Experimental Extrusion of Aluminum Cable Sheath at Bell Telephone Laboratories

By G. M. BOUTON, J. H. HEISS, and G. S. PHIPPS

New techniques for extruding aluminum directly over paper insulated cable core at low temperature and pressure are described. Pistons operate from opposite ends of a cylinder to force the aluminum through a circular orifice between a die and core-tube located on an axis perpendicular to that of the pistons and midway between them. The inter-relation of extrusion temperature, pressure and rate, as well as the quality of the sheath produced, are found to be dependent on the die and core-tube design. Special lubrication and press charging techniques are discussed.

INTRODUCTION

In recent years considerable attention has been focussed on the possibility of using aluminum instead of lead as cable sheath. Over fifteen years ago German publications[1, 2] described activities abroad. It was emphasized at that time that for a given temperature, aluminum would require much higher extrusion pressures than lead. Also, the pressure required for extrusion of commercially pure aluminum (99 per cent) was reported to be considerably higher than that for super purity aluminum (99.99 per cent) under a given set of conditions. The possibility of obtaining lower pressures by raising the temperature is limited by the danger of scorching the paper or other organic insulation of the core. It is evident, therefore, that improvements in extrusion techniques are required. Progress in this respect has been reported recently.[3, 4, 5, 6]

Lower cost is an important part of the incentive for using aluminum instead of other types of sheath. In the telephone industry lead has already been supplanted to a sizable extent by composite sheaths, such as alpeth or stalpeth. The former consists of a thin corrugated aluminum sheath covered with extruded polyethylene-carbon black compound. The overlap seam in the aluminum is sealed with an organic adhesive. Stalpeth has a thin corrugated aluminum inner sheath without overlap or seal. Outside of this there is a sheath of corrugated tinned, steel sheet

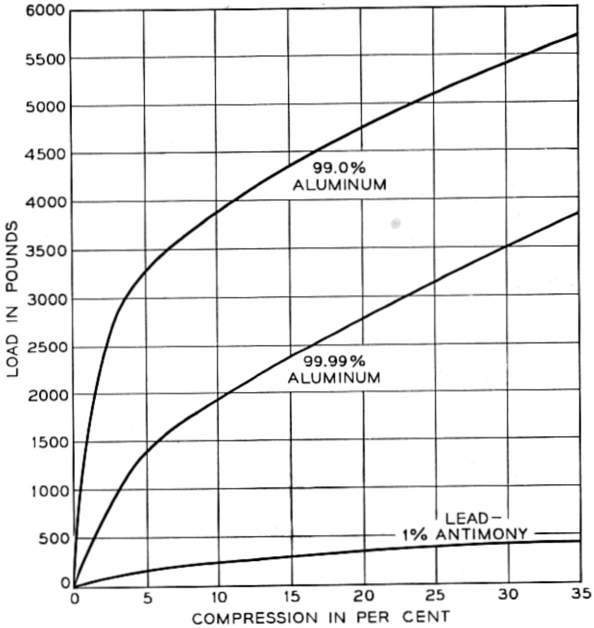


Fig. 1 — Compression tests at 265°C.

with a soldered seam. The whole is covered with extruded polyethylene compound. An all aluminum sheath would have a cost advantage over all types of sheath discussed. In addition, the aluminum sheath would be lighter and have greater tensile and creep strength.

Fatigue and corrosion must be explored further. The fatigue limit of aluminum at 10^8 cycles is considerably above that of lead on a stress basis. However, in aerial service, the strains might be similar in lead and aluminum sheaths since their temperature coefficients of expansion are similar and the copper core exerts a controlling effect on both types of sheath. Because of the higher modulus of elasticity of aluminum, a given strain results in a much higher stress than in lead. It is known that temperature fluctuations cause strains in aerial cable sheath considerably above the fatigue endurance limit. Until strain data are collected on sheath in service environments and fatigue tests are conducted at such strains, the field life expectancy of aluminum sheathed cables will be subject to question.

EXPLORATORY STUDIES

Plasticity studies were made at an early stage of the aluminum sheath investigation. The method used had proved quite successful in estimating extrusion pressure characteristics of lead alloys.[7] It consisted in compressing cylinders 0.92″ in diameter and 1.5″ long at a fixed temperature and a constant rate of 0.1″ per minute between parallel plates and plotting the load corresponding to the deformation. Fig. 1 shows some typical results obtained in this manner. By comparing the loads to produce a given deformation above the yield point, the relative extrudability may be estimated. The data indicate that about ten times as much pressure would be required to extrude 99.99 per cent aluminum compared to lead-1 per cent antimony at 265°C. The estimated pressure would be even greater for less pure aluminum. Since some 50,000 psi are required to extrude this widely used lead cable sheathing alloy through conventional extrusion passages, it is evident that the pressures required for aluminum extrusion would be far beyond the strength of available structural materials.

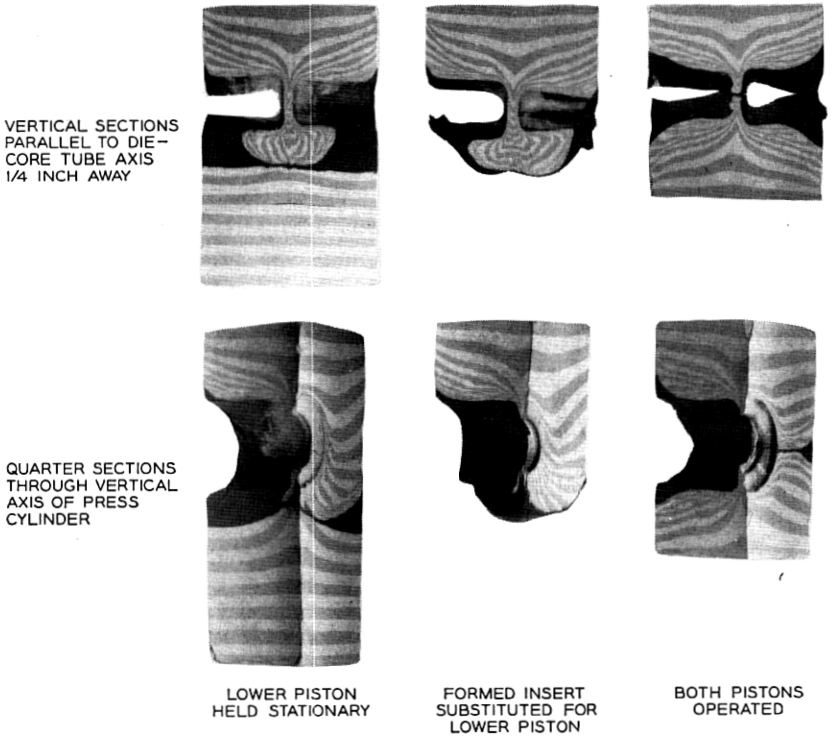


Fig. 2 — Flow patterns seen in sections cut through laminated modeling clay cylinder residues after extrusion.

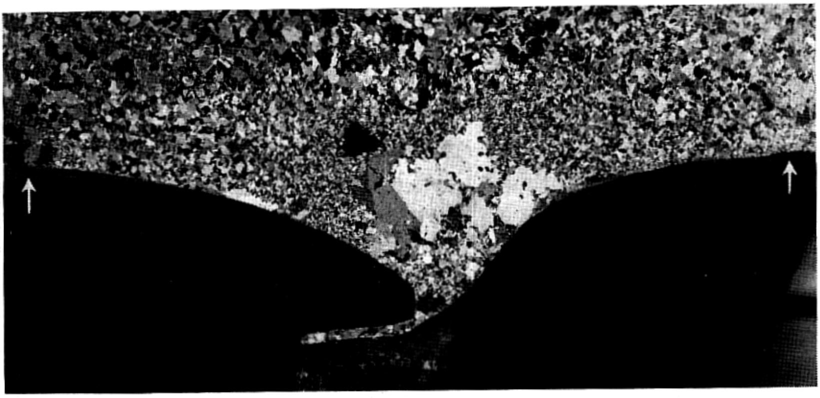


Fig. 3 — Section through a cylinder residue removed from the extrusion press. Arrows indicate the residual black layer of lead-0.1 per cent antimony from the original charge. Several subsequent charges of pure lead failed to remove the antimonial layer from the surface of the die and core-tube even close to the point of sheath formation near the middle of the picture.

With these considerations in mind, new designs of extrusion equipment were studied. An early experimental press was constructed with two axially opposed pistons and the die and core-tube located midway between them at 90° to the cylinder bore. Valuable information on flow patterns was obtained using colored modeling clay laminates. Fig. 2 shows typical results of these experiments. Early studies were made by fixing one piston and examining the flow of the laminates through an unlaminated different colored mass in the die and core tube region. This gave some clue as to what an ideal cavity would be for a one-piston extrusion where the clay was free to choose its own flow channels. Considerable volumes of the dark undisplaced clay can be seen in both sections in the first column of Fig. 2. By cutting away the stationary clay, the preferred shape of the shear surfaces in the central region could be obtained. A plaster mold was made to this shape and used in place of the bottom piston. Additional extrusion of laminates established that there was always a stationary layer of modeling clay next to the die-block surfaces as shown in the second column of Fig. 2. Flow took place by shear within the clay rather than by flow along the surfaces that were supposed to guide it. The third column shows flow when both pistons were operated. Here again much of the dark colored clay remained on the surface of the tools after several extrusions.

This stationary layer was further confirmed by experiments with lead. Incorporation of about 0.1 per cent antimony does not seriously alter the extrusion characteristics of pure lead. When this alloy is etched, it has a black matte appearance readily distinguished from that of the surrounding lead. Fig. 3 shows the results of extrusions using both pistons where first lead-0.1 per cent antimony was charged followed by several charges of pure lead. The etched residue shows the black adherent layer adjacent to the cavities left by the die and core-tube.

