HYDROSTATIC EXTRUSION OF ALUMINUM CLAD
SUPER CONDUCTOR WIRE

FINAL REPORT

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NOMENCLATURE

a	Strength ratio
A_T, A_{RC}	Cross-sectional area of the monoblock bore and the ratio chamber bore
C	Compressibility
F_D	Downward axial load applied externally
F_U	Upward axial load generated by pressure on the ratio piston
L	Die land length
M	Friction factor
P_T, P_{RC}	Extrusion chamber and receiver chamber pressures
R_{EQ}	Equivalent core radius
R_f	Final outer radius
R_{fi}	Final inner radius
R_o, R_i	Outer and inner radii
$\% RA$	Percent reduction in area
V_{AT}	Fluid volume at atmospheric pressure
V_{HP}	Fluid volume at high pressure
V_{oc}, V_{fc}	Initial and final core velocity
V_{os}, V_{fs}	Initial and final matrix or sleeve velocity
Y	Diameter ratio
Y_{EQ}	Equivalent diameter ratio

NOMENCLATURE

α	Die semi-cone angle
α_i	Core semi-cone flow angle
ΔP	Pressure difference between the extrusion chamber and the receiver chamber
σ_{oc}	Flow strength of the core material
σ_{os}	Flow strength of the matrix material
σ_{xf}	Front tension

ABSTRACT

An experimental study was conducted to determine the acceptable combinations of process variables for the production of a niobium - titanium superconducting alloy in a pure aluminum matrix by hydrostatic extrusion. Conditions for sound flow and defective flow are shown on plots of percent reduction in area versus die semi-cone angle.

The important process variables affecting the observed flow mode in hydrostatic extrusion of bi-metal rod are reduction in area (%RA), die semi-cone angle (α), core to matrix strength ratio (a), core to matrix diameter ratio (Y), bond strength between the core and the matrix, friction between the billet and the die (M), and receiver chamber pressure.

The superconductor used was a 56% Nb-44% Ti alloy surrounded by a matrix of 99.995% pure aluminum. The research was performed in three phases. Single core billets were extruded into atmospheric receiver pressure with reduction in area, die semi-cone angle, and area ratio being varied. Single core billets were extruded into receiver pressure with reduction in area and die semi-cone angle being varied. Billets with three cores were extruded with reduction in area, die semi-cone angle, friction, and receiver pressure being varied. In all cases there was a light mechanical bond between the two materials produced by interference fitting the cores into drilled holes.

Experimental results showed that increasing the receiver pressure increases the range of acceptable process variables to produce sound flow. Although it was possible to produce sound flow, the results were

not always consistent and repeatable. This is largely due to the great difference in strength between the soft aluminum and the hard superconductor. Also, with the present equipment and preparation methods it was difficult to accurately control the bond strength. It is expected that the beneficial effect of receiver pressure will be even more pronounced with a tighter control on bonding.

Because of these and other obstacles, the production of fine, multi-filament superconductor wire with a pure aluminum matrix was impossible in this study.

INTRODUCTION

Bi-metal, clad, or composite wires or rods consist of two dissimilar metals. One or more cylinders of one metal, called the core or cores, are surrounded by a matrix of another metal. The two metals are interlocked mechanically or metallurgically. The reason for the use of composite wires may be for increased strength to weight ratio, increased corrosion resistance, high temperature applications, cryo-static stabilization of superconductors, or for many other purposes. The clad billet may normally be produced by mounting a tube of one metal over a rod of another metal and taking a small reduction through a conical converging die (Fig. 1). This billet is the raw material for subsequent operations, which are usually standard processes such as drawing, extrusion, swaging, or rolling.

Superconductive composites are made to obtain the right combination of electrical, thermal, and mechanical properties for use in making electromagnets. Niobium - titanium/copper composites are available commercially. The niobium-titanium alloy is vacuum arc melted to form ingots. The ingots are clad, as described above, with the required amount of copper, then processed by standard metal forming techniques such as drawing, extrusion, rolling, or swaging. Multi-filament wires are produced by combining a number of rods at an early stage in the process [1].

Multi-filament billets have also been made by placing the superconductor cores in a matrix billet, the holes drilled to give the

desired filament arrangement and distribution. After assembly of the billet, a thick, solid copper lid is pressed on and welded. The billet is then ready for reduction by standard methods. [2]

Billets have also been made by casting aluminum around copper clad superconductor cores. [3]

The production of composite wires requires the proper choice of processing parameters. In order to produce a defect free product from a flow through conical converging die process, there must be homogeneous deformation of both the core and matrix materials, that is, both metals must simultaneously undergo the same reduction. It has been shown that the formation of defects in co-extrusion is not caused by an inherent property of either of the two metals, but is caused by improper choice of process variables [4]. In Figs. 2a and 2b the two metals are aluminum and copper. The process variables are the same except that in Fig. 2a the aluminum serves as the core with a copper sleeve, and in Fig. 2b the reverse is true. In one case there was homogeneous deformation, while a total failure resulted in the other case.

An analysis was made by Avitzur [4] to help choose the proper combination of process variables to give homogeneous deformation of the core and matrix materials for single core billets. Experimental studies have also been performed on single and multi-core billets. [5, 6, 7]

The first attempts were made to accomplish sound hydrostatic extrusion without receiver pressure. This is easier to envision as a production process than is hydrostatic extrusion with receiver pressure.

However, without the benefits of receiver pressure, the range of die angle and reduction combinations that produce sound flow was found to be very narrow, and the reproducibility of sound flow was found unreliable.

