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LUCAS HEIGHTS

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PART 2. THE HOT EXTRUSION OF BERYLLIUM

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ABSTRACT

A technique for the hot extrusion of beryllium powder within a mild steel sheath has been developed. Limitations exist with this technique in the control of extruded dimensions, particularly on complex sections or where the sheath thickness is greater than about 0.020 inch.

The use of pre-consolidated powder billets is recommended to reduce the danger of the sheath buckling or splitting during extrusion and to improve the surface finish and dimensions of the product.

Pick-up of oxygen and nitrogen by the beryllium was observed where the beryllium was not completely sealed from the atmosphere during heating and extrusion. This factor affected the mechanical properties of the material, particularly hardness.

The mechanical properties of the sections were determined as a function of extrusion conditions; these properties are sensitive to the choice of extrusion temperature, presumably reflecting a tendency for residual work hardening to increase at the lower extrusion temperatures.

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1. INTRODUCTION

This report is the second of a series dealing with experiments on the extrusion of beryllium; the work was done at the Research Establishment of the Australian Atomic Energy Commission as part of a programme to investigate the suitability of beryllium as a material for application in high temperature gas-cooled reactor systems.

The major objectives were:

(i) To develop a satisfactory technique for the extrusion of beryllium metal which was required for related projects including irradiation testing (Hickman and Stevens 1963) and chemical studies (Draycott et al. 1961).

(ii) To determine the mechanical properties of beryllium metal and the variation of these properties with extrusion conditions.

(iii) To extend the technique to the tandem and co-extrusion of (U Th)Be_{13}-beryllium dispersions clad in beryllium, such as would be suitable for H.T.G.C.R. fuel elements, and to determine the limitations of the extrusion technique in relation to this aim.

In Part 1 (Wright 1964) the theories of extrusion are reviewed. Part 2 (this report) deals with the basic technique and equipment for beryllium extrusion and the examination of the extruded product. The objectives of this phase of the work were to develop a technique for the extrusion of simple shapes in beryllium and to examine the problems in tool design, performance, and lubrication which were expected to arise. A further objective was to study the mechanical properties of the extruded sections and determine the relationships between these properties and the processing variables.

The programme was based mainly on the use of beryllium powder as a starting material; a few billets of material prepared by vacuum hot pressing (Clare et al. 1964) and cast material were included for comparison. The extrusion of complex shapes, other than rectangles, hexagons, and tubes, was not examined but various limitations in the technique for extrusion of complex shapes were established.

The technique of beryllium extrusion given here is of wide interest in the hot extrusion of a range of ferrous and non-ferrous metals (Haffner and Sejournet 1960; Cox et al. 1960; Chadwick 1959).

2. PREVIOUS WORK ON THE EXTRUSION OF BERYLLIUM

The first successful extrusion of beryllium was reported by Creutz and Gurinsky (1952) using a sheath of graphite 1/16 - inch thick around the billet for lubrication; the use of a magnesium sheath was also suggested, the magnesium melting in contact with the billet and acting as a lubricant. The use of conventional graphite-grease lubricants was unsuccessful owing to extreme wear and welding of the beryllium to the tools.

Kaufmann, Gordon, and Lillie (1950) modified this technique by enclosing the beryllium billet in a sheath of mild steel which protected the billet from oxidation and prevented contact between beryllium and the tools; with these sheathed billets conventional lubricants were satisfactory. Kaufmann et al. also determined the pressures required for extrusion at temperatures between 350° and 1100°C, and examined the properties of the product. (Temperatures above 1100°C cannot be used with mild steel sheath because of the eutectic reaction between beryllium and iron at 1165°C). The technique was modified by Loewenstein, Kaufmann, and Arnold (1955) to allow the extrusion of powder directly to the final shape; the powder was pressed into a mild steel sheath or "can" under a pressure of 1-2 t.s.i.; the can was evacuated and then completely sealed by welding. This process has been the basis of most work on the consolidation of beryllium powders, including the work in this report.

The technique was later modified by Loewenstein et al. (1955) using cans of powder which were not completely sealed at the back; the extrusion tools were arranged to push a "floating back plug" forward inside the sheath (Figure 7), thus consolidating the powder to a high density before extrusion properly commenced. This technique minimized the buckling of the sheath experienced with sealed billets and allowed better surface and dimensional control.

Experiments on the "warm" extrusion of beryllium without a sheath were also reported by Loewenstein, Kaufmann, and Arnold (1955) and similar work was done in the United Kingdom by W. Munro and J. Williams (unpublished). These experiments were based upon the existence of a peak in the tensile elongation values at about 450 °C; it was assumed that this would result in improved extrusion at this temperature rather than at higher temperatures where the tensile ductility was less, but no values of limiting compressive or shear strains were determined to confirm this point. Using graphite or silver as lubricants, moderate reductions in area, up to 10:1, were achieved at 450 °C under pressures of 120,000 to 200,000 p.s.i. The dimensional control on these warm extruded parts was excellent and the irregularities of surface associated with the use of a sheath were avoided. No systematic examination of the process or product has been reported however, and experiments at these temperatures have been largely discontinued in favour of higher temperatures.

An extensive programme on the extrusion of beryllium for aircraft and missile components was commenced by the Northrop Corporation (U.S.A.) in 1960 with the objective of producing 20-ft. lengths of a channel 0.12 x 1.0 x 1.5 inch in section, with minimum mechanical properties in the direction of extrusion of:

Ultimate tensile strength	60,000 p.s.i.
0.2% offset strength	35,000 p.s.i.
Elongation on 2 inches	10 per cent.

The first report in this programme (Christenson 1960) detailed experiments in the extrusion of unsheathed billets at 1000 °C using glass lubricants (Ugine-Sejournet process, British Patents); extensive cracking of the section and wear on the tooling was observed in all attempts and these defects were associated in each case with low efficiency of lubrication. Modifications to the technique, using various die designs and varying the method of applying the glass, were also unsuccessful.

More recently (Christenson 1961) the programme has been based on the use of mild steel sheathed billets, generally as used by Kaufmann; graphite was used as the lubricant and the die entry angle was small (30-45 ° included angle) to promote "streamline" flow. With these conditions, the long lengths of channel were extruded at 950 - 1000 °C with no evidence of cracking and with dimensional control to within ± 0.005 inch. The ultimate strength of this material in the extrusion direction was about 80,000 p.s.i., with elongation between 0 - 6 per cent.

Several investigations on the properties of extruded beryllium were presented at the Conference on the Metallurgy of Beryllium (Institute of Metals, London, October 1961) but extrusion conditions and techniques were generally as described by Kaufmann or Loewenstein et al. previously. The preliminary results of this work were also presented at this Conference (Wright and Silver 1961).

At present, research and development work on the extrusion of beryllium is confined largely to one organization (Nuclear Metals Inc., U.S.A.) and is directed towards production of components for the American aircraft and missile programmes.

3. TECHNIQUES FOR THE HOT EXTRUSION OF BERYLLIUM

3.1 Equipment

3.1.1 Extrusion press

The extrusions were carried out on the 1,000-ton vertical hydraulic press shown in Figure 1. Details of design of the press are given in Table 1. The press was capable of operating at ram speeds in excess of 10 inches per second, the ram being driven from an oil-nitrogen accumulator operating at 3,900 p.s.i. The accumulator pressure was reduced to 1,200 p.s.i. for the experiments with 2-inch diameter tooling, thus reducing the total available load to 300 tons and the unit loading on the smaller tooling to about 200,000 p.s.i. For the 4-inch diameter tooling the accumulator was operated at full capacity giving a unit load of 180,000 p.s.i. In both cases the reduction in accumulator pressure during a 12-inch stroke due to expansion of the hydraulic system did not exceed about 10 per cent. of the initial pressure (Wright and Spain 1961).

3.1.2 Tooling

Tooling was available for direct and inverted extrusion of a range of sections, both solid and hollow. Containers were designed to receive billets 2 inches and 4 inches in diameter and up to 10 inches long. Figure 2 shows the tooling arrangements for extrusion from a 4 inch diameter container.

(i) Containers

The container supports the billet around its circumference during extrusion. The container is therefore subjected to very high pressure and high temperatures on the inner face, and to considerable abrasion on this face as the billet is forced towards the die. Containers were designed to withstand the hoop stresses arising from extrusion pressures up to 200,000 p.s.i.

The container was made from a 5 per cent. chromium tool steel, heat treated to give a hardness of 43-45 Rockwell C; this steel has moderate wear resistance and high temperature strength as required, although it is inferior in both respects to the 9 per cent. tungsten alloy tool steels. The chromium steel was over-rated for the performance required in positions away from the hot inner face (that is, for low temperature, elastic stress containment) whereas improved performance at the inner face was desirable. Provision was made therefore to fit an inner sleeve or liner to the container which could be replaced after wear had occurred in operation; this was more economical than making repairs to the container proper.

Liners were made from a 9 per cent. tungsten- 3 per cent. chromium tool steel, heat treated to a hardness of 45 Rockwell C giving an estimated tensile strength of 200,000 p.s.i.; liners were shrunk into the container bore with an interference fit of 0.002 inches per inch of outside diameter. The liner was thus in compression by about 30,000 p.s.i.

A modified container system was used for the extrusion of 2-inch diameter billets as shown in Figure 3. The inner liner was made from 9 per cent. tungsten tool steel backed by an intermediate liner of 5 per cent. chromium tool steel and both were shrunk into the main container. With this arrangement, the container could be used for both 2-inch and 4-inch diameter billets and change-over from one system to another was accomplished within a short time. The inner liner could also be reversed; wear on the part of the liner immediately above the die was thereby minimised and the life of the liner considerably extended.

With composite containers, care was required to ensure uniform heating of the container and liners before use. In early experiments, the containers were heated from the outside by 10 kW radiant heaters achieving a temperature of 300 °C on the liner. With heating times up to 16 hours the temperature gradient across the liner and main container exceeded 100 °C and support for the liner was therefore decreased with increased probability of liner failure under extrusion stresses. A more satisfactory technique was to heat from the inner surface of the liner, thus tending to expand the liner against the container.

During extrusion the liner was subjected to abrasive conditions as the billet moved towards the die. The presence of scores or scratches on the inside surface of the liner was found to be relatively unimportant unless they became deep enough to mark the surface of the extruded section; in extreme cases, deep scores tended to increase the extrusion pressure or prevent removal of the discard.

(ii) Dies

The design of dies for sheathed beryllium extrusion was based originally on those used for steel extrusion; sections through these dies are shown in Figure 4. In all cases, the parallel length of bore or "land" was 3/16 inch and the entry radius was ½ inch. A range of die entry angles was investigated in relation to the studies on metal flow reported later. (Part 3 of this series). A die entry angle of 140° (semi-angle of 70°) was found most satisfactory, giving uniform metal flow with adequate control of cladding thickness and lubrication. Dies with smaller entry angles (70°, 90° included angle) did not improve dimensional control. Flat dies (180° angle) with ½ inch entry radius were used in some experiments but were quite unsatisfactory for control of cladding thickness; variations of 50–80 per cent. in cladding thickness were noted with frequent rupture of the cladding at the front end of the rods.

A major problem in the extrusion of beryllium (or other high-strength materials) at high temperatures is the choice of a die material which will enable an economical number of extrusions to be obtained. Various die materials were examined in this work including 9 per cent. tungsten hot-work die-steels, Nimonic 80, 18/4/1 (high speed steel), and 5 per cent. chromium tool steels. The problem with all these materials is to obtain a compromise between structures that are too hard and tend to fail by brittle fracture and those that are more ductile but weaker, so that the extrusion load cannot be fully supported.

Dies of 9 per cent. tungsten tool steel were originally specified at 43–45 Rockwell C hardness, but were modified to 46–48 Rockwell C; at the lower hardness, the dies tended to fail by wear at the orifice while at a hardness greater than 48 Rc there was a tendency for brittle fracture to occur, reducing the average die life. Dies for round sections were operated at the higher hardness range. These dies were readily and cheaply produced and could be repaired with simple tooling; even if these dies fractured, the financial loss was not great and the advantage could be claimed of closer dimensional control over a large number of extrusions. For dies producing angled sections such as hexagon, square, or triangle, the major cost was in the shaping of the original orifice; if these dies fractured, the financial loss was considerable and it was preferable therefore to specify a lower hardness (42–44 Rc) to minimise the possibility of brittle fracture. When flow occurred, the die orifice was remade to a slightly larger size and this could be achieved at a reasonable cost.

Several dies of Nimonic 80 were used in the age-hardened condition, with a hardness of 33 – 35 Rockwell C. In all cases these dies yielded at extrusion pressures over about 90,000 p.s.i. Various Nimonic grades have been found satisfactory for extrusion dies overseas (Graham 1960), but the performance of Nimonic 80 in relation to the costs suggests that few advantages are likely to be evident with this technique.

Dies made from 5 per cent. chromium tool steel with a hardness of 45 – 47 Rc tended to wear by plastic flow at the die throat at extrusion pressures above 110,000 p.s.i. Experience with this steel has not been extensive however and further examination would be warranted because of the relatively low cost of this grade.

Limited experience with dies made from 18/4/1 high speed steel at a hardness of 48 – 50 Rockwell C has been satisfactory with no tendency to plastic flow under pressures of 150,000 p.s.i. This material was the most expensive of the range examined however and a superior performance would be required to balance the cost.

This work suggests that 9 per cent. tungsten tool steel represents a satisfactory compromise between performance and costs for die materials; for simple rods, the die life with this material should be some hundreds of extrusions but re-dressing would be required after about 30 extrusions.

(iii) Stems

The function of the stem is to push the plastic billet through the die. Stems have been designed to support stresses up to 200,000 p.s.i. at temperatures not exceeding 500°C.

Stems made from 5 per cent. chromium tool steel, heat treated to produce a hardness of 46 – 48 Rockwell C have withstood compressive stresses of about 230,000 p.s.i. before failure; failure then occurred by plastic flow as shown in Figure 5 and the dangers of abrupt brittle fracture were absent. At stresses above 175,000 p.s.i., maintenance of uniform axial loading on the stem was particularly important to avoid premature yielding.

