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HYDROSTATIC EXTRUSION  
OF TUBULAR PRODUCTS

BY

JOHN LESTER ROTH, 1944-

A THESIS

Presented to the Faculty of the Graduate School of the

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Approved by

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## ABSTRACT

The production of quality tubular products by hydrostatic extrusion has been demonstrated to be a highly satisfactory method. The forming of tubes by the floating mandrel method has been accomplished on mild steel, aluminum alloy, and brass. This thesis describes the method, equipment design and operation, and the results obtained in the hydrostatic tube extrusion. A discussion on the advantages of the use of hydrostatic over conventional extrusion is included. The hydrostatic extrusion system designed for this study is described in detail.

## ACKNOWLEDGEMENT

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## TABLE OF CONTENTS

	Page
ABSTRACT. . . . .	ii
ACKNOWLEDGEMENT . . . . .	iii
LIST OF ILLUSTRATIONS . . . . .	v
LIST OF TABLES . . . . .	vi
I. INTRODUCTION AND LITERATURE SURVEY . . . . .	1
II. DESCRIPTION OF METHOD OF TUBE FORMING. . . . .	5
III. DESIGN OF HYDROSTATIC EXTRUSION SYSTEM . . . . .	8
A. Requirements . . . . .	8
B. Selection of Material and Vessel Design. . . . .	9
C. Analysis of Vessel . . . . .	10
D. Description of System. . . . .	11
E. High Pressure Seals. . . . .	12
F. Die Design . . . . .	13
G. Billet Design. . . . .	13
H. Floating Mandrel Design. . . . .	15
IV. AUTOFRETTAGING THE EXTRUSION VESSEL. . . . .	17
V. EXTRUSION PROCEDURE. . . . .	19
VI. PRESSURE FLUIDS AND LUBRICANTS . . . . .	21
VII. RESULTS. . . . .	24
VIII. DISCUSSION . . . . .	28
IX. CONCLUSION . . . . .	31
BIBLIOGRAPHY. . . . .	43
VITA. . . . .	45

## LIST OF ILLUSTRATIONS

Figures	Page
1. Conventional extrusion system. . . . .	33
2. Hydrostatic extrusion system . . . . .	34
3. Backward extrusion . . . . .	35
4. Fixed mandrel method . . . . .	36
5. Floating mandrel method. . . . .	37
6. Extrusion system . . . . .	38
7. Graph of extrusion pressure versus extrusion ratio .	39

## LIST OF TABLES

Table	Page
I. Summary of extrusion ratios. . . . .	40
II. Extrusion results. . . . .	41

## I. INTRODUCTION AND LITERATURE SURVEY

The production of finished parts by cold extrusion is a relatively new process in metal forming which was not used extensively until after World War II. Just prior to that time the process was developed in Germany and used in the production of ordnance. Soon after the war the method began to be used in the United States primarily to produce consumer goods. By the end of the 1950's, the method had sufficiently progressed so that some automobile parts were being mass produced by cold extrusion. Recently, the process of forming metal by extrusion has developed so rapidly that in 1969 more than 500,000 tons of steel parts were formed; a number ten times as great as in 1950<sup>1</sup>.

Hydrostatic extrusion, also known as ramless, fluid, or hydraulic extrusion, is one method of cold extrusion. This particular method differs from conventional methods in that the external force required to cause the metal to flow is transmitted to the free surfaces of the billet by means of fluid pressure instead of by direct force on the billet by a ram. Figures 1 and 2 show drawings of a conventional and hydrostatic extrusion system, respectively.

The use of hydrostatic pressure in the cold forming of metals came about largely as a result of early investigations by Bridgman, Ratner, Hu, Crossland, and Dearden. These workers were interested primarily with the effect of hydrostatic pressure on the ductility and fracture of metals.



The results obtained by these investigators are referenced in the paper by Pugh and Green<sup>2</sup> who further investigated this subject at the National Engineering Laboratory, Scotland. A major contributor to published literature on the subject of material testing in a high pressure environment is Bobrowsky<sup>3</sup>.

A great deal of work has also been done on formulating the theoretical aspects of cold forming. One approach is the formulation of bounded solutions; both upper and lower bounds on extrusion pressure and plastic flow stress<sup>4,5,6,7,8,9</sup>. An upper bound solution pertaining to pressure is useful in determining the maximum pressure required for flow, whereas the lower bound approach will give the minimum pressure necessary. These solutions are usually obtained directly from plastic flow laws or through the use of energy methods.

Actual experimental investigations of hydrostatic extrusion have been carried out in Scotland by Pugh<sup>10</sup>, and in Russia at the Institute for High Pressure Physics of the Academy of Sciences of the USSR by Beresnev and others<sup>11</sup>. In the United States work has been done by Avitzur<sup>12,13,14,15</sup>; by investigators at the Pressure Technology Corporation of America (see bibliography listed in reference 3); by Fiorentino, Sabroff, and Richardson<sup>16</sup> at the Battelle Memorial Institute. At Battelle considerable work has been done on tube forming by hydrostatic extrusion. It is this work which forms the basis for the method of extrusion investigated in the course of the work reported herein.

The advantages of hydrostatic over conventional extrusion are increasing the interest in this method by those involved in the forming of metal products. One very important, and probably the best, advantage is the fact that the high hydrostatic fluid pressure acts to increase considerably the ductility of the metal billet. Thus, it is possible to form under pressure metals which would normally fracture if subjected to the same deformation in a conventional forming operation. For example, materials such as cast iron, titanium, tool steel, and other normally brittle materials have been successfully extruded with hydrostatic pressure. More information on the effects of pressure on ductility can be found in references 13,14, and 15. Evidence of the hydrostatic extrusion of difficult to form metals can be found in reference 13.

A second advantage of the use of a high fluid pressure is its ability to strengthen the upper walls of the die thus permitting the use of thinner die walls and reduced cone angles. If the die seal is designed to be opposite the die orifice, the fluid pressure causing the billet to flow through the die also surrounds the walls of the die above the seals and supports the die against the force exerted by the billet.

An important and useful advantage of using fluid pressure over direct ram force is that the fluid acts as a lubricant to reduce friction between contacting surfaces during extrusion. The degree of lubrication furnished by the fluid

depends primarily on the fluid used and the speed of extrusion. This will be discussed later in section VI.

## II. DESCRIPTION OF METHOD OF TUBE FORMING

There are three commonly used methods for forming tubular products by hydrostatic extrusion. The first method, backward extrusion, makes use of a fixed punch and die and a solid billet. The top of the punch is aligned with the die orifice such that as the billet begins to extrude it simultaneously flows through the die and over the top of the punch forming the tube. This is shown in Figure 3.

A second method involves a fixed mandrel, die, and hollow billet. The hollow billet is placed over the mandrel which is then fixed above the billet. The lower end of the mandrel extends into the die opening. As extrusion begins the billet flows around the mandrel through the die forming a hollow tube of reduced section. Figure 4 shows a drawing of this method.

The third method uses a floating mandrel, die, and hollow billet. It is this method which was used during this study. In this case the mandrel is not supported at either end but follows the billet through the die during extrusion. The mandrel is placed through the billet into the die opening prior to extrusion. This set-up is shown in Figure 5.

Upon completion of the extrusion process it is necessary to separate the mandrel from the extrudate. For this reason a slight taper is provided on the mandrel. This taper, however slight, will affect the overall tolerance on the inside diameter of the extrudate. Where strict tolerances must be maintained this method is not recommended

except when a final drawing operation could be performed. However, for long extrusions the taper would be less on the extrudate than on the mandrel and may be within acceptable limits.

Use of the floating mandrel has an advantage over the other two methods of tube forming in that there is an extra load acting on the billet end by an amount equal to  $p(A_m/A_b)$ , where  $p$  is the fluid pressure,  $A_m$  is the mandrel cross-sectional area, and  $A_b$  is the billet cross-sectional area. The sum  $(A_m + A_b)$  is equivalent to the cross-sectional area of a solid billet of equal outside diameter. It can be seen from the relation

$$P = p + p(A_m/A_b),$$

where  $P$  is the extrusion pressure, that the fluid pressure is less than the extrusion pressure required to extrude a solid billet of the same size as the hollow billet. Thus, for a given hydrostatic fluid pressure a greater reduction in area could be obtained in the forming of a tubular part using the floating mandrel than could be obtained in the forming of a round-to-round solid part from billets of equal outside diameter. This, of course, assumes that the friction between mandrel and billet during extrusion is negligible. This is not the case as will be discussed later.