On the basis of these studies, attempts to develop a preferred die-block contour were abandoned. Instead, the chamber in the region of the extrusion orifice was left as open as possible. This permits the flowing material to choose its preferred path, which, indeed, may change slightly for different temperatures, extrusion rates and materials.

EXPERIMENTAL EXTRUSION PRESS DESIGN

As a result of this work a new experimental press was designed to permit additional study of basic principles of the plastic flow of metals

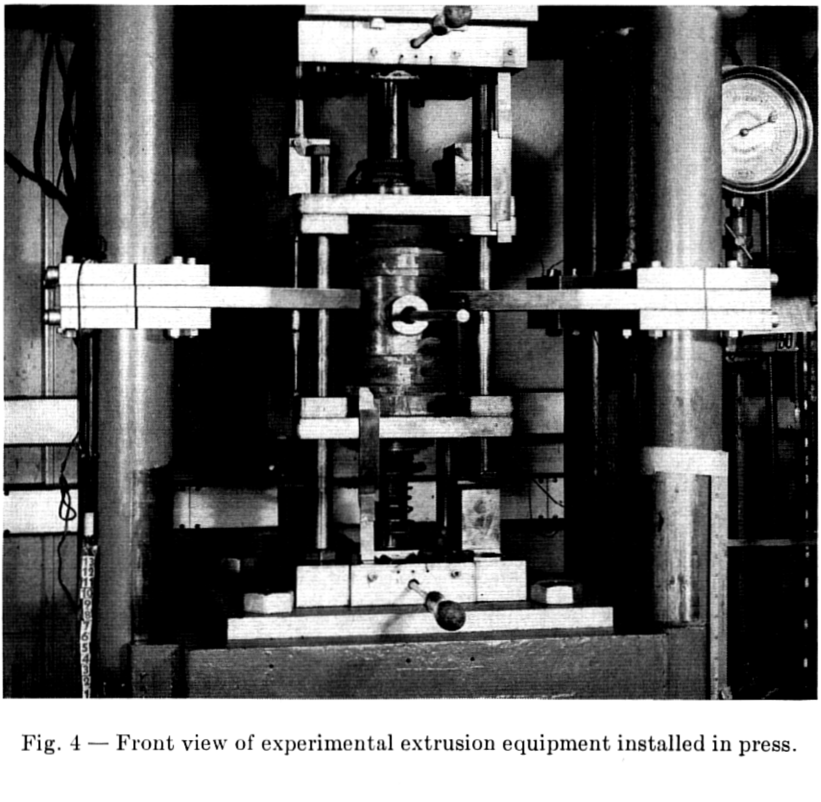


Fig. 4 — Front view of experimental extrusion equipment installed in press.

through chambers and extrusion dies. The pressure source is a single hydraulic cylinder press of 180-ton capacity. The extrusion equipment has two pistons operating from opposite ends of the extrusion cylinder. The ratio of bore to stroke was made as large as possible because considerable pressure is lost through friction and shear of aluminum at cylinder walls. The use of two pistons operating from opposite ends of the cylinder insured a reasonable amount of material extruded per stroke. Two cylindrical aluminum billets measuring 2.2 inches in diameter and approximately 3.5 inches in length produce about 50 feet of cable sheath, one-half inch in diameter with an 0.028-inch wall. Fig. 4 shows the over-all picture of the extrusion equipment installed in the hydraulic press.

A schematic side view of the press showing the relative positions of the members is shown in Fig. 5. The cylinder block is constructed of three concentric shell tubings heat-shrunk together to provide a fairly high residual compressive stress on the inner wall of the cylinder. They

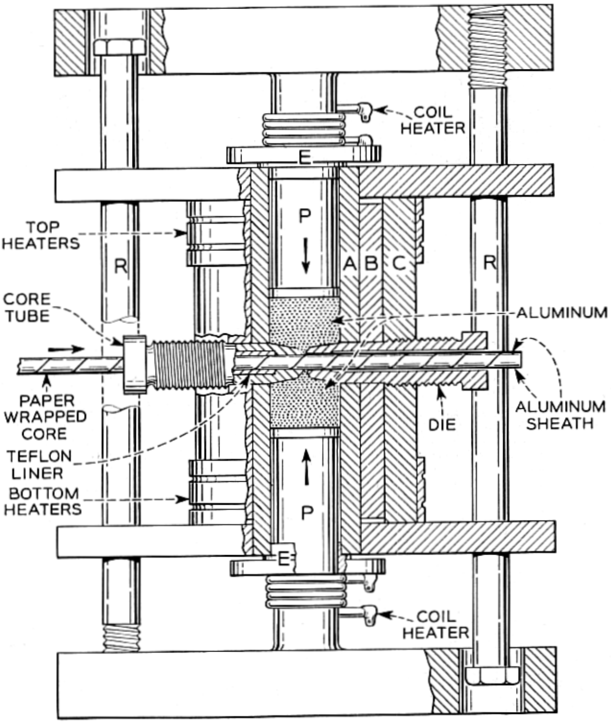


Fig. 5 — Diagram of experimental press assembly.

are shown schematically by the cross-hatched areas A, B, and C. The block is held in place by end plates having porous bronze bearings which slide on guide rods, R, and serve to keep the freely floating press in fairly exact alignment. When the press is opened, the pistons, P, slide back in guides, not shown, to permit introduction of fresh aluminum cylindrical billets into the extrusion cylinder. Sliding bronze bushings, E, attached to the pistons fit into the top and bottom of the cylinder and aid in maintaining alignment of the pistons in the cylinder during the application of extrusion pressure. The die and core-tube are shown in position at the middle of the cylinder. Their distance from each other determines the wall thickness of the sheath. Also pictured schematically is the formation of the cable sheath near the axis of the cylinder. The paper wrapped core is introduced from the left hand side and is carried through the press to the right by the extruding sheath. The core tube has been recessed over a large portion of the guide hole in order to accommodate a teflon liner. This plastic liner acts as a heat insulator which protects the paper wrap from being seriously scorched, especially during a recharge period. Heat is fed to the ends of the cylinder by means of the two sets of band heaters which are regulated by a recording controller. The pistons are heated by sliding coil heaters also shown in position. These extra heaters serve to balance the heat lost by conduction through the pistons and thus tend to provide fairly good temperature distribution along the cylinder wall.

The press may be operated either at constant applied pressure or constant extrusion rate. To operate at constant pressure the valves are manually controlled. A sliding brush attached to the platen of the press makes contact with a slide wire to indicate each ½-inch platen travel by sounding a buzzer and marking an indication on the recorder chart. Each time the buzzer sounds, a mark is placed on the sheath. This designates specimen lengths which are numbered 0 to 13, inclusive, over one full press stroke. Thus, matching the appropriate time from the recorder chart, the rate of extrusion may be obtained for any portion of the piston stroke.

The other method of operation, at constant extrusion rate, consists in regulating the rate of travel of the platen of the press. This is accomplished manually by making an indicator attached to the platen coincide with markings on a vertical tape which can be set to travel at a fixed speed. A recording pressure gauge coupled to the moving platen gives the pressure continuously during the piston stroke.

The location of the die and core-tube offers many advantages. The opposing operation of the pistons minimizes the bending moment on

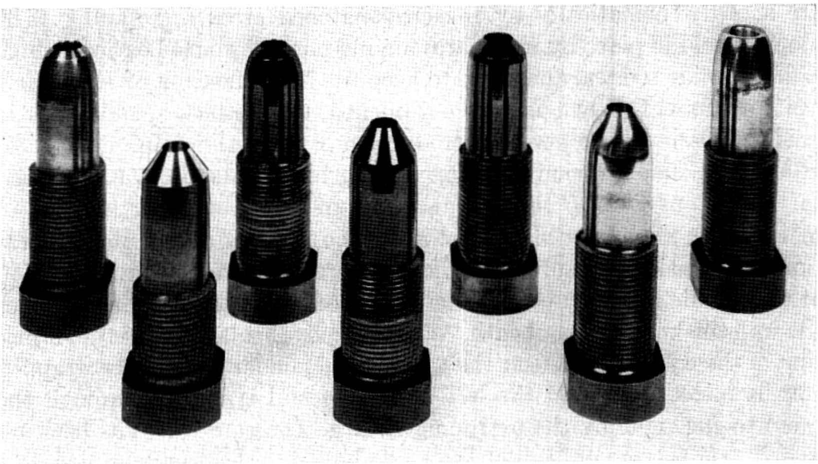


Fig. 6 — Some experimental dies and core-tubes. The three middle tools have baked on oil finish.

the tools and also greatly reduces the shear surfaces within the aluminum as it approaches the extrusion orifice. This construction results in far less dissipation of pressure than the conventional single piston lead presses in which some of the material from the top must flow completely around the core-tube, join and then flow through a highly restricted path to the point of sheath formation. Locating the tips of die and core-tube at the axis of the extrusion cylinder further reduces the shear surfaces over which the aluminum must move. Another advantage of this axial position is that the core-tube has greater rigidity because of its shorter cantilever length. There is a slight disadvantage in the placement of the die tip in the center of the cylinder because of greater bending moment, but this is greatly outweighed by having both the die and core-tube move in unison under any fortuitous pressure unbalance between the pistons thus helping to maintain sheath concentricity.