Stems made from 18/4/1 high speed steel at 55 – 58 Rockwell C hardness have been operated at stresses exceeding 250,000 p.s.i. and in some cases have been used in cold extrusion of steel at stresses of 300,000 p.s.i. (Pugh et al. 1961). However, particular attention is required in alignment and loading of these stems at stresses above 150,000 p.s.i.; this material will not yield plastically to accommodate unequal loading but fails by brittle fracture as shown in Figure 6. Stems made from 9 per cent. tungsten – 3 per cent. chromium steel at similar hardness fail in a brittle manner under slight non-axial loading at stresses above 200,000 p.s.i.; at lower hardness, (43 – 45 Rockwell C) this steel will yield plastically, but stresses are limited to below 200,000 p.s.i. Further modifications to the heat treatment of both the 18/4/1 and 9 per cent. tungsten – 3 per cent. chromium steel may improve the loading characteristics of the stems, but at present the 5 per cent. chromium type is regarded as superior in performance. The 5 per cent. chromium steels are also about one half the cost of the alternatives.

(iv) Pressure Pads

The pressure pad or "dummy block" protects the stem from the high billet temperatures and is thus subject to high temperatures and pressures during extrusion.

The only material considered for these pads was the 9 per cent. tungsten tool steel, heat treated at 44 – 46 Rockwell C, and performance was excellent. Periodically the pads were machined to restore alignment and clearance in the container.

(v) Mandrels

The press arrangement shown in Figure 2 allowed the use of a fixed mandrel to produce hollow sections. These mandrels were subjected to high temperatures and appreciable tensile stresses. With this arrangement of a fixed mandrel in the billet, mandrel temperatures commonly reached 700 °C and several mandrels made from 9 per cent. tungsten tool steel have necked down into a tensile failure.

This poor performance arose mainly from the tooling arrangement rather than any considerations of mandrel design or steel quality. When the mandrel is held on an auxiliary press ram, it may be positioned accurately in the die orifice, withdrawn quickly after extrusion, and cooled, in which case the temperature can be controlled below 500 °C. The use of a fixed mandrel and the tooling arrangement for producing tubes shown in Figure 2 was only practical for mandrel sizes above ½ inch and with high ram speeds (> 2 inches per second) when heat transfer to the mandrel could be minimised.

3.2 Preparation of Billets

3.2.1 Materials

Four types of beryllium were used in this work:

(i) Powder prepared by electrolytic reduction of beryllium chloride obtained from the Pechiney Co. (France).

(ii) Pechiney powder which had been vacuum hot pressed in graphite dies at 1080 °C under a pressure of 1200 p.s.i., (Clare et al. 1964).

(iii) Vacuum cast billets prepared from thermally reduced beryllium by the Brush Beryllium Co. U.S.A. (QMV grade).

(iv) Arc melted-vacuum cast billets prepared by consumable arc melting of Pechiney powder, previously extruded into a rod electrode.

The typical levels of impurities in each of these materials are shown in Table 2.

3.2.2 Billet design

A typical arrangement of the billet showing the sheath or "can" is given in Figure 7.

The functions of the sheath were to act as the primary container when extruding powder and to reduce friction and wear on the tooling by providing a "non-galling" surface. The sheath was also necessary to minimise the health hazard arising from dispersion of oxide or metal dust during extrusion.

Materials other than mild steel have not been examined for use as sheaths; any alternative must be readily available and cheap, readily removable from the rod after extrusion, and should possess extrusion characteristics very similar to those of beryllium. Mild steel is suitable on all counts; the extrusion constants for mild steel and beryllium match to within 10 per cent. over the range 750–1100 °C as discussed in Part 3 of this series.

Mild steel sheaths were made from:

(a) tubing, one end being spun over to make a base integral with the wall,

(b) tubing, a flat base plate being welded to the walls, or

(c) bar stock machined to the required size.

For extrusion from the 4–inch diameter container, the outside diameter of the sheath (and hence the assembled billet) was 3.900 ± 0.005 inch and for the 2–inch container 1.950 ± 0.005 inch. The sheaths were machined all over to a medium finish.

The thickness of the sheath on the billet was normally 0.1 inch on 4–inch billets or 0.06 inch on 2–inch billets but was varied with extrusion ratio with the object of producing the thinnest clad on the final product, commensurate with the ideas above. Final clad thicknesses as low as 0.010 inch were prepared on simple rods and these had the advantages of promoting better surface and dimensional control and requiring minimum effort in removal from the product. More commonly, a clad thickness of 0.020 – 0.040 inch was preferred to reduce the danger of the clad splitting; this splitting arises from unequal metal flow and was therefore a greater problem with irregular sections or where sharp cornered shapes were being extruded. The clad thickness largely determined the control over dimensions which was possible.

Very thick sheaths, up to ¾ inch on the billet, were sometimes used to allow undersize beryllium billets to be extruded from standard size containers; for example 1 inch diameter beryllium billets were sheathed with ½ inch of mild steel for extrusion from 2 inch diameter containers. These arrangements were not attractive, particularly in the control of extruded shapes; the only advantages arose from the convenience of being able to extrude any size billet up to the limits of the container.

The maximum length of billet was dictated by the container length (13 inches) and by the length of the well below the press, which limited the length of extrusions to less than 18 feet. These limitations are related by the expression:

$$L_e = (L_b - L_d)R \quad ,$$

where L_e, L_b, L_d = length of extruded rod, original billet or discard respectively,

and R = extrusion ratio = $\dfrac{\text{area of billet cross section}}{\text{area of extruded cross section}}$.

3.2.3 Billet assembly

Powder was loaded into the sheath by vibrating small increments (about 100 grams) into place until the required weight of powder was loaded; no separate compacting stages were used since this tended to promote a "layered" structure in the billet and inhomogeneities in the extruded sections. The density of packing of the powder was about 1 g/cm³.

Cast or preconsolidated powder billets were machined with an interference fit of 0.005 inch per inch diameter on the sheath; the sheath was heated to 400 °C to facilitate loading of the beryllium.

The billets were sealed as shown in Figure 7, by pushing a heavy mild steel plug into the back end; the sides of the plug were tapered 2° to assist in sealing against the sheath. A pressure of 1–2 t.s.i. was used in pushing the plug into place and this was applied using the container of the press for support; higher pressures tended to expand the billet against the container, leading to difficulties in loading the billet after heating. After pressing, the plug in powder billets was tack welded in two places, about ¼ inch to ½ inch long to keep the plug in position during subsequent handling. For solid billets the plugs were completely welded into place after the billet had been evacuated to less than one micron mercury pressure.

For billets containing powder, the tack welds on the plug were designed to shear as the ram descended on the billet in the early stages of extrusion; the plug then moved forward within the sheath, consolidating the powder to near theoretical density before extrusion commenced. The tack welds were required to be small or the initial load on the ram was transferred to the sheath, which buckled and caused a defective surface ("fold") on the extrusion. For pre-consolidated billets, the plug did not move in this manner and complete sealing of the back end by welding reduced the possibility of ingress of air and oxidation of the beryllium.

The plug was made long enough to ensure that all beryllium was extruded through the die, leaving a discard of mild steel; the discard was then sheared from the extrusion without exposing beryllium.

The yield of acceptable extrusion was increased considerably by shaping the back plug as shown in Figure 7. This shape compensated for the unequal flow of metal across the extruding section and the final interface between the beryllium and plug was reasonably plane; the characteristic "back end defect" was thus avoided. The development of the shapes required on the plug for maximum yield and the associated problems relating to metal flow are discussed in Part 3 of this series.

Billets for extrusion to tubes consisted of a mild steel outer sheath with an inner tubular sheath welded to the base; the inner sheath had 1/8 inch clearance on diameter over the mandrel to minimise writing off of lubricant during loading. Beryllium billets were bored out to fit over the inner sheath or powder was vibration packed between the sheaths as required; the mild steel back plug was also bored out to fit over the inner sheath.

3.3 Extrusion Technique

3.3.1 Heating for extrusion

The problems involved in heating billets for extrusion were mainly those of achieving a uniform temperature and minimising oxidation of the sheath and the solution to these problems was largely determined by the type of equipment available.

Billets were preheated to 500 °C for half to one hour in an electrically heated furnace without a protective atmosphere before transfer to a controlled atmosphere furnace operated at the required extrusion temperature between 750 °C and 1050 °C. The use of a preheat furnace increased the allowable throughput of the main furnace and eliminated the tendency for some unsealed billets to release powder if placed directly in the hotter furnace.

The main furnace had a capacity of nine 4 inch diameter billets on a hearth approximately 48 inch long 18 inch wide. The furnace was heated by silicon carbide elements with a maximum temperature of 1350 °C.

The temperature of the furnace was controlled by a sheathed Pt – Pt/13% Rh thermocouple suspended from the centre of the furnace roof. This thermocouple was positioned in the furnace so that the recorded temperature agreed with that on a standard thermocouple located in a mild steel billet on the hearth. Both temperatures were in agreement with recordings from radiation pyrometers focused on the billet surface. The temperature gradient within the furnace was then checked by moving the billet and thermocouple through the furnace; the maximum gradient from the centre to door of the furnace was 20 °C at 1000 °C.

Billets were held for about one hour at temperature before extrusion. A protective atmosphere of 10 per cent. hydrogen-nitrogen dried to a dewpoint of −40 °C was maintained around the billets during heating above 500 °C; a flow rate of about 200 cu ft/hr was sufficient to prevent any scale forming on the mild steel sheaths and the billet surfaces were normally quite clean when placed in the container for extrusion.

3.3.2 Extrusion

With the tooling arranged as in Figure 2, the die, container and press pad were coated with a 30 per cent. colloidal graphite-grease mixture for lubrication. The hot billet was then rolled from the main furnace and transferred by tongs to the container; the press pad was immediately placed in position as the main ram and stem were lowered to commence extrusion.

The time required to transfer a billet from the furnace and commence extrusion was 15 – 20 seconds, and extrusion was completed in a further 2 – 5 seconds at a ram speed of 2 – 4 inches per second. The temperature of the billets during extrusion was accepted as that of the furnace; the rate of cooling of a 4 inch diameter billet in the extrusion container was measured by placing thermocouples at the centre, half-radius, and 1/8 inch from the surface, and cooling rates are shown in Figure 8. The outside of the billet cooled very rapidly, about 70 °C/minute under these conditions but the centre cooled slowly (about 15 °C/minute); the billets were therefore extruded with a significant temperature gradient across the section and this is unavoidable. Since 75 per cent. of the total volume of billet lies between the half-radius position and surface, a significant criterion of cooling rate is obtained by averaging the temperature at these points and if this is accepted the billet temperature falls to less than 20 °C below furnace temperature after 15 seconds.

The speed of extrusion was varied between 0.5 and 8 inches ram displacement per second. The lower speeds promoted a better surface on the extruded section with fewer folds arising from collapse of the cladding; however the temperature of the billet towards the end of these slow strokes had fallen sufficiently to increase the extrusion pressure and with a longer period of contact with the billet, the tooling became undesirably hot (about 600 °C on the die). Moderate speeds of 2 – 4 inches per second were therefore used for most of this work; with these speeds and with the billet design shown in Figure 7, using a heavy back plug, the temperature of extrusion of the beryllium was controlled within an estimated 20 – 30 °C along the length of extrusion.

The length of discard remaining in the containers at the end of the stroke was controlled by modifying the thickness of the stop ring on the container (see Figure 2); a length of about 1 inch was chosen for most billets. This discard was sheared from the extrusion by moving the back-up tooling on an auxiliary hydraulic ram and the die, discard, and pad were then pressed from the container. The sheared extrusion was held by tongs and placed in a vertical rack below the press to cool. If required, the extrusions were reheated to 1000 °C and straightened by hammering in a V-guide.

3.3.3 Removal of the sheath

The mild steel sheath was removed from the extrusions by chemical attack with nitric acid or by turning in a lathe; the more convenient technique for this work was attack by 1:1 v/v nitric acid solution for half to one hour in a stainless steel trough. Reaction between the acid and the sheath was rapid and copious fumes of nitrogen oxides and nitric acid spray were evolved. These fumes contained up to 30 micrograms beryllium per cubic metre (about 15 times the maximum permissible concentration for safe working) and provision was made to draw the fumes through a scrubbing tank containing marble chips and dilute sodium hydroxide before exhausting to atmosphere. The rate of attack of 1:1 nitric acid on beryllium was negligible and the beryllium in the fumes probably arose from small amounts of unconsolidated powder on the surface of the beryllium beneath the sheath.

4. EXAMINATION OF THE PRODUCT

4.1 Surface Finish

The surface finish of the beryllium sections was determined in part by the original finish on the sheath; any scale or heavy machining marks on the sheath were reproduced on the section. With care in preparation and by use of a medium-machined finish on the sheath, surface irregularities were controlled to less than 0.001 inch deep. The sections extruded from powder had a smooth matt surface as shown in Figure 9, whilst those from cast billets had a rougher "bark-like" finish attributed to indentation of the sheath by the coarse grains during deformation.

Major surface defects occurred occasionally owing to buckling or splitting of the sheath, giving a fold or indentation on the beryllium surface as shown in Figure 10. Buckling of the sheath occurred when the tack welds between the back plug and sheath of powder billets did not shear readily or if the back plug was not correctly aligned in the sheath. The tendency for the sheath to split during extrusion was greater for complex sections than for simple rods and this was attributed to the irregular metal flow over the die surface.

In some cases, extrusion proceeded so quickly that gases entrapped in the unconsolidated powder billets did not escape through the back of the billet; these gases expanded the cladding as it came through the die, forming a bubble as shown in Figure 10. The beryllium surface at this point was irregular with a depression up to 0.05 inch deep. Any tendency for this defect to occur was removed by extruding at a slower speed.

Minor surface irregularities occured when there was inadequate protection against oxidation of the sheath during heating; if the outside surface of the sheath became heavily scaled, the scale tended to break during extrusion making an impression in the sheath and through to the beryllium surface.

Most extrusions showed no major defects; typical examples of the product are shown in Figure 11.

4.2 Straightness

No provision was made for guides to straighten the extrusions as they emerged from the die although this would be normal industrial practice. Long extrusions (> 7 ft.) were therefore bowed to about 0.05 inches per foot and some shorter lengths were bowed much more. Tubes, which were extruded with a fixed mandrel, were straighter and the bow did not exceed 0.02 inch per foot.