To furnish results for this investigation extrusions of various reductions in area were conducted. Different methods were used to obtain the various ratios. One method was to use the same mandrel and same billet sizes with dies

of different opening sizes. A second method involved the use of one size of billet and die, and different mandrel sizes. The hole in each billet had to correspond to the mandrel to be used. The final method, found to be the most successful, was to use one mandrel and die size, and vary the outside diameter of the billets.

### III. DESIGN OF HYDROSTATIC EXTRUSION SYSTEM

A. Requirements. An important part of this investigation was the actual design of the extrusion system used in the process. In stating the problem there were certain limitations and requirements posed to the author. These were:

- 1) the maximum outside diameter of the extrusion vessel must not be greater than 3.0 inches and no longer than 12.0 inches in total length;
- 2) the vessel must be capable of holding an internal to external differential pressure of 200,000 psi;
- 3) there must be provision for supplying and maintaining a back pressure, below the die, of 125,000 psi;
- 4) a provision must be made to provide for an extruded product length of approximately 3 inches with an outside diameter of at least  $\frac{1}{2}$ -inch;
- 5) the cost must be kept to a minimum.

The restrictions of diameter and length of the extrusion vessel were required because it was desired to use an existing pressure vessel available in the Engineering Mechanics Department of UMR to house the extrusion vessel. This large monobloc chamber is rated at 125,000 psi and has internal dimensions of 3 inches diameter by 12 inches long. The advantages of using this existing chamber to house the extrusion system are: 1) to provide a rigid support for the high pressure extrusion vessel; 2) to provide back pressure on the die; 3) to allow for the internal pressure in the extrusion vessel to be increased beyond 200,000 psi while still maintaining the same pressure differential across the wall thickness.

B. Selection of Material and Vessel Design. The first problem encountered was the selection of material for the high pressure extrusion vessel. This automatically suggested the use of a superhigh strength alloy steel. The selection of material was based on the need of a metal with good fatigue life, high yield strength, and good machineability. After many preliminary calculations based on simple thick-walled cylinder design using the yield data for many commercially available materials, the decision was made to use an 18% Nickel Maraging 300 superhigh strength alloy steel. This material exhibits those qualities previously mentioned and has a 0.2% offset tensile yield strength, following heat treatment, of approximately 282,000 psi.

Using such a high strength material was not the complete solution. A simple monobloc pressure vessel of this material is not capable of holding the 200,000 psi pressure differential. Therefore, various methods of prestress were considered. One such method was that of shrink-fitting two or more layers together. However, after calculations to find the temperature necessary for fitting, it was found that the temperature required was high enough to cause annealing of the material. Other methods such as wrapping an inner core with many thin layers or with wire were also disregarded due to difficulty in machining and assembling, and lack of facilities.

After considering the above methods of prestressing, the autofrettage method was selected. No special facilities or



machining are required for autofrettaging, and the vessel can be machined and heat treated as a monobloc pressure vessel. The method of autofrettaging will be discussed further in section III. References 17, 18, 19, and 20 provided the information used in the design of the vessel.

C. Analysis of Vessel. Relatively simple formulas have been developed for the stress analysis of pressure vessels; however they generally all assume that the material is represented by an elastic-perfectly plastic type of stress-strain curve. But this is not the case for Maraging steel for which the stress-strain curve has a sharp negative slope past the ultimate stress point.

The simplified formulas were used to obtain a rough idea of the capabilities of the vessel. To obtain a more complete analysis of stress throughout the entire vessel a finite-element analysis was performed. The first step toward this type of analysis is to draw a finite-element grid giving all nodal points, elements, and boundary conditions. The vessel was analyzed as an axisymmetric body with the R-axis parallel to and at the base of the vessel, and the Z-axis along the centerline.

The computer program used was a modified program originally developed by E. L. Wilson<sup>21</sup>. This program is on permanent disk memory at the UMR computer center. All that is required to use this program is the proper data cards giving nodal point, element, boundary condition, and material property data. To obtain a plastic analysis the slope of the

stress- strain curve beyond the elastic region is required.

The output of this program yields all nodal point displacements and element stresses (effective, normal, shear, and principal). The displacements of the nodes on the inside wall subjected to the pressure boundary condition can be used to determine the amount of plastic deformation outward from the inner bore. Also, by examining the effective stress of each element, the location of the elastic-plastic interface can be determined. The effective stress is a single quantity based upon the complete triaxial state of stress, which is useful in predicting yielding. The calculation of effective stress used in this program is based upon the von Mises yield criterion.

D. Description of System. The high hydrostatic fluid pressure is generated in the vessel by means of a moveable ram which is forced into the upper high pressure chamber past a pressure seal. Below this upper chamber is the extrusion chamber, which contains the die blank, floating mandrel, and the die. The die is supported by a cylindrical die support. A drawing showing a section view of the hydrostatic extrusion system is given in Figure 6.

As was mentioned earlier use was made of the existing 125 ksi pressure vessel. The extrusion system was designed to make use of this large vessel to support the extrusion vessel during operation. The smaller ram used in the extrusion vessel for generating pressure was designed to couple

to the large ram which, in a similar manner, generates pressure in the 125 ksi vessel. By inserting the end plugs in the larger 125 ksi vessel, longitudinal support is provided for the extrusion vessel. This is necessary since there are cross-sectional changes in area in the extrusion vessel which would cause an upward force tending to lift the vessel off the die during pressurization.

E. High Pressure Seals. An important factor in the design of any closed high pressure system is the design of the seals to hold this pressure. Use was made of the mitre-ring-O-ring combination except on the seal through which the ram moves. In this case an additional thin cylindrical piece is placed below the O-ring which compresses upward on the mitre-ring. This acts to cause initial compression of the O-ring and also to hold the rings in place. The single combination of mitre-ring and O-ring was also used on the die. The cylindrical and mitre-ring seals were machined from brass.

The pressure holding value of the O-ring-mitre-ring seal combination is largely dependent on the surface finish and overall tolerances on the parts against which the seal must be made. Hence, the diametral tolerances on the moveable ram and outside of the die was  $+0.0000$  to  $-0.0004$  inch and on the inner diameter of the extrusion chamber was  $+0.0006$  to  $-0.0000$  inch. The requirement of these tolerances is attributed to Pugh<sup>3</sup> who uses similar types of seals.

Although the investigation reported herein is primarily concerned with extrusion of thin-walled tubes using the floating mandrel method, it should be noted that this system has also been designed to perform backward and forward extrusions. The extrusion vessel can, therefore, be used to form a variety of small parts by using the appropriate die and billet.

F. Die Design. The dies used were already available which eliminated the need for a new design. A total of two different dies were used. Each has a  $45^\circ$  tapered converging opening. The die opening, or orifice, for die number 1 is 0.312 inch in diameter; for die number 2, 0.250 inch in diameter. These dies will be referred to again when discussing the various combinations of area reductions investigated. The dies are made from Maraging 300 steel and were hardened after machining.

G. Billet Design. Each billet was designed to simultaneously seal at the die and at the top of the floating mandrel. The seal at the die was accomplished by making each billet with a  $45^\circ$  included taper at the nose. The seal at the mandrel involved a  $60^\circ$  countersink into the billet on center with the longitudinal hole for the mandrel.

The hole drilled through each billet was selected to be slightly over the maximum diameter of the mandrel to be used. This provided for a film of lubricant to be applied to the mandrel with a thin coating remaining between billet and

mandrel. For each size mandrel a different hole size must be drilled in the billet. These are, for mandrel number 1, 0.147 inch diameter; for mandrel number 2, 0.196 inch diameter; for mandrel number 3, 0.222 inch diameter.

The length of the billets was selected to provide for a final extruded length of at least two inches.

