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# Improving solids conveying in plasticating extruders : an investigation into manufacturing processes and manufacturing systems for profiled thermoplastic pellets

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ABSTRACT

**Title of Thesis:** Improving Solids Conveying in Plasticating Extruders: An Investigation into Manufacturing Processes and Manufacturing Systems for Profiled Thermoplastic Pellets

Oommen Cherian, Master of Science in Manufacturing Engineering, 1990.

**Thesis Directed by:** Dr. Keith T.O'Brien.

The objective of the thesis is the manufacture of thermoplastic bilobal and trilobal profiled pellets for the determination of the interparticulate co-efficient of friction exhibited by solid beds of such pellets. The enhancement of the interparticulate coefficient of friction is expected to lead to ameliorated solids conveying rates in plasticating extruders.

Predicting the product shape from a profile die is very difficult due to the elastic memory of plastics and the complex boundary conditions. Consequently the cost involved in experimenting with different profile dies is high. Therefore a standard die with several die inserts of varying cross-sections were used to manufacture the bilobal and trilobal shapes, at reasonable cost, and for a variety of materials.

After much "trial - and - error" and different "sizing" techniques, bilobal and trilobal pellets were manufactured for the materials tested, using a variety of dies under specific operating conditions.

This project is being performed in several parts:

1. The manufacture of the profiled pellets, which is the subject of this thesis.
2. Measuring the interparticulate coefficient of friction which is the subject of concurrent work (12).
3. Field trials using a full size extruder to determine if solids conveying is enhanced, which will be a future thesis.

# IMPROVING SOLIDS CONVEYING IN PLASTICATING EXTRUDERS: AN INVESTIGATION INTO MANUFACTURING PROCESSES AND MANUFACTURING SYSTEMS FOR PROFILED THERMOPLASTIC PELLETS.

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Thesis submitted to the faculty of the Graduate School of
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## PREFACE

According to the Society of Plastic Industries (SPI) the production of plastics grew at an average annual rate of 5.0 % between 1978 and 1988. Much of the growth in plastics has come from the replacement of such materials as wood, glass, paper, and metals.

This in turn has required considerable capital investment in new plant either as -

1. The expansion of the current plant, or
2. The commissioning of new plants.

Only a breakthrough in plastics processing can delay this investment.

One of the ways this breakthrough can possibly be achieved is if plastic production rates can be increased using the same machinery in existence today. Improving the solids conveying capacity of existing extruders by using solids with improved interparticulate coefficients of friction is postulated as a way to delay capital investment. If solids conveying improvements result, then improved outputs could be attained with the existing machinery.

An integral part of such a program is the production of the profiled pellets postulated to improve solids conveying capacity.

## DEDICATIONS

To my beloved

wife and parents...

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CHAPTER I

# INTRODUCTION

Plastics may be conveniently divided into two groups, thermoplastics and thermosetting plastics. Thermoplastics when heated to a sufficiently high temperature will soften and flow under pressure. On cooling they harden. This process may be repeated over and over again. In contrast thermosetting resins, as their name implies,can be hardened and set by submitting them to a heating process. During the heating cycle they soften and can be moulded or extruded, but on further heating under pressure undergo an irreversible chemical change and once they have set they cannot be re-softened by subsequent heating. Therefore this work is applicable only to thermoplastics. The primary objective of this project is to develop a manufacturing system to produce the non-circular pellets for inter-particulate friction coefficient measurements and for use later in extrusion operations.

## A. RATIONALE

Plasticating screws are used to convey polymeric particulates prior to melting them for shaping into useful plastic products. The first thorough analysis of particulate conveying in plasticating screw channels was performed by Darnell and Mol (6). This analysis was extended by Tadmor and Klein (1). Refinements by Klein (13) have continued to appear. Some conclusions by these researches include,

(i) the particulates slip on the screw,

(ii) the particulates are conveyed by the friction between the barrel and the particulates,

(iii) the rate of melting of the particulates is maximized if the particulates form an integral solid bed,

(iv) the break-up of the solid bed is undesirable, and

(v) if solid bed break-up does occur, the process parameters surge, and control of the quality of the finished product is poor.

If the inter particulate coefficient of friction between the pellets can be increased then the break-up of the solid bed is minimized. This would result in better heat transfer between the channel and the screw whereby the melting conditions of the polymer are improved. If the solid bed doesn't break too easily, the high temperature fluctuations in the melting zones can be controlled due to the lumps of melt present in between pieces of solid. In short the quality of the extrudate depends primarily on the melting performance of the extruder and melting mechanism (1).

A key to ensuring good solids conveying is the use of the correct coefficients of friction in the design equations. Jenike (14) and Evan (15) have studied how to measure these coefficients under processing conditions, and Klein (13) has incorporated sophisticated algorithms to describe these coefficients into computer-aided design.

## B. BACKGROUND

About 50 billion pounds of polymeric particulates are consumed in the United States each year. In reference to Table I (17) it can be observed that there is a steady increase in the production of plastics. Most of it must be conveyed as a solid, prior to conversion into useful plastic products. Marginal improvements on the large volumes produced can bring about significant savings to the industry. This project is directed at inexpensively modifying an existing strand die to produce bilobal and trilobal pellets so that they can be tested for their inter particulate friction coefficients.

The materials for manufacture of the pellets have been taken from several base resins, ranging from soft to hard, that is low modulus to high modulus. The low modulus materials tend to deform under pressure in contrast to that of the high modulus as illustrated in Figure 29. Therefore some of these materials contain fillers and reinforcements, to represent the industrial situation. The cross section of the die inserts are presented in Figures 18-21.

The project started with a literature survey of the existing processes for extrusion methods and, in particular, profile extrusion. The key elements of interest on this project are the basic principles of extrusion, the principles of die design, the selection of materials, the test equipment and the test results.

This thesis should be a useful guide for further research in the area of plastics extrusion and in particular, interparticulate friction coefficient enhancement and its effect on solids conveying in a plasticating extruder.

**U.S RESIN SALES FOR EXTRUSION APPLICATIONS**

**Table I**

| Sl. No. | Material | Market | Million Lbs 1988 | 1989 |
|---|---|---|---|---|
| 1 | Low-Density Polyethylene | Extrusion | 7760 | 7311 |
| 2 | Polypropylene | Extrusion | 2735 | 2850 |
| 3 | Polystyrene | Extrusion | 2179 | 2156 |
| 4 | High-Density Polyethylene | Extrusion | 1769 | 1795 |
| 5 | Polyesters Thermoplastic (PET and PBT) | Extrusion | 510 | 520 |
| 6 | Acrylonitrile Butadiene Styrene (ABS) | Extrusion | 420 | 445 |
| 7 | Acrylics | Molding & Extrusion Compounds | 200 | 220 |
| 8 | Nylons | Extrusion | 148 | 151 |
| 9 | Cellulosics | Extruded film & sheet | 17 | 17 |

Source: Modern Plastics, January 1990, Pages 100-104

CHAPTER II

# MANUFACTURING SYSTEMS FOR PLASTICS EXTRUSION

## A. THE COMPLETE EXTRUSION PROCESS

The practical art of extrusion, which consists of the manufacture of marketable products of high dimensional uniformity, and general quality, at economic output rates, requires considerably more than the mere provision of a uniform melt of correct form at the die orifice. Regardless of the section being produced, some form of take off or other handling system is always necessary and the quality of the finished product, once it has left the extruder, is completely determined by the regularity and smooth functioning of such mechanisms. It is, therefore, impossible to consider the extrusion process seriously unless various standard types of take off systems are discussed in detail.

### 1. Wire covering

This process is used to coat continuous lengths of wire, cable, tube and a variety of products with a layer of thermoplastics material. The tremendous demand for covered cable in the radio and electrical industries makes this one of the most important of the many extrusion processes (2).

The basic requirements for the complete process are shown diagrammatically in Figure 1, from which it may be seen that there are six units including the extruder in the complete arrangement.

Drums of uncovered wire are mounted on a payout stand and these drums may be free to rotate, friction braked or power driven, depending on their size and on the requirements of the system. From the payout drum the wire is led through the covering crosshead which is mounted on the extruder. On leaving the crosshead, the coated wire passes through the whole system at a constant rate. The wire then enters a constant tension device which controls the speed of a reel-up drum on to which the covered, cooled product is finally reeled.

a. Wire-covering crosshead :- A section through a typical wire-covering crosshead is shown in Figure 9 and the perpendicular disposition of the covering die with respect to the direction of the material feed can be clearly seen. Other wire-covering assemblies in which the crosshead is disposed at angles of $45^o$ or even $30^o$ are also used, the purpose being to minimize the flow disturbances due to the change of direction of the material whilst still retaining the advantages of the crosshead arrangement.

In the arrangement shown, which is one of many in common use, the molten material is forced through an orifice which conducts the material to the closely fitting wire guide mantrel or 'point'. This mandrel is so shaped that the material flows around either side of it and joins again on the side remote from the supply. The complete annulus of material then flows towards the die orifice and ultimately contacts the wire and the forming land. In this way a tube of plastics material is deposited over the wire which moves continuously through the crosshead acts as an internal forming mandrel.

In addition to changing the dimension of the die orifice, the thickness of the plastics coating on the wire can be affected by changing the relative speeds of the extrusion and the wire travel, as well as by changing the position of the wire guide with respect to the die ring. It is necessary to provide some means of ensuring that the plastics coating is concentric with the wire, since such concentricity cannot be guaranteed merely by wire and the die ring symmetry. The uneven flow conditions engendered by the method of feed of material to the wire guide and the inability to ensure even heating around the crosshead itself make the construction of the fixed die which will produce a concentric covering extremely difficult. In Figure 9 it will be seen that the die ring is separate from the die body and that its position relative to the wire guide can be changed by means of centering screws. Inspite of the difficulty of constructing a fixed die to give a concentric covering, many such dies are infact used with success in the smaller sizes.

In order to accomodate different wire diameters and covering thicknesses, a series of wire guides and die rings are made, each having a different bore, for each of several sizes of die body. Thus each size of die body or crosshead can be used to cover a wide range of wire diameters in many coating thicknesses.

Temperature control on the wire covering crosshead is usually effected by thermocouples at two or more positions, one of which is located as near as possible to the die orifice whilst the others control the average temperature of the die body.

b. Payout :- The payout is essentially a reel stand and on rudimentary setups the reel of uncovered wire is merely supported on centers so that it may revolve as the wire is taken off and some form of simple braking is provided to prevent the inertia of the drum from affecting the tension of the wire. In more complex systems and for fine wires, the payoff reel is driven so that a greater degree of control may be exercised on the tension of the wire throughout the system and to minimize the tension on wires of very small diameters. The payoff drum may be mounted with its axis at $90^{o}$ to the line or parallel to it.

In the latter case, the width of the conductor as it pays out is controlled by a metal bell shaped hood through which it is passed.

c. Cooling bath :- From the extruder the wire passes into a cooling bath, or trough, the size of which varies according to the diameter or the volume of the thermoplastics material to be cooled. Different covering thicknesses require different degrees of cooling and the troughs are, therefore, generally made up in sections to enable the correct length for any particular job to be assembled. The cross section of the trough depends on the size of the covered wire or cable it is to handle.