The straightness which can be achieved is dictated by the alignment of tooling, the homogeneity of the billet (particularly the uniformity of temperature) and the uniformity of lubrication on the die. Particular attention was given to these factors in this work and further improvements in as-extruded straightness may be difficult to achieve.

The extrusions could be straightened if necessary by hammering within a V-guide, to achieve a bow of less than 0.01 inches per ft., that is, about 1/8 inch in a 10 ft. piece.

4.3 Dimensional Control

For sections extruded with about 0.02 inch clad thickness, the variations in dimensions on the beryllium were ± 1–3 per cent. of nominal value for sections between ½ inch and 2 inch diameter or equivalent. For example, 0.750 inch diameter rods were extruded to ± 0.020 inch on diameter; these variations arose mainly along the length of the rod and variations around the diameter measured at any point were less than ± 0.005 inch. Tubes 1¼ inch o.d. x ¾ inch i.d. were extruded to ± 0.020 inch on o.d., ± 0.010 inch on i.d., and 0.010 inch on concentricity; hexagon sections 1 inch and ¾ inch across flats were extruded to ± 0.025 inch on these dimensions.

Minor improvements in dimensional control of rods were achieved by reducing the sheath thickness to achieve a clad thickness of 0.015 inch or even 0.010 inch; the use of very thin sheaths increased the danger of splitting during extrusion. In the extrusion of sections with sharp angles, (squares, triangles, hexagons), a thin sheath was found to allow better control at the sharp corners; thick sheaths tended to give excessive rounding of these corners as shown in Figure 12.

The dimensional control achieved with unconsolidated powder billets and pre-consolidated billets was similar, provided that the surface defects referred to in Section 4.1 were avoided.

4.4 Yield of Material

For billets extruded with no shape compensation on the back plug the yield of beryllium, expressed as weight of satisfactory product over the original weight of beryllium was 70 – 80 per cent.; the intrusion of the mild steel plug into the beryllium ("back–end defect") was the major contribution to this loss. A further small loss in yield occurred owing to dimensional variations at the front of the extrusion, associated with irregular metal flow in the initial stages of extrusion.

The yield of beryllium was increased to 95 – 98 per cent. by shaping the face of the back plug to compensate for non–uniform shear across the section. With uniform lubrication of the tooling and uniform temperature in the billet, the extent of intrusion could thus be controlled within 1 – 2 inches even for reductions above 30:1. The development of optimum plug shapes is discussed in Part 3 of this series.

4.5 Variations in Density

Theoretical density of 1.85 g/cm³ was attained on all pre–consolidated (hot pressed or cast) billets, irrespective of extrusion conditions.

The density of extruded sections prepared directly from powder varied from 1.81 to 1.845 g/cm³ with a mean over all samples of 1.835 g/cm³; the theoretical density was not attained on any samples. The trend in results was for higher densities to be associated with higher extrusion pressures but this was not conclusive.

The density of extruded powder billets varied from front to back of the extrusion; over all samples tested, the mean values were as shown in Table 3.

The low density at the front was not confined to a particular area; rather the density increased more or less regularly along the length of the extrusion. Two factors probably contributed to this:

(i) the tendency for the front of the billets, originally over the die orifice, to receive less work than the rest of the billet, and

(ii) the pick–up of oxygen and nitrogen at the back of the billet which would give an "apparent" increase in density. This effect is discussed in Section 4.6.

It is doubtful whether the technique of extrusion of beryllium powder directly to shape is capable of producing material of theoretical density. The presence of 0.5 – 1.5 per cent. porosity in the material, which was confirmed by metallographic examination (Section 4.8) probably affected the mechanical properties (Section 4.7) and the performance of the material.

4.6 Variations in Composition

The sections were checked for variations in composition after extrusion. No significant variation in metallic impurities in the beryllium were noted and in particular there was no evidence of iron contamination from the sheath.

Significant variations in oxygen and nitrogen content were noted on billets prepared from unconsolidated powders; in some cases the oxygen content (expressed as per cent. BeO) increased from 0.3 – 0.4 per cent. in the original powder to 1.6 per cent. in the extruded rods, whilst the nitrogen content increased from about 200 p.p.m. to over 7000 p.p.m. The mean values expressed as a function of position in the bar and extrusion temperature were as shown in Tables 4 and 5.

Tables 4 and 5 show that pick–up of both nitrogen and oxygen was mainly confined to the extreme back end of the extrusions and this was associated with ingress of air and furnace gases into the back of the unsealed billets during heating for extrusion. The high pick–up of nitrogen relative to oxygen probably arose from the particular atmosphere control in heating. No effects of temperature on the extent of contamination were noted.

These variations in composition affected the mechanical properties of extruded sections, particularly hardness, and these effects are discussed below.

The pre-consolidated (hot pressed or cast) billets, which were sealed completely within the sheath during heating, showed no significant pick-up of oxygen or nitrogen.

4.7 Mechanical Properties

(i) Hardness

The trend of hardness values determined on samples extruded from powder billets over the range of temperatures is shown in Figure 13; each test was made on a transverse section about half-way along the extrusion and at mid-radius, thus avoiding the variations in density and composition associated with the extreme front and back and the edge-centre effects as discussed below. Measurements were made on a Vickers hardness machine under a 30 kg load with a 136° diamond indenter. The hardness values were sensitive to the method of surface preparation and up to 0.008 inch was etched from the machined surfaces before reproducible low values were obtained. The existence of surface hardened layers from machining was confirmed in subsequent annealing tests and by metallography.

The decrease in hardness with increasing extrusion temperature is attributed to partial recrystallisation of the heavily worked structure in cooling from the extrusion temperature. A similar trend in hardness was noted previously (Klein et al. 1955). The times required for complete recrystallisation were determined (Tuer et al. 1955) as about 5 minutes at 800°C, or less than one minute at 900°C; cooling rates of rods after extrusion were not determined in detail but were estimated as 1 – 2 minutes to reach dull red heat (700°C) which probably allowed some recrystallisation. The mean hardness of fully annealed extruded sections (1 hour at 800°C in vacuum) was determined as 134 V.P.N. and this was further evidence of residual work-hardening in the specimens.

The hardness on surfaces parallel to the extrusion direction was generally 10 – 15 V.P.N. greater than that measured on the transverse faces although conclusive results were not obtained. Within the scatter band shown in Figure 13, no consistent effects of varying the reduction in area were noted.

Table 6 shows values for mechanical properties determined on a small range of specimens taken from front, middle, and back of the extrusions. In most cases a tendency towards higher hardness at the back of the extrusions was noted with extreme values about 20 V.P.N. higher than the result from the middle position; the fronts of the extrusions were generally somewhat lower in hardness than the middle position. These trends require confirmation on more samples but the results are consistent with some hardening of the material due to pickup of oxygen and nitrogen during heating.

The hardness values varied across the extruded section as shown in Figure 14; this effect was not removed by annealing at 800°C for one hour and was therefore attributed to variable oxygen or nitrogen content from edge to centre rather than variable strains in extrusion. Moreover, these variations in hardness were less evident in cast or hot-pressed material where the variations from edge to centre were less than 3 V.P.N.

The mean hardness of cast material extruded at 1050°C was 125 V.P.N. and the hardness of hot-pressed material was 133 V.P.N.; the lower hardness of these materials is attributed to their lower oxygen and nitrogen content.

(ii) Tensile properties

The variations in ultimate strength, 0.1 per cent. proof stress and elongation determined in tension at room temperature are shown in Figure 15 as a function of extrusion temperature. Specimens for these tests were prepared from the centre of extruded sections with 0.25 inch gauge diameter and 1.5 inch gauge length; all specimens were chemically polished with phosphoric-sulphuric acid solution to remove the work-hardened surface resulting from machining, and tested at a strain rate of 0.002 inch per inch per minute. All specimens were strained in the direction of extrusion.

The ultimate strength showed a consistent reduction with increasing extrusion temperature, from 100,000 p.s.i. at 750 °C to about 70,000 p.s.i. at 1050 °C. The stress required for 0.1 per cent. elongation varied in a similar manner from 61,000 p.s.i. at 750 °C to 37,000 p.s.i. at 1050 °C. The elongation to rupture varied from 6 per cent. for an extrusion temperature of 750 °C to 12 per cent. for 1050 °C. These effects are attributed to work hardening during extrusion at the lower temperatures and partial annealing at the higher temperatures.

As shown in Table 6 there was some evidence of a trend towards greater strength and lower ductility at the back end of the extrusions compared with the middle position but this effect was not marked and could be explained by other variations in the test procedure. The presence of oxide-nitride impurities and porosity at the extreme front and back of the extrusions apparently had a minor effect on these properties. Moreover the mechanical properties did not vary consistently with extrusion ratio and this suggests that these properties are also insensitive to changes in the extent of preferred orientation, (see Section 4.8 (ii)).

Further experiments are required to characterise fully the effects of residual work, preferred orientation, and impurities on the mechanical properties of beryllium; it now appears well established however that the properties may be varied widely by appropriate choice of the extrusion temperature.

4.8 <u>Structure</u>

(i) <u>Metallography</u>

The structure of extruded sections prepared directly from powder showed evidence of residual porosity at grain boundaries to an extent consistent with the variations in density noted previously. The unetched sections also showed the presence of grain boundary film which was presumably oxide and nitride and this also varied from front to back of the extrusion as expected from the chemical analyses. Typical sections of these materials are shown in Figure 16 (a – c).

Hot pressed and cast materials showed no evidence of significant porosity; both contained a film of oxide–nitride around the grain boundaries, although to a lesser extent than in the powder billets.

Comparison of the longitudinal and transverse sections of the extrusions showed a marked "fibre" structure with the grains elongated in the direction of extrusion (Figure 16 (d – e)). Calculations of the average grain volume in powder, and hot–pressed and extruded sections, showed that the grain volume was comparable with the particle volume in the original powder and in fact little grain growth had occurred during the hot–pressing or extrusion operations. The adherent oxide film on the original powder was apparently ruptured during working but remained at the interface as particles which effectively inhibited grain growth across the interface.

The original particle size of the powder was determined as 7 per cent. less than 20 microns, 80 per cent. between 20 and 80 microns and 13 per cent. between 80 and 100 microns. Assuming a mean particle size of 50 microns, the calculated grain diameter viewed in the transverse section of the extruded rod, and assuming no significant grain growth, would be 10 – 15 microns for extrusion ratios between 10:1 and 30:1; the measured grain size in these sections was 10 – 20 microns, which generally supports the premise of negligible grain growth.

Variations in grain size and shape were noted towards the outer rim of the rod extrusions; these areas showed evidence of greater shear in the grains than in the centre of the rod as would be expected and the grain size varied from 5 to 50 – 70 microns in the transverse section. It is possible therefore that the extensive shear strains in these areas largely dispersed the original oxide film and initiated a form of "discontinuous" grain growth.

No major variations in structure were noted in powder billets extruded at different temperatures or with widely varying extrusion ratios.

(ii) <u>Preferred Orientation Measurements</u>

Extruded specimens were examined on a Siemens two–circle texture goniometer; longitudinal and transverse sections from each specimen were examined. The type and degree of texture was determined by comparing the X-ray intensity from particular planes for all orientations of the specimens with that reflected by a randomly oriented specimen previously prepared by cold pressing and sintering.

In the extruded rods the orientation was such that the basal planes tended to lie parallel to the extrusion direction. Representative pole figures are shown in Figure 17 (a – d). The effect on the extent of preferred orientation of varying the extrusion temperature for a constant extrusion ratio (Figure 17(b) and 17(d)) was negligible, but the extent of preferred orientation increased markedly with increasing extrusion ratio (Figures 17 (a – c)). Basal pole scatter in the direction of working also decreased as the extrusion ratio was increased. Although full pole figures were not determined, the basal planes tended to be aligned with the $(10\bar{1}0)$ direction in the extrusion direction. These results are in close agreement with those of Hill and Williams (1960).

The effects of increasing degree of preferred orientation on the mechanical properties of the extruded section were small as mentioned previously. At extrusion ratios above 10:1, the orientation effects were well developed as shown in Figure 17 and the effects of increased preferred orientation were probably small and within the scatter noted in the mechanical test results. On the other hand, the orientation was not well established at extrusion ratios as low as 4:1 and some effects on mechanical properties would be expected. The only experimental evidence on this point is that of Klein et al. (1955) who noted a marked increase in tensile ductility with extrusion ratios up to 15:1 with negligible further increase at higher extrusion ratios. Further work is required to clarify these effects.

5. DISCUSSION

The work described in this report established the principles for the successful extrusion of beryllium and by implication, the sheathed extrusion of powders generally. However, there are various limitations in the technique.

In terms of technique alone, the most obvious difficulties in sheathed powder extrusion are associated with the control of dimensions. Adequate control of shape and dimensions requires the use of thin sheaths, probably not greater than 0.020 inch on simple sections or 0.010 inch on complex sections; with unconsolidated powder billets these thin sheaths tend to rupture owing to unequal strain during passage through the die or to buckle and split in the early stages of consolidation. The use of very thin sheaths on powder billets is feasible only when extreme care is taken in billet preparation, tool alignment, and lubrication and extrusion conditions; these conditions were attained in laboratory extrusion but could not be assured in large scale operations. On the other hand, thin sheaths may be used with pre-consolidated billets to achieve adequate dimensional control and the work at the Northrop Corporation (Christenson 1960, 1961) discussed previously suggests that this technique can be applied to complex sections on a commercial scale.

The pick-up of nitrogen and oxygen during the heating and extrusion of unconsolidated beryllium powders is a further disadvantage of the technique giving rise to variable properties. Again, the use of pre-consolidated billets with complete sealing of the sheath would avoid these difficulties. The variation in density along the extruded section further suggests that billets should be pre-consolidated before extrusion if a uniform high density is required.

The importance of these factors must be assessed however in terms of the proposed application for the material and the allowable costs. The pre-consolidation of billets by vacuum hot pressing (Clare et al. 1964) for example, would probably double the costs of fabrication and severely limit the economic field of application for the material. No single acceptable solution to this problem is evident.

The design and performance of tools in this work were satisfactory; some of the problems in tooling associated with high temperatures and pressures did not arise and in particular there was no evidence of excessive wear or premature failure. However it is emphasised again that the conditions of extrusion in these experiments differed from those to be expected in industrial practice; somewhat different conclusions may be valid when high production rates and strict economics are considered.