In some cases a billet of stepped cross-section was used. This consisted of making the billet such that the top  $\frac{1}{4}$ -inch was of 0.500 inch diameter; the remaining length was machined to the proper outside diameter to achieve the desired reduction in area upon extrusion. This was done to prevent complete extrusion of the billet, since the reduction in area at the enlarged section would require a higher fluid pressure than for the desired reduction. This is desirable since a complete extrusion of a billet generally occurs at such a high rate that the extrudate is destroyed when it impacts the bottom of the receiving chamber.

The materials used for the billets were 1026 hot-rolled steel, Nittany No. 2 brass, and 2017-T4 aluminum. Rockwell "B" hardness tests were conducted on the material from which the billets were machined, and the values were converted to equivalent values of Vickers (Diamond Pyramid) hardness. The Vickers hardness values for each material are: hot-rolled 1026 steel; 163; 2017-T4 aluminum; 132; Nittany No. 2 brass; 105.

H. Floating Mandrel Design. The original concept for a floating mandrel was for one mandrel to be used with both dies and one billet size such that the extrudates would be of two desired wall thicknesses. This would minimize the number of different sized parts necessary. This mandrel was labeled mandrel number 1.

A second mandrel was designed and machined after the failure of the first floating mandrel. The new mandrel was increased in size over the first by 33% on the diameter. This gave an 86% increase in mean cross-sectional area. Since the cross-sectional area has been increased more than the lateral area, the new mandrel can sustain a greater shear load along its surface (this shear load is exerted by the billet) without failure.

Instead of using two die sizes and one billet size as with the first mandrel, it was decided that with mandrel number 2 only the largest die would be used. Two different area reductions were possible, however, by using two sizes of billet outside diameters. Using mandrel number 2 also necessitated drilling a larger hole in each billet.

A third mandrel was designed and machined in hopes of eliminating the possibility for failure which again occurred to mandrel number 2. Mandrel number 3 represents a 50% increase in diameter over the first and a 137% increase in cross-sectional area. As with mandrel number 2 only the largest die was used. The area reduction was varied by using different sized billets.

The material used for mandrels number 1 and 2 was Maraging 300 steel hardened following machining. This steel can be hardened to a maximum of Rockwell "C" 54. Mandrel number 3 was machined from oil hardening drill rod which was hardened to about Rockwell "C" 58. This last mandrel was polished to a very fine finish following heat treatment. It was discovered that working with a very smooth surfaced mandrel aided in helping prevent billets from grabbing onto the mandrel during the extrusion process.

All mandrels were designed to have a taper on the diameter of approximately 0.007 inch per inch of length. This is to provide for easy separation of extrudate and mandrel. For calculations of extrusion ratios the mean diameter of the mandrel was used as the inside diameter of the extruded tube.

A summary of the possible extrusion ratios with all three mandrels, the two dies, and the various sized billets is given in Table I. All of the combinations were attempted; some with more success than others.

#### IV. AUTOFRETTAGING THE EXTRUSION VESSEL

Autofrettage is one method of prestressing a pressure vessel to increase its pressure holding capability. It consists of subjecting the inner bore of the cylinder to a fluid pressure which causes inelastic deformation to begin in the portion of the material near the bore where the stresses are relatively large and extend outward as the pressure is increased. When the pressure is released, the outer portion of the cylinder exerts radial pressure on the inner portion, which causes circumferential compressive residual stresses near the bore and tensile stresses near the outer surface.<sup>17</sup> Thus, the same pressure used to autofrettage may be applied internally without causing further inelastic deformation.

As was previously mentioned, an internal pressure capability of 200,000 psi was desired. If an external pressure surrounding the vessel is used the internal pressure may be increased by this amount and still maintain a pressure differential across the cylinder wall of 200,000 psi.

Since the small ram is forced through close-fitting seals into the fluid-filled extrusion vessel to generate pressure, it was necessary to run preliminary calculations and tests to determine ram load versus internal fluid pressure data. This was accomplished by pressurizing the vessel with a pump through a specially made end plug. The vessel was assembled with the end plug and ram in place and positioned in a testing machine such that the testing machine holds the vessel and ram simultaneously.



As the pressure pump increased the internal pressure in the Vessel, readings were made of load on the testing machine for various pressures. The maximum pressure at which load was recorded was 65,000 psi. The load read at the machine accounts for both the pressure of the fluid and the static friction of the seals against the ram. A plot of this data correlated almost exactly with a plot of calculated points yielding a linear relationship between fluid pressure and ram load. The slope of this line was used to determine the ram load required for higher pressures.

The actual autofrettage was conducted using the 125 ksi pressure vessel. With the extrusion vessel in place in this larger vessel and the ram and autofrettage plug in place, a pressure of 50 ksi was applied to the inside of the larger vessel external to the extrusion vessel. This permitted an internal pressure of 250,000 psi to be applied to the interior of the extrusion vessel. The required load was applied and held for five minutes. At this time the extrusion vessel was considered to be capable of withstanding an internal pressure of 200,000 psi without causing further inelastic deformation. This process was repeated three times.

Throughout the calibration tests and autofrettage process the fluid used in the system was Plexol 262. This is a thin, clear fluid exhibiting good properties in the very high pressure range.

## V. EXTRUSION PROCEDURE

The first step in the procedure to form the tubular product is proper lubrication of the billet, floating mandrel, and die. These parts are cleaned free of oil or previous lubrication before each extrusion. The mandrel is located with the lubricant to form a uniform coating. The billet is then placed over the mandrel with the excess lubricant removed from the mandrel. This excess and any additional lubricant is then applied to all the free surface of the billet. Finally, all regions of the die which come into contact with the billet and extrusion are coated with the lubricant.

The top of the mandrel is placed in the recessed area of the die blank and these are lowered into the inverted extrusion chamber of the extrusion vessel coming to rest on the shoulder at the top of the chamber (see Figure 6). The pressure fluid is poured over the billet until it is covered. Although the die blank is not sealed against the vessel walls the clearance is narrow enough to prevent fluid from flowing past the die blank when not under pressure.

With the mitre-ring- O-ring seal in place on the die it forced into the extrusion chamber onto the billet tight enough to form a temporary seal between billet and die. The hollow cylindrical die support is next lowered into the chamber coming to rest on the bottom of the die. Then the extrusion vessel is turned right-side-up and lowered into the chamber of the 125 ksi vessel onto a base plate which sets

on top of the bottom base plug.

The extrusion vessel is then filled with the pressure fluid to a level above the top ram seal. The top plug is lowered into the large vessel and threaded into place but not too tight. The ram designed for the extrusion vessel is mated to the larger ram for the 125 ksi vessel and inserted into the extrusion vessel through the opening in the top plug. This is done to assure proper alignment before tightening the top plug. Once this has been accomplished the top plug is forced tight onto the extrusion vessel. The force applied through the top plug onto the extrusion vessel causes the billet to be further sealed against the die. The whole system is then placed between the tables of the high capacity, 300,000 pounds maximum, Riehle compression testing machine.

Pressure is increased inside the extrusion vessel as load is applied to the ram causing it to move through its seals into the vessel. The actual extrusion of the metal is noted to begin when the load indicated by the testing machine is seen to drop suddenly while the ram is simultaneously moving into the vessel. Complete extrusion of the billet is easily detected as the load will instantly drop to a very low value, sometimes zero.

The hydrostatic fluid pressure which causes the extrusion is obtained from the load reading. This load is then multiplied by the pressure-load factor which was obtained during the autofrettage process.

## VI. PRESSURE FLUIDS AND LUBRICANTS

Probably the two most important factors in any successful hydrostatic extrusion process are the proper choice of pressurizing fluid and billet lubricant. When operating in the high pressure region above 100,000 psi the possibility of choosing a single fluid which will, at the same time, remain in its original state during pressurization and have good lubrication properties becomes a difficult task. Many commonly used hydraulic fluids and oils which perform this dual task at lower pressures will tend to change their state by becoming extremely viscous or, in some cases, begin to solidify under high pressures. Thus, it becomes necessary to use one fluid for providing the high hydrostatic pressure in the system and a second fluid or compound to coat the billet and other parts affected by high friction forces during the extrusion.