EFFECT OF DIE SHAPES

Early in the program of extrusion studies it became evident that the shape of the tip of both the die and core-tube would have an important bearing on the quality of the sheath and the extrusion rate. Fig. 6 shows a few of the dies and core-tubes used. Fig. 7 shows details of the shapes of the tips of some of the dies that were studied while Fig. 8 shows shapes of core-tubes used in various combinations with these dies. Each letter shows a separate step in the modification of these tools. Early indications were that a sharp edge on the die (as in 8A, Fig. 7) resulted in high extrusion speeds, but in most circumstances the sheath lacked both roundness and smoothness, for example, the left-hand tube in Fig. 9. To correct for this condition the first studies involved the introduction of various radii at the extrusion point. This improved smoothness slightly but still frequently produced sheath that was either very much out of round or perhaps had flattened portions on the sides. This flattening was believed to be due to the easier distribution of pressure to the top and bottom rather than to the sides of the die and core-tube; thus a variable ex-

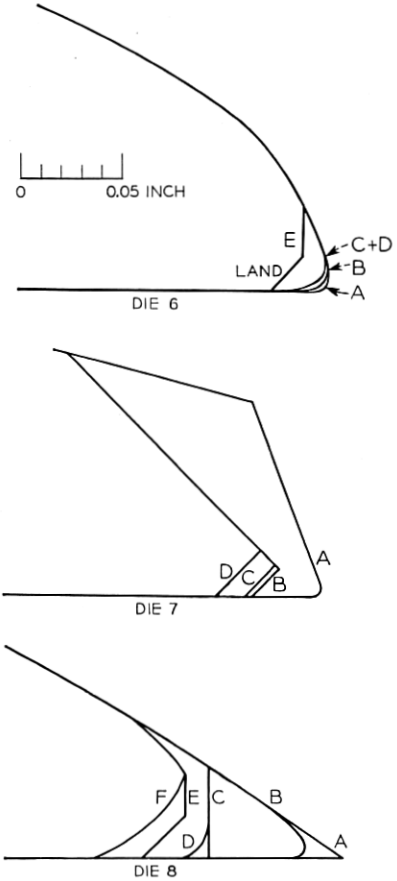


Fig. 7 — Longitudinal sections through upper tip of dies at various stages of modification.

trusion rate was produced around the annulus. In order to equalize this pressure the radius at the tip of the die was replaced with a 45° conical section ground as shown in 6E of Fig. 7. This provided a land whose length could be varied as required. A land, as the term is used in this paper, consists of a short conical ring section extending forward at some particular angle to the die axis toward the tip end of the die. This land, then, formed the outer sheath gate surface of the annulus, and produced a large improvement in both smoothness and roundness of the sheath when used in conjunction with core-tube 5D. However, an adverse effect on extrusion rate was noted. Since sharp shear edges had previously shown beneficial effects, another 45° cut was made as shown for 7B in Fig. 7. This change resulted in considerable improvement in extrusion speed. Fig. 10 shows typical data obtained when comparing the effect of two die shapes under conditions of constant pressure and core-tube design. In these two extrusions variations were made in both the sharpness of the leading edge of the die and the length of the restricting path

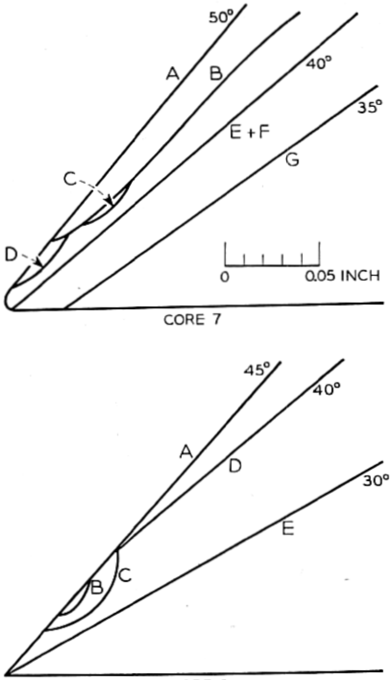


Fig. 8 — Longitudinal sections through upper tip of core-tubes at various stages of modification.

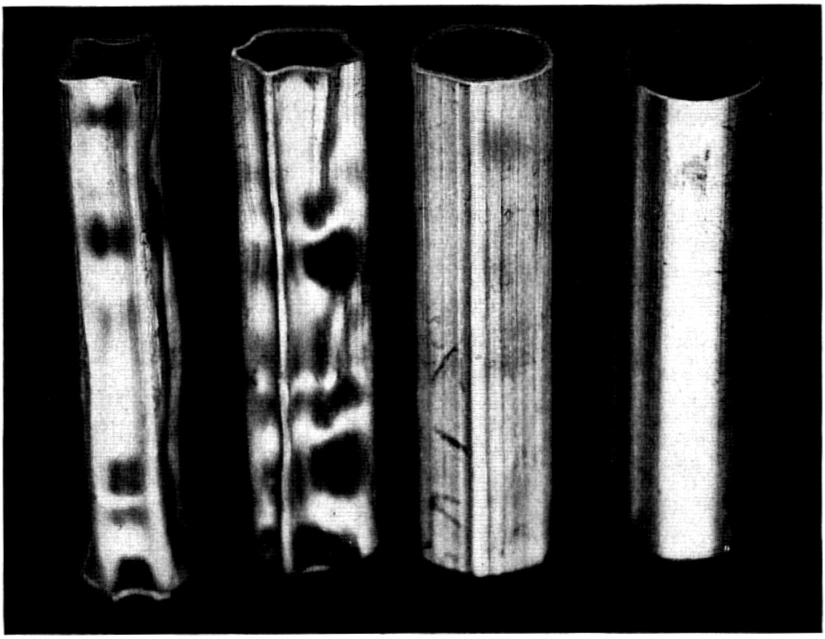


Fig. 9 — Evolution of tubing as extrusion tool contours were improved.

through which the aluminum must travel while being formed into sheath. Toward the end of the stroke the extrusion speeds through the two die shapes differ by a factor of about ten. While the extrusions start at constant temperature, the severe plastic working near the tips of the die and core-tube causes an increase in temperature. This is particularly true near the end of the charge where extrusion rates increase greatly. Exact instantaneous temperatures at this point are extremely difficult to measure. The abscissa designations along the top and bottom of the graph show the interrelation between specimen numbers and per cent of stroke.

Many other details of the die and core-tube design have been found to be of importance. Increasing the length of the land from 0.020 to 0.033 inches produces a reduction of extrusion speed. Decreasing the land from 0.020 inches below approximately 0.005 inches tends to give rough, irregular sheath. Increasing the angle of the core-tube beyond the 45° angle of the die land results in sheath that is rough and not round. The best results were obtained when the core-tube angle was slightly less than the die land angle which, in these studies, was fixed at 45°. This produced a slight restricting effect as the aluminum approached the final point of wall thickness formation. The minimum angle is somewhat dependent on the strength of the steel and its resistance to collapsing under the extrusion pressure. Another effect of the angle of the core-tube is in establishing the exit direction of the formed aluminum. It is known that the outside diameter of the sheath is smaller than the minimum diameter of the die orifice as shown schematically in Fig. 11. The sheath is funnel-shaped to a distance of about ⅛ to ¼ inch past the extrusion point. The exact curvature followed in this funnel-shaped region is a function of extrusion orifice contours, temperature, extrusion rate and purity of the aluminum. Thus, different grades of aluminum might require slightly different die and core-tube combinations.

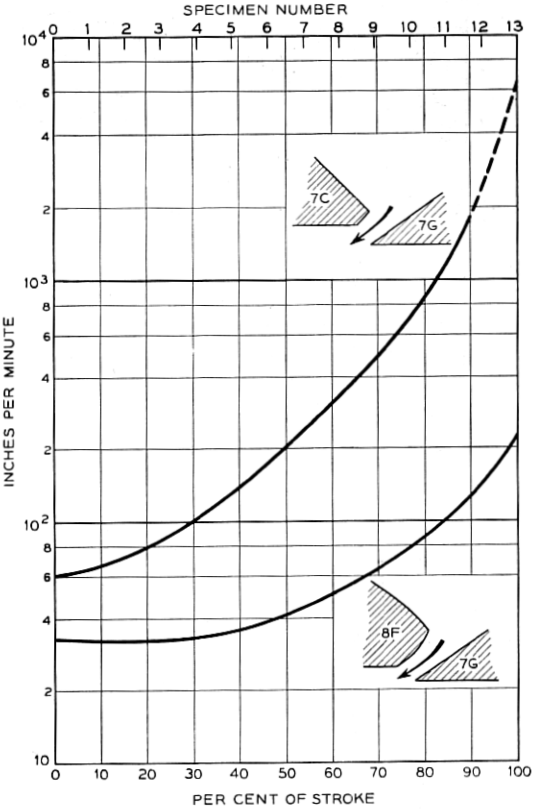


Fig. 10 — Effect of die shape on extrusion rate at 335°C and 62,500 psi. Note change of rate as extrusion progresses.

Another detail shown in Fig. 11 is the thin adherent layer of aluminum (cross-hatched sections) both on the land surface and a corresponding ring around the tip of the core-tube. The wetting of these surfaces appears to be of paramount importance for ease of extrusion and smoothness of sheath. The first few lengths produced by a clean coated die and core-tube are usually not as smooth as succeeding lengths. Until this annulus is wetted by aluminum, variations between slipping over the steel and shearing within the aluminum result in rough sheath.

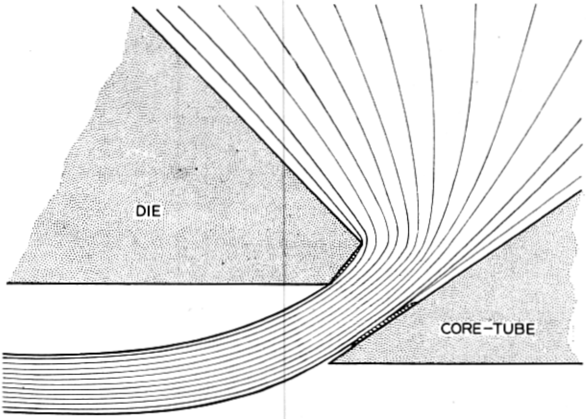


Fig. 11 — Schematic representation of flow of aluminum through a section of the extrusion orifice.

EFFECT OF TEMPERATURE ON EXTRUSION RATE

Extrusion rates were obtained for several temperatures using die 7C and core-tube 7G and an applied pressure of 65,000 psi. These are plotted in Fig. 12 for a stroke position which is designated as specimen 2 corresponding to approximately 15 per cent of the total piston movement. A small increase in extrusion temperature results in a relatively large increase in extrusion rate. This emphasizes the need to operate at as high a temperature as is consistent with no detrimental effect on the paper insulation of the core.