Further developments in the technique will almost certainly emphasise the use of glass lubricants in an effort to eliminate the sheath from pre-consolidated billets. Experiments in the use of glass lubricants, associated with this work (Wright and Silver, unpublished) show considerable promise of reduction of extrusion pressures by improved lubrication; no evidence of surface oxidation of the beryllium has been noted but slight reaction occurred between the beryllium and the types of glass used to date. (For nuclear applications, the glass must be free from boron; this severely limits selection from the available glasses).

The properties of the extruded sections are largely determined by the conditions of extrusion; the mechanical properties in particular are sensitive to the choice of extrusion temperature. This suggests that variable mechanical properties would be associated with poor temperature control or conditions of extrusion which resulted in a significant temperature gradient within the billet. Some temperature gradients between the hot billet and the relatively cold tooling are unavoidable but these may be minimised by the correct choice of extrusion speed. For 4-inch diameter billets, a speed of 1 - 3 inches ram movement per second appears to be the acceptable minimum and higher speeds are desirable with smaller billets. The choice of lubricant can also affect the extent of these temperature gradients; glass lubricants are relatively efficient heat insulators and billets extruded with glass lubricant tend to have low internal temperature gradients.

6. CONCLUSIONS

1. A technique was developed for the hot extrusion at 750 - 1050 °C of unconsolidated beryllium powder contained within a mild steel sheath. The powder may thus be consolidated to near-theoretical density and worked to the required shape in one operation.

2. The limitations of the technique for sheathed extrusion of beryllium powder are most evident in the poor control of extruded dimensions, in the contamination of the beryllium by oxygen and nitrogen from the heating atmosphere, and in variations in density along the extruded section.

3. The mechanical properties of the extruded section vary with extrusion temperature; the hardness and ultimate strength increase as the extrusion temperature is decreased from 1050 °C to 750 °C while the elongation values decrease over the same range. These effects are consistent with increased residual work hardening at the lower extrusion temperatures.

7. ACKNOWLEDGMENTS

The Analytical Chemical Services Section carried out all chemical analyses on the beryllium powder and extruded sections. The Materials Physics Section was responsible for preparation of specimens for metallography and for preferred orientation measurements.

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TABLE 1

DETAILS OF 1000 TON PRESS

CAPACITY	
Main Ram	1000 ton
Return Rams	2 x 15 ton
Tooling Rams	2 x 30 ton
Shear Ram	40 ton
POWER	
Oil–Nitrogen Accumulator	3920 p.s.i.
SPEED	
Power Stroke max.	10 in/sec
Approach	5 in/sec
DIMENSIONS	
Ram Diameter	27 in
Daylight	50 in
Plattens	40 x 26 in
Height of Press	19 ft
Accumulator Height	23 ft
Depth of Pit	20 ft

TABLE 2

IMPURITIES IN THE MATERIALS

Element	Impurity p.p.m.	
	Powder	Cast billets
Ca	50 – 100	100
Ni	100 – 200	200
Al	400 – 500	500
Si	100 – 200	200
Mg	50	500
Fe	200 – 300	1300
Halogens	50 – 100	not detected

TABLE 3

VARIATION IN DENSITY WITH EXTRUSION RATIO AND POSITION IN EXTRUDED RODS

Extrusion Ratio	Density g/cm³		
	Front	Middle	Back
11:1	1.829	1.832	1.836
21:1	1.811	1.834	1.844
31:1	1.827	1.828	1.840
Overall	1.822	1.831	1.840
% Apparent Porosity	1.5	1.0	0.5

TABLE 4

VARIATIONS IN OXYGEN CONTENT WITH POSITION IN EXTRUSION

Oxygen Content (% BeO)

Temperature	Front	Middle	Back
750 °C	0.56	0.57	0.61
850 °C	0.63	0.51	0.90
950 °C	0.58	0.50	0.78
1050 °C	0.38	0.38	1.08
Overall	0.55	0.48	0.97
Original	0.3 – 0.4 per cent.		

TABLE 5

VARIATIONS IN NITROGEN CONTENT WITH POSITION IN EXTRUSION

Nitrogen Content (p.p.m. N_2)

Temperature	Front	Middle	Back
750 °C	415*	3400*	3950*
850 °C	280	200	3600
950 °C	430	460	5510
1050 °C	270	250	3040
Overall	350	1100	4000
Original	200 – 300 p.p.m.		

* These billets were held for 2 – 3 hours at temperature before extrusion.

TABLE 6

VARIATION IN MECHANICAL PROPERTIES WITH POSITION IN EXTRUDED BAR

Extrusion Temperature °C	Extrusion Ratio	Extrusion Pressure (p.s.i.)	Hardness V.P.N.			Density g/cm³			U.T.S. (p.s.i.)			0.1% Proof Stress (p.s.i.)			Elongation %		
			F	M	B	F	M	B	F	M	B	F	M	B	F	M	B
750	11:1	132,000	199	206	203	1.841	1.841	1.839	94,100	88,600	101,200	60,250	46,300	61,850	4.1	7.8	8.2
	21:1	153,000	169	208	200	1.793	1.831	1.844	88,750	116,600	116,700	–	–	–	12.4	6.8	7.4
	31:1	Did not extrude															
	Means		184	207	202				91,400	102,600	109,000	60,250	46,300	61,850	8.3	7.3	7.8
850	11:1	103,000	162	169	187	1.827	1.833	1.842	78,400	95,800	101,200	–	–	–	11.4	13.4	11.4
	21:1	122,000	158	208	232	1.801	1.843	1.850	63,300	101,800	92,550	44,600	63,900	74,400	1.8	6.2	1.2
	31:1	144,000	162	165	198	1.835	1.822	1.851	79,600	91,400	74,600	41,700	46,100	50,400	6.3	6.0	2.2
	Means		161	181	206				73,800	96,300	89,400	43,200	55,000	62,400	6.5	8.5	4.9
950	11:1	82,000	150	152	182	1.828	1.831	1.842	76,300	78,200	89,500	–	–	–	17.0	14.8	4.1
	21:1	110,000	157	155	194	1.827	1.827	1.841	68,500	67,500	87,500	37,400	36,000	45,100	2.6	5.2	5.2
	31:1	119,000	166	163	183	1.828	1.839	1.841	74,500	71,650	83,200	42,900	42,900	54,350	5.3	9.0	2.8
	Means		158	156	190				73,100	71,000	86,700	40,200	39,100	49,700	8.3	9.7	4.0
1050	11:1	67,000	143	142	149	1.819	1.822	1.820	72,100	72,100	72,800	–	37,400	–	10.0	15.0	14.2
	21:1	92,000	130	138	140	1.822	1.836	1.842	67,200	72,300	62,300	33,900	33,000	30,000	12.9	12.0	5.8
	31:1	103,000	136	147	162	1.817	1.823	1.829	78,200	66,900	77,650	–	37,000	–	6.1	14.0	14.0
	Means		136	142	150				72,500	71,040	70,900	33,900	35,800	30,100	9.7	13.7	11.3