Such lubricants as dry soap and heavy grease or oil are often used in conventional fluidless extrusion or drawing operations. When, as in hydrostatic extrusion, a fluid is used to provide the extrusion pressure, the use of a soap or grease which may become soluble with the pressure fluid, would be of no advantage. It is necessary, therefore, to choose the lubricant and pressurizing fluid to be compatible such that they will work together to the best advantage of each.

Various pressure fluids which are commonly used for hydrostatic extrusion are castor oil, a solution of glycerin

and ethylene glycol, pure glycerin, and SAE 30 oil with and without additives. Three different fluids were used during this work: castor oil, a solution of Glycerin plus 20% Ethylene Glycol, and a commercially manufactured high pressure fluid, Plexol 262. The last two fluids were used predominately.

A lubricant should be chosen which will remain on the surfaces between moving parts to reduce the friction force as much as possible. Lubricants which were used are natural beeswax,  $\text{MoS}_2$  grease, ordinary automotive lithium grease, and a silicone based valve lubricant grease FS-3452 manufactured by Dow Corning Corporation.

Although the beeswax and lithium grease aided in providing an initial seal between billet, mandrel, and die, neither acted as a suitable lubricant during extrusion. The  $\text{MoS}_2$  grease also failed to lubricate sufficiently; however, it was an improvement over the previous two. The  $\text{MoS}_2$  appeared to be washed away from the contact surfaces. A mixture of this with powdered lead or copper may have been an improvement but this was not investigated.

Of the four lubricants used the most successfully was the silicone grease. This noticeably retained a thin film between surfaces during extrusion. It is a clean and easy to use lubricant of high viscosity. It can be applied to the parts and subjected to high fluid pressure without being washed away or becoming soluble with the pressure fluid. This lubricant did not appear to flow very well with the

extruding metal which led to the necessity of assuring that all surfaces of contact be thoroughly coated prior to each extrusion.

## VII. RESULTS

The one parameter which had the most effect on obtaining good extrusion was proper lubrication. From the beginning of this study various combinations of pressure fluid and lubricant (if used) were tried in order to arrive at a satisfactory combination. Once this was found it was possible to concentrate on extruding various ratios.

The results of the sixteen most successful extrusions are given in Table II and plotted in the graph in Figure 7. The scattering of points is due in part to improper lubrication. It can be seen that those extrusions obtained at the extrusion ratio of 2.93:1 are farthest from the grouping of points along the straight lines for each material. This ratio was the first to be extruded. Of the four points below the lines two of these, aluminum and steel, resulted in broken mandrels. As the billet seated itself into the die and started to extrude, the larger shearing force due to friction exerted on the mandrel would cause it to fracture. As soon as the mandrel broke the billet would be free to flow through the die at a pressure below that required for tube forming with the mandrel since there was no friction between mandrel and die; the reduction in area was considerably less.

Also resulting in a broken mandrel was the extrusion number 10. Upon examination of this extrusion it was noted that much of the billet was forming over the mandrel and the full ratio of extrusion had begun. This leads to the

acceptance of this extrusion as valid data. The reason for mandrel failure can again be attributed to insufficient lubrication. Up to a point just prior to breakage the fluid was lubricating the mandrel. As the extrusion began, the fluid was squeezed from between contacting surfaces leaving no lubrication with the result of rapidly increasing friction; a build-up of static friction.

Using mandrel number 3, which proved to be the most reliable, the highest ratio of extrusion obtained for steel was 3.08:1. As can be seen, the point on the graph representing this extrusion is far out of line with those of other ratios. Several attempts were made to obtain a successful extrusion at this ratio with only one result which, upon subsequent examination, showed a shiny and irregular surface finish indicative of insufficient lubrication throughout the forming. It should be noted that attempts were made to extrude at a ratio of 4.02:1 without success.

In a number of instances only the nose portion of the billet extruded. However, in these cases the mandrel separated easily from the partially extruded billet which implies that the region of contact experiencing the high friction forces was between the billet and the land region of the die. This led to the conclusion that the lubricant applied to the billet was not entering the billet-die contact area. To help eliminate this problem a liberal amount of lubricant was applied over the land region of the die.

The final surface finish of the extrudates gave the



best indication of the amount of lubrication for the most successful extrusions. In the cases where the fluid pressure required to extrude was thought to be unusually high for the particular extrusion ratio, subsequent examination of the extrudate showed alternating rough and shiny surface finish. The rough finish exhibited a shearing effect taking place between billet and die. This alternating finish resulted from an uneven flow of metal; extrusion occurring in the form of jerks. The resultant surface finish of a good extrusion was shiny throughout, which implies that hydrodynamic lubrication by the pressure fluid predominated over the applied billet lubricant. Another factor contributing to this smooth, shiny finish was rapid pressurization. The more rapid the pressurization rate the less the dependence on excessive lubrication. This effect was noticed throughout the work; however, loading at a rapid rate was not always done.

The highest quality extrusions exhibited a uniform dull but smooth surface finish. It was noticed upon examination that these products still had some of the lubricant on the surfaces. This surface is equivalent in smoothness to a finely machined and ground piece of metal. The results of these extrusions tended to follow along a linear path on the pressure versus extrusion ratio graph.

It was found that the fluid-lubricant combination of Glycerin plus 20% Ethylene Glycol and silicone valve lubricant grease gave the most consistent and highest quality

products. These are seen as extrusion numbers 12 through 16 in Table II, and involved the use of 1026 steel billets of different diameter with mandrel number 3. One inconsistency did arise at the extrusion ratio of 2.22:1 involving numbers 13 and 15. Number 13 was found, by examination of surface finish, to have exhibited the qualities of insufficient lubrication. This set of products can be considered to form the basis for successful results obtained in this study.

Of the three materials used for billets, the most difficult to form was the aluminum. The cause for most of this difficulty lies in the fact that the aluminum-steel interfaces developed very high frictional forces. If the flow began slowly (low pressurization rate) the friction built up to overcome fluid pressure thus resisting any further flow. In the case of rapid fluid pressure increase, more complete extrusion became possible. Once this rapid extrusion rate began the aluminum product would flow at such a speed through the die as to cause the product to break into pieces.

## VIII. DISCUSSION

The conditions required to form a tube, and the quality of the product, is greatly dependent on the rate of pressurization, or ram speed. Those cases in which a more rapid rate was used provided better quality extrusions at lower pressures. The more rapid flow of lubricant with the billet succeeded in overcoming the static friction build-up which is greater than the kinetic friction. The faster loading rate was able to keep the fluid pressure high enough for continuous flow of metal, whereas with a slow loading rate the pressure would drop as extrusion began and build up again each time making it necessary to overcome static friction forces. However, the extrusion rate must be fast enough to develop hydrodynamic lubrication. This lubrication becomes unstable as the speed decreases below a certain level permitting slip-stick to occur. The workers at Battelle<sup>16</sup> used a ram speed of 20 inches per minute with great success.

The static friction build-up is more pronounced with softer materials as aluminum and brass where the coefficients of static friction are greater against steel than with steel against steel. Thus, a combination of rapid pressurizing rate and lower coefficient of friction is the reason for the better results obtained with the steel billets. The faster the rate of pressurizing the faster will be the extrusion rate.

The size of the mandrel obviously was also a factor.

It was noted that best results were obtained using the largest mandrel, number 3. The reasons for this are its ability to resist more shearing load without yielding due to its increase in cross-sectional area, and the smooth surface finish and extreme hardness. The size of the floating mandrel used at Battelle was on the order of 0.75 inch mean diameter.

The retention of lubricant throughout the process is largely dependent on the original surface finish of the billet. All billets were machined from stock material; however, the surface finish varied considerably. Those billets, especially the aluminum, which were finished very smooth did not extrude well. Those with machining grooves present, but not prominent, extruded the best. The small grooves acted as tiny reservoirs to hold fluid and lubricant during extrusion. The most consistent set of extrusions were made from steel billets with similar surface finish. Pugh<sup>13</sup> states advantages to sand-blasting smooth billets and using cast billets.