EFFECT OF PRESSURE ON EXTRUSION RATE

Data on this subject are obtained by keeping the temperature fixed and extruding at different constant pressure levels. These data are treated as in the study of the effect of temperature. The curve obtained is shown in Fig. 13, again for die 7C and core-tube 7G at 335°C. It would not be expected that this relationship would hold over an extended pressure range since below some limiting value, corresponding to the yield point of the material, practically no extrusion would take place. Once the conditions of reasonable extrusion rate are obtained much greater rates can be developed by relatively small increases in pressure. For example, a press that would produce sheath at 100 ft. per minute could, with only a relatively small increase in pressure, produce at 200 or 300 feet per minute.

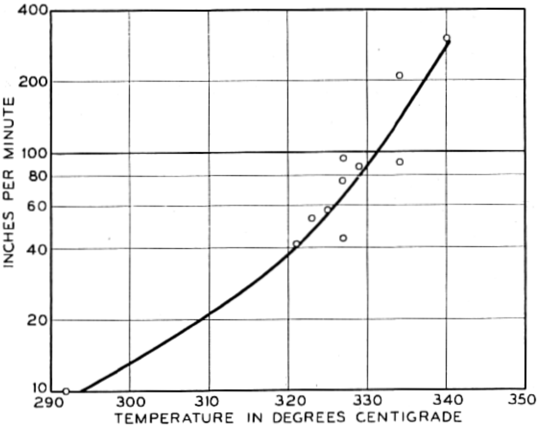


Fig. 12 — Effect of temperature on extrusion rate at constant pressure of 65,000 psi.

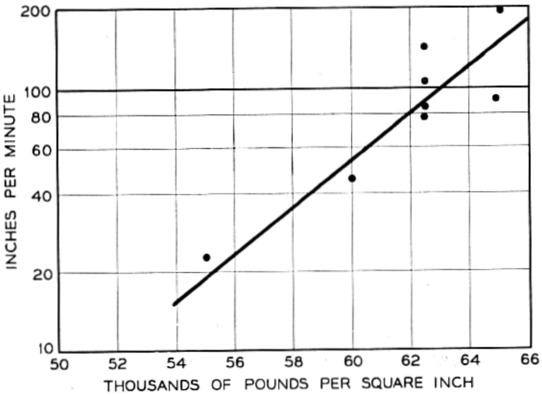


Fig. 13 — Effect of pressure on extrusion rate at 335°C.

EFFECT OF CHARGE LENGTH

The present studies, as well as reports of other investigators[8] of extrusion phenomena, show that considerable pressure is lost in forcing the billets to advance through the cylinders. Under some circumstances the material next to the wall slides when properly lubricated while in others the layer next to the wall remains essentially stationary and flow takes place by shearing within the aluminum. The degree to which these effects are present depends on the pressures required for extrusion. Under conditions of slight restrictive forces at the extrusion end of the cylinder, such as might be involved when a low extrusion ratio* is used, the pressure applied by the piston might be low. With these circumstances the pressure multiplied by the coefficient of friction would result in a frictional force less than the shear strength of the aluminum layer directly in contact with the cylinder wall. In these instances flow would take place by slip between the aluminum and the steel. When high extrusion ratios and correspondingly high pressures are used, the frictional force may exceed the shear strength of the aluminum, in which case flow takes place by shear within the aluminum. In either case there is a relatively rapid decrease in pressure at constant extrusion rate as the distance of the piston surface from the extrusion port becomes smaller.

The decrease of pressure with charge length is shown in Fig. 14 for several purities of aluminum at a constant extrusion speed of 25 feet per minute and a temperature of 331 ± 6°C. At this slow rate only a slight increase in temperature takes place at the die tip. The decrease in pressure is, therefore, nearly directly the result of decreasing charge length. The effects of purity are also apparent, of which more will be said later.

EFFECT OF TEMPERATURE ON EXTRUSION PRESSURE

This subject is of great importance since it affects the design and capacity of extrusion equipment. Data collected at a constant extrusion rate of 25 feet per minute are presented in Figs. 15 and 16 for 99.99 per cent and 99 per cent aluminum, respectively. The decrease in the slopes of the curves as the temperatures are raised or as the purity increases is evident. These slopes correlate most closely with initial pressure, which in turn is probably related to the shear strength of the materials and the consequent force necessary to push the aluminum billets through the cylinders. If the billets moved by sliding along the cylinder walls, the force would also be related to the initial pressure through the coefficient of friction. Since there is less loss in pressure due to shear and

---

* Cross-sectional area of the cylinders divided by that of the sheath.

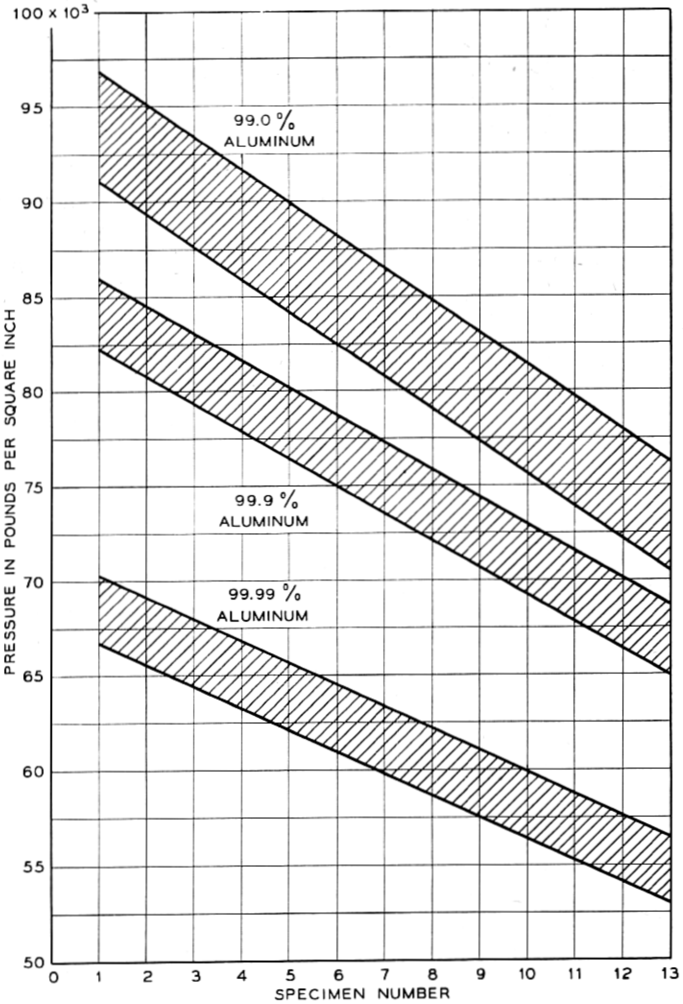


Fig. 14 — Effect of charge length and purity on extrusion pressure at constant rate.

friction at higher temperatures, there would thus be less need to maintain a low ratio of billet length to diameter. This is possibly the reason for some European success reported using long billets.[4] Fewer charge welds, press-marks and charging delays would result.

Further consideration of the pressure-temperature relationships gives some insight on the plastic behavior of aluminum during extrusion.

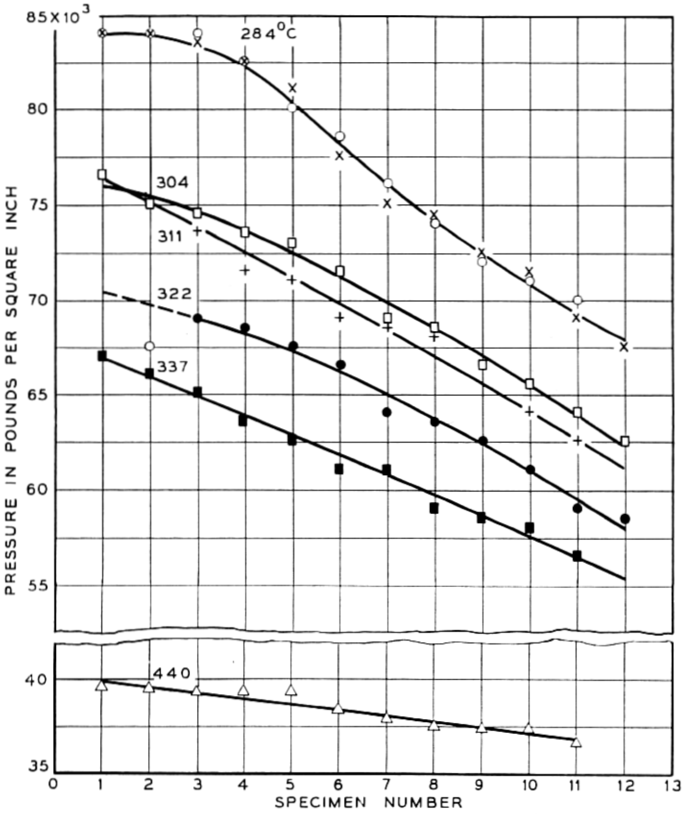


Fig. 15 — Effect of charge length and temperature on extrusion pressure at constant rate for 99.99 per cent aluminum.