Therefore, the effect of increased receiver pressure in hydrostatic or fluid to fluid extrusion on the flow mode of hard core, soft matrix composites was investigated. The effect of receiver pressure was chosen as the variable of interest because of the known positive effect of increased environmental pressure on the deformation of brittle materials and materials with holes and/or inclusions. [8, 9]

The basic modes of flow for hard core composites are core fracture, core waviness, sound flow with homogeneous core deformation, non-uniform core deformation (multi-core only), and sleeve ironing.

If the core is excessively harder than the matrix it will tend to resist deformation and elongate less than the matrix. The core resists deformation briefly, necks down and then fractures, as in a ductile tensile test. This is called core fracture or pinch off, and the process repeats periodically during the extrusion. (Fig. 3a)

The wavy failure is similar to pinch off except that fracture does not occur. The core starts to neck, but because of the process variables, the necking is arrested. Waviness is also a periodic flow mode and the phenomena is repeated during the extrusion (see Fig. 3b). If by changing the parameters, the necking and fracture is replaced by waviness, it is safe to say that the change is in the right direction,

approaching sound flow.

The mode of flow that is desired is sound, homogeneous flow. The core and matrix metals must simultaneously undergo the same reduction (Fig. 3c). In the case of the multi-filament billets, all cores must deform uniformly, that is all cores must have undergone the same reduction as the matrix. (Fig. 4a)

In a multi-filament billet all cores may not deform uniformly. For example, in a three core billet, two of the cores may undergo deformation while the third remains essentially undeformed (Fig. 4b).

The fifth flow mode is that of sleeve ironing. Figure 5a shows that the core acts as an ironing punch with the matrix or sleeve behaving like a thick-walled tube. The tube is reduced in wall thickness as it passes through the die. The punch, in this case the core, remains undeformed. The matrix is ironed backward, giving a product that is actually tubular.

There are other defects which might occur in the extrusion of composites, but these are the only ones observed in this study.

The effects of some of the independent variables on the flow mode in the hydrostatic extrusion of bi-metals can be predicted, based on the previous discussion. If the core metal is harder than the matrix metal, the fracture mode will likely be core fracture. The greater the ratio of the core strength to the matrix strength, the greater is the tendency for core fracture.

The bond between the cores and the matrix can vary anywhere from a lubricated interface, that is, no bonding to a metallurgical bond where

the bond is equal in strength to the softer metal. Bond strength has a large influence on the sleeve ironing and non-uniform core deformation flow modes.

At low reductions the die exit may be large enough to allow the core or cores to pass through undeformed if the matrix or sleeve metal is ironed backward, relative to the core. Since the wire must move as a rigid body at the die exit, in order to maintain volume constancy the core must move faster than the sleeve at the die entrance. (Fig. 5b) Since the wire moving into the die entrance tends to move as a rigid body, the bond between the core and sleeve must be overcome, to allow the core to move faster, if sleeve ironing is to occur. Therefore, as bond strength decreases, the tendency for sleeve ironing increases. Non-uniform core deformation may also be a transition mode between sound flow and sleeve ironing, and is also strongly dependent on bond strength.

Friction tends to retard core fracture in hard core clad rods. However, friction increases the tendency for sleeve ironing by increasing distortion, which essentially slows down the sleeve relative to the core.

The effect of increasing the receiver pressure is to increase the mean pressure of the operation. The higher the mean pressure the wider the range of variables for which sound flow is expected. The tendency for core fracture is reduced by decreasing the tensile axial stress in the deformation zone. The tendency for sleeve ironing is reduced by increasing the bond strength, and thus the amount of energy necessary

to break the bond between the two metals.

In summary, for hydrostatic extrusion of hard core clad rod the process variables are:

- 1) Percent reduction in area (%RA)
- 2) Die semi-cone angle (α)
- 3) Friction (M)
- 4) Relative size of the core. This is expressed as a diameter ratio for single core billets ($Y = R_i/R_o$). For multi-core billets an equivalent diameter ratio can be calculated by considering that the cross sectional area of all cores were one core, that is, the area of that equivalent core is the sum of the areas of all the actual cores. This is for comparative purposes only. ($Y_{EQ} = R_{iEQ}/R_o$)
- 5) Ratio of the flow stress of the core metal to the flow stress of the matrix metal. ($a = \sigma_{oc}/\sigma_{os}$)
- 6) Prescribed body tractions, (front tension, σ_{xf} , in extrusion) or receiver pressure
- 7) Bond strength between the two materials; die land length, L, is also a variable, but was constant throughout all the experiments.

BI-METAL EXTRUSION EXPERIMENTS

Objective

The objective of the experimental program was to determine the acceptable combination of process variables to produce, in multiple passes, multi-filament, composite wires. Because of technical interest for use as a cryostatic stabilizer [3], the matrix metal chosen was very pure grade aluminum (99.995% pure). The core metal used was a niobium-titanium alloy consisting of fifty-six percent niobium and forty-four percent titanium. This alloy shows superconductivity at low temperatures.

Experimental Design

The most practical processes which could possibly be used for the production of composite wires are wire drawing, conventional extrusion, rolling, and hydrostatic extrusion. Anticipating the immense difficulties associated with the chosen combination of very hard core metal with a very soft matrix, the conventional processes were assumed doomed to failure.

The axial tensile stress produced by the front tension in wire drawing severely limits the possible reduction. Ductile fracture, as in a uniaxial tension test, will occur at relatively low reductions. Also it would be very difficult to determine whether this fracture initiated in the core or the sleeve material. A lead wire would be required to start the billet through the draw die. This would increase the amount of billet preparation necessary.