At both ends of the cooling bath, the wire passes over V-shaped weirs or through rubber seals which reduce water leaks and along the length of the bath it is sometimes held submerged by free running rollers.

The length of the cooling trough can be calculated provided the properties of the material, the conditions of extrusion - that is output rate, stock temperature and extrudate volume - and the temperature of the cooling water are known.

An important factor which affects the appearance of the insulation is the setting of the cooling bath relative to the extruder. The distance which the hot coated conductor must travel before contacting the cooling water - known as the air-gap, allows the surface of the coating to become annealed and to obtain a gloss as well as reducing strains. The gap length of this is varied according to the linear speed of the coated wire and can be as much as 3.3 feet or more on high speed installations.

d. Capstan :- The capstan, as its name implies, consists of a large winding drum - or two drums - around which the wire is passed four or five times before being led to the take-up or wind-up stand. The diameter of the drums must be suited to the type and dimensions of the wire being produced and may vary from 12 inches for very fine wires up to 5 feet or more. The drive for the capstanis capable of variable speed adjustments with precise control which may be linked to the speeds of the extruder, payout and take-up.

e. Take-up :- The final unit in the wire covering take-off is the take-up stand which is most of its features is very similar to the payoff. The unit, ideally, caters for two reels and is necessarily power driven. A further refinement of this unit is a laying device which guides the wire onto the reel in such a way that it is neatly and regularly laid into possition and does not bunch in one spot. It should be possible on this unit also to transfer the incoming wire quickly and automatically from a full reel to an empty one with a minimum retardation to the system and the laying device must transfer itself automatically to the empty drum. An automatic cut-off is also necessary and the rotation of the full drum must be stopped automatically so that it can be unloaded and replaced without stopping the operation.

Because of the change in diameter of the coil of finished wire on the wind up drum, as production proceeds there must be some mechanism interposed between the capstan and the wind up which will automatically control the tension on the wire by progressively reducing the windup speed. Such a mechanism must also accomodate the erratic changes in tension which occur when drums are changed. A "dancing jockey" type of a system is commonly used.

**2. Sheet extrusion**

It is often not possible to reel thick sheet material nor is it usually advisable to pass the thick material through a water bath. The type of take-off system used for the production of polystyrene sheet is shown in Figure 10. On leaving the die the sheet passes round a triple roll system in which the rolls are heated and maintained at constant temperatures.

After leaving the initial polishing rolls, the sheet is supported on a belt or roller conveyor and is led into one or two pairs of nip rolls with a set of edge trimming knives introduced between the roll stations.

a. Sheet Dies: A diagrammatic arrangement of a typical die for the extrusion of sheet in materials such as polystyrene, polyethylene, acrylics is shown in Figure 11. This die, which is used for products from 0.025 to 0.25 inches or thereabouts in thickness, consists of a split die body with a longitudinal manifold, an adjustable restrictor bar and adjustable and interchangable lip members. By careful adjustment of the die lips and the restrictor bar, using the setting bolts provided, the required pressure for file can be obtained, thus ensuring uniform delivery of material from the lips. The ends of the die are sealed with plates to which are attached profiled plugs which fit into the ends of the manifold and help to direct the flow towards the die lips. In some cases adjustable bleeder holes are provided in the end plates to speed-up colour or material changes.

### 3. Tubular film

Figure 2 shows a typical arrangement for making film by the tubular film blowing process. The polymer is extruded vertically through a die into a thin tube which is then inflated with air, cooled, flattened between rollers and wound up.

Although suitable for many thermoplastics, the tubular process is used mainly for making large quantities of polyethylene film.

Two operational terms need to be defined:-

a. The blow up ratio - This is the ratio of the diameter of the bubble to the diameter of the die annulus. In practice, blow up ratios between 2:1 and 6:1 are most commonly used.

b. The draw down ratio - This is the ratio of the velocity of the film through the nip rolls compared to the velocity of the extrusion.

a. Tube dies :- Typical straight-through extrusion dies for the production of tube in rigid or semi-rigid materials are shown in Figure 12 and dies of crosshead and offset form are shown in Figure 13.

The straight-through die is seen to consist essentially of a die body which supports the main structure and an outer die ring and die mandrel which together give the orifice dimensions. The mandrel is supported on a multi-spoked piece called a "spider" which fits into a recess in the die body where it can be rigidly planned. Adjustment for tube concentricity may be obtained by means of centering screws which move the spider and the attached mandrel as shown in illustration of the smaller die or by moving the outer ring in relation to a fixed mandrel as shown in the other illustrations. In the latter system, which is the most frequently used, the adjusting screws bear on the outer ring which is recessed into the die body and clamped in position by means of a separate clamping ring or other device. The fixed mandrel and spider give a more rigid construction which is essential for tubes of larger diameter.

b. Polishing rolls :- The polishing rolls are usually hard chrome plated and various diameters upto about 12 inches are used. In all cases the rolls are provided with individual temperature control, usually by means of oil, and must be designed internally to give uniform heat transfer over the entire surface. The speed of the rolls must be controlled to correspond with the output of the extruder or fractionally faster in order to compensate for the slight swelling of the extrudate as it leaves the die. The function of the unit is to impart a good surface to the product without warpage and to reduce its temperature to a level at which it can be handled without distortion.

**4. Monofilament**

Extruded monofilament finds a variety of uses such as for the manufacture of filter cloths, garden furniture, radio grilles, fishing lines, racquet strings and brushes. The main thermoplastics used are polyethylene, nylon, polyvinylidene chloride and one amorphous polymer, polystyrene (3).

The monofilament process consists essentially of three stages:

a. Extrusion into a quench bath;

b. Orientation;

c. Setting and cooling.

A typical arrangement for making high density polyethylene monofilament by a single stage process is shown in Figure 3.

Monofilament is extruded through a multi-hold die vertically downwards into a quench bath. The filaments are wound round two pairs of rolls known as godet rolls separated by an orientation bath. The second pair of rolls is rotated at a higher velocity than the first pair and, provided the monofilament is at a temperature above the glass transition temperature ( a sort of softening temperature ), the molecules and crystals are able to orient leading to a considerable increase in strength in the axial direction.

To ensure that all monofilaments emerging from the die have the same characteristics it is important that the polymer in each monofilament should have undergone the same amount of heating and shear in the extruder head and die. The die should therefore be designed so that all the holes are similarly disposed to the screw as shown in Figure 13.

## 5. Rod and Profile Extrusion

The rod and profile extrusion are grouped because they both represent simple shaping operations primarily in the extrusion die. Rods are one of the standard stock shapes produced in plastic along with strip, square bars, thick narrow slab stock and other shapes generally used in machining and other fabrication operations. The principles used in designing profile dies apply equally to the stock shapes and the main difference is one of end use rather than of die and process. The die details have been extensively dealt with in the next chapter.

## 6. Blown film

Two different types of plastics film are made and the lines required to make them involve some differences in the down stream equipment. They are:-

1. Blown film
2. Slot cast film

The equipment required for a blown film operation are:-

- a. Venturi ring support
- b. Bubble cooling units
- c. Cooling and blow up tower
- d. Pinch draw rollers
- e. Bubble collapsing slats
- f. Winder units
- g. Film treater

The venturi cooling rings serve two functions. First, it is used to stabilized the blown bubble of material by venturi action of air passed outside of the expanding plastic tube. The other function of the rings is to cool the outside of the bubble with the flow of cool air.

The use of cooling units is to double the output of a system if the limiting factor in the production is the rate of cooling of the material in high output systems.

The tower used for handling the bubble is a vertical stand unit which carries the blown film bubble upto the pinch draw rollers.

The bubble collapsing slats are used to collapse the blown film bubble so that it can be brought into the pinch draw rollers. The slat surfaces are covered with a silicone rubber material to minimize the possibility of leaving marks on the film. The slat units have an adjustment to control the collapsing effects so that they have a minimum interference with the bubble.

Various types of pinch draw rollers are used, but typically, the units consist of one polished steel roller and one rubber surfaced roller driven by a controlled speed drive to the speed required for the production rate.

In most blown film operations, the product is collected by winding onto rolls. In some equipment the tubular collapsed film is slit to remove the edges so that two single layer films are made.

Since one of the major applications for plastics film is in packaging, printing is an important product requirement. Polyethylene and the other polyolefins are among the most extensively used films for this purpose, and they have waxy surfaces that make printing difficult or impossible. To overcome this problem the surface of the film is treated to oxidize the surface layer. The most widely used device to do this is a corona discharge unit (5).

## 7. Extrusion of products based on special materials

There are wide variety of products where the ability to extrude special materials into shapes is a key factor in the product utility. One of the simple applications is the use of glass or other fiber reinforced materials for structural members. The reinforcement can either be chopped fibre or continuous filament. One of the effects of the extrusion is to align the fibers in the extrusion direction making products with high unidirectional strength. With the continuous fibers, the process is a continuous operation on the filaments yielding materials with 60 - 80 % of the physical properties of the reinforcement material. Fishing rod stock is just one example of how the product is used (5).

## B. BASIC PRINCIPLES OF SCREW EXTRUSION

Fundamentally a plasticating extruder consists of a screw of special form rotating in a heated barrel in which a feed opening is placed radially or tangentially at one end, and an orifice or die axially at the other. A schematic of an extruder is shown in Figure 4. A restriction in the form of a breaker plate is sometimes placed between the end of the screw and the extruding die in order to act as a flow straightner, and to avoid helical elastic recovery in the post die region. A screen is used to filter foreign material and protect the die channels form damage (2). The die details have been explained in greater detail in Chapter 3.

The rotating screw takes the material - which is usually in the form of free flowing cold chips, powders or cubes - from the feed opening, through the heated barrel zones, and compacts it, so that a pressure is built up. During this period the material is forced into intimate and substantially sliding contact with the hot barrel and the heat due to internal friction in the material causes the thermoplastic to soften and melt. Once it is fully molten it may be forced through a restriction ,or extrusion die, where it attains the required cross sectional form.

The advantages of a mechanism of this type will be readily apparent as the material is heated uniformly in a closed system and the process is continuous. Considerable mixing also takes place due to the action of the screw, and system is, to some extent, self compensating in that the heat due to internal friction decreases with the viscosity of the melt.

The plasticating extrusion process is a relatively complex one, and unlike the melt extrusion process, the detailed physical mechanisms - in particular, the melting mechanism - cannot be easily visualized, predicted, and modeled from basic principles without some experimental investigation. Throughout most of the extruder, the solid and liquid phases coexist, but rather clearly segregated from each other, with melt phase accumulating and the pushing flight in a melt pool and the solids segregated and the trailing flight as a solid bed. The width of the melt pool gradually increases in the down channel direction, whereas that of the solid bed generally decreases. The solid bed, shaped as a continuous long, helical ribbon of varying width and height, slowly turns in the channel ( much like a nut on a screw ) sliding toward the exit, while gradually melting. Upstream from the point, where melting starts, the whole channel cross section is occupied by the solid bed, which is composed, as the hopper is approached, of less compacted solids. The continuity of the solid bed provides an explanation for the capability of the screw extruder to generate melt that is free of air bubbles: the porous continuous solid bed provides uninterrupted air-filled passages from deep in the extruder all the way back to the hopper. Thus particulate solids forming the solid bed move down channel while the air is stationary.