F = front

M = mid-section

B = back

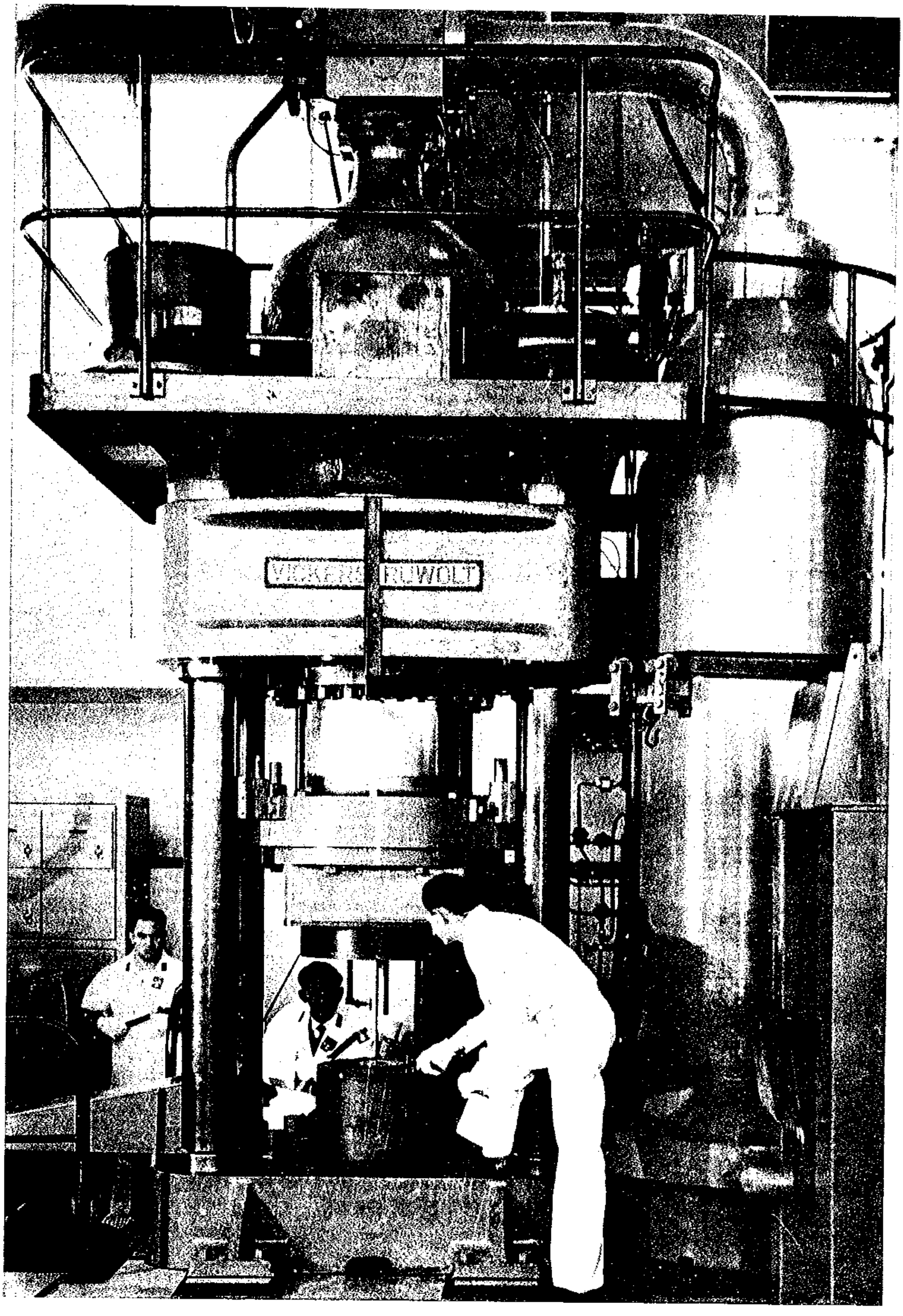


FIGURE 1. GENERAL VIEW OF 1000 TON HYDRAULIC EXTRUSION PRESS

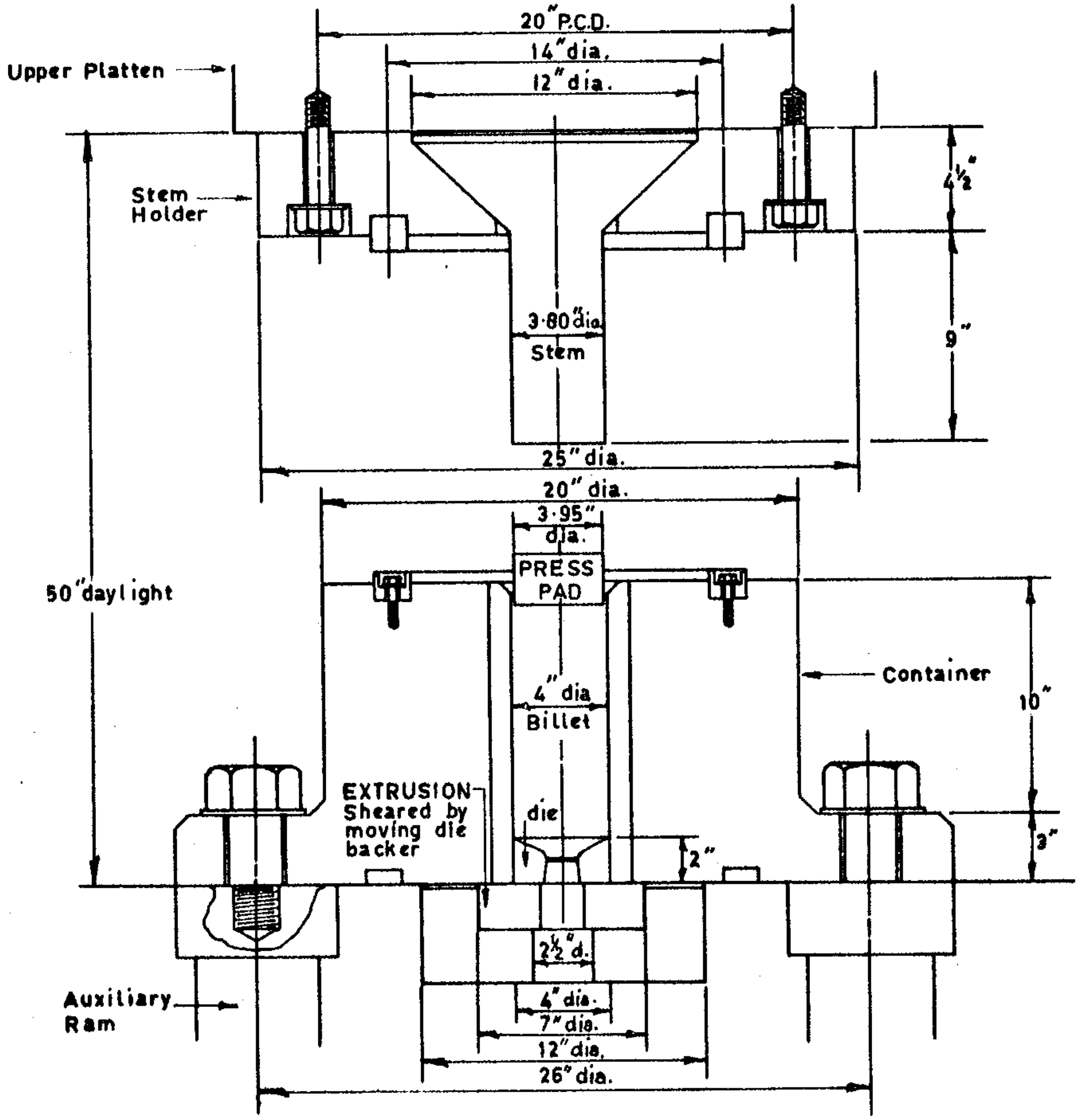


FIGURE 2(a) DIAGRAMMATIC ARRANGEMENT OF TOOLING FOR 1000 TON EXTRUSION PRESS – DIRECT EXTRUSION

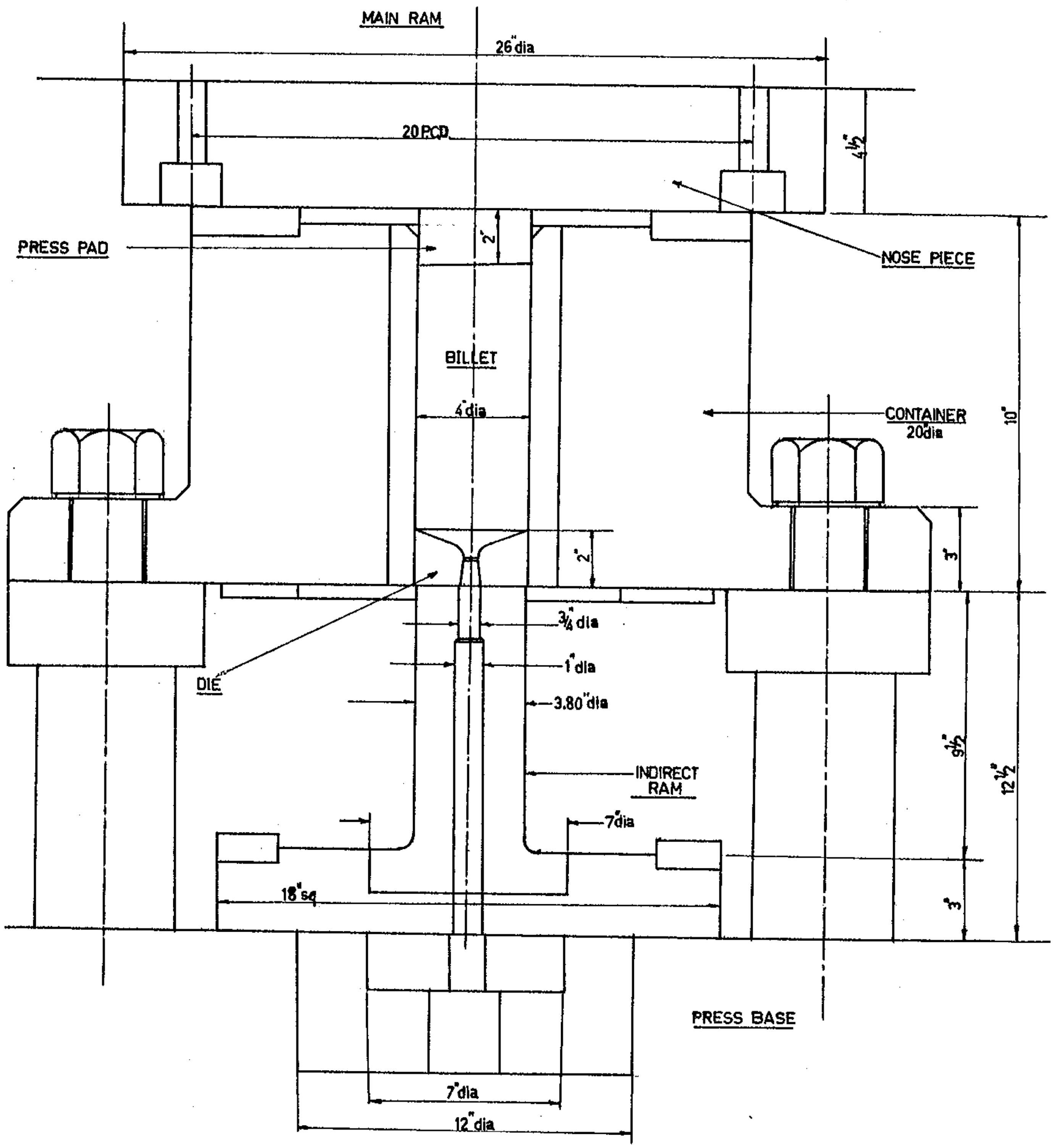


FIGURE 2(b) DIAGRAMMATIC ARRANGEMENT OF TOOLING FOR 1000 TON EXTRUSION PRESS – INDIRECT EXTRUSION

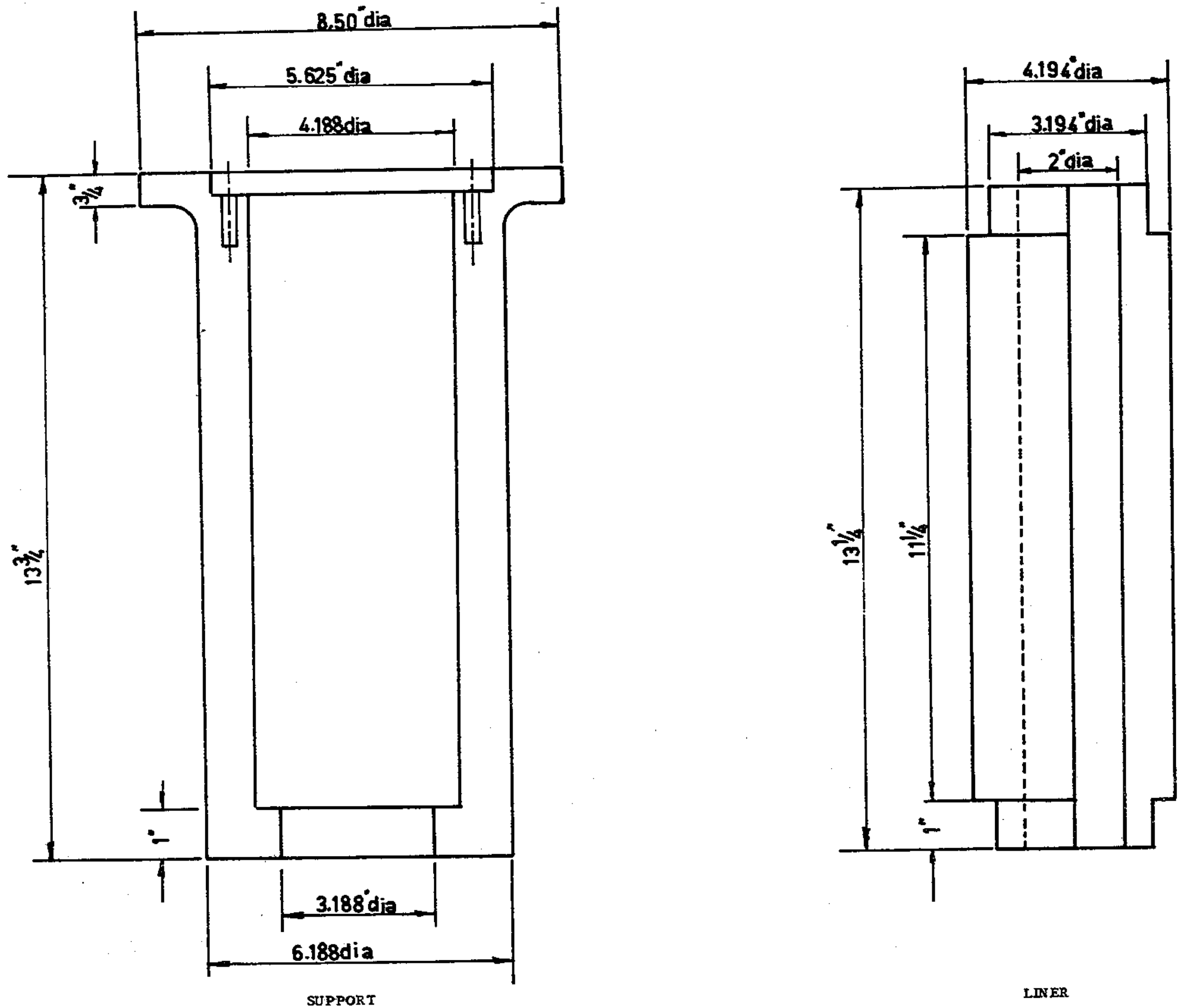


FIGURE 3. MODIFIED LINER ARRANGEMENTS