Once the yield point of the aluminum has been well exceeded, it might be expected that it would flow in a manner analogous to true plastic behavior. A plasticity relationship would normally follow an equation of the Arrhenius type:

$$\text{Log } \eta' = \text{Log } K + \frac{E}{2.3RT}$$

where η' is the plasticity, K is a proportionality factor, and E is the activation energy for plastic flow. If the aluminum were behaving in this manner, the pressure necessary to force a definite volume of aluminum through a specified orifice in unit time would be directly proportional to the plasticity. After about the fifth specimen has been extruded,

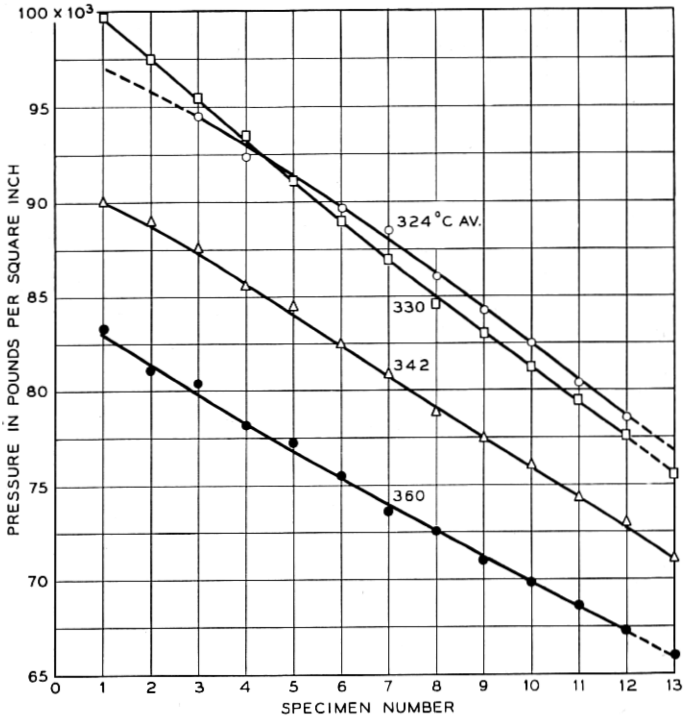


Fig. 16 — Effect of charge length and temperature on extrusion pressure at constant rate for 99 per cent aluminum.

relatively stable conditions are established and the data may be compared further. When the logarithms of pressures for this specimen are plotted against the reciprocal of their absolute temperatures, the straight line shown in Fig. 17 is obtained for 99.99 per cent aluminum. The data for the 99 per cent are not sufficiently extensive to fix the exact slope but it is probably similar. This linearity indicates that aluminum has a plastic behavior under the conditions of temperature and pressure used in these experiments. Other indications point to a tendency to form a stationary layer at the cylinder wall and die parts similar to viscous behavior. Assuming such a relationship, the activation energy for plastic flow may be calculated as 3.6 kilo-calories. This is a low value compared to activation energies for viscous flow of $\sim$ 10 kilocalories for a soft rubbery plastic such as polyisobutylene at 217°C, or 150 kilocalories for glass at 600° to 700°C.

PURITY OF ALUMINUM

Several factors enter into the choice of grade of aluminum for cable sheath. Among them are ease of extrusion, cost, availability, corrosion resistance and mechanical properties. The extrusion behavior has been shown in Figs. 14 through 17 and is summarized in Fig. 18. The first increments in impurity have proportionately much greater effects on extrusion pressure than subsequent increases have. Our plasticity studies indicate that iron is more responsible for increase in pressure than are the copper and silicon which are also normally present in commercial aluminum. The total spread of pressure required over the purity range studied is enough to influence the design of extrusion equipment. The maximum pressure for even the least pure material is not beyond commercial feasibility.

There is a large differential in cost between 99.99 per cent and 99.9 per cent aluminum. The difference between 99.9 per cent and 99 per cent is much less. The same relationship holds true for availability. There is at present no major source of the super-pure material in this country.

Tensile tests have been made on extruded pipe produced from the three grades of aluminum studied. The results are noted in Table I and shown graphically in Fig. 19 for specimens extruded at about 330°C.

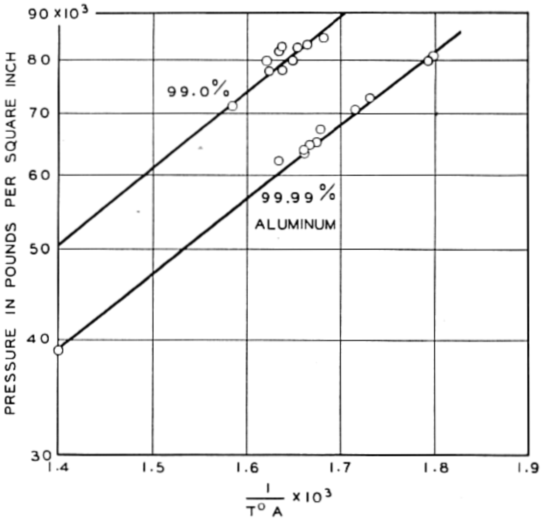


Fig. 17 — Dependence of log pressure on reciprocal of absolute temperature.

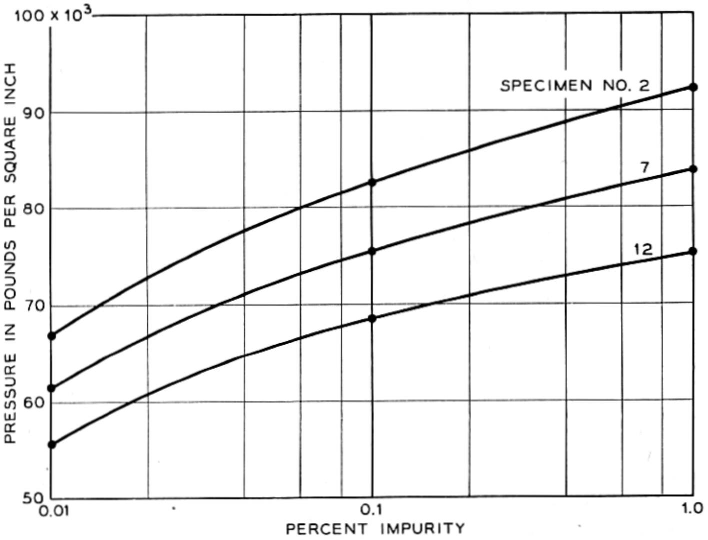


Fig. 18 — Effect of impurity on extrusion pressure at constant speed.

The tests were made by gripping flattened ends of pipe in the jaws of a testing machine. The gage length used was 10 inches and the cross-head was moved at the rate of 1 inch per minute. Stress-strain curves were plotted automatically by the machine.

Table I — Tensile Strength of Three Grades of Aluminum

	Tensile Strength (psi)			Elongation (per cent in 10 inches)		
Purity in Per Cent	99.99	99.9	99.0	99.99	99.9	99.0
Specimen No. (Position in Charge)						
1	9,750			45.5		
2	10,000	11,600	17,400	45.0	21.7	24.2
3	10,300	11,120	16,500	44.3	26.2	24.2
4	10,420	12,200	16,400	42.9	29.0	28.0
5	10,540	12,120	16,300	43.9	30.0	27.0
6	10,700	12,200	16,000	42.5	33.5	27.0
7	10,850	12,200	15,900	42.9	36.5	
8	10,750	12,080	15,900	42.5	27.8	
9	10,630	12,200	15,600	42.6	34.3	
10	10,500	12,150	15,600	40.4	24.0	
11	10,200		15,450	42.8		
12	10,000		15,250	39.7		
13			15,100			

The increase in tensile strength and the decrease in elongation with increasing impurity are of the magnitude to be expected. The variation of strength along the length of the charge may be related to differences in degree of recrystallization observed in the microstructure. In the case of both the 99.9 per cent and the 99 per cent materials the ratio of amounts of impurity in and out of solution may also have an effect on the strength.

Typical stress-strain curves for the three materials are reproduced in Fig. 20. The abrupt change in direction in the early part of the curve for the highest purity material represents a yielding of the coarse soft grains while work hardening capacity is being built up. The less pure materials have a finer grain structure, and, having a higher recrystallization temperature, may well retain some of the strain resulting from extrusion.

EFFECTS OF EXTRUSION TEMPERATURE ON CORE WRAP PAPER

A major consideration in the production of aluminum cable sheath has been the need to limit the extrusion temperature in order to prevent damage to the core wrap paper. An extrusion temperature of 325°C was found to result in slight discoloration of red and white undried core wrap paper. At this temperature, when the press is stopped in the order of 30 seconds for recharging, the paper assumes a distinct brown coloration but does not appear to be embrittled. Studies were made of the

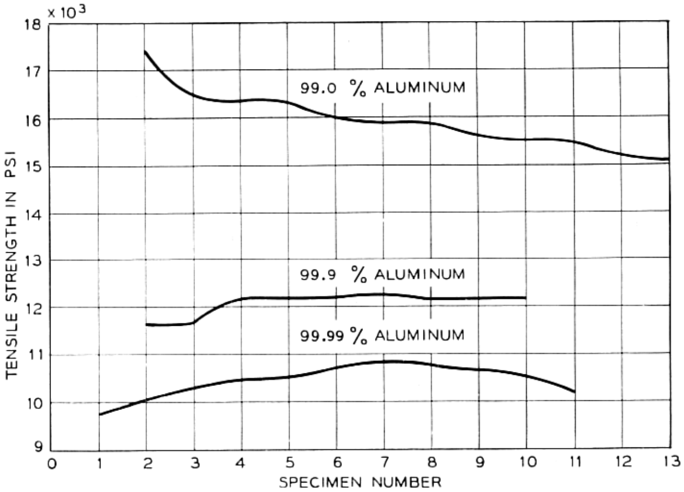


Fig. 19 — Tensile strength of extruded aluminum pipe.

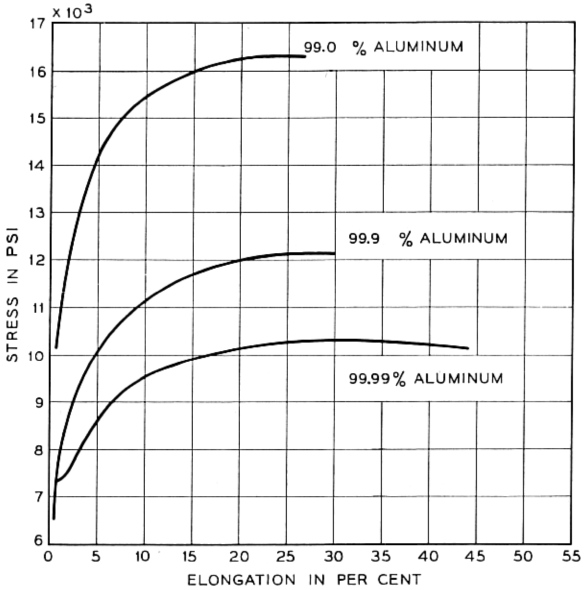


Fig. 20 — Stress-strain curves for extruded aluminum pipe.

temperatures existing in the core by attaching thermocouples to the outside, under one, and two layers of paper. The thermocouples were connected to sensitive recorders and showed the following results when an extrusion temperature of 325°C was used:

Couple on outside of core: 279 to 295°C.
Couple under one layer of paper: 225 to 235°C.
Couple under two layers of paper: 197 to 215°C.