In conventional open die extrusion the length of the billet would be limited because of possible buckling. In closed chamber extrusion, container friction would make the selection of a lubricant much more critical. The increase in friction, even with excellent lubrication, because of the container would vastly increase the tendency for sleeve failure.

Hydrostatic extrusion virtually eliminates container friction because of the low shear strength of the hydrostatic fluid. The problem of buckling is eliminated, for the pressure on the billet is equal in all directions. The stress state in hydrostatic extrusion gives a higher environmental or mean pressure than does wire drawing. The possibility of tensile fracture due to front tensions is also decreased, which increases the size of possible reductions. By increasing the pressure in the receiver chamber, the mean pressure can be further increased, which widens the range of acceptable combinations of process variables. No lead wire is needed, as was in drawing. This minimizes the amount of billet preparation required for the first and successive reductions. Hydrostatic extrusion was chosen for all of these reasons.

Another factor favoring hydrostatic extrusion is the amount of experience and equipment which has been accumulated at Lehigh University. Also, during the development stages it is very important that each variable be controlled individually. Hydrostatic extrusion offers the most process control.

In the study by Zoerner, Austen, and Avitzur [5,6], the forerunner to this investigation, 1100H14 aluminum was used and only single core billets were tested. No receiver pressure was used in that study.

There are a number of advantages for using aluminum as a stabilizer for superconducting wires rather than oxygen free high conductivity copper [3]. The resistivity of 99.995% pure aluminum is less than that of OFHC copper at temperatures below 70°K. The magnetoresistance effect of aluminum is smaller than that of copper in high magnetic fields. These two reasons would result in higher current densities than an identical superconducting magnet stabilized with copper. The specific heat per unit volume of aluminum is less than that of copper at low temperatures. This results in reduced cool-down costs. The thermal conductivity of aluminum is better than that of copper. With the higher conductivity and lower resistivity of aluminum good thermal diffusion and relaxation of magnetic flux improve the stabilization of the magnet. The density of aluminum is less than one-third of that of copper. This results in more versatile applications of superconducting magnets, such as aerospace applications. Finally, the cost per unit volume of high purity aluminum is less than that of OFHC copper.

The Nb-44% Ti core material was used because of its superconducting properties.

A common diameter ratio (γ) for clad superconductors is 0.5. In the previous study [5,6] the diameter ratio used was 0.47. In this study, diameter ratios of 0.46, 0.624 and 0.708 are used for the single core specimens. The equivalent diameter ratio for the three core speci-

mens was 0.56. The strength ratio of the Nb-44% Ti clad with 1100H14 was 5. In this experiment, the Nb-44% Ti clad with VP aluminum, the strength ratio (a) was approximately 7.

The requirements for a hydrostatic fluid are as follows. The fluid must act as a high pressure medium to transfer the force from the moving ram to the billet. The fluid should also lubricate the billet during the extrusion operation. The fluid must have sufficient viscosity at high pressure to lubricate the billet, but the viscosity should not be so high as to cause the liquid to approach solidification, rendering it ineffective as a transmitter of the hydrostatic pressure.

Bobrowsky and Stack show a method for determining the solidification point for fluids at high pressure [10]. Natural compressibility is defined as:

$$C = \ln \left(\frac{V_{AT}}{V_{HP}} \right)$$

where C is compressibility

V_{AT} fluid volume at atmospheric pressure

V_{HP} fluid volume at high pressure

A semi-log plot of compressibility versus pressure will be piecewise linear, with changes in slope representing solidification of the fluid or a component of the fluid.

Soy oil and a mixture of soy oil and kerosene (75% soy oil - 25% kerosene) were chosen as the hydrostatic fluids. They were chosen because their viscosity at room temperature made them easy to handle and

because of their availability. Soy oil is effective as a hydrostatic fluid up to about 100 kips/in.² while the soy-oil kerosene mixture is effective up to about 140 kips/in.².

Billet Preparation

The 99.995% pure aluminum was received in one half inch diameter, cold swaged bars. An extended stress-strain curve was constructed for the aluminum. This is a method, described in Ref. [11], for extending the stress-strain curve beyond the limit imposed by necking in simple tension by plotting the locus of yield points of samples which have undergone various degrees of cold work (see Fig. 6). The aluminum samples were swaged to 0.363 inch diameter and then cold drawn to various sizes (see Table 1) to determine the yield strengths of the aluminum after each of the successive reductions to be performed on the billets. The 0.2% offset method was used to determine the yield strengths for the aluminum.

The extended stress-strain curve for the Nb-44% Ti, Fig. 6, was taken from Fig. 9 of reference [6].

The strength ratio, a , was calculated and is plotted in Fig. 6. The initial strength ratio for the three core billets was approximately 6.7 and did not vary significantly with subsequent reductions.

The aluminum rod used for the single core billets was received in 0.26 inch diameter bars. It was used in the "as received" condition. The yield strength was 9020 psi. This gave an initial strength ratio, a , of 7.1.

The three core billets were prepared by swaging the 0.50 inch diameter aluminum bars to 0.363. Holes .120/.119 were then drilled at a radial distance of .082 from the center, 120° spacing to a depth of 1.61 inches. (See Fig. 7)

The billet cores were prepared by cold swaging 0.5 inch diameter Nb-44% Ti bars to 0.125 and cutting to length. A taper was then ground on one end of each of these cores. The cores were then annealed one hour at 800°C and water quenched. This reduced the Knoop hardness number (100 gram load) from 586 in the cold swaged condition to 133 in the annealed condition. The cores were then turned to .119/.118 diameter.

