.4
2367	600	145/74	97/62	62/55	16.00	13.50	14.00	17.4	12.0	13.0

NOTE: H - 12 Tool Steel (Room temperature hardness, RC 46-48) at 800° F.

TABLE IX

SUMMARY OF INTERFACE SHEAR STRESSES FOR BARE AND GLASS-COATED BILLETS

Temperature (°F)	Glass Coated Average Interface Shear Stress (ksi)			Bare Actual Interface Shear Stress (ksi)								
	For All Material			1018 Steel			Maraging Steel			Titanium Alloy (Al-4V)		
	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3
1550	9.10	4.78	7.35	-----	----	----	----	-----	-----	19.30	17.40	35.40
1600	8.20	5.20	6.20	15.40	9.60	8.70	20.2	-----	-----	-----	-----	-----
1700	2.90	2.70	2.00	-----	----	----	----	-----	-----	-----	-----	-----
1750	3.80	2.90	2.50	-----	----	----	----	-----	-----	15.80	24.70	25.50
1800	5.20	3.20	5.50	22.20	23.10	23.90	15.10	12.30	24.40	10.60	8.60	8.40
1850	5.60	5.30	6.00	-----	----	----	----	-----	-----	19.30	17.40	35.40
2000	5.00	4.20	8.30	18.50	18.00	24.10	11.70	7.30	14.30	-----	-----	-----
2050	9.10	4.50	5.00	-----	----	----	----	-----	-----	-----	-----	-----
2150	4.60	3.90	4.60	-----	----	----	----	-----	-----	15.80	24.70	25.50
2200	6.15	5.75	6.20	15.50	26.20	72.50	8.10	5.90	9.50	-----	-----	-----