Frequently the continuity of the solid bed is broken, and a melt filled gap appears. This tendency of solid bed break up seems to occur in the tapered sections of the extruder, and it appears to be a source of ' surging ' of the extrudate at the die as well as a source of entrapping some air bubbles into the melt stream.

**1. Flow rate**

The flow equation of the solid plug can be expressed in terms of the unknown velocity of the plug in the axial direction $V_{pl}$ (see Figure 5 ). This velocity is independent of channel depths. The flow rate or solids conveying rate is obtained by multiplying this velocity by the cross sectional area of the plug:

$$Q_s = V_{pl} \int_{R_s}^{R_b} \left( 2\pi R - \frac{pe}{\sin\theta} \right) dR \qquad \ldots 1$$

$R_s$ and $R_b$ are radii at the root of the screw and at the channel surface, respectively, e is the flight width, $\theta$ the helix angle and p is the number of flights in parallel. The second term in the above integral represents the part of the cross sectional area occupied by the flights. The helix angle $\theta$ is a function of the radius, and this dependence will complicate the integration. However, this dependence can be neglected without introducing appreciable errors by taking an average angle $\bar{\theta}$ . Thus integration of equation 1 gives:

$$Q_s = V_{pl}\left[\frac{\pi}{4}\left(D_b^2 - D_s^2\right) - \frac{pe\,H}{\sin\bar{\theta}}\right] \qquad \ldots 2$$

The velocity of the plug in the down channel direction at the barrel surface is $V_{pz} = V_{pl}/\sin\theta_b$ (Figure 6 ), the velocity of the plug at the barrel surface in the tangential direction is $V_p = V_{pl}/\tan\theta_b$. The friction forces acting between the plug and the barrel depend on the angle $\phi$ , at which the plug moves relative to the barrel. Since this angle can be calculated from the force and torque balances, the velocity $V_{pl}$ can also be conveniently expressed in terms of this angle in equation 2. Figure 6 shows the various velocity components and the angles between them.

If the frictional force between polymer and screw is so large that the polymer in effect adheres to the screw, the plug does not move with respect to the screw, that is $Q_s = 0$ and $V_{pl} = 0$, as well as the angle $\phi$ will be zero. If the frictional force between polymer and screw is negligible it is seen in Figure 6 that the plug acquires a down channel velocity which equals that of the barrel surface. Normally, this results in the maximum flow rate and the angle $\phi = 90 - \theta$ . Higher flow rates can be achieved, in principle, if the friction coefficient between barrel and plug in the tangential direction is very large (no slip), compared to that in axial direction. This would be the case if the barrel has longitudinal or helical grooves. The theoretical upper limit of the flow rate would occur at $\phi = 90^\circ$. The tangential components of the velocity of the plug equals then the velocity of the barrel surface. This would be a case when the plug slides toward the exit similar to a nut held in a wrench, rotating on a constrained bolt.

Thus, maximum flow rate can be achieved by polishing or coating the screw, thereby minimizing the friction on the screw surface. In all real cases, the angle $\phi$ will be in the range $0 < \phi < 90^\circ$. Physically the direction $\phi$ is that in which the barrel will appear to move for an observer "sitting" on the plug.

From Figure 6 it is easy to see that the following relationship holds for the angle :

$$\tan\phi = \frac{V_{pl}}{V_b - V_{pl}/\tan\theta_b} \qquad \ldots 3$$

Rearrangements of equation 3 gives:

$$V_{pl} = V_b \frac{\tan\phi \tan\theta_b}{\tan\phi + \tan\theta_b} \qquad \ldots 4$$

Substituting equation 4 into equation 2 and recalling that $V_b = \pi ND_b$ will give an expression for the flow rate of the solid plug in terms of measurable quantities and as a function of the angle $\phi$:

$$Q_S = \pi N D_b \frac{\tan\phi \tan\theta_b}{\tan\phi + \tan\theta_b} \left[ \frac{\pi}{4} \left( D_b^2 - D_S^2 \right) - \frac{peH}{\sin\bar{\theta}} \right] \quad \ldots 5$$

Equation 5 can be further rearranged into a more convenient form by substituting for $D_b^2 - D_S^2 = 4H(D_b - H)$:

$$Q_s = \pi^2 NHD_b \left( D_b - H \right) \frac{\tan\phi \tan\theta_b}{\tan\phi + \tan\theta_b} \left[ 1 - \frac{pe}{\pi (D_b - H) \sin\bar{\theta}} \right] \quad \ldots 6$$

If the flight width is negligible, the term in brackets reduces to 1 and equation 6 becomes identical to that derived by Darnell and Mol (6). (Although they did not include the effect of the flights in the derivation, they included it in the numerical examples).

Equation 6 can also be written in terms of the average channel width:

$$\bar{W} = \frac{\pi}{p} \left( D_b - H \right) \sin\bar{\theta} - e$$

$$Q_s = \pi^2 N H D_b (D_b - H) \frac{\tan\phi \tan\theta_b}{\tan\phi + \tan\theta_b} \left(\frac{\bar{W}}{\bar{W} + e}\right) \quad \ldots 7$$

**2. Principle of screw design**

Regardless of the parameters of the screw - size, L/D ratio, pitch and channel configurations - the success of any screw will be ultimately measured by the efficiency it displays in accomodating the solid bed melting mechanism(7).

A study of the flow path showed that melting is not homogenous, but rather that the outer layer near the barrel receives far more shear energy than the inner layers closer to the screw roots. Mixing is thus frustrated, since the cooler, unmelted resin ends up near the screw root for a quick ride out of the machine.

The details of mixing in an extruder are shown in Figure 7. Resin in the feed section is compressed first by a frictional drag and then by viscous drag at the polymer/barrel interface, where a melt film forms. In addition, the compression force packs the material into a discrete mass earlier referred as the solid belt.

Melting continues at the barrel surface as the screw drags the solid bed down the channel. When the melt film thickness exceeds the screw flight clearance, the flight begins to wipe the melt from the barrel surface and deposits it at the rear of the channel behind the solid bed, where a melt pool accumulates. As the solid bed enters the transition section, melting is accelerated by the steadily decreasing channel depth, which forces the bed radially outward against the barrel.

Melting rate drops significantly in the metering section as the channel depth again becomes constant and outward pressure drops off. The solid bed destabilizes enough to break up into pieces that mix with the melt pool. Here the solid bed mechanism no longer applies and remaining solids must be melted by heat conduction from the melt pool and by the metering section's relatively low shear forces.

It is easy to see how a considerable quantity of unmelted material can pass the die with this simple screw design. Screw designers have been searching for a solution to this problem.

The first plastics extruders, adapted from rubber extruders used a single flighted screw with a deep feed section, short transition and shallow metering section. It soon became obvious that the basic screw would have to be modified to achieve complete melting and mixing. One of the earliest modifications was placing restrictions at the outlet to raise head pressure, even though output would be reduced and melt temperature raised. An early alternative was the introduction of very long metering sections to increase residence time at relatively high shear levels. Still another was the placement of pins or other impediments in the metering channels, a technique that increased usable output by as much as 15%. At the same time the Maddock head began to come into general use. The Maddock head used a barrier to separate solids from melt, thereby allowing only melt to reach the metering section and leave the screw. But since the barrier generated high shear energy and melt temperatures, the head was placed in the middle of the metering sections in an effort to use downstream turns for cooling. The design could not counteract large temperature changes. Even so, the Maddock head was a significant step forward in the search for higher usable output.

## BARRIER SCREWS

Uniroyal and Maillefur (7) developed the first true barrier screws. Their designs employed conventional feed and metering sections and a transition section that incorporated a narrow barrier flight (Figure 7) over which only melted resin can pass. The barrier clearance is five to six times greater than the primary flight ; it rises from the rear of the channel of the main flight where the feed section ends. Because of its greater pitch, it moves closer to the front of the channel as it continues down the transition section until it meets the primary flight at the metering section.

Although a substantial advance, this type of barrier screw has drawbacks. The squeezing action, by which the melted resin is forced from the solids channel over the barrier into the melt channel, is thought by some to cause surging if the rate of change of channel width and depth is not adjusted to each resin type. Consequently, many applications of the Uniroyal concept use a short mixing section of two or three turns similar to the Maddock concept. Many improvements have been made since then and some of the screw designs are illustrated in Figure 8.

**C. SOLIDS CONVEYING IN EXTRUSION SYSTEM**

It must first be recognized that at least three processes are involved, more or less distinct, and any one of these may influence output. These are flow in the hopper or feed pipe, filling of the screw channel from the feed throat, and conveying by the screw from the open feed section into the closed barrel and subsequent compaction in the latter in the screw channel.

1. HOPPER FLOWS: Flow in the hopper is usually by gravity and is analogous to flow in the silos and bins. However, some practical points are worth noting, the first being that the hopper should be as wide as possible, especially for feeding coarse or angular material to reduce the possibility of 'bridging'. It should have fairly steep sides, which should be smooth and free from ledges and bolt and rivet

heads, etc., but not so steep as to appreciably lengthen the one of restricted cross-section. Long pipes are particularly undesirable since they can form a compacted lug of material which is difficult to break up. Internal corners, which may cause a wedging action, should be avoided, example, by generous rounding of the corners of a rectangular-section hopper or better by circular section. The hopper shape must ofcourse be a compromise with the entry into the feed section proper. Tendency to bridging will be increased by factors affecting the friction between particles, including softer materials, angular or irregular shapes, a wide distribution of sizes permitting packing, and superimposed pressure, example by a deep head of material.

2.SCREW CHANNEL / FEED THROAT INTERACTIONS: Filling of the screw is usually by gravity, with a relatively close clearance of a hardened feed pocket liner around most of the circumference of the screw to prevent the feed material falling out again and provide some resistance so that it is conveyed into the barrel instead of merely being carried round by the screw. With a purely radial inlet to the screw, the latter can result in material being forced back into the feed throat and hindering the in-flow of fresh material, especially if the particles are elastic or large relative to the dimensions of the screw channel. For this reason the opening is frequently made tangential to the downgoing side of the screw, though some designers argue that at high speeds the screw will 'run away' from the feed, whereas on the upcoming side the screw cuts into descending column of material. Experience shows that a substancial chamfer is helpful, both on the downgoing side and the end leading to the barrel, in leading material outside the path of the screw flight into the channel rather than ejecting it by hitting a near-radial surface, Especially with large particles or elongated strips it can be seen that a wedging action occurs not only between the screw root and the feed pocket liner, but also between the flight tip and the liner - in absence of a chamfer, the flight tends to cut and/or eject the particles.

3. SOLIDS CONVEYING IN THE CHANNEL: The third stage of conveying by the screw has been the subject of theoretical studies, the most notable being by Darnell and Mol (6), who also published confirmatory experiments. Since it is the difference between friction forces at the screw and the barrel surfaces which causes conveying, the rate achieved is highly dependent on operating conditions. The usual strategy is to maintain the feed pocket liner cold, by water jacketing, and leave the screw 'neutral'. Especially when extruding polymers with low melting/softening points, this places some restriction on the set temperature on the rear end of the barrel because of heat conducted through the metal parts, which has even been known to cause solid particles to stick to the front face of the feed opening.