JUNCTIONS BETWEEN CHARGES

At the outset of the laboratory studies it was realized that considerable trouble might be expected when successive billets were added to cylinder residues. In ordinary commercial extrusion where continuous lengths of tubing are not required, the common practice is to remove the cylinder residue from the press after each extrusion stroke. Attempts to introduce successive billets have often resulted in poor welds or pinholes in the tubing. Beside contamination from improperly prepared surfaces, another basic source of junction difficulty may occur. When a cylinder of plastic material such as aluminum is compressed between parallel plates, "barreling" takes place due to the restrictive effect of friction on the two ends of the cylinder. Thus, when a cylindrical billet is placed in the press cylinder, there is a tendency for the billet to become thicker in the middle as pressure is applied to one end. This may effectively seal the cylinder at this point and entrap a fairly large amount of air between this restriction and the old charge material. It was found that this situation could be corrected to a major degree by scoring the billet with four equally spaced longitudinal "V" shape grooves approximately 0.010 inches in width and depth. When pressure is first applied to a billet so scored, "barreling" takes place as before, but the pressure against the cylinder wall at the mid-point of the billet is not sufficient to seal off the inscribed grooves. Continued application of pressure to the piston then forces all portions of the billet into contact with the previous charge and the cylinder walls. Final increase in pressure to near extrusion value causes the grooves to close thus trapping a minimum amount of air. Sheath and pipe produced under this technique have been tested under 60 psi air pressure and found to be free from pinholes.

Air entrapment can be further minimized by maintaining the preheating temperature of the billets slightly below that of the residual charge in the press cylinder. The end of the billet in contact with the hotter residual charge increases more in diameter than the cooler portions closer to the piston, thus reaching the cylinder walls near the old charge residue first. As temperature equilibration takes place under pressure, the increased diameter moves outward along the axis of the billet toward the piston forcing the air out of the cylinder. A combina-

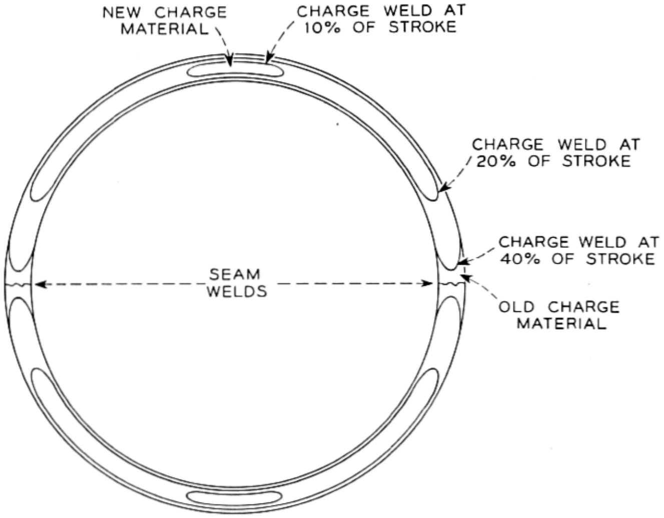


Fig. 21 — Diagram of sheath cross-section at various stages of extrusion.

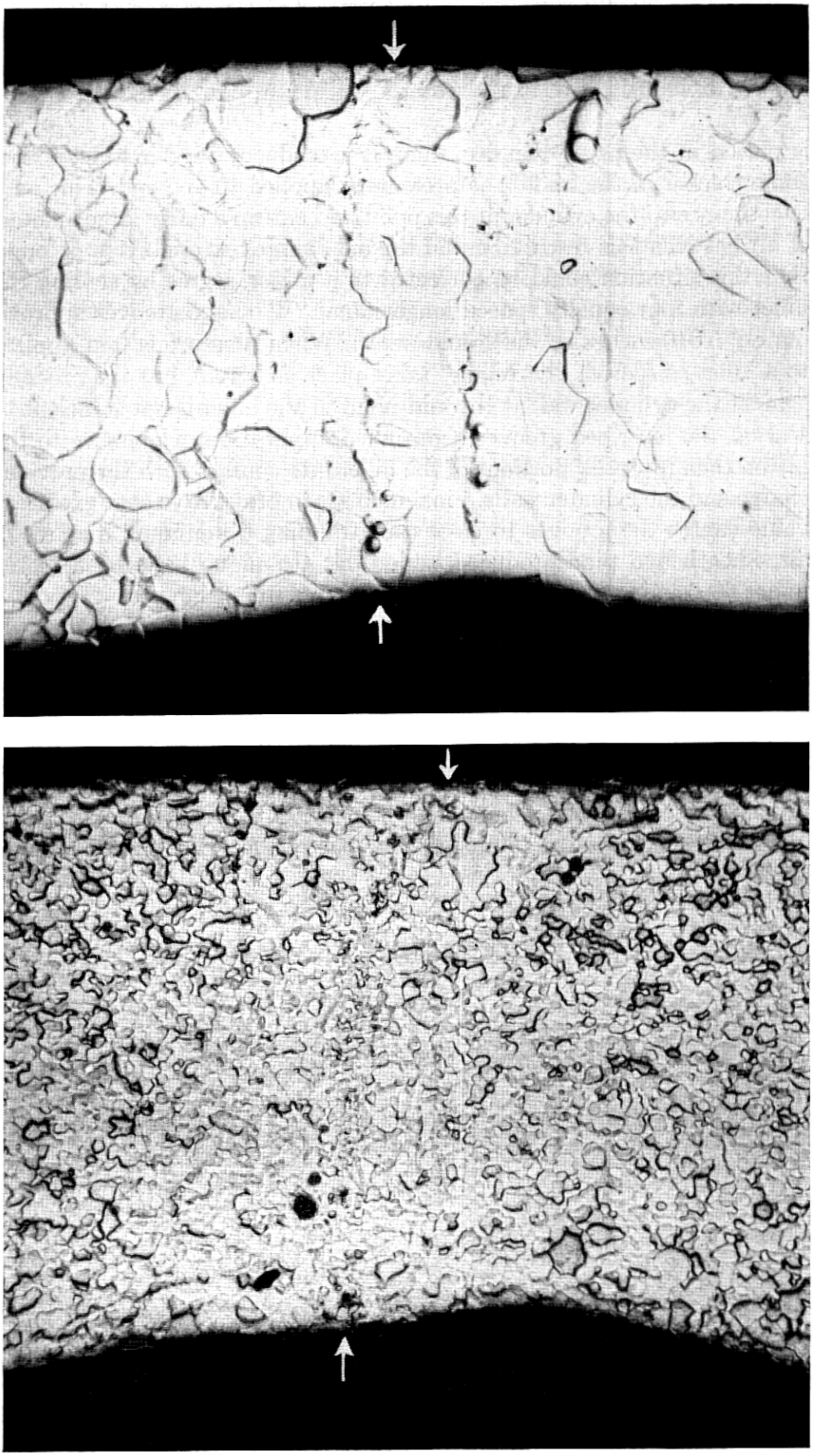
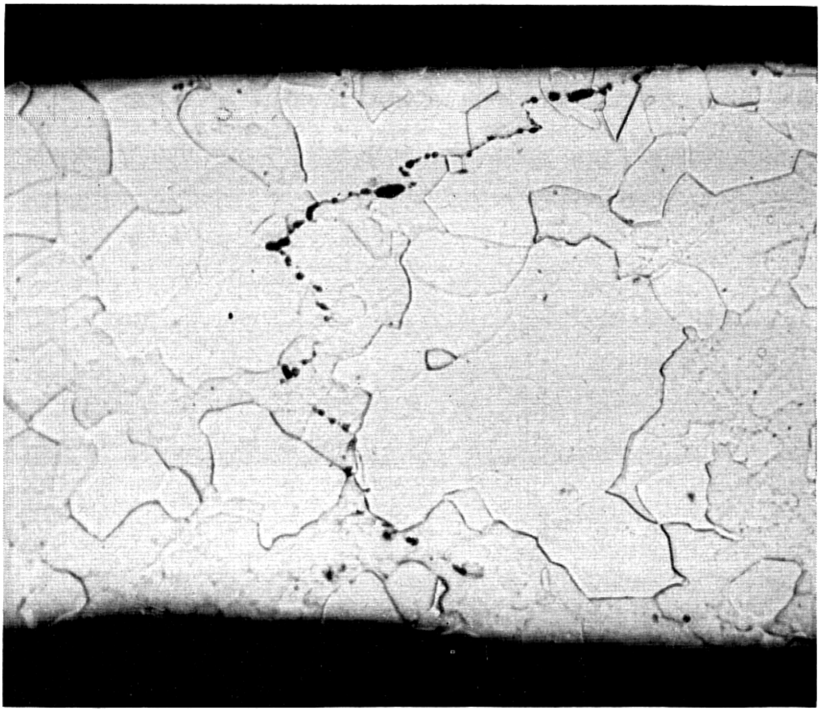


Fig. 22 — Transverse microsection of extruded 99.99 per cent aluminum sheath. Above, seam weld coarse grained material, and below, seam weld fine grained material, both at 150x.