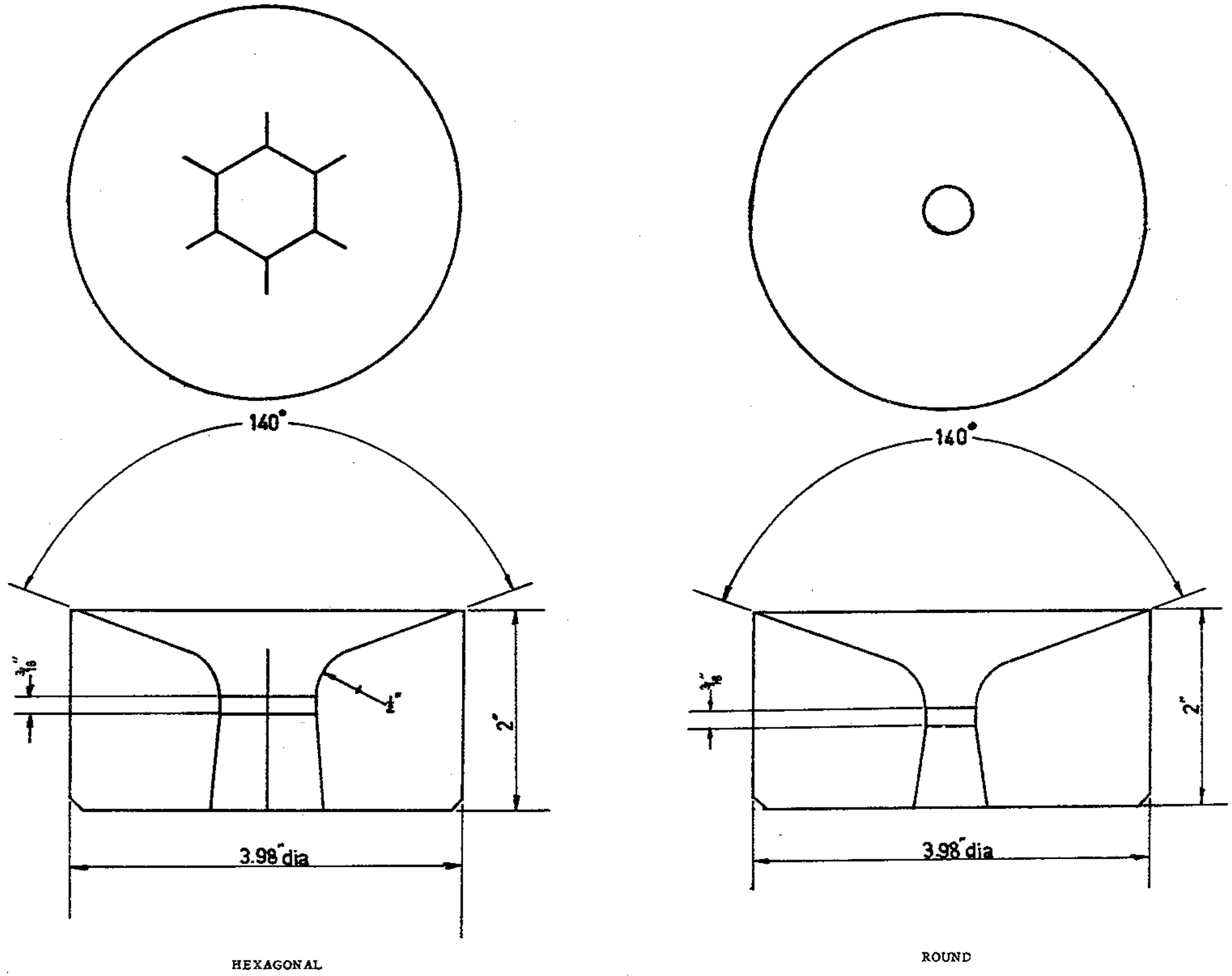


FIGURE 4. BASIC DIE DESIGNS

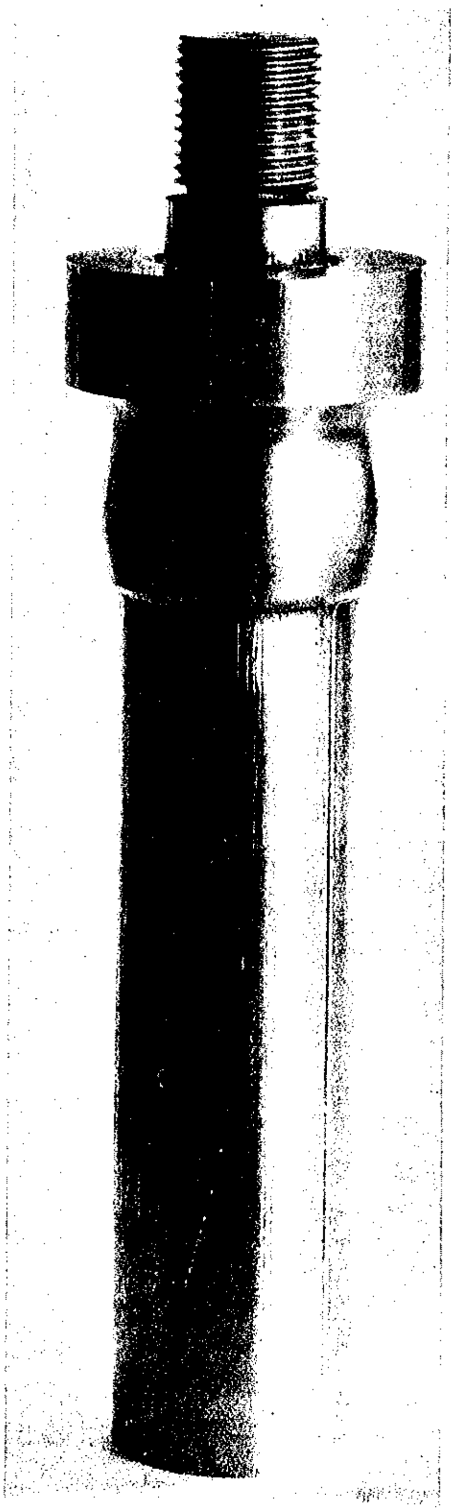


FIGURE 5. PLASTIC FAILURE OF STEM MADE FROM 5%-CHROMIUM TOOL STEEL

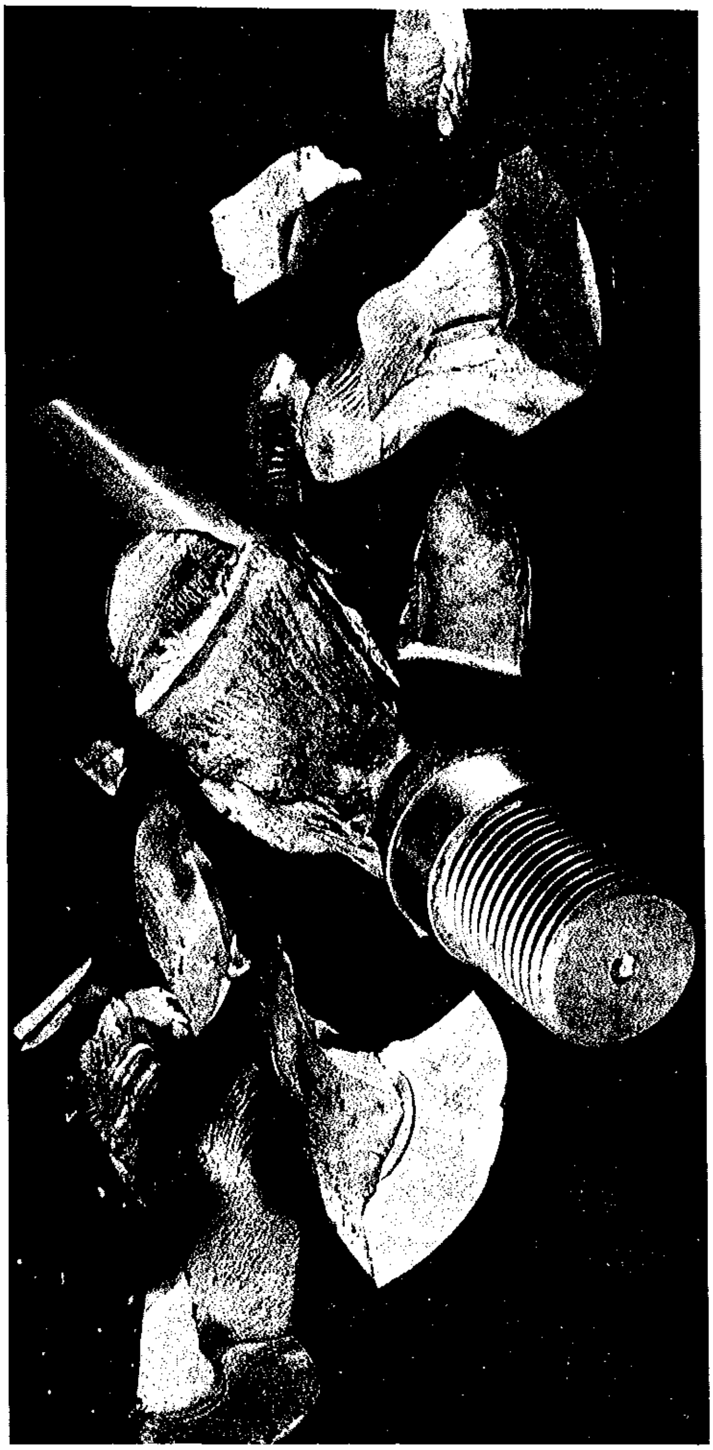


FIGURE 6. BRITTLE FAILURE OF STEM MADE
FROM 18/4/1 HIGH SPEED TOOL STEEL

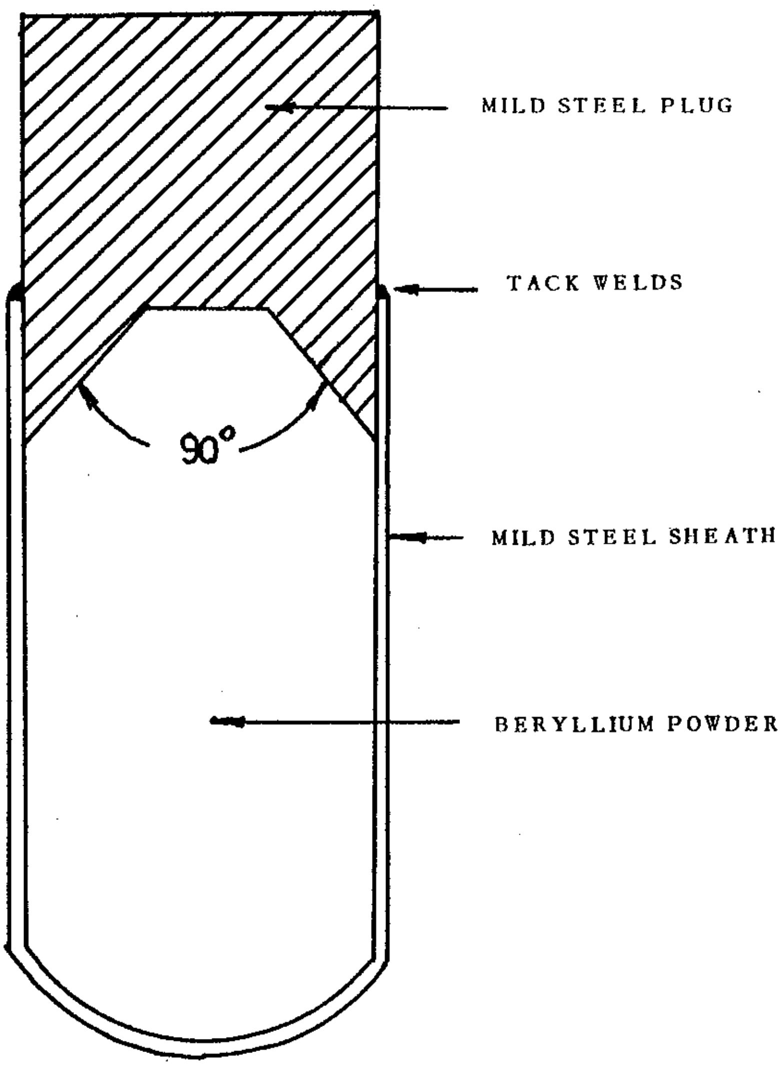


FIGURE 7. SCHEMATIC ARRANGEMENT OF BILLETS FOR EXTRUSION

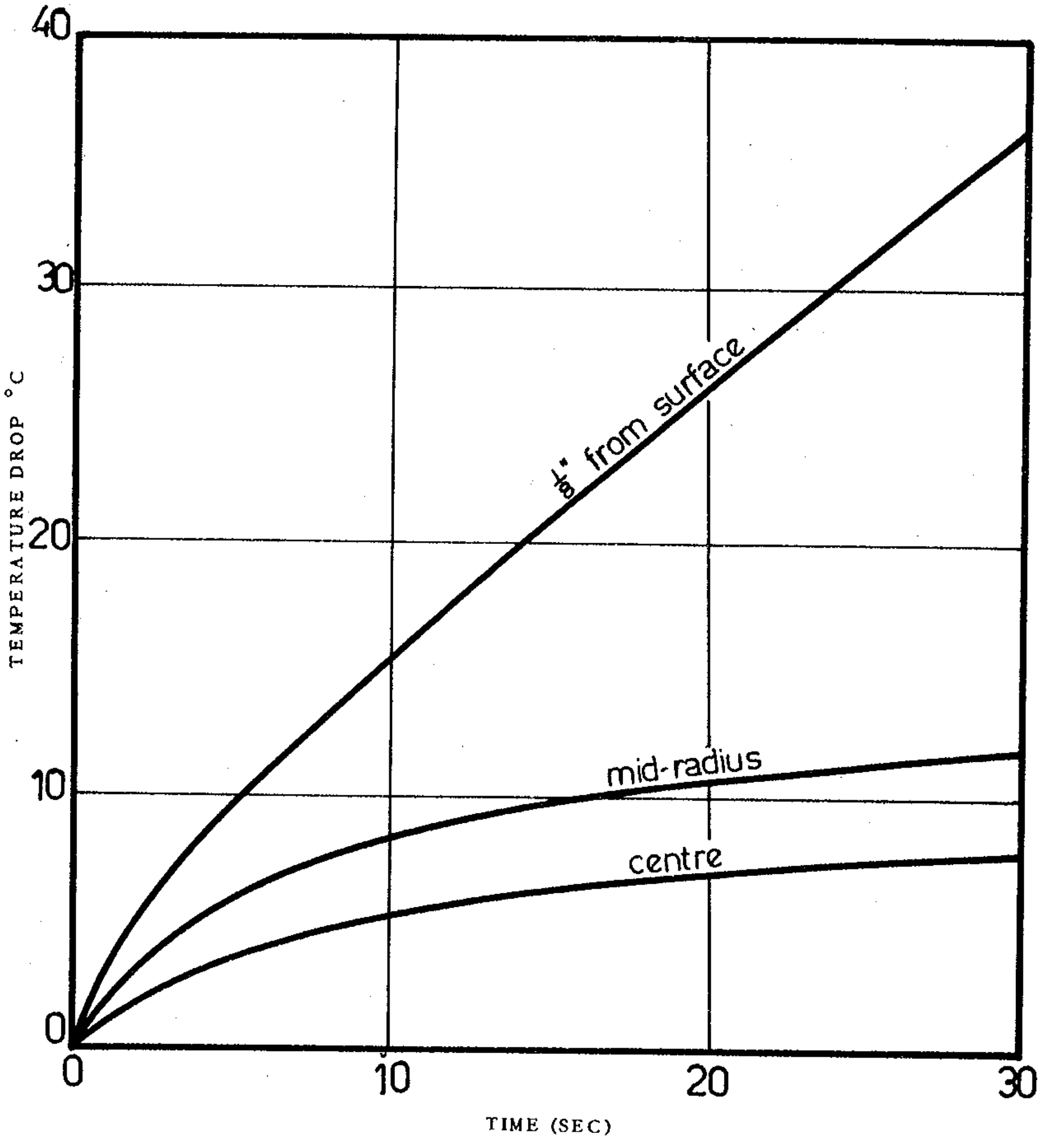
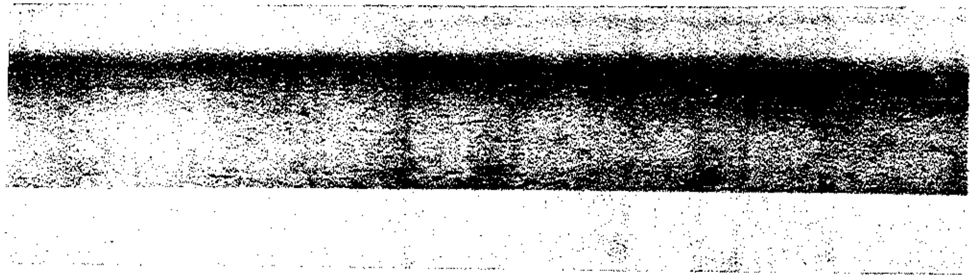
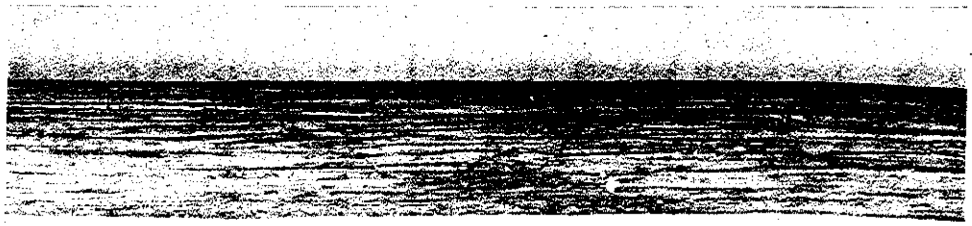