The screw surface is usually hardened and highly polished and, in an attempt to improve conveying, some manufacturers have used deliberately roughened feed pocket liners. Experiments where conveying occurs along several turns of screw in an unheated barrel without discharge restriction, generally show solid conveying to be continuous and steady provided the feed is adequate. Feed sections are therefore usually made smooth for ease of cleaning but deep enough to ensure a potential solids flow rate greater than that of the melt pumping section, in which case exact prediction of the solid flow is irrelevant. In case of large machines of 150 to 200 mm (6in or 8in) diameter there is little difficulty in providing a great depth of feed section which is also several times the size of the feed particles; in small machines it is sometimes necessary to use finer-cut feed material (especially regrind which tends to be irregular), but also the depth is limited by the torsional strength of the screw root.

**D. INTERPARTICULATE COEFFICIENT OF FRICTION :**

Friction is the tangential resistance offered to the sliding of one solid body over another, and it is fashionably classified now under the heading of - tribology a science which in addition to friction deals with wear,lubrication and related effects.

Bowden and Tabor (18) in 1964 proposed that friction arises from two main factors. " The first, and usually the more important factor is the adhesion which occurs at the regions of real contact: these adhesions, welds, or junctions have to be sheared if sliding is to occur. The second factor arises from the ploughing, grooving or cracking of one surface by the asperities on the other." The interparticulate contact between the pellets when acted upon by a normal force for the calculation of the coefficient of friction, illustrated in Figure 29. Sometimes for better compaction the pellets under test can be vibrated first before the application of the tangential force. The size of the pellets can be varied accordingly and some of the factors are:-

1. Controlling the feed so that the volumetric flow can adjusted 2. Adjusting and varying the cutter speed. 3.Temperature of the material under extrusion.

FIGURE-1

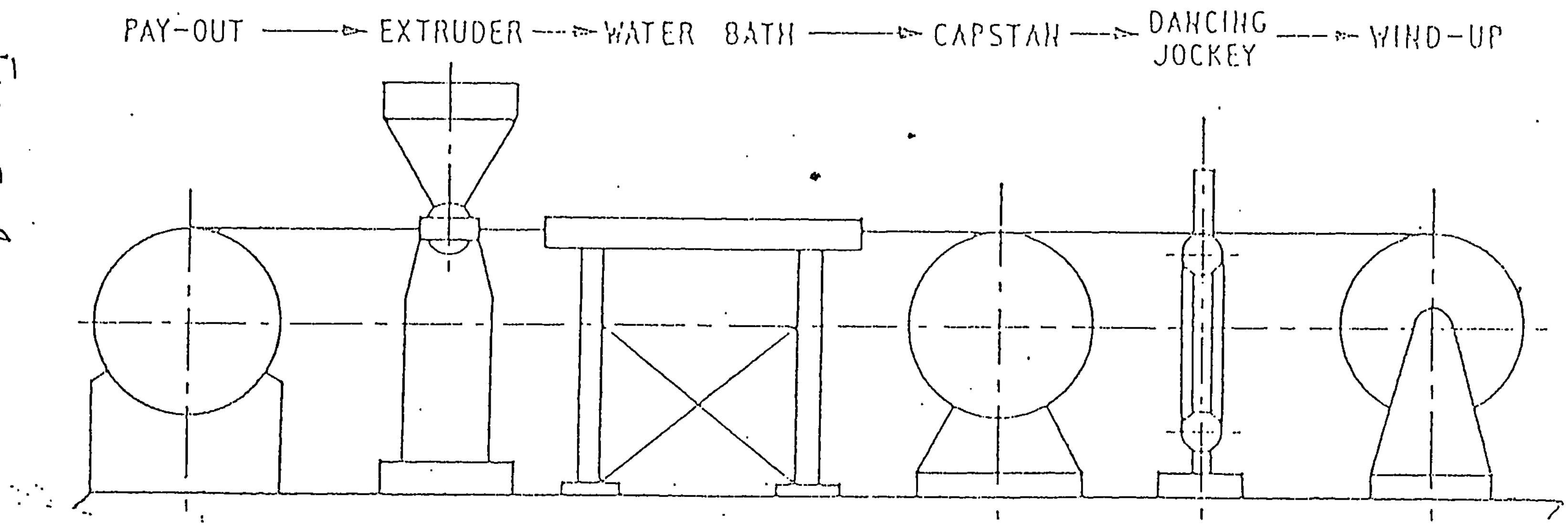



Figure 1 Diagram of wire-covering process

SOURCE :- EXTRUSION OF PLASTICS, E.G. FISHER
PAGE 248

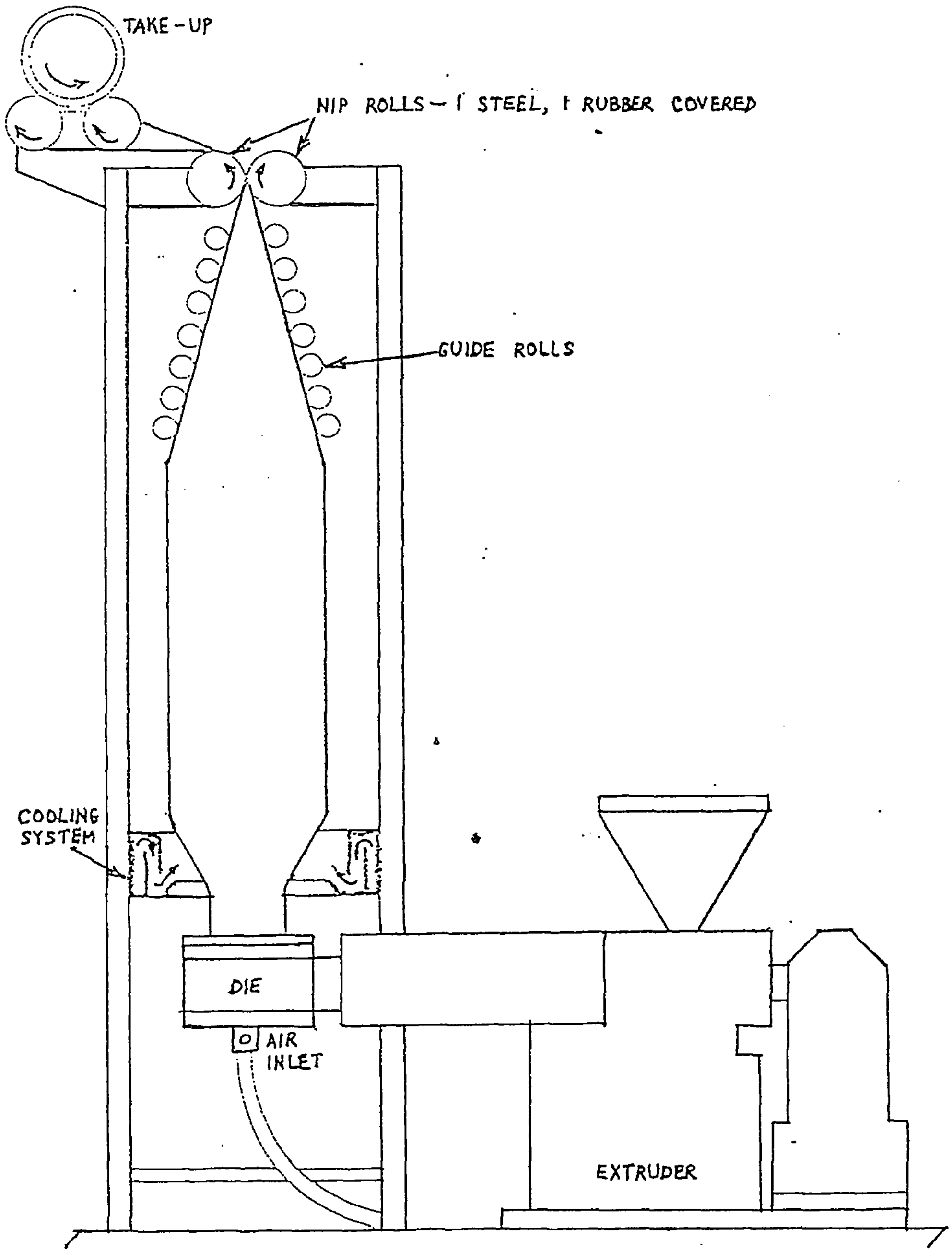



*Figure 2 Diagram showing one process for tubular film extrusion*

SOURCE :- 'EXTRUSION OF PLASTICS' BY FISHER, PAGE 267

FIGURE 3

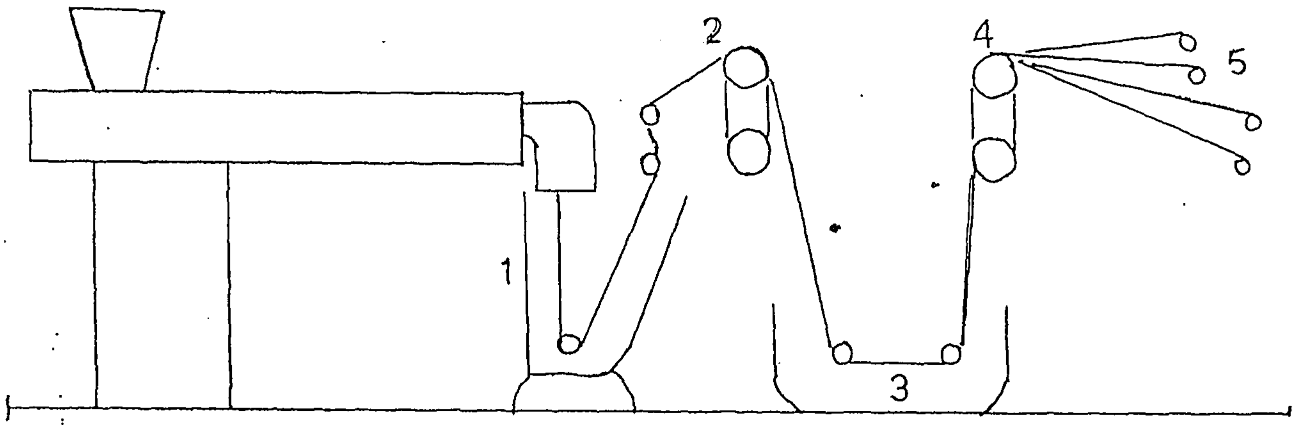



Fig. 3

1. QUENCH BATH
2. FIRST PAIR OF GODET ROLLS
3. ORIENTATION BATH
4. SECOND PAIR OF GODET ROLLS
5. FINAL TAKE OFF BOBBINS

SOURCE :- 'PRINCIPLES OF PLASTICS EXTRUSION' – JA BRYDSON & DG PEACOCK
PAGE 88

SCHEMATIC REPRESENTATION OF A PLASTICATING EXTRUDER

FROM :- ENGINEERING PRINCIPLES OF PLASTICATING EXTRUSION, PAGE 8 [TADMOR & KLEIN]