The cores were then pressed into the holes in the aluminum, giving an interference fit (the holes drilled in the aluminum seemed always to be undersize). The billets were then re-mounted in a lathe chuck and the nose angle was turned. The compression of the chuck should also have increased the bond.

Before extrusion the entire outer surface of the billet was polished using steel wool. A cap was bonded to the top of the billet using a methyl-cyanoacrylate adhesive. This fully encapsulates the core so that the hydrostatic pressure will not tend to push the core through the matrix.

The single core billets were prepared in the same manner. See Fig. 8, a drawing of a typical single core billet.

Equipment

The tests were performed in a Model 6 Monoblock hydrostatic extrusion unit. Power was supplied by a 30 ton hydraulic press. (see Fig. 9)

An important feature of the Model 6 Monoblock is that it allows the use of receiver pressure by using ratio chambers. Figure 10 shows a cross section of the Model 6. At the start of the test the receiver piston is supported by a stand-off, usually a piece of cardboard. As the ram moves downward, the top chamber is pressurized. This force is transmitted downward, collapsing the stand-off and pressurizing the fluid below the receiver piston. As the billet starts to extrude, the emerging product further pressurizes the fluid in the receiver chamber. This pressure is transmitted around the snubber and through the hole in the receiver piston into the ratio chamber. The area of the receiver piston is larger than the extrusion chamber, so the resultant force on the piston is upward. The receiver piston moves upward as the product enters the receiver chamber. As the emerging product continues to displace the receiver fluid, the piston continues moving upward. The downward pressure in the top chamber acts on the top of the billet and die. The upward force is caused by the receiver fluid pushing up on the receiver piston. To determine the ratio of pressures, consider one point during the extrusion as static equilibrium.

The downward force is $F_D = P_T A_T$

The upward force is $F_U = P_{RC} A_{RC}$

$$P_T A_T = P_{RC} A_{RC}$$

$$P_T / P_{RC} = A_{RC} / A_T$$

where P_T is top pressure, measured by dividing the applied external load by the area of the monoblock bore

P_{RC} is the receiver pressure

A_T is the area of the monoblock bore

A_{RC} is the area of the ratio chamber

Three ratio chambers were available for use with the Model 6 Monoblock. Table 3 shows the diameters of these chambers and their ratios. In Table 3, ΔP is the pressure drop across the die, that is, the top pressure that would be required to extrude into atmosphere.

The manometer tube is connected into an atmospheric chamber, which is isolated from the fluid chambers. Motion of the receiver piston changes the pressure in the manometer chamber, allowing the operator to monitor the movement of the piston by viewing the manometer.

The upward motion of the receiver piston causes the entire column of spacers and the die to also move up. This movement performs an indirect extrusion of the billet, thus giving more product per unit ram displacement than would be predicted by volumetric calculation based on ram displacement alone. The operator must be well aware of this fact if complete extrusion of the billet is undesirable.

The seals used in the extrusion experiments were the "O" ring type, backed by a mitre ring (see Fig. 11a). This type of seal was most successful at low top pressure and very low receiver pressure. In general, the "O" ring-mitre ring seal can be expected not to function well in pressure to pressure extrusion. The ram seal tends to fail by excessive friction at high pressures, and at the die, the "O" ring fails by collapse. In pressure to pressure extrusion, the seal is surrounded by pressurized liquid, causing it to shrink in volume and wrap itself tightly around the die, thus leaving a gap between the die and the chamber. Occasionally, because the "O" ring shrinks, it shortens in length, wraps itself around the die and fractures in tension.

There are a number of ways to overcome this problem:

- 1) A self actuated seal, such as a Bridgman seal, can be used.
- 2) A material with a different bulk modulus, such that the volumetric contraction will be less, can be used to make the "O" ring.
- 3) An "O" ring with the same inside diameter and larger outside diameter (see Fig. 11b) can be shaved along the O.D. until it fits in the chamber. This will give a larger cross section, thus putting more volume of material in the same space. With more volume, more contraction can take place before the seal fails.

Because of the large die exits caused by the small semi-cone angles and small reductions, the use of a self actuated seal was impractical in

this case. A larger outside diameter ring was altered and functioned well in these experiments.

For a more complete coverage of seal design, see reference [12].

The tapered nose of the billets were coated with a thick layer of bee's wax prior to extrusion. This was done to facilitate sealing between the billet and the die. If this seal is not made the unit cannot be pressurized. The top fluid will leak past the billet, through the receiver piston and into the ratio chamber. The receiver piston is forced upward without the top chamber being pressurized.

Care must be exercised when using the soy oil-kerosene mixtures. Kerosene tends to dissolve bee's wax. The extrusion must be performed quickly after the billet has been sealed and the top fluid added.

Lubrication

As mentioned previously, the ideal hydrostatic fluid will also provide adequate lubrication. If the fluid does not provide adequate lubrication, then a solid lubricant may be applied in the form of a coating.

A phenomenon which often occurs during the hydrostatic extrusion of aluminum is called stick-slip, which is, as the name indicates, intermittent extrusion and sticking of the billet. When the top fluid is compressed at the start of a test, a great amount of elastic energy is stored in the compressed fluid. The extrusion will not start until the coefficient of static friction has been overcome. If the coefficient of dynamic friction is much lower than the static value, the

billet will be rapidly accelerated. This de-pressurizes the fluid and stops the extrusion. The extrusion will not start again until the pressure is once more great enough to overcome static friction.

If the reduction in area is small or the billet short, the entire billet may be extruded during the initial pulse. This did occur during this investigation. One pulse stick-slip seems to interfere with the proper functioning of the ratio chamber. There is no run-out pressure and thus there is no constant receiver pressure. The ratio piston cannot respond to the emerging product.