FIGURE 8. COOLING CURVES FOR 4-INCH BILLETS AT 950°C

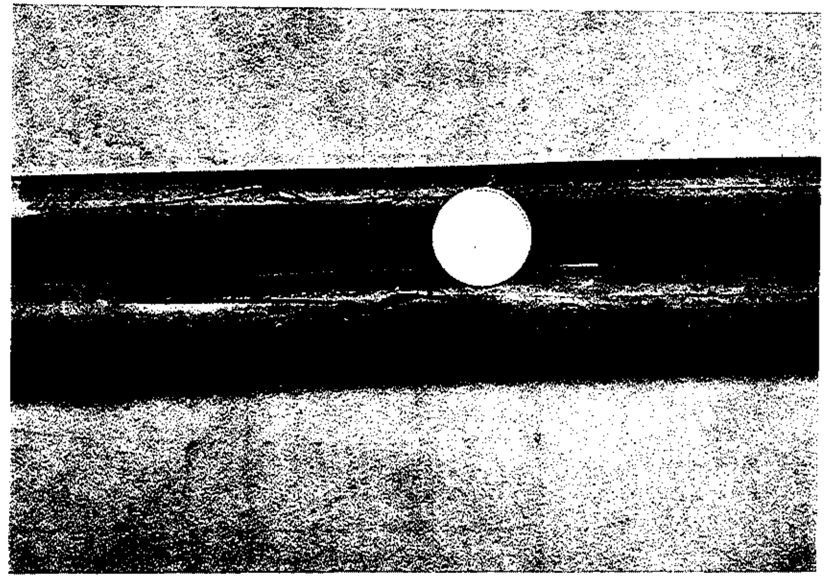


(a) Extruded from powder



(b) Extruded from vacuum cast billet

FIGURE 9. SURFACE FINISH OF SECTIONS EXTRUDED FROM POWDER AND CAST MATERIAL



(a) Buckling of the sheath

(b) Splitting of the sheath resulting from air entrapment

FIGURE 10. TYPICAL EXTRUSION DEFECTS

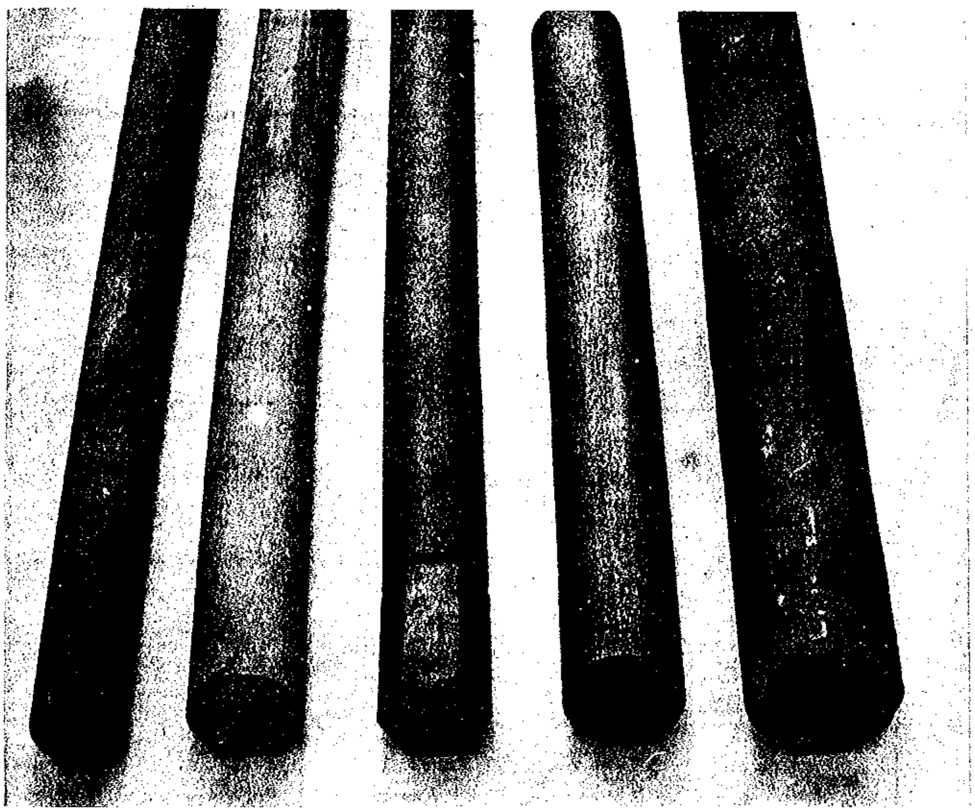


FIGURE 11. TYPICAL SATISFACTORY EXTRUDED SECTIONS

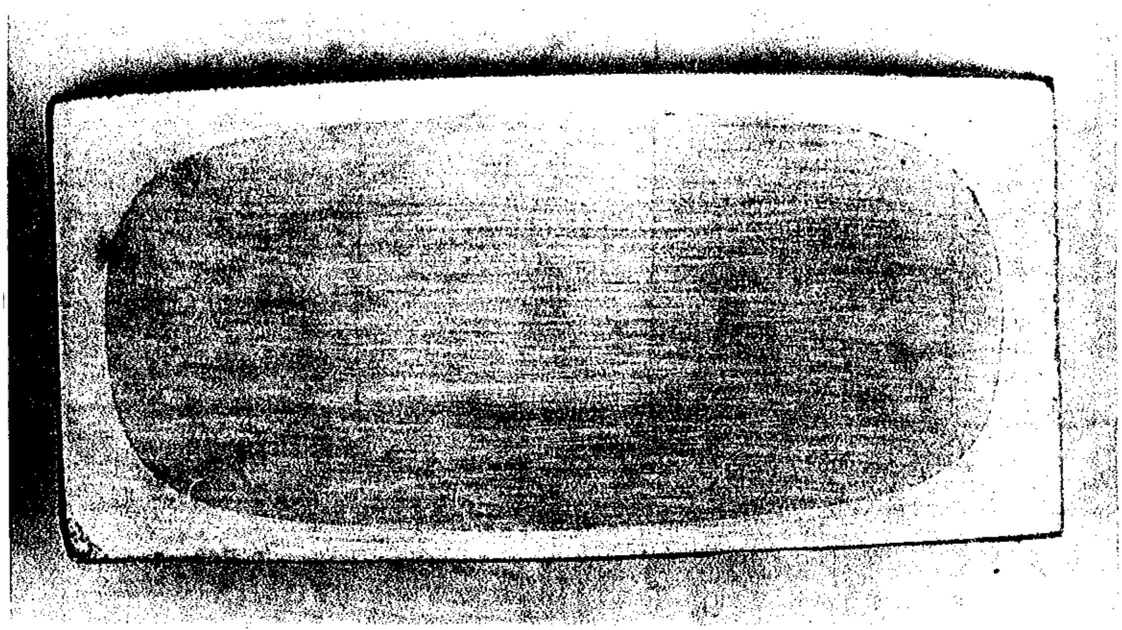


FIGURE 12. ROUNDING OF THE CORNERS OF A RECTANGULAR SECTION EXTRUDED WITHIN A MILD STEEL SHEATH

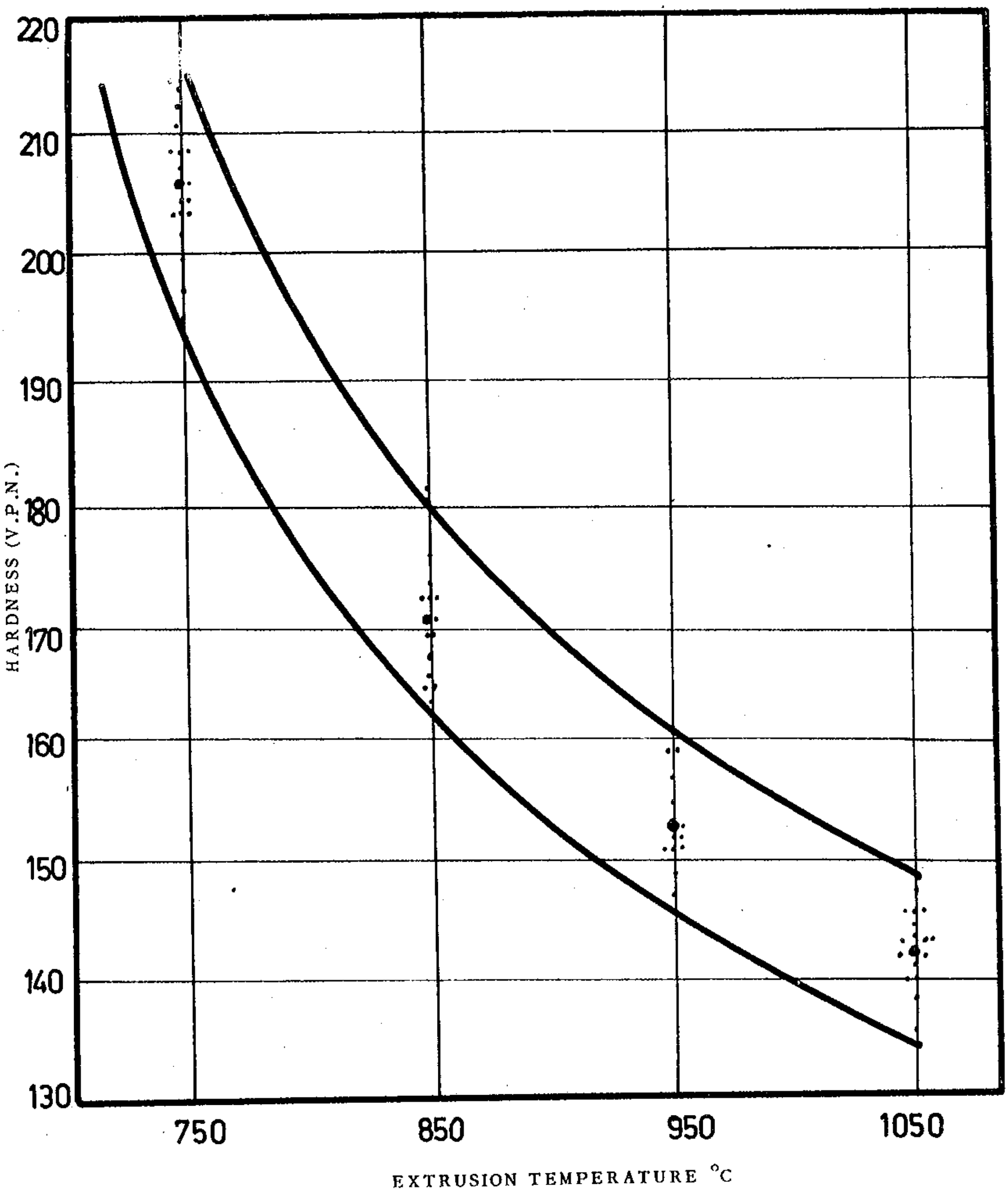


FIGURE 13. VARIATION IN MEAN HARDNESS WITH EXTRUSION TEMPERATURE

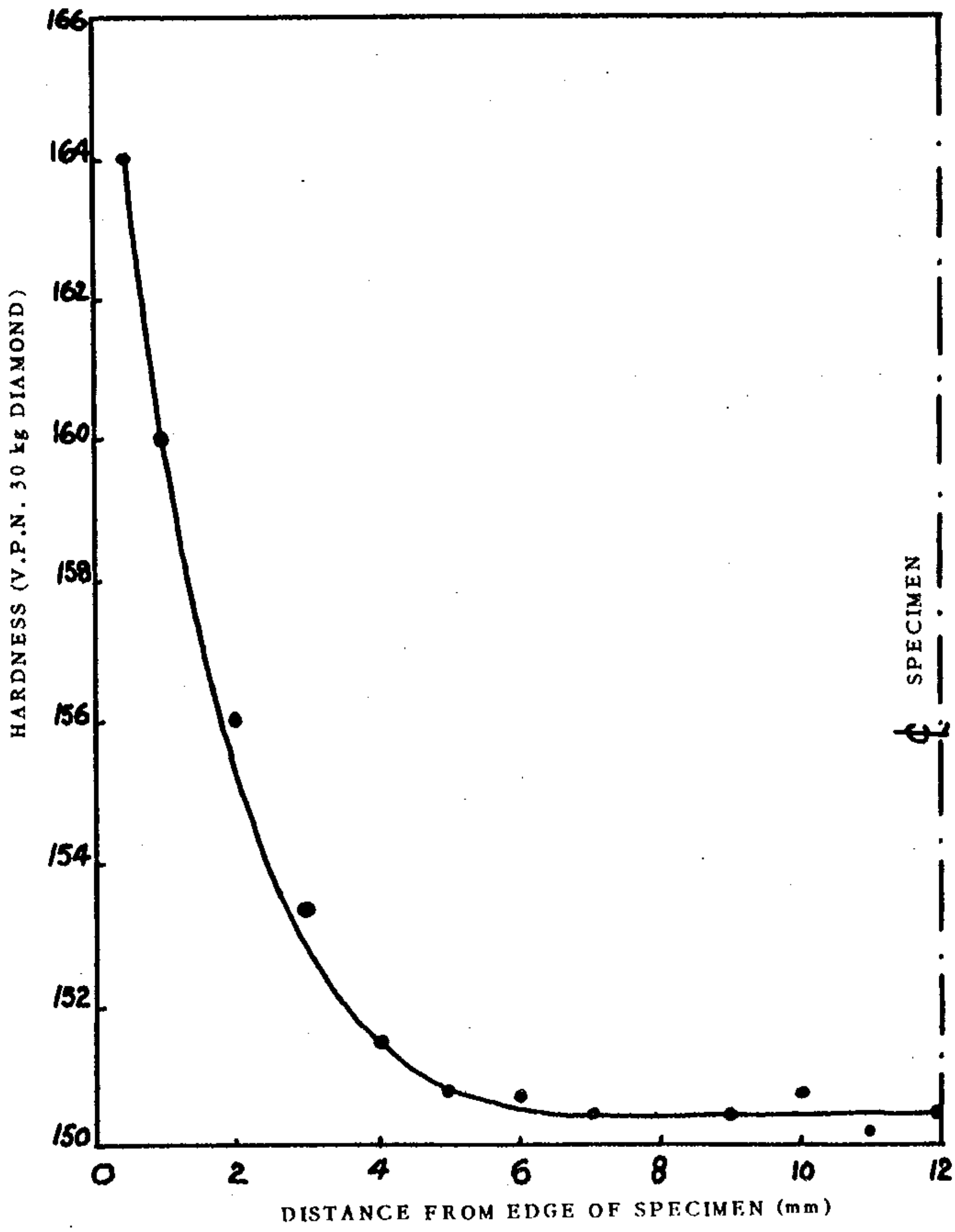
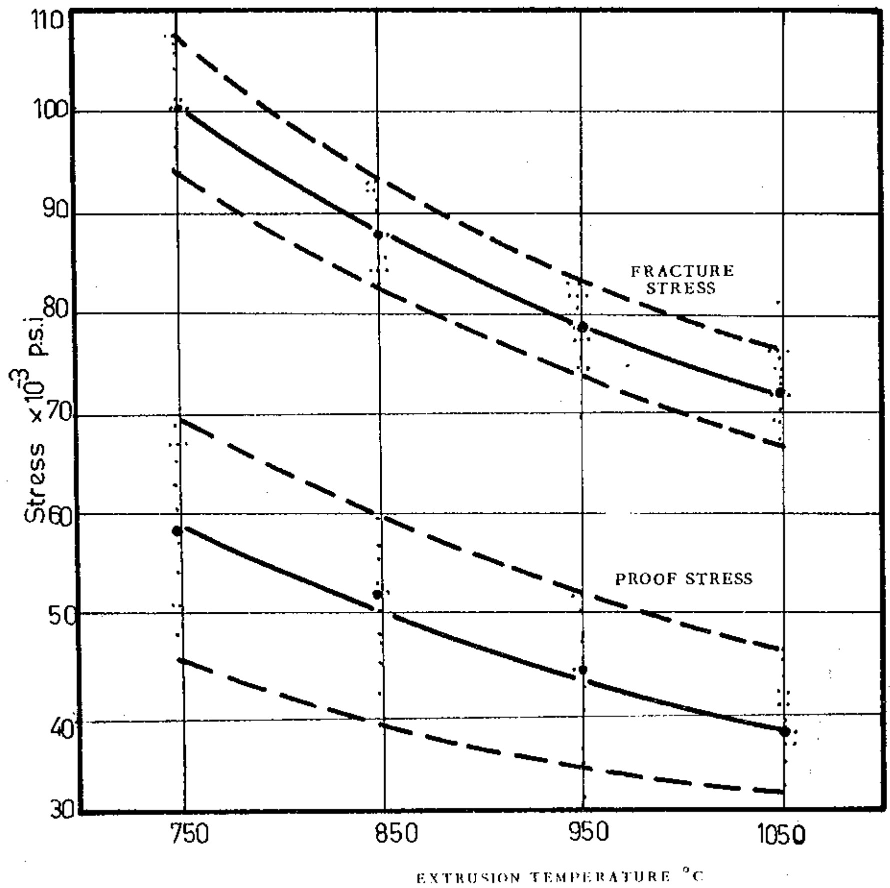
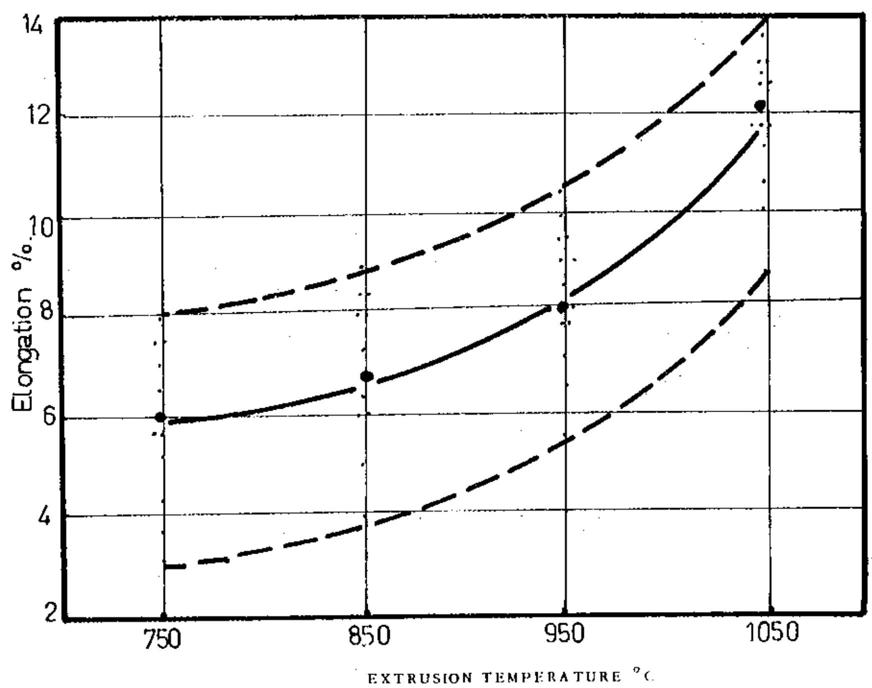