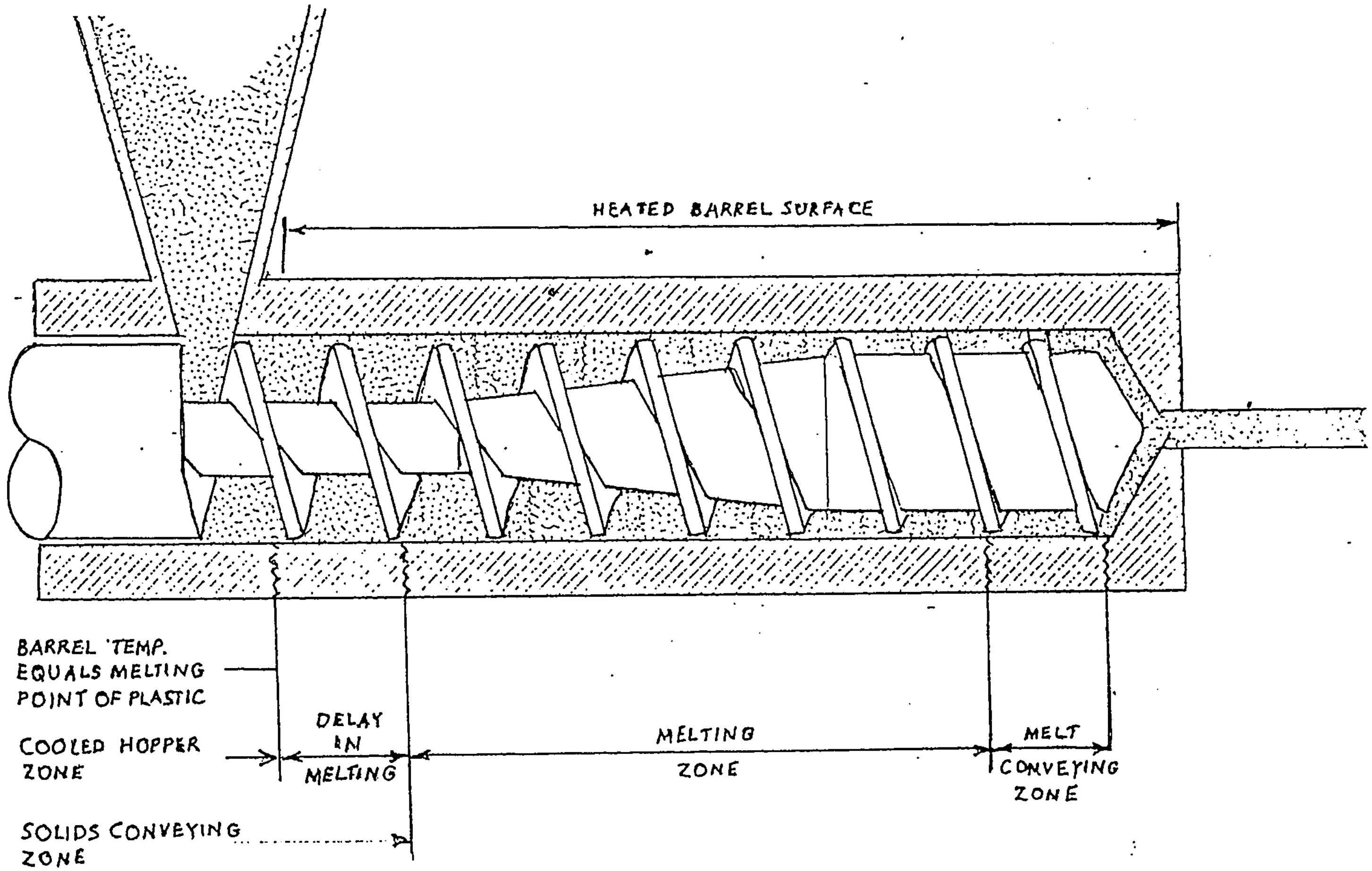



FIGURE 4

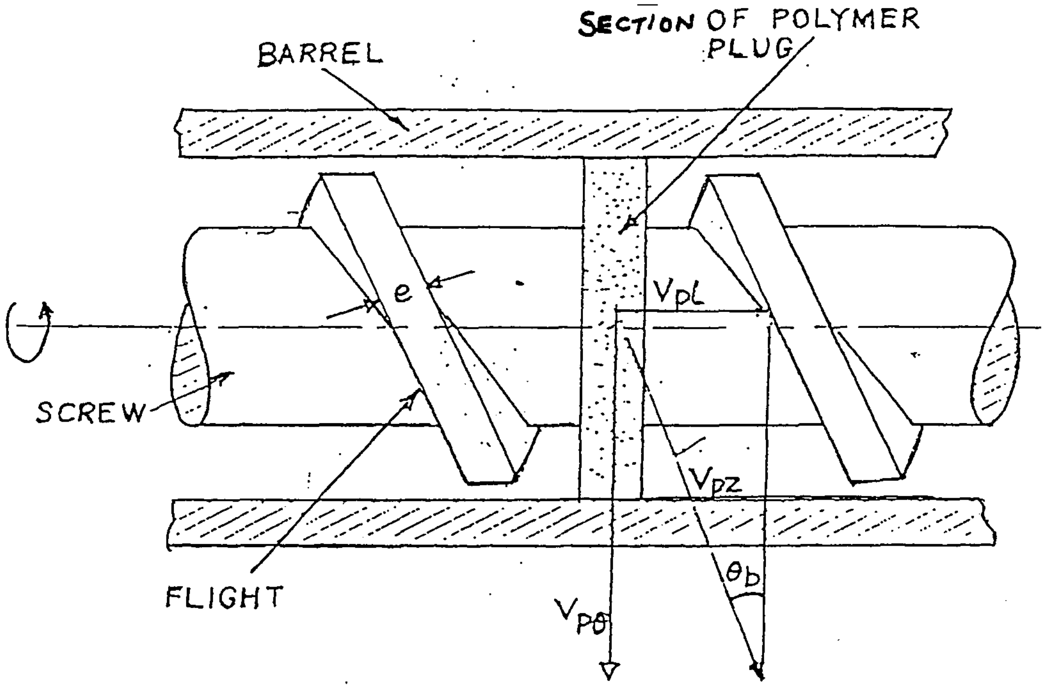



Figure 5 Section of the solid plug. Velocities are measured relative to the screw. $V_{p\theta}$ $V_{pz}$ are measured at the barrel surface. $V_{pl}$ is independent of channel depth.

FIGURE – 5

SOURCE :- 'ENGINEERING PRINCIPLES OF PLASTICATING EXTRUSION BY TADMOR & KLEIN, PAGES 55 & 56

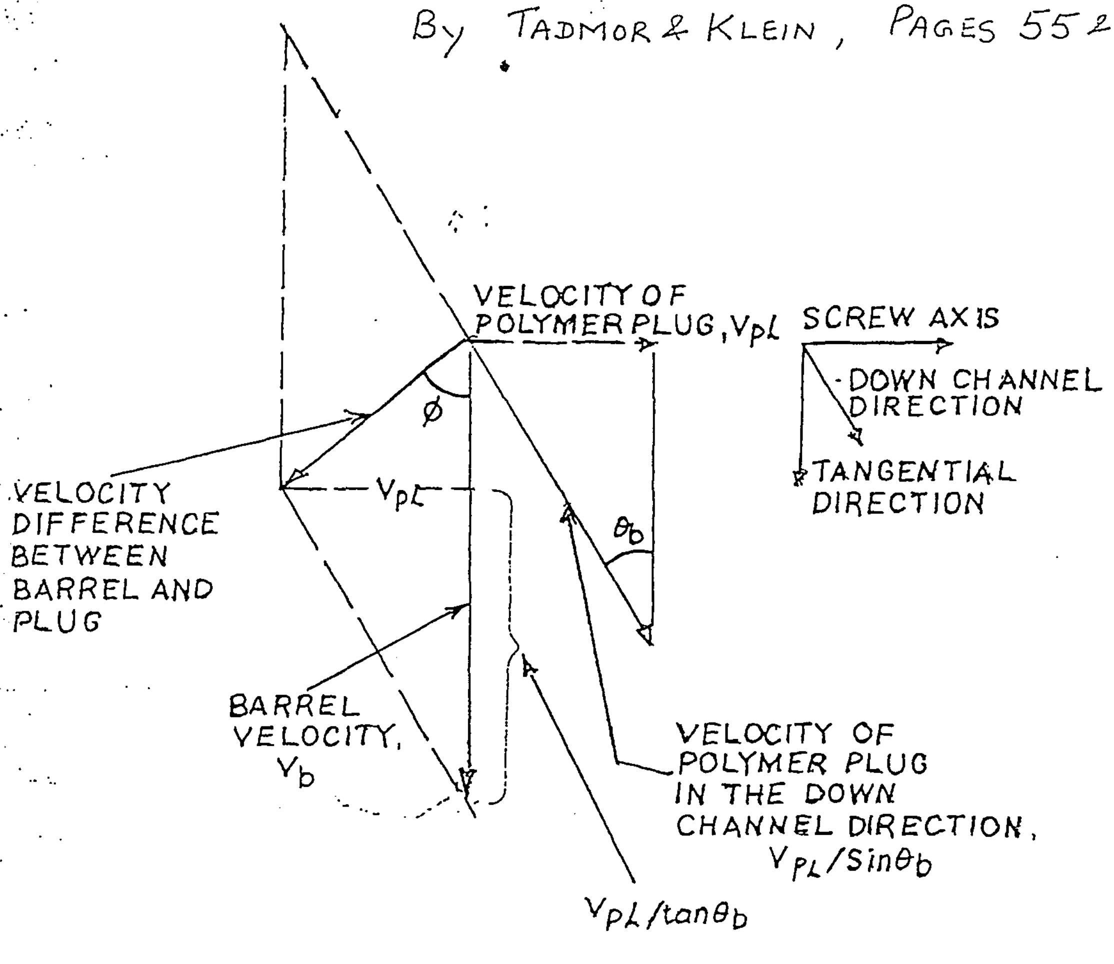
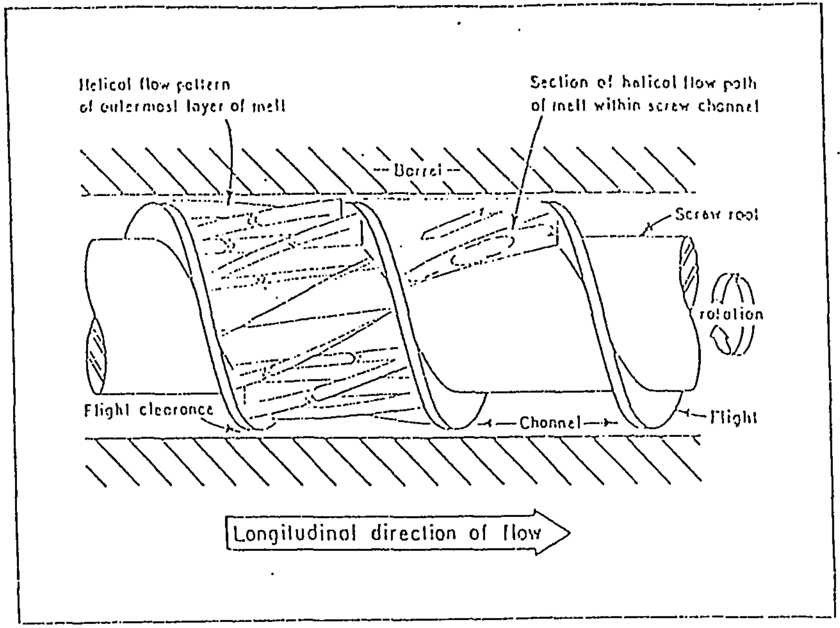
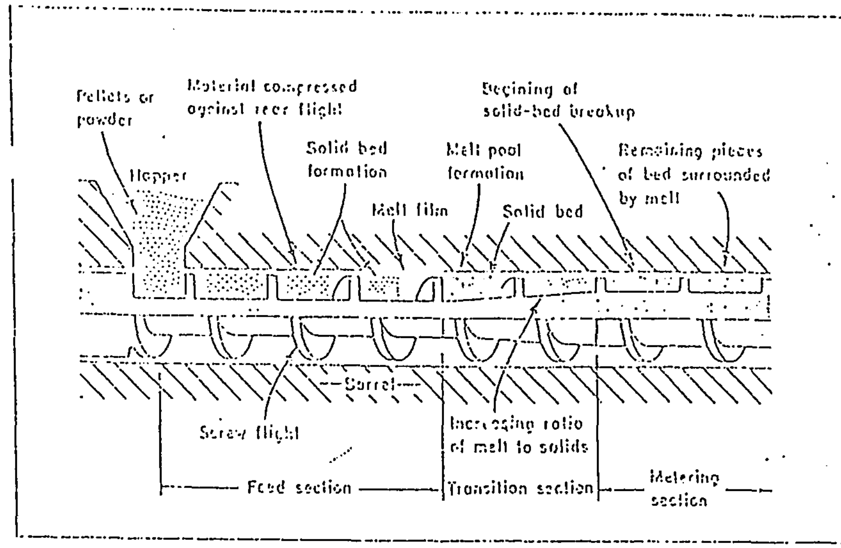