The problem of stick-slip may be lessened or overcome by changing lubrication, changing the die angle, increasing the strain rate, and minimizing the amount of fluid used to minimize the stored energy. Changing the lubrication and minimizing the fluid were the methods used to combat stick-slip in this study. Stick-slip was eliminated and a constant extrusion pressure was often observed.

There will usually be a peak pressure, higher than the run-out pressure in hydrostatic extrusion. The causes are inertia, bulge formation, dead zone formation, and frictional conditions. The smaller difference between the peak and run-out pressures, the greater the control the operator will have and the less the chance of stick-slip. This peak can be minimized in the same ways as mentioned for stick-slip, and by proper design of the billet nose [13]. A billet with a nose angle smaller than the semi-cone angle of the die (Fig. 12) will change the initial frictional condition in the die and reduce the peak pressure.

Billets were extruded in the coated and uncoated conditions. Stick-slip was a problem in almost all of the uncoated billets. Coatings used were bee's wax, a wire drawing compound, and a deep drawing compound. See Table 4 for brand names and manufacturers.

No significant change in extrusion pressure was noted among the coatings. The rule of mixtures was used to calculate the flow stress of the composite. Knowing flow stress, extrusion pressure, die semi-cone angle, and reduction, Figure 11.10 on page 306 of reference [13] was used to estimate the friction factor, m , to be 0.12. Crouch and Bassett [7] said that the rule of mixtures was not accurate in predicting composite strength. However, Avitzur has shown [14] that for homogeneous deformation the rule of mixtures prevails. Lower strengths and pressures prevail when non-homogeneous deformation occurs.

The extrusion dies had an initial surface finish of approximately eight micro-inches, root mean square. The dies were polished with diamond paste between runs to remove any pick-up from the aluminum.

Collection of Data and Inspection of Samples

Load versus displacement plots were made during the extrusions using a deflectometer and a chart recorder which was an integral part of the hydraulic press. Figures 13 and 14 show typical pressure versus ram displacement plots for pressure to pressure extrusion with and without stick-slip. Figure 15 shows a typical plot in which core fracture occurred.

Products which seemed to be successful were checked by radiography. Specimens showing signs of internal defects, that is indentations on the surface, were mounted in bakelite and sectioned longitudinally. Many specimens, not long enough for further reductions, were cross sectioned to view the core or cores.

RESULTS AND DISCUSSION

Single Core Billets - Atmospheric Receiver Pressure

Single core billets with diameter ratios of 0.708, 0.624 and 0.46 were extruded into atmospheric receiver pressure. Three semi-cone angles, $\alpha = 5, 10$ and 15 degrees were used. Various reductions were attempted. The cores were used in the cold swaged and annealed condition and the aluminum sleeves were in the "as received" condition. The strength ratio, a , was 7.1.

At the diameter ratio $Y = 0.708$ there were no successful extrusions at either the 10 or 15 degree semi-cone angles. In all cases the core was either wavy or pinched off.

When a five degree semi-cone angle was used, all reductions attempted 65% RA and below were successful, with sound flow and homogeneous deformation in all cases. Results are shown in Fig. 16.

No sleeve iron occurred at this diameter ratio. However, the smallest reduction attempted was 39% RA.

At a diameter ratio of $Y = 0.624$ the sound flow area was considerably increased. Once again, for the 5 degree dies flow was sound for 65% RA and below. Flow was also sound at 10 and 15 degree semi-cone angles for 56% RA and below. Again, the smallest reduction attempted was 39% RA and no sleeve ironing was observed for any of the semi-cone angles. See Fig. 17.

The only point for which sound flow was observed when using billets with a diameter ratio of $Y = .46$ was at 47% RA using a 15 degree semi-cone angle die. All other attempts produced waviness or core fracture, with sleeve ironing at the lowest reductions (See Fig. 18).

Comparing these results to the results of Zoerner, Austen, and Avitzur [5] yields one definite conclusion. Increasing the strength ratio slightly significantly lowers the maximum reduction which can be taken without a failure, regardless of die angle used. Zoerner, Austen, and Avitzur showed in their Figure 3 that for a strength ratio of 5 and a diameter ratio of 0.47, where commercially pure aluminum was used, the line dividing the waviness or core fracture zone from the sound zone lies at approximately 50% RA. Fig. 18 shows that for a strength ratio of 7.1 and a diameter ratio of 0.46, using very pure aluminum, this line is no higher than 39% RA. In fact, the line may lie even lower, between 34 and 39% RA. As Fig. 18 shows, if there is a sound flow region it is very small.

In summary, the conclusions which can be made from the single core billets extruded into atmosphere are:

- 1) Large reductions, above 70% RA, will fail by core fracture, regardless of semi-cone angle.
- 2) Increasing the strength ratio will lower the maximum possible reduction for sound flow at a given semi-cone angle.

- 3) There seems to be an optimum diameter ratio. At this diameter ratio semi-cone angle seems to have little effect on the boundary between sound flow and waviness. Above this diameter ratio the maximum possible reduction for sound flow decreases rapidly with increasing semi-cone angle. Below this diameter semi-cone angle again has little effect on the boundary between waviness and sound flow, but the maximum reduction for sound flow decreases with decreasing diameter ratio.

Multiple Passes on Single Core Billets

Various reduction schedules were tried within the sound flow regions determined previously. Because the strength ratio, diameter ratio, hardness, etc., all change slightly after each reduction, the sound flow regions determined previously may not accurately predict the composite behavior after these parameters have been changed.