The greatest cause for the inconsistency seen in the graph of extrusion pressure versus extrusion ratio lies in the variation of pressure fluid and lubricant. Much of the work done and reported is based on a trial and error procedure to arrive at the most satisfactory combination of the two. There are many fluids and lubricants which have been successfully used by other investigators which were not tried here. The final choice decided upon provided good

quality extrusions with the greatest consistency of results.

## IX. CONCLUSION

It has been shown that tubular products can be formed by hydrostatic extrusion using the floating mandrel method. With the proper choice of fluid and lubricant high quality products can be expected requiring a minimum, if any, post-extrusion sizing and finishing. This method is ideally suited for use with hydrostatic pressure, which in itself has many advantages over conventional means of metal forming.

From the beginning of this investigation the author has attempted to gain experience in the field of hydrostatic extrusion in order to obtain a better understanding of the effect of the many variables which are encountered in the forming of a finished product. Different pressurizing fluids, lubricants, and mandrel sizes were used, each time overcoming some of the difficulties present in the previous operation. The effect of increasing the pressurizing rate was noted to result in better quality extrudates and better consistency in data. The use of the glycerin plus 20% ethylene glycol solution is recommended as exhibiting both good pressure and lubrication qualities. The silicone valve lubricant performed favorably, but it is suggested that some of the other commercially manufactured die lubricants be tried.

The lack of published literature on extrusion with a floating mandrel has left the author with no direct basis for data comparison. However, some conclusions can be drawn from these results. The slope of the line on the extrusion pressure versus extrusion ratio graph should be lower for a

lower strength material such as aluminum than for material such as steel. The principal problem encountered with aluminum is proper lubrication. This suggests that choice of lubricant be investigated first when working with aluminum. Primary emphasis during this work was placed on extrusion of steel which yielded the most consistent data. Therefore, the curve representing steel on the graph can be used to predict the extrusion pressure required for a given extrusion ratio for use in the hydrostatic extrusion of tubes by the floating mandrel method.

It is hoped that this investigation will encourage others to study further the possibilities of the hydrostatic extrusion of tubes. The author is currently investigating the method of backward extrusion with limited success to date. To state that any one method of tube forming is best would be impossible. The advantages and disadvantages of every method should be studied in conjunction with the required set-up time, tooling costs, and resultant quality of finished product to fit the particular job requirement.

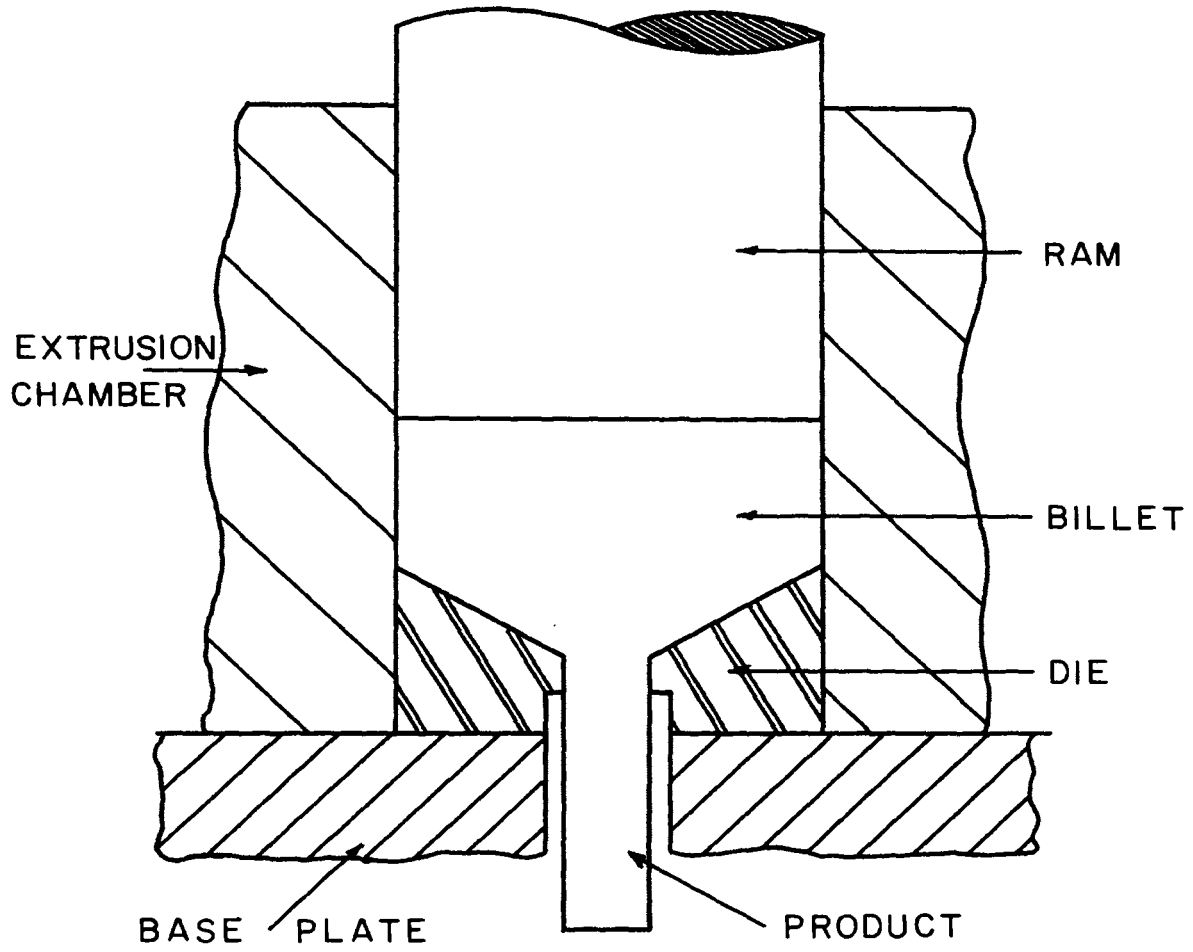


Figure 1. Conventional extrusion system.