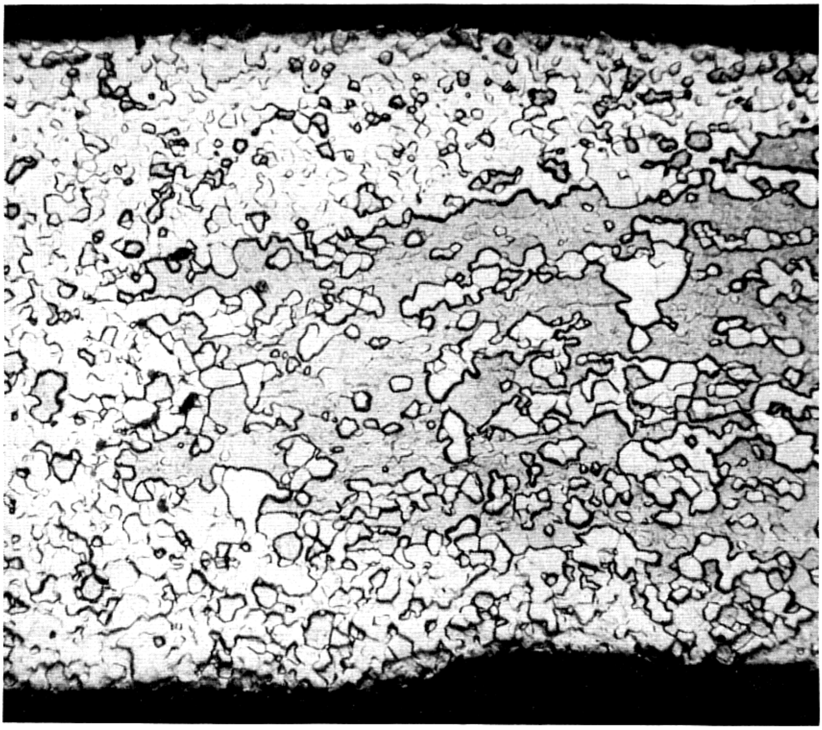


Fig. 23 — Transverse microsection of extruded aluminum sheath. Above, charge weld — line of demarcation is plainly visible. Below, charge weld — the new charge material appears darker because the grains have a different orientation. Both at 150x.

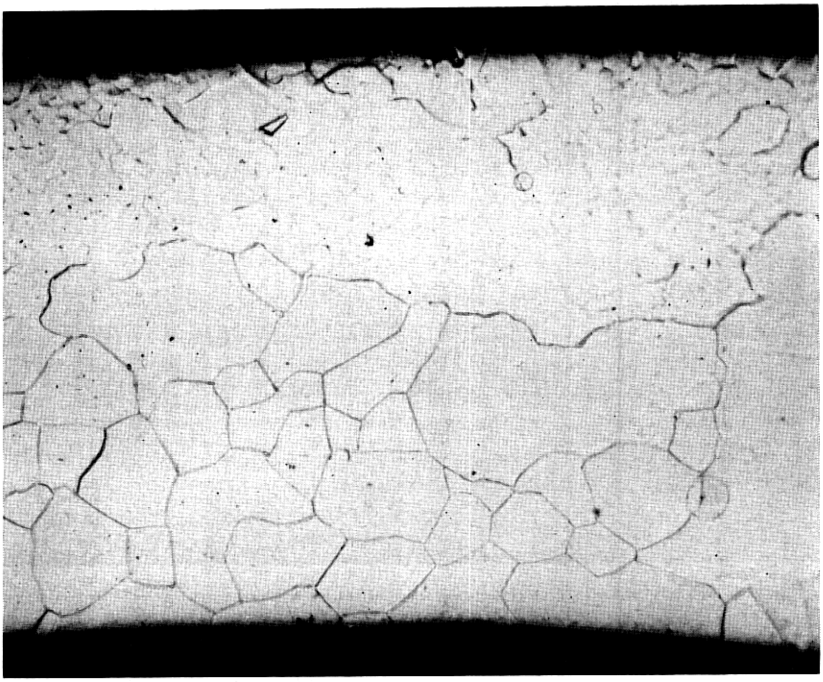


Fig. 24(a) — Top of sheath away from welds. Material near top of photo is not recrystallized. At 150x.

tion of these techniques coupled with care in preparing billets and elimination of lubricant during the charging operation has given tubing free from holes.

Samples cut from various positions along the length of pipe extruded from a single charge have been subjected to expansion tests using a tapered steel plug similar to the technique used in testing welds in lead cable sheath. The welds have proved sound and expansions of 30 to 40 per cent are found. The location of the breaks occurred at random with respect to the position of the welds.

MICROSCOPIC EXAMINATION

As would be expected from the double ingot charging procedure, seam welds are present in the aluminum sheath diametrically opposite on a horizontal plane as shown schematically in Fig. 21. The progressive displacement of the old charge residue is also indicated. If considerable dross is present, there may be sharp lines of demarcation. Fig. 22 shows

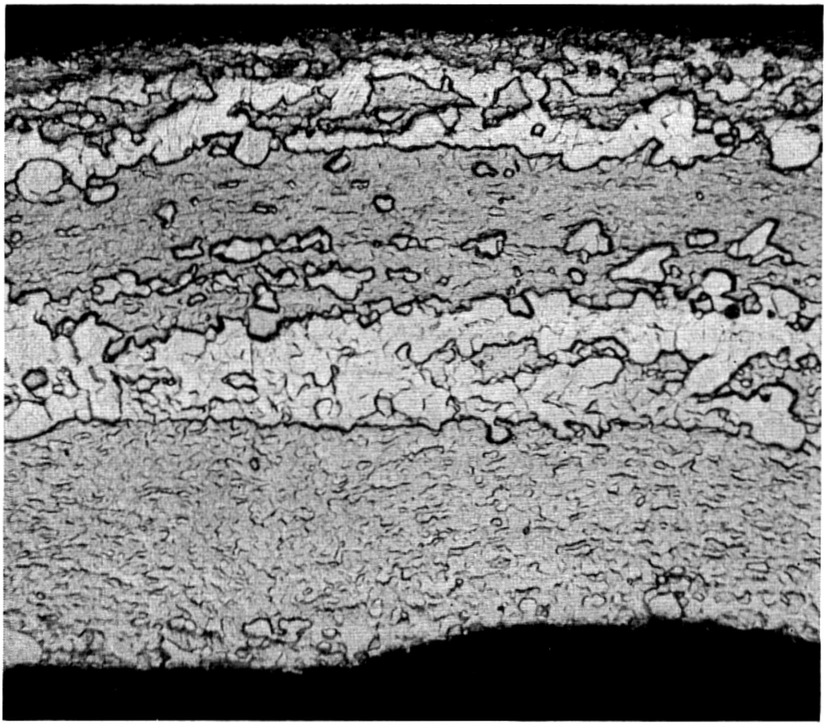


Fig. 24(b) — Away from weld region. Partial recrystallization, 150x.

average conditions at the seam welds. The interlocking of the grains across the junction indicates good welding. The samples were prepared by electropolishing followed by anodizing to show the grain structure. The difference in grain size is a function of the extrusion conditions. Fig. 23 shows charge welds after about 25 per cent of the charge has been extruded. In the upper picture a distinct line of oxides and voids is present. The weld, however, is still quite sound as was shown by expansion tests. In the lower photograph practically no inclusions are present. The junction is visible because of the difference in orientation of the new charge material which causes it to appear darker. Two sections away from the weld region near the top of the sheath are shown in Fig. 24. Here again the marked difference in grain size is visible. In addition, differences in grain structure are apparent in each sample. The crystal structure in the lower half of Fig. 24(a) which corresponds to the inside of the sheath is well defined. The indistinct structure in the outer region is caused by lack of recrystallization after extrusion. Examination under polarized light shows preferred orientation and lineage in this region. The irregularity in recrystallization is even more pronounced in Fig. 24(b). The extrusion temperature range used is very near to the recrystallization temperature for material of this purity. The extent of recrystallization is also a function of the amount of plastic deformation prior to exposure of the material to maximum temperature as it passes through the die orifice. Since the cross-section may be composed of material from the center and outer portions in different proportions which would undergo considerable variation in deformation before reaching the point of sheath formation, the structural differences are not surprising. Structure varies along the length of charges due to the combined effect of deformation variation and the temperature cycle usually accompanying an extrusion cycle especially when fast extrusion rates are used. There are also some indications that the structure of the charged billets has an effect on the extruded pipe. The photomicrographs shown are for super purity aluminum. As would be expected, grain size and degree of recrystallization decreases with decreasing purity for a given set of extrusion conditions.

Apart from low pressure advantages gained by extrusion at temperatures above 330°C, more uniform grain structure might be obtained. Low temperature extrusions often result in mixtures of coarse and fine grained material. The latter may be either imperfectly recrystallized and filled with much lineage or may have the badly distorted appearance of unrecrystallized material. It is not known if this mixed structure might have an adverse effect on service life. It is reasonable to suppose, however, that some benefits might result from uniformity in grain size.

PREPARATION OF BILLETS

The high purity aluminum was received in two different forms; either direct chill castings, three inches in diameter and approximately four feet long or pigs which were melted at the Laboratories and cast into graphite molds. The 99.9 per cent aluminum also was melted and cast. The 99 per cent aluminum was in the form of extruded rod.

All of the cast surfaces, even those produced by direct chill, showed some folds and ripples. Those cast in graphite molds had in addition a certain amount of oxide inclusions and voids. In order to minimize inclusions in the final billet, the cast surfaces were removed by shaving. The ingots were first sawed to suitable lengths, then heated to 400°C. At this temperature, they were placed in a hydraulic press and a sharp edged shaving tube forced over them lengthwise. This removed about ¼ to ½ inch of material from the outer surfaces. The resulting billets were generally smooth and clean after this operation. The surface was far superior to those observed on billets to be extruded in commercial plants even though some of their billets had been turned in a lathe. Before the billets were used, the surfaces were cleaned with trichloroethylene to remove traces of lubricant left from the shaving operation. Generally, the billets were stored in an oven at 300°C prior to insertion into the cylinder of the extrusion. In conformance with commercial practice in handling aluminum billets, no attempts were made to prevent oxidation during any of the melting or subsequent heating operations.