FIGURE 14. VARIATION IN HARDNESS ACROSS SECTION OF EXTRUDED POWDER BILLETS



(A) STRESS



(B) ELONGATION

FIGURE 15. VARIATION IN TENSILE PROPERTIES OF EXTRUDED SECTIONS WITH EXTRUSION TEMPERATURE

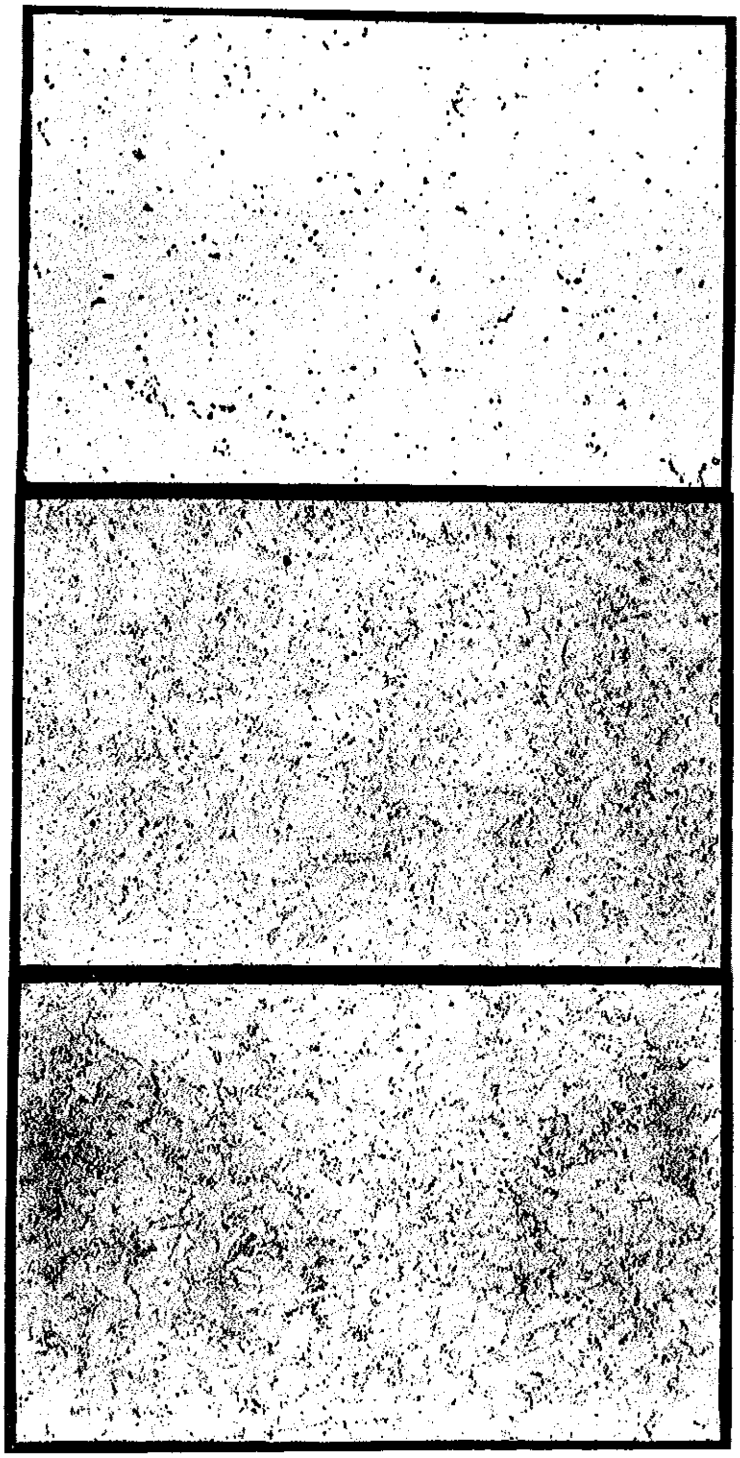
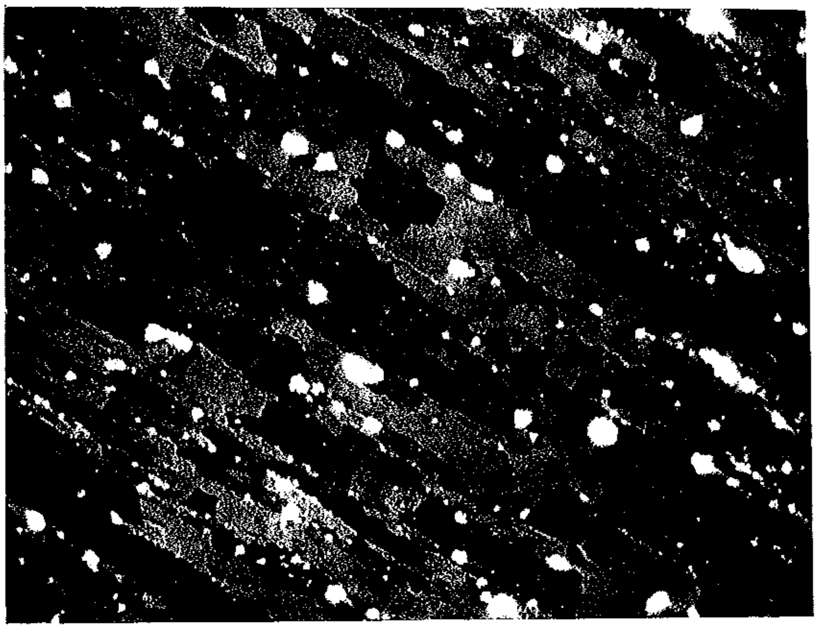
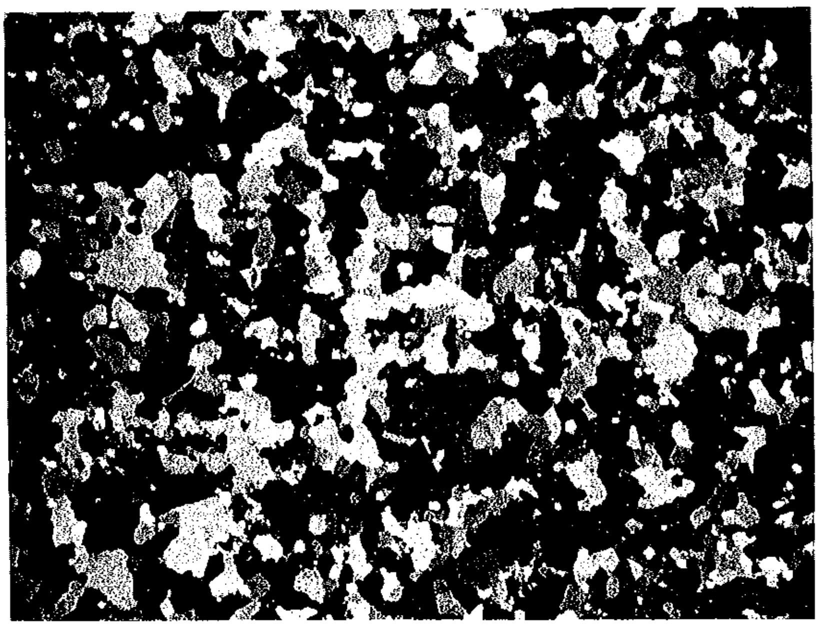


FIGURE 16. (a–c) TYPICAL STRUCTURE OF EXTRUDED RODS
(showing porosity and oxide–nitride inclusions)



(d) Longitudinal
Section



(e) Transverse
Section

Polarised light X 250

FIGURE 16. (d–e) TYPICAL STRUCTURE OF EXTRUDED RODS

(white areas are polishing artefacts
associated with inclusions)

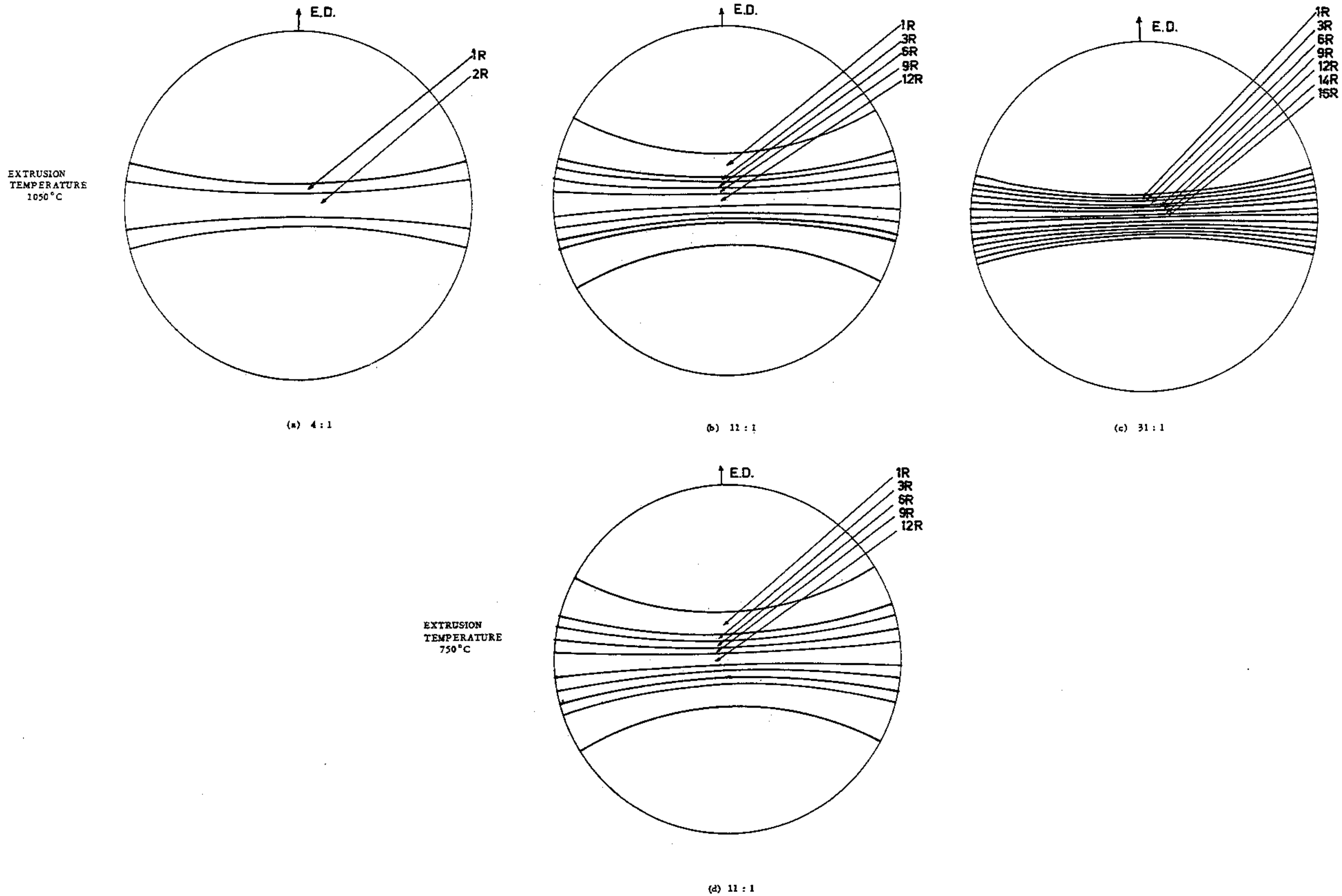


FIGURE 17. POLE FIGURES OF BASAL PLANE ORIENTATION IN EXTRUDED RODS AS A FUNCTION OF EXTRUSION RATIO AND TEMPERATURE