Because the largest range of possible reductions was for 5 degree semi-cone angles, 5 degree dies were used for the multi-pass experiments. At $\alpha = 5$ degrees diameter ratios of $Y = 0.708$ and $Y = 0.624$ can be used.

The following schedule produced sound product with both diameter ratios being used:

5°	(All die sizes in inches)			
DIE SIZE	.250	→ .148	→ .102	→ .079
	65%RA	52%RA	40%RA	

Single Core Billets - High Receiver Pressure

Single core billets with a diameter ratio of 0.46 were extruded into high receiver pressure using the 3:1:2 ratio chamber. Semi-cone angles of 5 and 10 degrees were used with various reductions being attempted. The Nb-44% Ti was used in the cold swaged and annealed condition and the aluminum was used in the "as received" condition. This gave a strength ratio, a , of 7.1.

Figure 19 shows that the boundary between sound flow and waviness or core fractures falls at about 37% RA for both the 5 and 10 degree semi-cone angle dies when extruded into high receiver pressure. By high receiver pressure it is meant here that the receiver pressure is at least twice the magnitude of the top pressure necessary to extrude the same billet into atmospheric receiver pressure. Again comparing to the results of Zoerner, Austen, and Avitzur, where this boundary fell at 50% RA, Fig. 19 shows that increasing the receiver pressure will not counteract small increases in strength ratio. Further increase of receiver pressure will probably drive this boundary back up, however, this is beyond the capacity of the Model 6 Monoblock.

Comparing Fig. 19 to Fig. 18 shows that at a given strength ratio, diameter ratio, and semi-cone angle, an increase in receiver pressure will widen the range of reductions resulting in sound flow.

No sleeve ironing was observed in the single core - high receiver pressure experiments. There may or may not be a lower boundary at low reductions.

Three Core Billets - Low Receiver Pressure

Three core billets with an equivalent diameter ratio of 0.56 were extruded into low receiver pressure using 5 and 15 degree semi-cone angle dies. The Nb-44% Ti cores were used in the cold swaged and annealed condition, while the aluminum matrix was reduced 47% RA from the "as received" condition. This gave an initial strength ratio of 6.7. Various reductions were attempted.

Figure 20 shows that no region of sound flow with uniform core deformation was determined when using low receiver pressure. By low receiver pressure it is meant here that the receiver pressure is one-half the top pressure which would be required to extrude the billet into atmospheric pressure using the same process variables. Figure 20 does show that there was a region of sound flow with non-uniform core deformation. It would be difficult to say whether this non-uniform deformation was due to difficulty in accurately controlling bond strength or due to the improper combination of the other process variables.

Multi-pass experiments were not made using low receiver pressure since there was no successful region. The results of these and the single core experiments would lead one to believe that with a further increase in receiver pressure there may be a sound flow - uniform core deformation region where the non-uniform region exists in Fig. 20. Therefore, receiver pressure was increased.

Three Core Billets - High Receiver Pressure

Three core billets with an equivalent diameter ratio of 0.56 were extruded into high receiver pressure using 5 and 15 degree semi-cone angle dies. The Nb-44% Ti cores were used in the cold swaged and annealed condition, while the aluminum matrix was reduced 47% RA by cold swaging from the "as received" condition. This gave an initial strength ratio, α , of 6.7. Various reductions were attempted.

Figure 21 shows that by increasing the receiver pressure that there is a significant region where sound flow with uniform core deformation can be expected. The ratio chamber used gave a receiver pressure which was twice the top pressure which would be necessary to extrude a given billet into atmospheric receiver pressure.

Using a 5 degree die, Fig. 20 shows that there is no reduction which results in uniform core deformation when using low receiver pressure (15-20 KSI). Fig. 21 shows that with high receiver pressure (75-100 KSI) uniform core deformation can be expected anywhere between 30% RA and 47% RA.

It was mentioned previously on page 6, that in order for sleeve ironing to occur the bond between the core and the matrix metals had to be broken. It often happened that the flow mode changed during an extrusion. At the start of an extrusion the cores were long, giving a large contact area between a core and the surrounding matrix. A great deal of work would be needed to overcome this interface friction, so flow was sound and core deformation was uniform. As the extrusion pro-

gressed the remaining unextruded portion of the cores was shorter with correspondingly less contact area. There was often a point where the power needed to break the bond became less than the power needed to deform the cores. At this point the flow mode changed to sleeve ironing.

Because of the way in which the three core billets were assembled it is impossible to estimate the bond strength. The billets are small and the cores are close together so the stress fields around each core due to the interference fit do interact. The bond strength between one core and the matrix may be significantly lower than the others. This would lead to non-uniform core deformation.

The flow of a composite billet through a conical converging die can be broken down into four phases:

- 1) mono-metallic extrusion of the nose where no core metal has reached the die exit
- 2) initial instability where the cores first pass through the die
- 3) steady state region where sound flow will occur if the proper variables are used
- 4) final instability where the cores end and the core effect is significant

When Fig. 21, three core billets extruded into high receiver pressure, is compared to Fig. 17, single core billets extruded into atmosphere, one notices that the upper boundary of the sound flow region is significantly higher for the single core billets. Bond strength

has no effect on the upper boundary, so that is not a factor. An explanation for this has to do with diameter ratio. The equivalent diameter ratio calculated earlier was used to calculate flow strength of the composite. It would not be expected that a three core billet would deform in the same manner as a single core billet with the same amount of core area in a cross section.