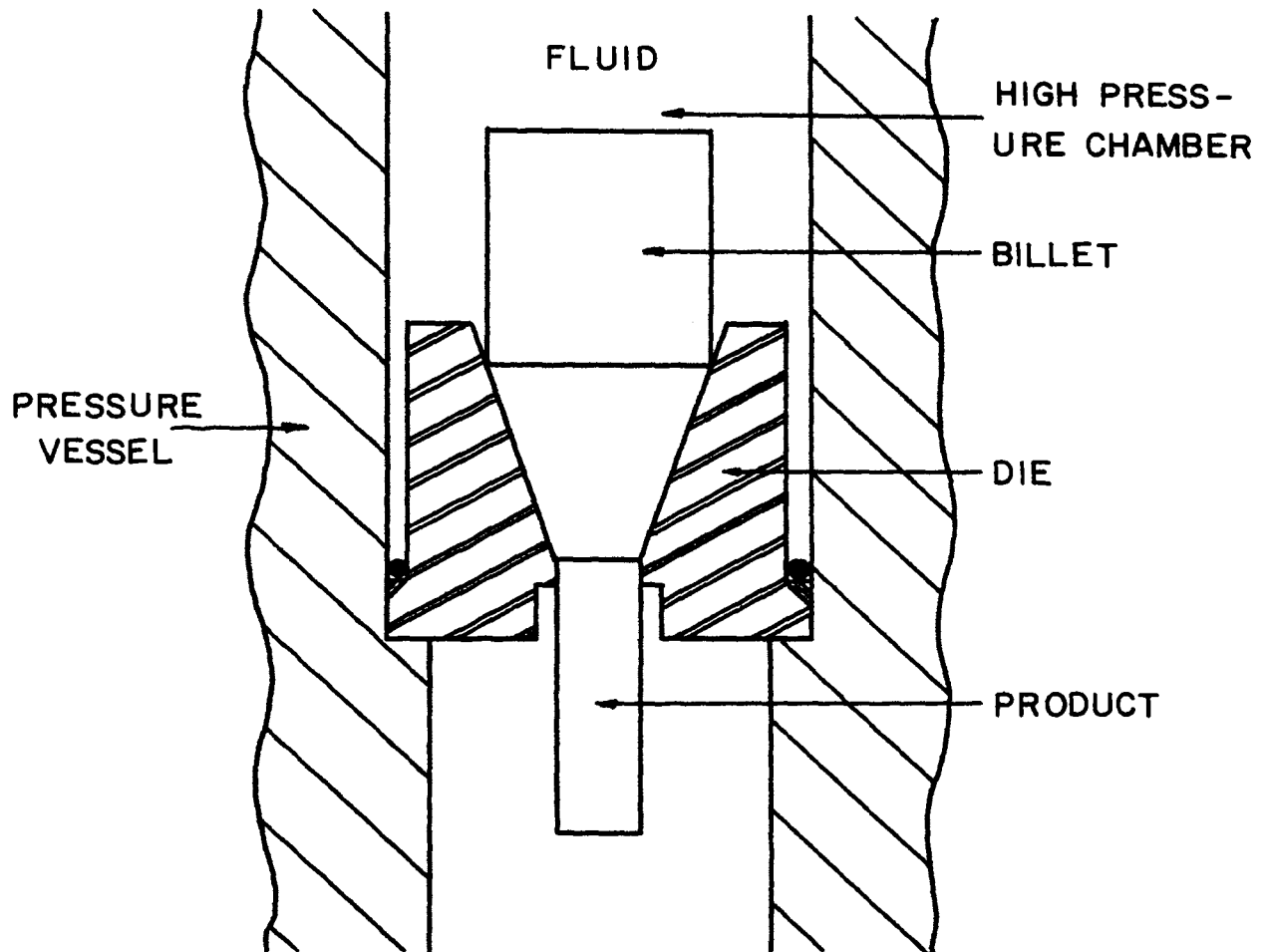


Figure 2. Hydrostatic extrusion system.

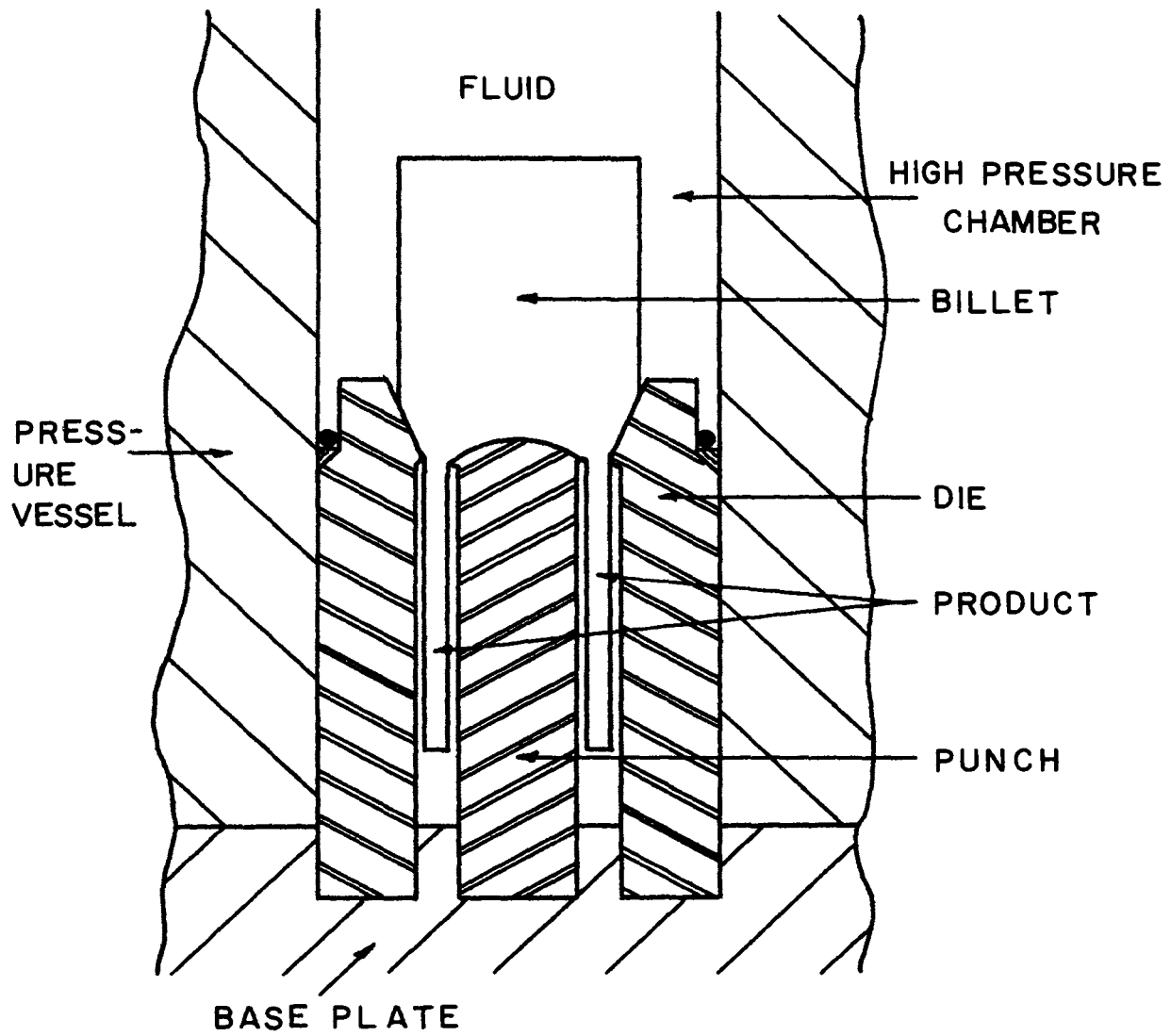


Figure 3. Backward extrusion.

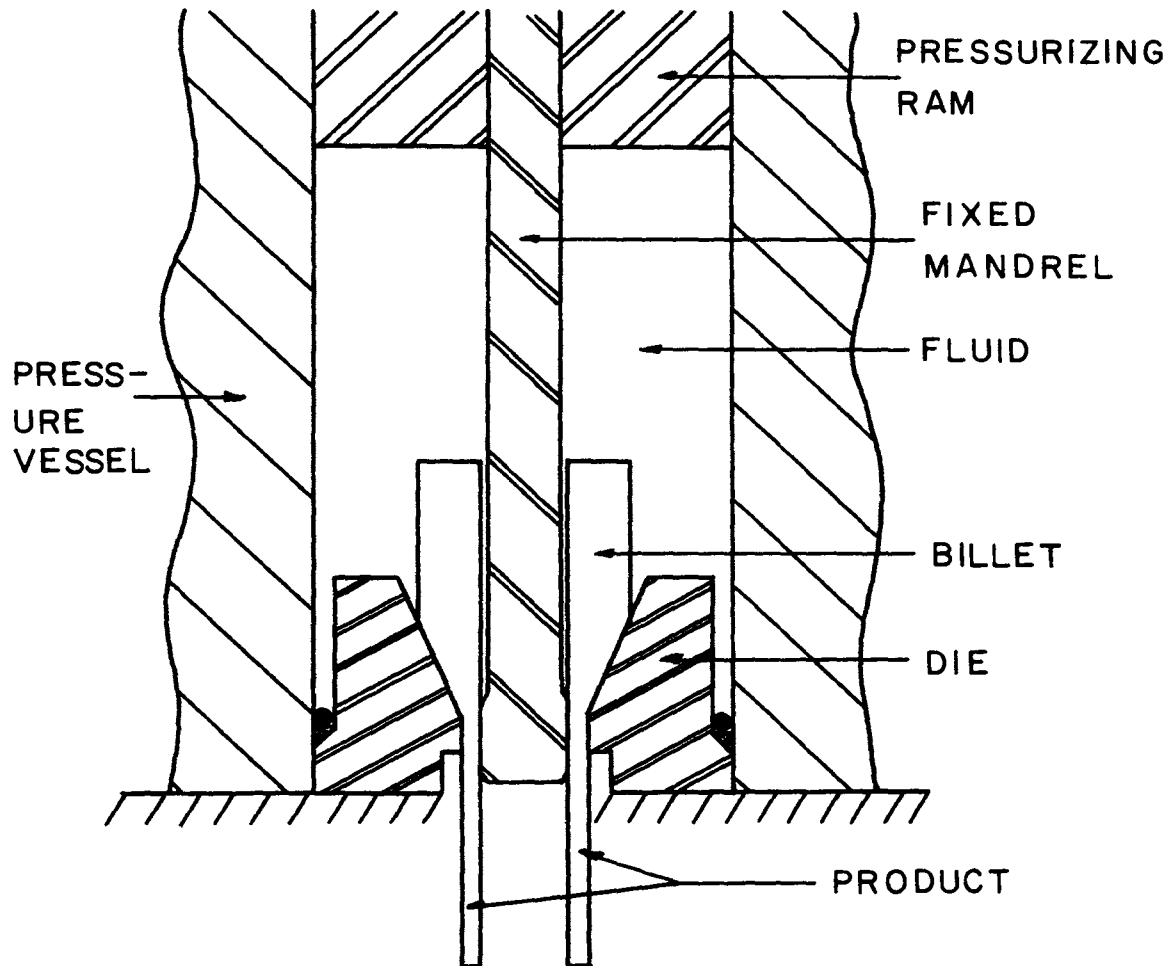


Figure 4. Fixed mandrel method.