The start, middle, and end of a shaving operation is shown in Fig. 25. Fig. 26 shows the shaving tool partly removed from the billet at the end of an operation. The force required for shaving is about 20 tons. It seems probable that such a procedure would lend itself to commercial operation. Chip breaking knives and cutters to form the longitudinal grooves on the billet would be desirable on a commercial shaving tool.

WEAR ON PRESS PARTS

It was anticipated that the aluminum would cause a certain amount of erosion on the steel parts of the press. However, during experimental operation this has not been evident. For example, the clearance between the piston and the cylinder wall originally was approximately 0.002 inches and through this space a slight back extrusion has always taken place. During many months of press operation, the amount of this back

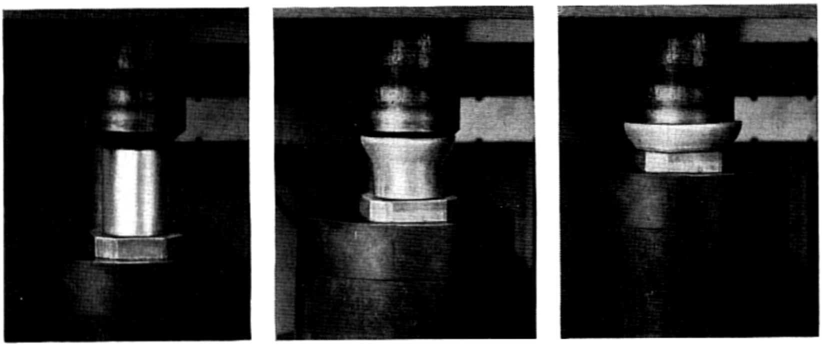


Fig. 25 — Start, middle, and end of shaving operation for removing outer surface of cast aluminum billets.

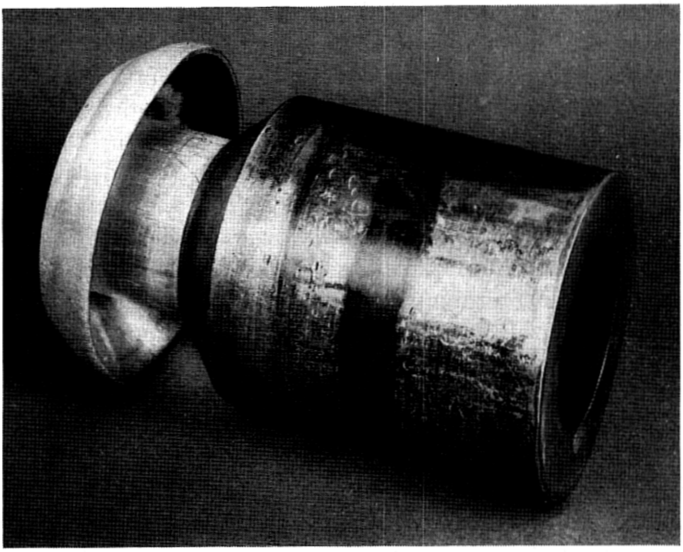


FIG. 26 — Shaving tool partly removed from billet after operation.

extrusion or scarf has not increased visibly, indicating no wear on cylinder or piston edge which would have been very noticeable here. Examination of the core and die surfaces also have shown little, if any, erosion and there has been no evidence of alloying between aluminum and steel.

Attack and wear by the aluminum is probably prevented by the relatively stationary layer of aluminum which adheres to the steel surfaces during extrusion. The large proportion of motion takes place by shear within the aluminum rather than by sliding over the steel surface.

LUBRICATION

The initial experiments showed that application of oil coatings to successive billets had a favorable effect on decreasing the extrusion pressure. However, this practice invariably resulted in poor welds in the sheath and was discontinued. Over a period of many months no lubricant of any type was applied to the billets which were used for recharging the press. Coatings on the core-tube and die, however, have beneficial effects on press operation. Among the materials investigated as die and core-tube lubricants were Teflon coatings baked on at 350°C, various silicone greases, mixtures of petroleum jelly and mutton tallow, heavy paraffin-base cylinder oil, copper flashes produced by replacement from especially prepared copper bearing solutions, and finally a heat polymerized oil coating. This latter coating, which proved to be by far the most effective, was produced by dipping the parts in high temperature motor oil and then heating them in air to an estimated 350°C by a radiant heater. The resulting partly-polymerized, partly-carbonized hydrocarbon produced a very adherent, hard, black, glossy finish which has proved of considerable value in reducing adhesion of aluminum to the extrusion surfaces. While some of the coating is removed as a result of continued extrusion, the parts so coated are relatively free from massive aluminum adhesions when removed from the press. The coating did not prevent the beneficial wetting by aluminum of the land and opposite core-tube region (Fig. 11).

SIZE FACTOR

Because of the complexity of pressure distribution which causes the flow through the extrusion passages, it is difficult to calculate the forces to be expected in different shapes and sizes of extrusion equipment. This anomalous pressure distribution was demonstrated by the existence of voids at particular locations in the cylinder residue after considerable extrusion of lead at room temperature under a pressure of 20,000 psi. Considerable data[8] and theoretical considerations point to a straight line relationship between the logarithm of extrusion ratio and the extrusion pressure as shown in Fig. 27. For this reason, if attempts were made to

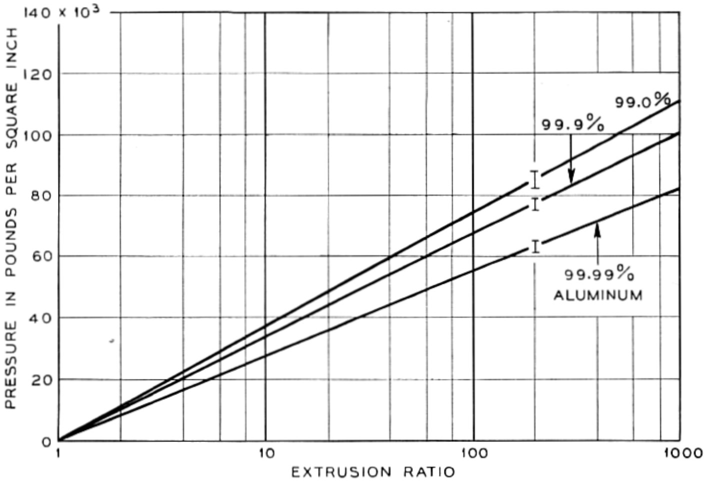


Fig. 27 — Effect of degree of reduction on extrusion pressure at constant speed.

extrude ½ inch diameter sheath using a press having a cylinder five times the area of the experimental laboratory press, it could be estimated that a pressure increase from 63,000 psi for the laboratory press to 82,000 for the larger press could be expected for 99.99 per cent aluminum. For 99.9 per cent aluminum, the increase which might be expected would be from 77,000 to 101,000 psi. With 99 per cent aluminum the increase would be from 85,000 to 111,000 psi. These values are all well below the 150,000 psi figure commonly used in commercial extrusion. Were some of the larger sizes of sheath to be produced, the extrusion ratio would decrease and result in a correspondingly lower extrusion pressure. Up to the present time, sheath of only one size has been extruded on the Laboratories press. It has, therefore, not been possible to confirm the extrusion ratio-pressure relationships on the two piston type of press. It might be emphasized in connection with Fig. 27 that no account has been taken of the 90° change in direction so that the extrusion pressure at a 1 to 1 ratio would most certainly be somewhat higher than zero pressure. An increase at this point in the abscissae would pivot all curves about the intercepts at 200 and lower the extrapolated points at higher ratios.

SUMMARY

A survey has been made of the factors involved in extruding aluminum directly over paper insulated cable core. Since the upper temperature limit is restricted by the presence of the paper and the force to deform aluminum is many times greater than that for lead, conventional lead sheathing equipment cannot be used. An experimental two-opposed piston arrangement with die and core-tube located on an axis 90° to that of the pistons and midway between them has been found to operate at much lower pressures. The shapes of die and core-tubes have been shown to be critical with respect to pressure required and perfection of the sheath. Data are presented to show the effect of purity of aluminum on the interdependence of temperature, pressure and extrusion rate. Special lubrication coatings for the die and core-tube are discussed. Entrapment of air between successive charges was prevented by placing longitudinal grooves on the billets. These were then charged at a temperature somewhat lower than that of the press. Using these techniques, the seam welds produced were as strong as the rest of the sheath. Tensile properties of some of the extruded sheath are given. Microstructures of extruded sheath are shown.

ACKNOWLEDGEMENT

The authors wish to express their appreciation for the encouragement and advice of E. E. Schumacher, to R. E. Elicker who was associated with the early studies, and to M. J. O'Brien who aided materially in obtaining the data.

REFERENCES

1. G. Sachs and W. Linicus, Pressure Requirement and Flow Processes in Extrusion, Mitteilungen der deutschen Materialprüfungsanstalten — Special Issue XVI, pp. 67–96, 1931.
2. W. Deisinger, Production of Aluminum Cable Sheath, Zeit. f. Metallkunde **31,** pp. 305–310, 1939.
3. K. S. Wyatt, Sheathing of Cables With Aluminum, Wire and Wire Products, Oct., 1953.
4. H. Borchardt and G. Hosse, Cable With Extruded Aluminum, Siemens-Zeitschrift **4,** pp. 203–211, 1953.
5. Aluminum Cable Sheathing, Electrical Journal, pp. 1951–1952, May, 1954.
6. Cable Sheathing by Direct Extrusion, Light Metals, pp. 214–215, July, 1954.
7. G. M. Bouton and G. S. Phipps, Compression of Lead Alloys at Extrusion Temperatures, Proc. A.S.T.M., **51,** pp. 761–770, 1951.
8. C. E. Pearson, The Extrusion of Metals, John Wiley & Sons, N. Y., 1949.