A model of loosely packed composites has been used in making analyses of elastic properties of composites [15]. This model is shown in Fig. 22. The core and its surrounding matrix can be treated as a single filament composite when calculations are made. When this approach is used, the diameter ratio of the three core billets could be considered to be between 0.68 and 0.74. Since there is more matrix metal between a core and the outside diameter of the billet than there is between cores, this excess along the outside diameter might tend to be ironed backward, increasing the diameter ratio. A diameter ratio of 0.7 is slightly higher than what seems to be optimum for the single core billets. The increased receiver pressure used in extruding the three core billets may alter the "optimum" ratio. These could be reasons for the much lower allowable maximum reduction for the three core billets.

Multiple Passes on Three Core Billets

After the regions where sound flow could be expected were determined, further reductions were attempted on products from successful first passes. The 3:1:2 ratio chamber was used to give the highest

receiver pressure. Five degree semi-cone angle dies were used because of the greatest range of reductions resulting in successful extrusions in the previous tests. The same fluids and billet coatings were used. Figure 6 shows that the strength ratio does not vary significantly with increasing reduction.

The following four-pass reduction schedule was used to produce sound, .148 inch diameter wire from a .362 inch diameter billets. After four reductions the product was too short for further reduction. This is because the sections of initial and final instability had to be removed after each reduction. Figure 23 shows a cross section of this specimen in the original condition and after the third and fourth passes.

36%RA	34.5%RA	37.5%RA	34%RA
.362	---> .289	---> .234	---> .182 ---> .148

Products in which one or more of the cores were slightly wavy were re-extruded. It was determined that further reduction of a product with slightly wavy cores will tend to even out the deformation so that the cores will be less wavy after that reduction. If the cores were initially very wavy, almost pinched off, further reduction will result in core fracture.

When sleeve ironing has occurred around one or more of the cores the bond between that core and the matrix has been broken. A very light mechanical bond will exist where the matrix metal has been ironed over the core, but further reduction will probably result in more sleeve ironing with no core reduction.

Once a successful reduction has been performed a strong mechanical bond is formed and any ironing which occurs in subsequent reductions is the result of improper variables.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Viewing as a whole the entire program of hydrostatically extruding hard-core composite billets, the following statements can be made.

The important process variables for the hydrostatic extrusion are reduction in area, die semi-cone angle, diameter ratio, strength ratio, bond strength, friction, and receiver pressure. When reduction in area is plotted versus semi-cone angle, with the other process variables as parameters, the proper selection of these parameters may result in a region on the plot where successful extrusion is expected. There may be an upper boundary, above which failure by core fracture or waviness will occur. There may also be a lower boundary, below which sleeve ironing will occur. Changes in the parameters will result in the movement of these boundaries.

Some important conclusions about the effect of some of the process variables are:

- 1) There seems to be an optimum diameter ratio, above and below which the size of the successful region will be significantly smaller.
- 2) The range of acceptable reductions in area will tend to decrease with increasing die semi-cone angle.
- 3) The strength ratio is very critical. A slight increase in strength ratio, 25 to 50 percent, will significantly reduce the size of the safe or successful zone.

- 4) Increasing receiver pressure will increase the size of the safe zone. In the range of receiver pressures used here, 120 KSI MAX., the positive effect of increasing receiver pressure is not as strong as the detrimental effect of increasing the strength ratio.
- 5) The selection of the billet coating and hydrostatic fluid, and the billet nose design are important in the prevention of stick-slip and in reducing peak pressures.
- 6) Bond strength, diameter ratio, receiver pressure, and friction all influence sleeve ironing. Accurate control of bond strength and friction is necessary to accurately locate the lower boundary between the safe region and sleeve ironing.

Difficulty in controlling bond strength, limits in equipment capacity, and difficulties inherent in the trial and error experimental technique have caused this study to be terminated at this point. If it were to be continued a few more things could be done.

Accurate control of bond strength could make the experimental results more consistent and repeatable. The cores could be produced by centerless grinding to give closer tolerances. The holes in the matrix could then be accurately drilled and reamed. Then, after proper gaging of the holes and cores, approximate interface pressures could be calculated, using equations such as given in chapter 7 of reference [16]. The model of reference [15] may also have to be applied when calculating the interface energy of the three core billets.

Using the results of the above calculations, the loosely packed composite model, and the analysis of reference [4], the theoretical "safe" regions could be compared to the experimental results.

Slight modifications of the existing ratio chambers could allow longer billets to be used. More successive reductions could then be taken before the product became too small due to waste of the initial and final instability regions.

A ratio chamber could be designed and built to give a higher receiver pressure. This would probably have to be used with an extrusion chamber with a pressure capacity larger than the 200 KSI Model 6 Monoblock.

The production of composite wires is a desirable end to a research project such as this. This study has barely scratched the surface of the problem of possible commercial production of composite wire.

FIG.1 CORE AND SLEEVE : FIRST OPERATION
OF CLADDING.

a

b

FIG. 2 BI-METAL ROD OF COPPER AND ALUMINUM

a) Copper Clad Aluminum

b) Aluminum Clad Copper

FIG. 3 PICTURES OF LONGITUDINAL PRODUCT SECTIONS

- a) Core Fracture
- b) Core Waviness
- c) Sound Flow

MAG 2X

FIG. 4 PICTURES OF PRODUCT CROSS SECTIONS

a) Non-Uniform Core Deformation

b) Uniform Core Deformation

a)

MAG 2X

FIG.5 SLEEVE IRONING (BACKFLOW) MODE

a) PICTURE (LONGITUDINAL SECTION)

b) SCHEMATIC

FIG. 6 EXTENDED STRESS - STRAIN CURVES FOR ANNEALED Nb-44%Ti AND 99.995% PURE ALUMINUM, COLD SWAGED 47% RA FROM THE "AS RECEIVED" CONDITION.