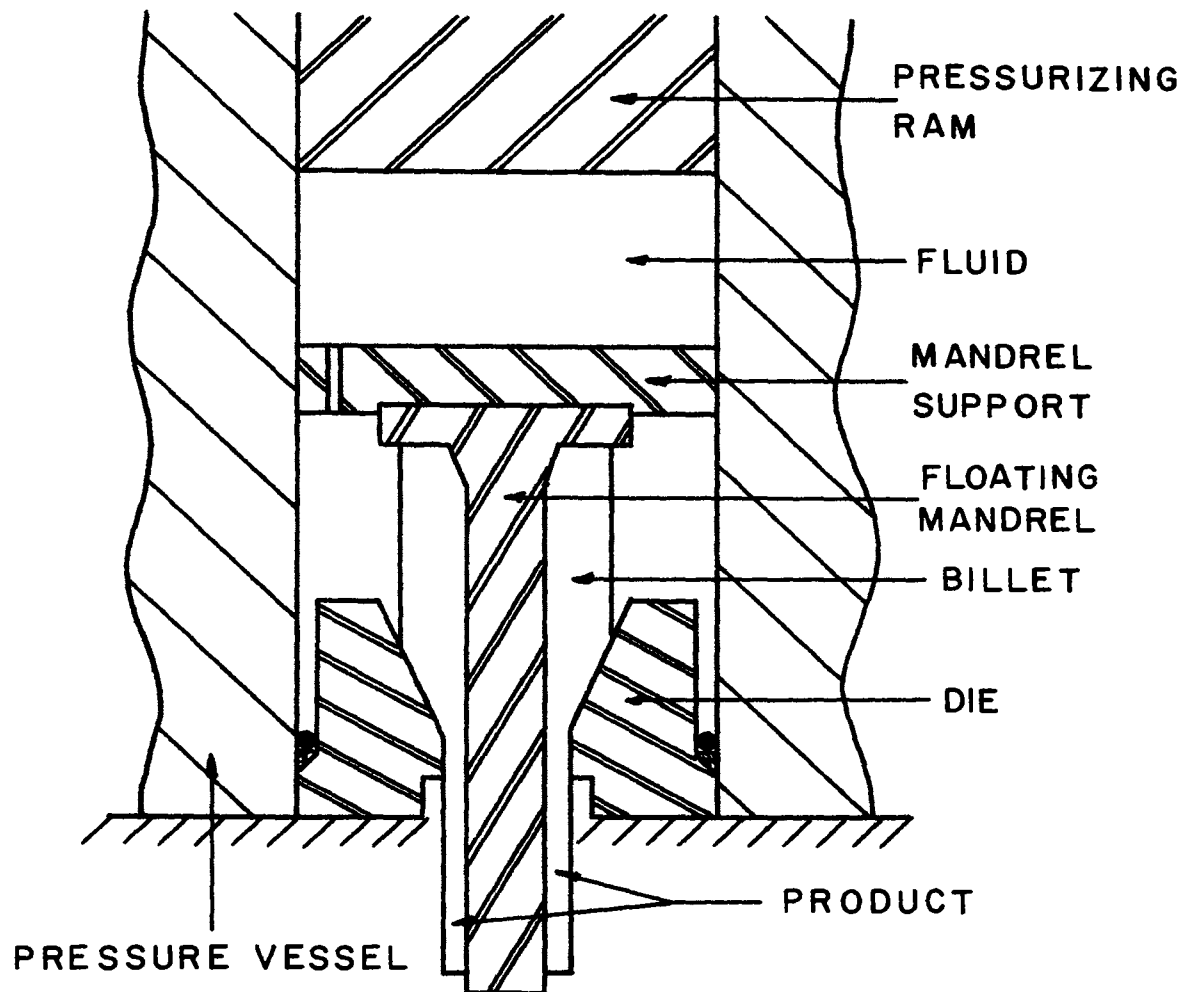


Figure 5. Floating mandrel method.

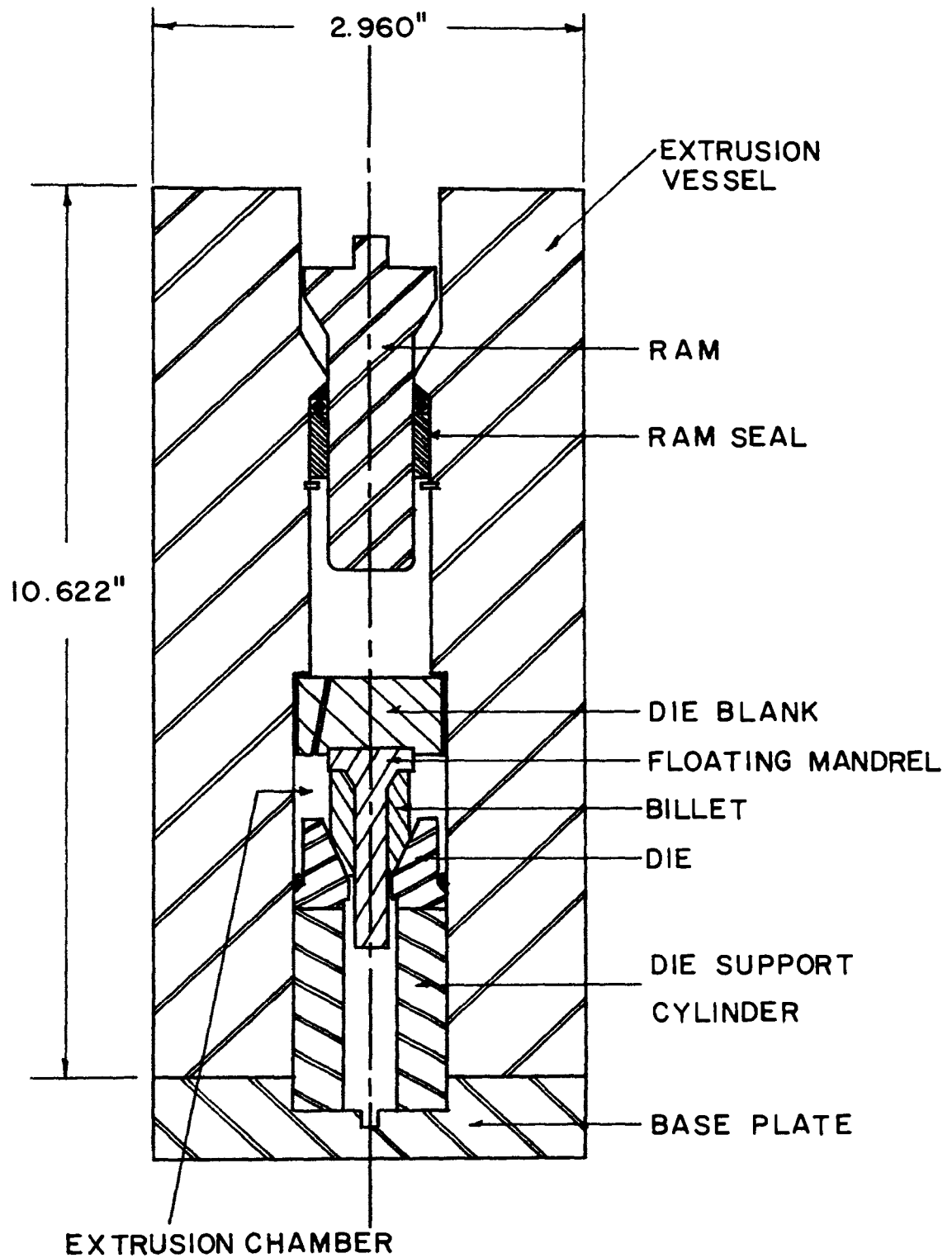


Figure 6. Extrusion system.