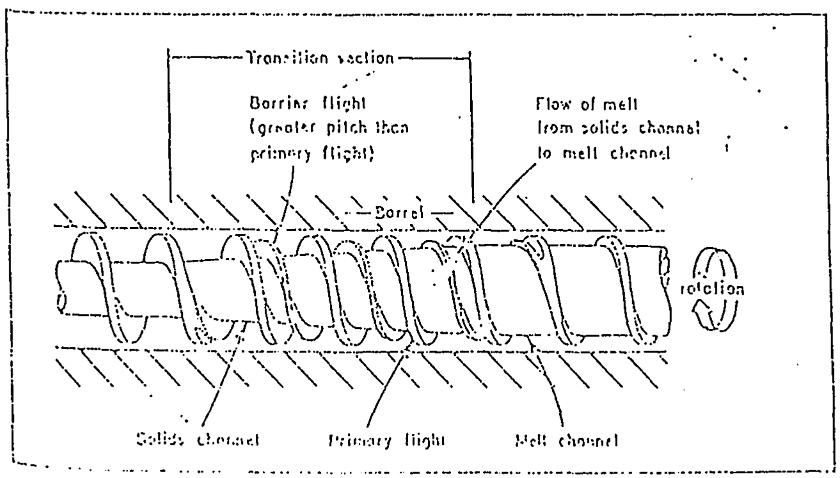

Figure 6 Velocity vector diagram for calculating the velocity difference between barrel and solid plug.




The melt flows helically within the screw channel down the barrel. The screw geometry and direction of rotation cause the barrel surface to drag the melt towards the rear of the channel, where the flight directs it first towards the screw root and then to the front of the channel, where it strikes the flight and is directed, once again, to the barrel surface further along the channel to begin a new cycle.



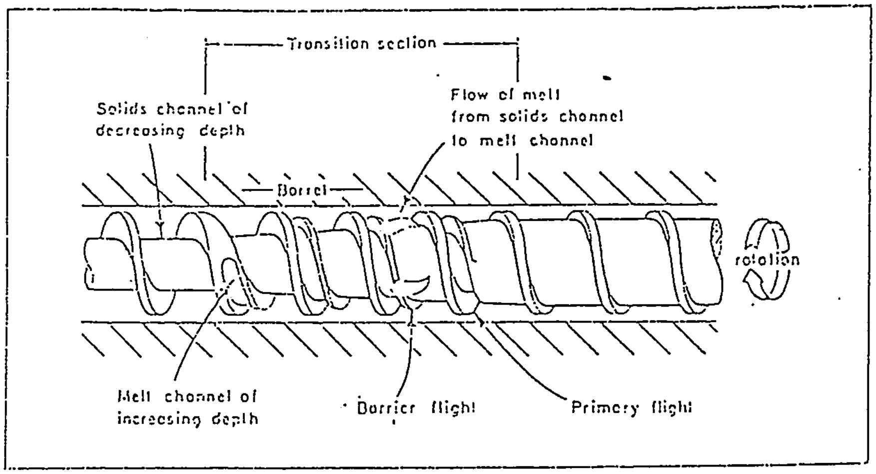

Solid-bed formation begins in the feed section as the resin mass is compressed against the flight at the rear of the channel. Melting begins along the barrel surface in the transition section and ends in a melt pool behind the solid bed. The process continues into the metering section, when radial pressure drops off and the solid bed breaks into particles.



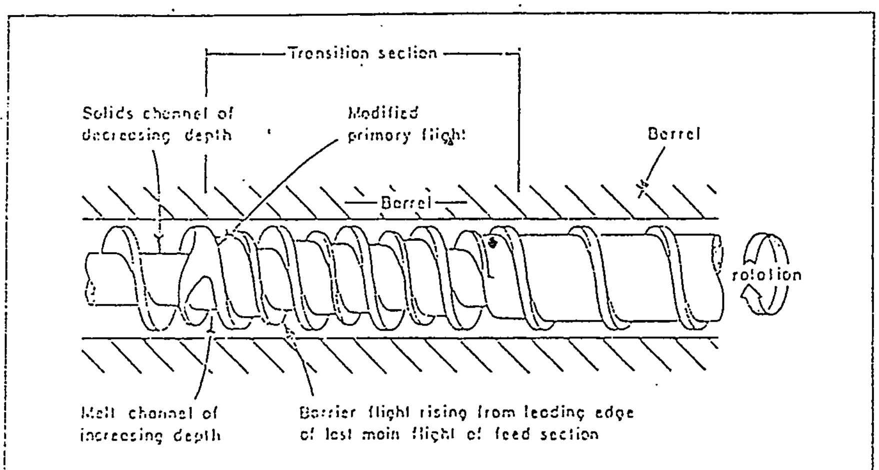

To reach the die, material must be able to flow from the solids channel across the barrier to the melt channel. Greater barrier-flight pitch changes the volume ratio of the two parallel channels as the barrier travels down the screw. (Uniroyal, Inc., N.Y.)

FIGURE 7

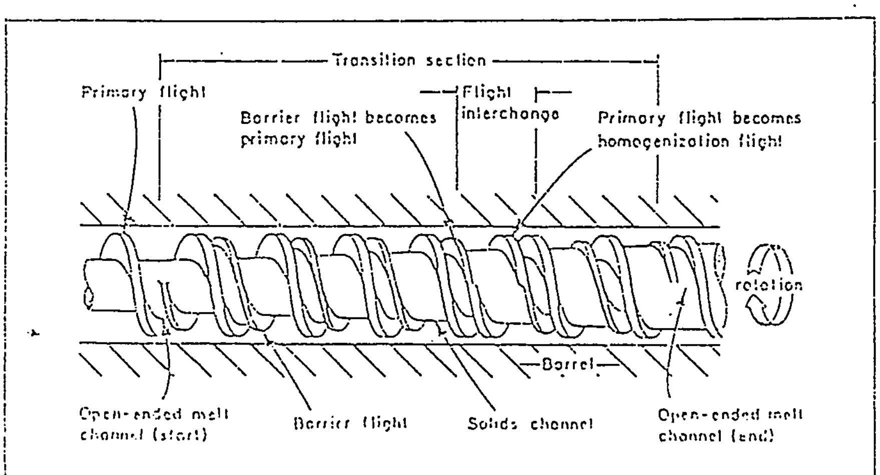
SOURCE :-
"PLASTICS ENGINEERING" JOURNAL, JANUARY 1981
PAGES 37 to 41




The MC-3 barrier screw uses varying channel depth to produce an increasing volume ratio of melt channel to solids channel along the transition section. (Waldron-Hartig Div., Midland-Ross Corp., Cincinnati)




In the Maxmelt screw, the barrier flight is created from the rear of the main flight and a new main flight is introduced. The flow path remains undisturbed, and the solid bed moves smoothly from the feed section into the solids channel of the transition section. (Hoover Ball and Bearing Co., Saline, Mich.)




The Barr-2 screw uses open-ended melt and solids channels to reduce localized shear, melt hangup, and degradation. A homogenization section has been added at the end of the primary flight (at the start of the metering section) to provide low-shear blending to avoid temperature gradients. (Robert Barr, Inc., Virginia Beach, Va.)