FIG. 7 TYPICAL THREE CORE BILLET

FIG. 8 TYPICAL SINGLE CORE BILLET

FIG. 9 THE MODEL 6 MONOBLOCK HYDROSTATIC EXTRUSION UNIT
SHOWN IN 30 TON BALDWIN HYDRAULIC PRESS

FIG.10 MODEL 6 MONOBLOCK , $\frac{1}{2}$ INCH BORE ,
200,000 PSI HYDROSTATIC EXTRUSION UNIT .

FIG. II a. "O" RING - MITRE RING SEAL

b. "O" RING WITH SAME I.D. AND LARGER O.D. ALTERED TO GIVE LARGER CROSS SECTION.

FIG. 12 NOSE MISMATCH

FIG. 13 TYPICAL PRESSURE VS. RAM DISPLACEMENT
CURVE FOR A THREE CORE BILLET WITH ONE-
PULSE STICK-SLIP.

FIG. 14 TYPICAL PRESSURE VS. RAM DISPLACEMENT
CURVE FOR A SINGLE CORE BILLET WITH NO
STICK-SLIP.

FIG. 15 TYPICAL PRESSURE VS. RAM DISPLACEMENT
CURVE FOR A SINGLE CORE BILLET IN WHICH
CORE FRACTURE OCCURRED.

- X CORE FRACTURE
- x CORE WAVINESS
- SOUND FLOW

$$Y = 0.708 \quad \alpha = 7.1$$

FIG. 16 SOUND AND FAILURE ZONES FOR SINGLE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO ATMOSPHERIC RECEIVER PRESSURE. $Y = 0.708$

- X CORE FRACTURE
- x CORE WAVINESS
- SOUND FLOW

$$Y = 0.624 \quad \alpha = 7.1$$

FIG.17 SOUND AND FAILURE ZONES FOR SINGLE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO ATMOSPHERIC RECEIVER PRESSURE. $Y = 0.624$

- X CORE FRACTURE
- CORE WAVINESS
- SOUND FLOW
- O SLEEVE IRONING

$$Y = 0.46 \quad \alpha = 7.1$$

FIG. 18 SOUND AND FAILURE ZONES FOR SINGLE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO ATMOSPHERIC RECEIVER PRESSURE. $Y = 0.46$

X CORE FRACTURE

x CORE WAVINESS

● SOUND FLOW

$$Y = 0.47 \quad a = 7.1$$

3:1:2 RATIO CHAMBER

FIG. 19 SOUND AND FAILURE ZONES FOR SINGLE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO HIGH RECEIVER PRESSURE.

$$Y = 0.47$$

- X CORE FRACTURE OR VERY WAVY
 ⊙ SOUND FLOW, NON-UNIFORM CORE DEFORMATION
 ○ SLEEVE IRONING

$$Y_{EQ} = 0.56 \quad \alpha = 6.7$$

$$\frac{3}{2} : 1 : \frac{1}{2} \text{ RATIO CHAMBER}$$

FIG. 20 SOUND AND FAILURE ZONES FOR THREE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO LOW RECEIVER PRESSURE.

- x CORE FRACTURE OR VERY WAVY
- ⊙ SOUND FLOW, NON-UNIFORM CORE DEFORMATION
- SOUND FLOW, UNIFORM CORE DEFORMATION
- SLEEVE IRONING

$$Y_{EQ} = 0.56 \quad \alpha = 6.7$$

3:1:2 RATIO CHAMBER

FIG. 21 SOUND AND FAILURE ZONES FOR THREE CORE, PURE ALUMINUM CLAD Nb-44%Ti (LIGHT MECHANICAL BOND) HYDROSTATICALLY EXTRUDED INTO HIGH RECEIVER PRESSURE.

FIG. 22 MODEL FOR ANALYZING LOOSELY PACKED COMPOSITES

MAG 2X

FIG. 23 PICTURE OF THREE CORE CROSS SECTION SHOWING ORIGINAL
CONDITION AND THE PRODUCT AFTER THE THIRD AND FOURTH PASS

DRAWN SIZE	% RA	YIELD STRENGTH (PSI)
.363	0	9,640
.288	37.0	11,460
.232	59.2	11,530
.193	71.7	11,920

Table 1. Yield Strengths for cold drawn aluminum. The .363 diameter sample was cold swaged 47% RA from the "as received" condition.

% RA	σ_{oc} (KSI) Nb-44 Ti	σ_{os} (KSI) Al	a
0	64.5	9.64	6.69
20	72.5	10.4	6.97
40	76.0	11.25	6.76
60	78.5	12.2	6.43
80	81.0	13.0	6.23

Table 2. Strengths and strength ratios for the three core billets. The 0% RA Ti-44% Nb is in the annealed condition and the aluminum is cold swaged 47% RA from the "as received" condition.

CHAMBER BORE (INCHES)	TOP PRESSURE	EXTRUSION PRESSURE	RECEIVER PRESSURE
.866	3/2 ΔP	ΔP	1/2 ΔP
.707	2 ΔP	ΔP	ΔP
.612	3 ΔP	ΔP	2 ΔP

Table 3. Ratio chambers for the Model 6 Monoblock.

MATERIAL AND DESCRIPTION	SOURCE
56% Nb-44% Ti ROD	Kawecki Berylco Industries Reading, Pennsylvania
VP ALUMINUM ROD	Materials Research Corp. Orangeburg, New York
KEYDRAW 301 LUBRICANT	Keystone Lubricating Co. Philadelphia, Pennsylvania
LUBRX 2009 LUBRICANT	Lubrx Products, Inc. North Attleboro, Massachusetts

Table 4. The sources of the experimental materials.

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