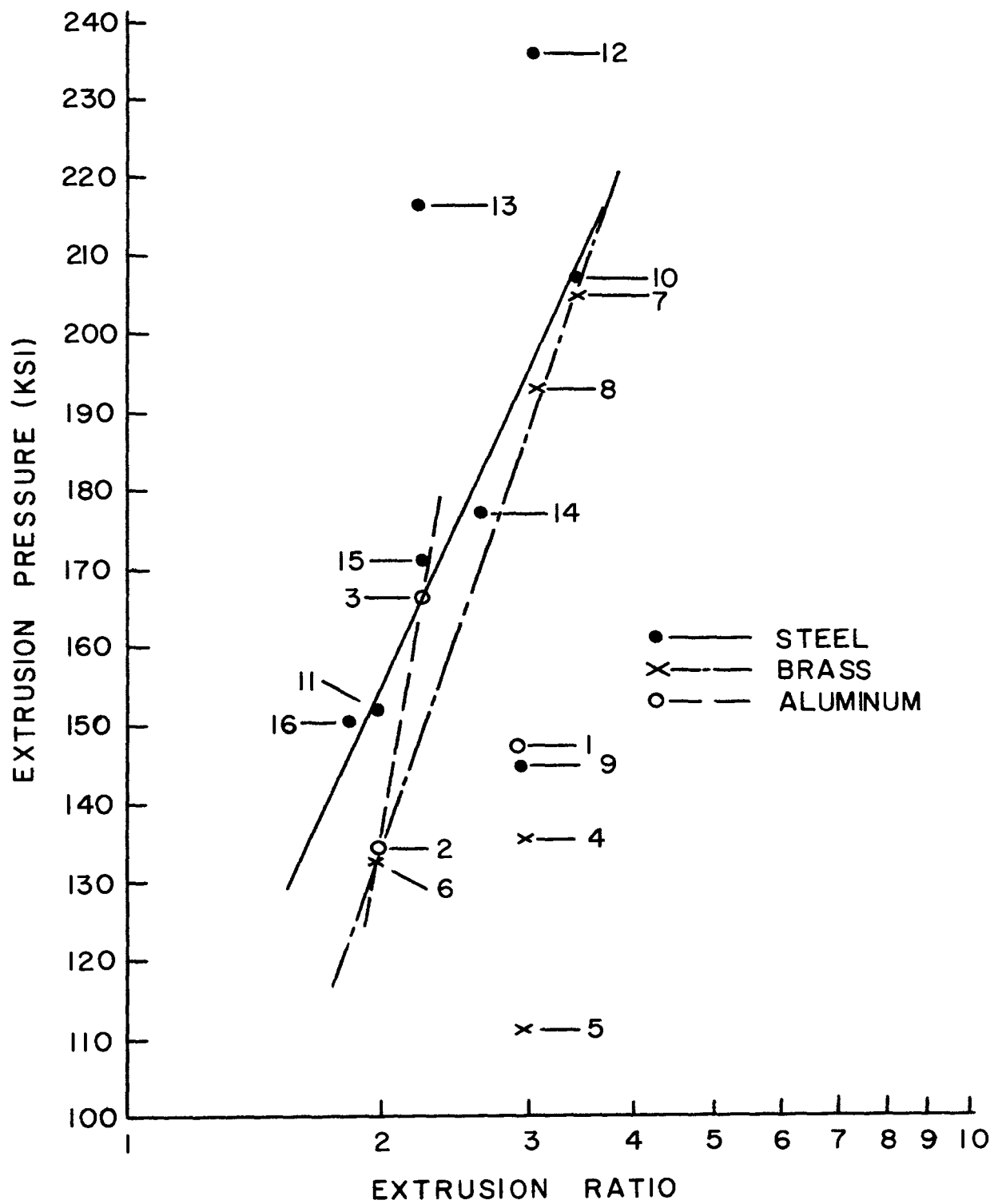


Figure 7. Graph of extrusion pressure versus extrusion ratio.

Mandrel Number	Mean Diameter	Die Opening	Billet Size	Mean Wall Thickness	Extrusion Ratio	Area Reduction
1	.139	.312	.500	.0865	2.93:1	19%
1	.139	.250	.500	.0555	5.29:1	43%
2	.190	.312	.500	.0610	3.45:1	25%
2	.190	.312	.400	.0610	1.98:1	10%
3	.218	.312	.500	.0470	4.02:1	75%
3	.218	.312	.450	.0470	3.08:1	68%
3	.218	.312	.425	.0470	2.64:1	62%
3	.218	.312	.400	.0470	2.22:1	55%
3	.218	.312	.375	.0470	1.83:1	46%

All dimensions are in inches.

Table I. Summary of extrusion ratios.

Extrusion Number	Material	Extrusion Ratio	Lubricant	Fluid	Fluid Pressure	Extrusion Pressure
1*	Aluminum <sup>a</sup>	2.93:1	None	Plexol	135,000	147,800
2	Aluminum <sup>a</sup>	1.98:1	Si Grease <sup>1</sup>	Castor Oil	102,000	134,300
3	Aluminum <sup>a</sup>	2.22:1	Si Grease <sup>1</sup>	Castor Oil	114,960	166,100
4	Brass <sup>b</sup>	2.93:1	None	Plexol	122,000	135,600
5	Brass <sup>b</sup>	2.93:1	Beeswax	Plexol	100,800	110,400
6	Brass <sup>b</sup>	1.98:1	Si Grease <sup>1</sup>	Plexol	101,520	133,700
7	Brass <sup>b</sup>	3.45:1	Si Grease <sup>1</sup>	Castor Oil	174,000	205,500
8	Brass <sup>b</sup>	3.08:1	Si Grease <sup>1</sup>	Plexol	144,000	193,400
9*	Steel <sup>c</sup>	2.93:1	Beeswax	Plexol	130,800	143,200
10*	Steel <sup>c</sup>	3.45:1	None	G.E.G. <sup>2</sup>	175,200	206,900
11	Steel <sup>c</sup>	1.98:1	Si Grease <sup>1</sup>	Castor Oil	115,440	152,000
12	Steel <sup>c</sup>	3.08:1	Si Grease <sup>1</sup>	G.E.G. <sup>2</sup>	178,800	236,400
13	Steel <sup>c</sup>	2.22:1	Si Grease <sup>1</sup>	G.E.G. <sup>2</sup>	150,000	216,750

Table II. Extrusion results.



Extrusion Number	Material	Extrusion Ratio	Lubricant	Fluid	Fluid Pressure	Extrusion Pressure
14	Steel <sup>c</sup>	2.64:1	Si Grease <sup>1</sup>	G.E.G. <sup>2</sup>	127,800	177,000
15	Steel <sup>c</sup>	2.22:1	Si Grease <sup>1</sup>	G.E.G. <sup>2</sup>	118,800	171,700
16	Steel <sup>c</sup>	1.83:1	Si Grease <sup>1</sup>	G.E.G. <sup>2</sup>	97,680	150,000

a. 2017-T4 Aluminum

b. Nittany No. 2 Brass

c. 1026 Hot-Rolled Steel

1. Dow Corning Silicone Valve Lubricant FS-3452

2. Glycerin and 20% Ethylene Glycol Solution

\* Extrusion resulted in broken mandrel

Pressures are in pounds per inch<sup>2</sup>.

Table II. Extrusion results (continued).

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## VITA

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