SOURCE :- JOURNAL OF PLASTICS ENGINEER. PAGES 37 to 41

FIGURE 8

SOURCE :- 'EXTRUSION OF PLASTICS'
— FISHER
PAGE 214

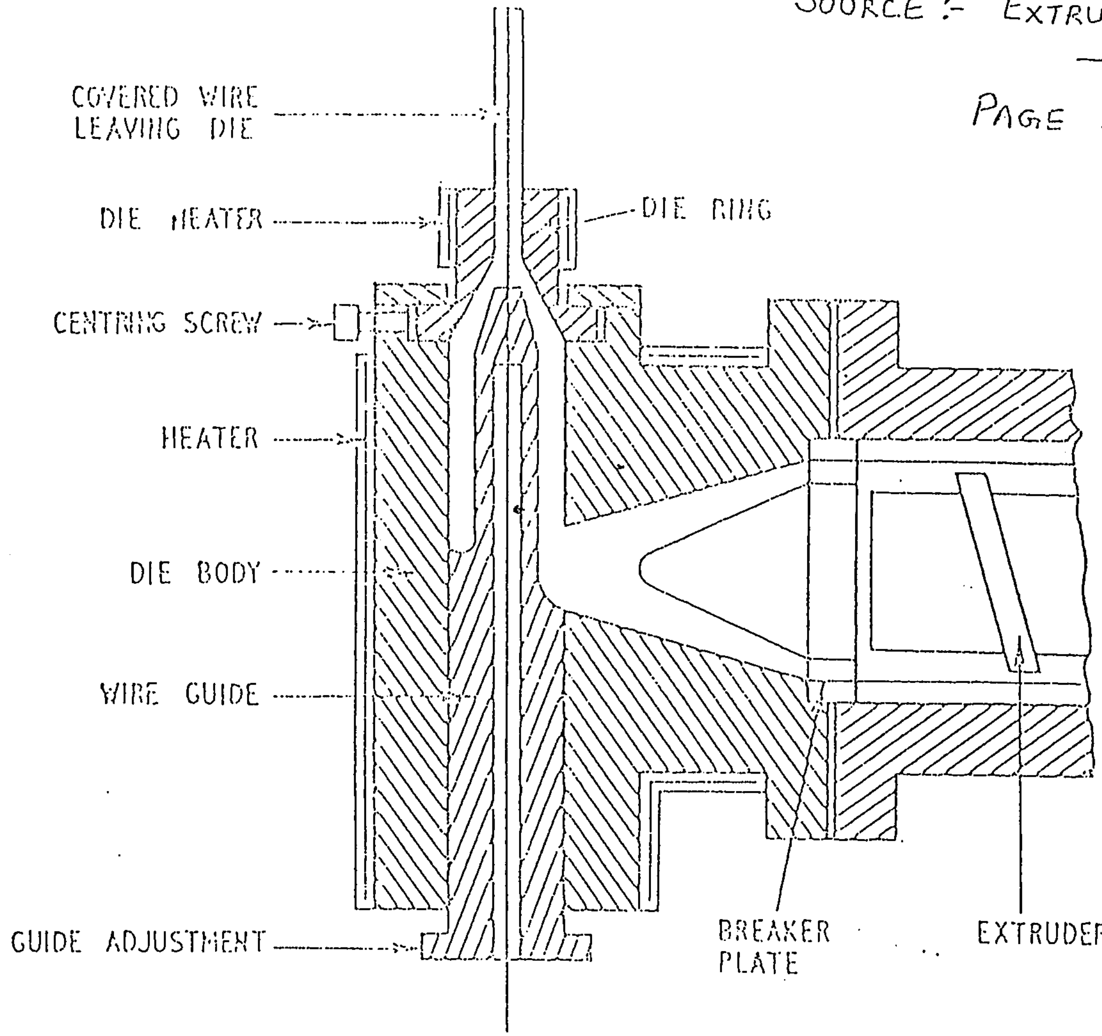



*Figure 9 Schematic diagram of wire-covering crosshead*

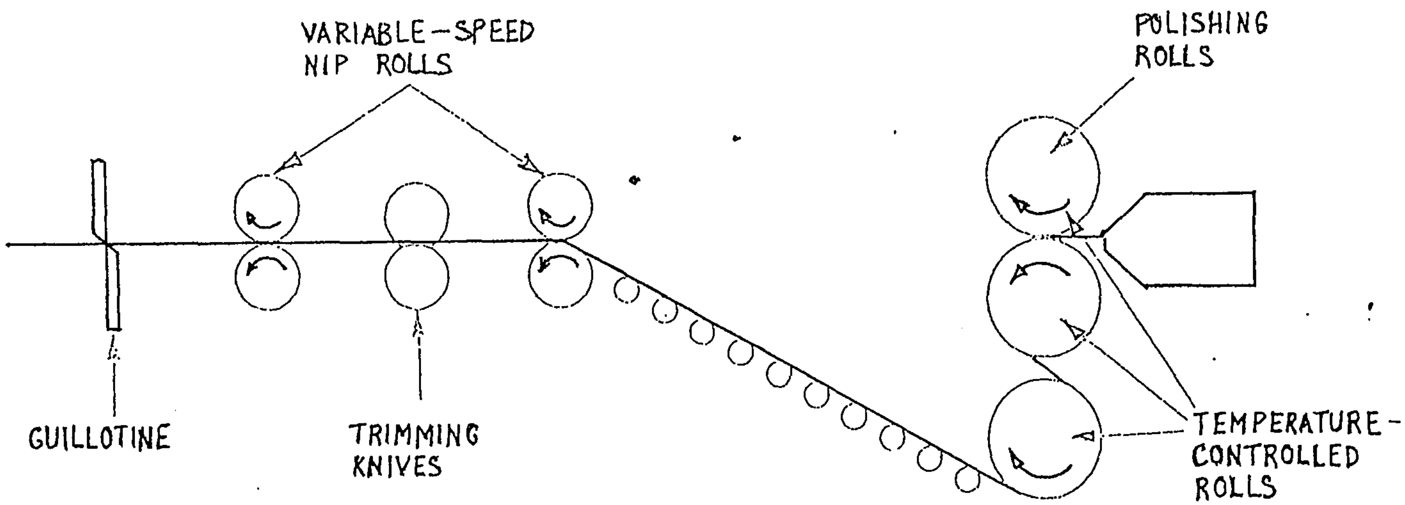



*Figure 10 Diagram of process for extruded sheet*

SOURCE :- 'EXTRUSION OF PLASTICS' – FISHER
PAGE 260

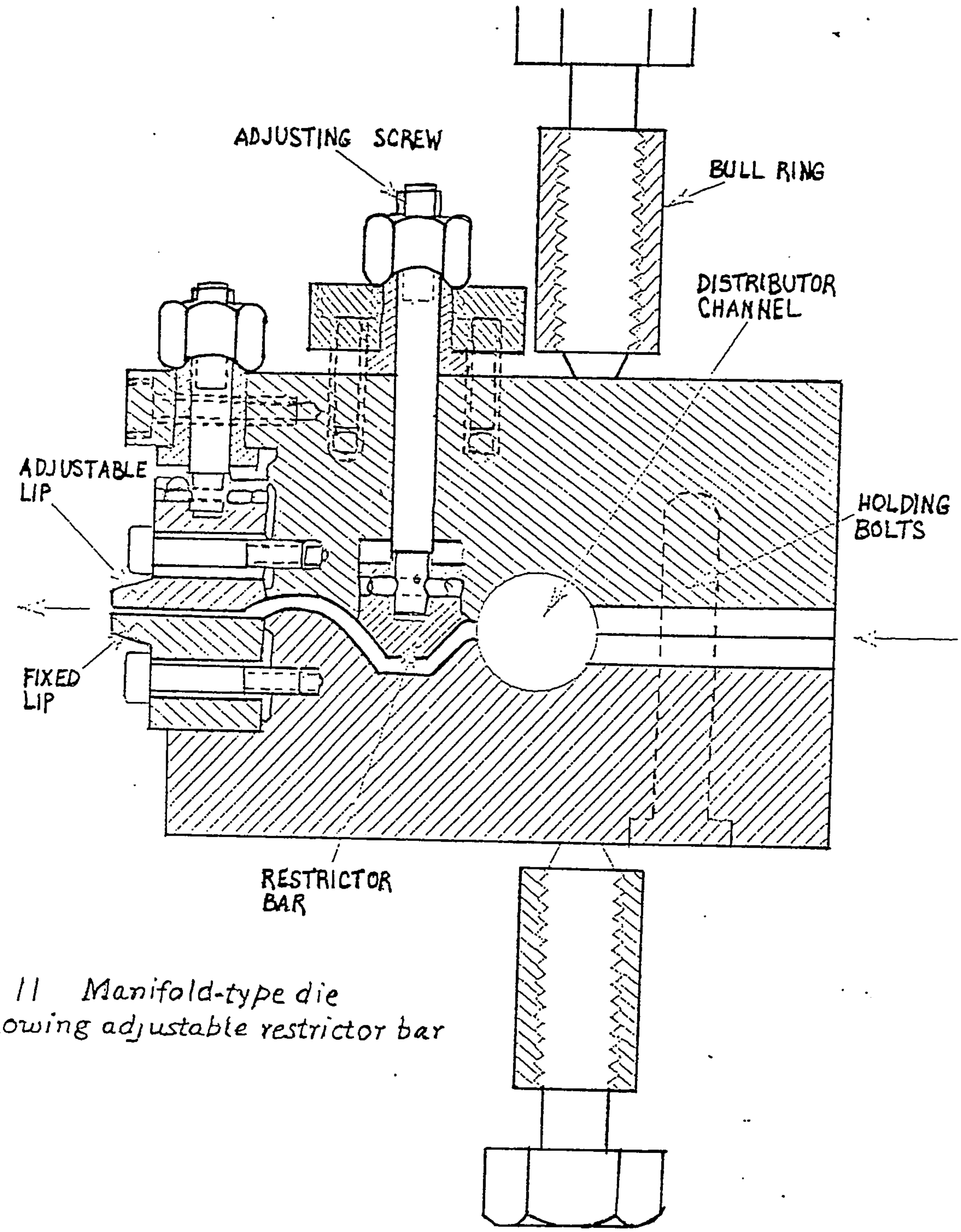



Figure 11 Manifold-type die for sheeting showing adjustable restrictor bar

SOURCE :- 'EXTRUSION OF PLASTICS' – FISHER
PAGE 223

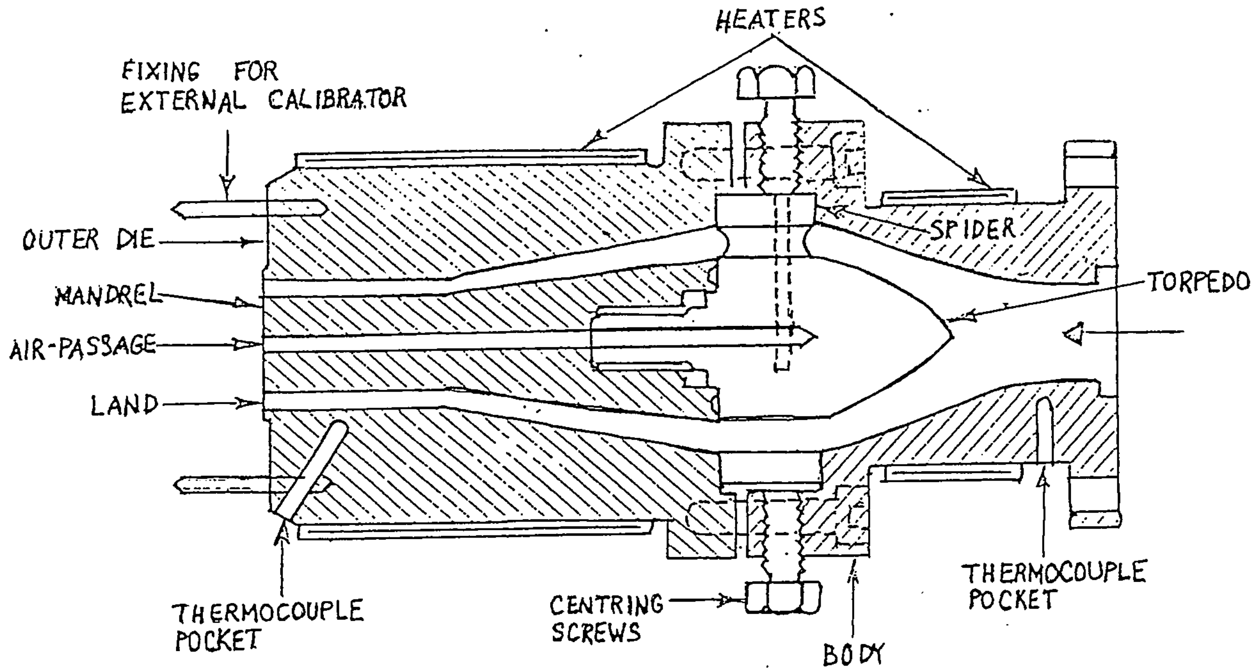



*Figure 12 Schematic drawing of a die design for small and medium-sized tu*

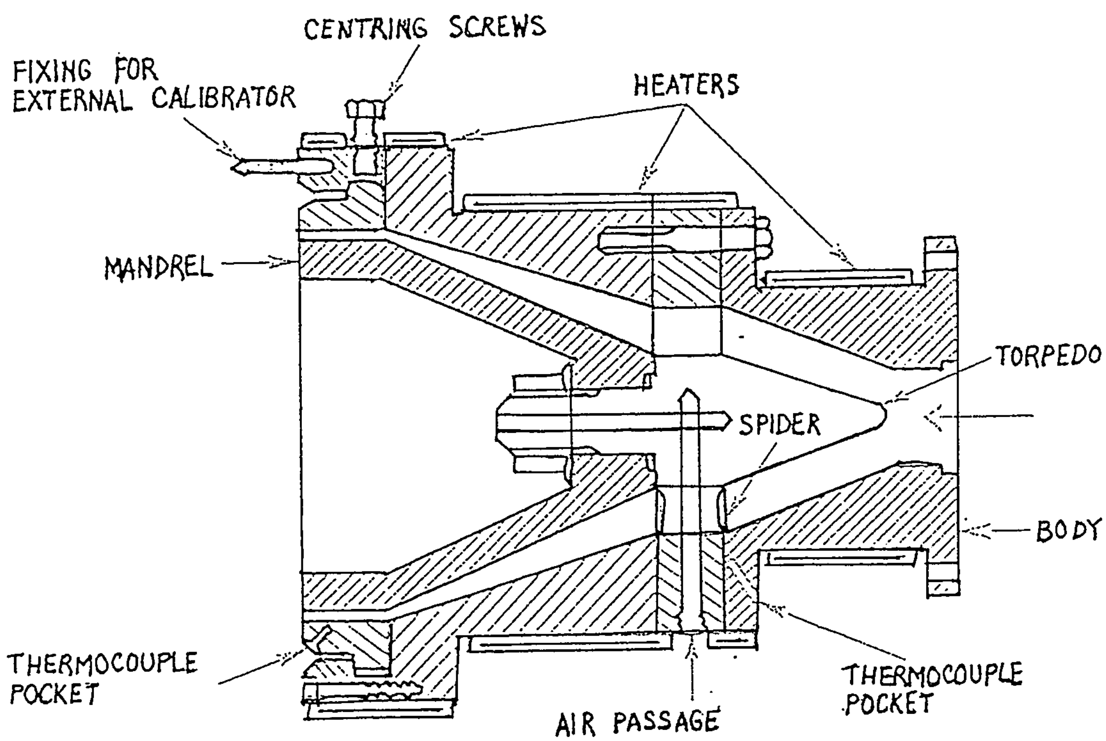



*Figure 12 Schematic drawing of a large tube die*

SOURCE :- 'EXTRUSION OF PLASTICS' – FISHER, PAGE 226

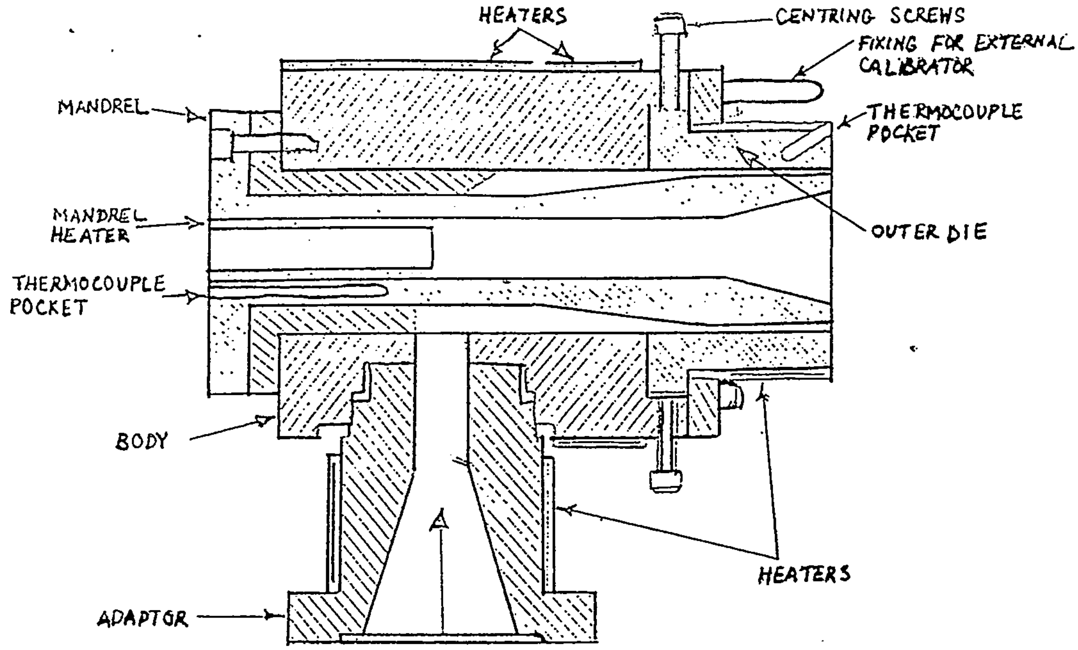



Figure 13 Schematic illustration of a crosshead tube die

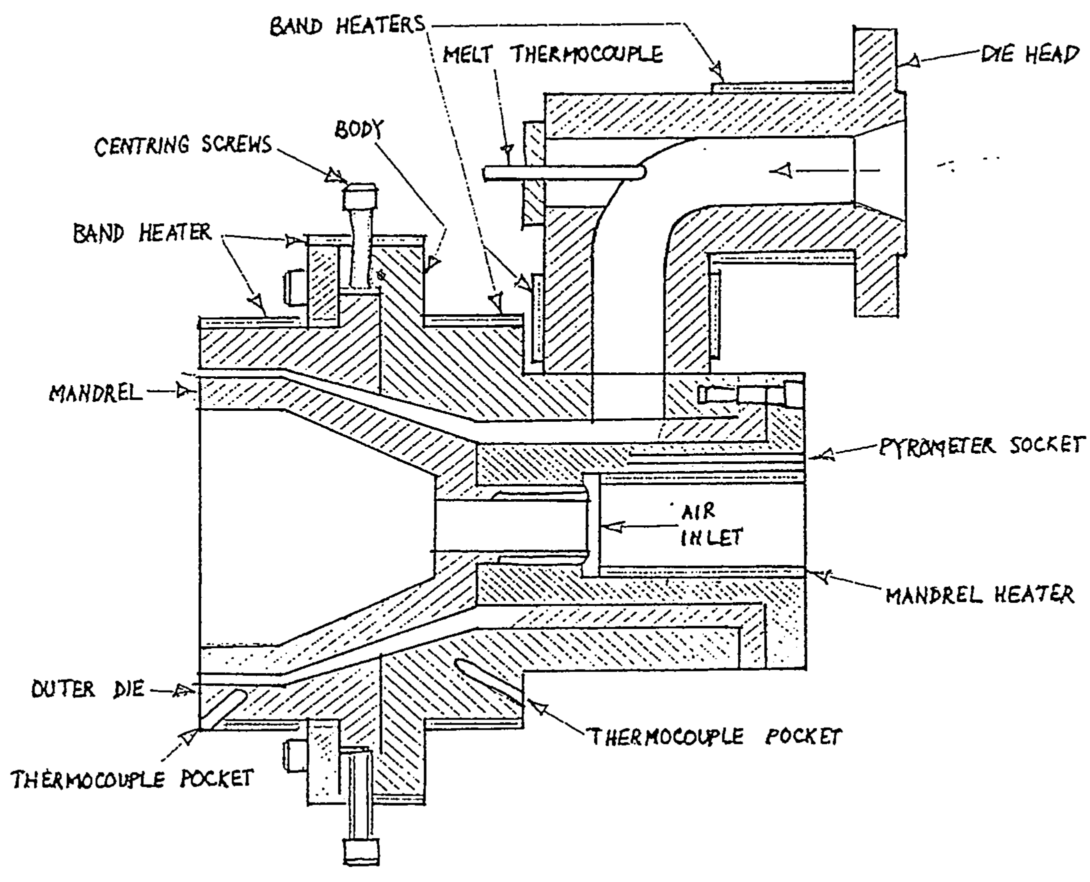



Figure 13. Schematic illustration of an offset die for tube

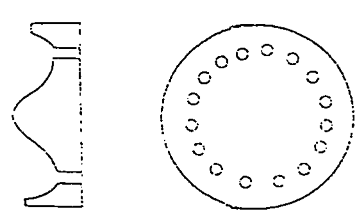


FIG 13

SOURCE - 'EXTRU[illegible]
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CHAPTER III

## DESIGN OF DIES FOR PROFILED PELLETS

### A. PRINCIPLES OF DIE DESIGN

The function of an extrusion die is to form the molten material delivered by the screw into a required cross section. The die is, therefore, a channel whose profile changes from that of the extruder bore to an orifice which produces the required form. In order to predict the behaviour of a thermoplastics melt in such a channel, it is necessary to know the viscosity of the melt over the required range of shear rates and temperatures, and to be able to relate this viscosity with the flow of the melt under pressure through the different sections of which the channel is composed. Then, since the pressure drops are additive, the total pressure drop and throughput through the whole assembly can be calculated.

#### 1. Newtonian and Non-Newtonian Flows

It is known that there is a difference in the flow between the two types of flow, Newtonian and non-Newtonian. The behavior of thermoplastics melts departs from Newtonian flow as the rate of shear increases. The velocity gradient at the tube walls where the rate of shear is highest, is much steeper in the case of the non-Newtonian thermoplastics melts than with the true Newtonian fluid (4). Since the shear rates encountered in most thick-section extrusion dies working under normal conditions are quite low, it follows that the relatively simple classical flow expression can still be used in many interesting die calculations. It is possible for example to compare the effects of changes in die path shape and the relative merits of increase land length as against reduced channel width as a means of restriction in particular cases.

For a given pressure, and ignoring considerations of non-Newtonian flow, the output of the tube die is

approximately linear with diameter.

approximately proportiomal to the cube of the wall thickness, and

inversely proportional to the channel length (1).

**2. Land length**

The wall thickness and the tube diameter are usually fixed leaving only the land or channel length to be determined by the designer. Practical experience has to some extent determined this factor also in the form of a rule of thumb for the land length/orifice thickness ratios. For example a ratio of 10:1 is often specified for materials of high viscosity such as unplasticised polyvinylchloride (PVC), whereas longer lands up to a ratio of 30:1 may be used for low density polyethylene (5).

The die land/orifice thickness ratios referred to above for example take into account, according to the experience of the designer, such considerations as surface finish, compound lubrication and filler loading, the construction of the die upstream of the land and the system of product sizing to be used, to mention only a few. It is obviously difficult to describe such factors in mathematical terms so that experience must be used in the final form as the basis for most practical die designs.

### 3. Melt fracture

Melt fracture sometimes occurs when operating an extruder at high throughput rates. The extrudate takes on a rough irregular appearance which cannot be attributed to any other cause than the physical breakdown of the melt or 'melt fracture'. This phenomenon occurs when the shear stress of the melt exceeds its shear strength such as for example in an extrusion die where, due to a substantial reduction in channel width, a sudden increase occurs in the shear rate. Original investigations by Tordella (8) showed that melt fracture occurred at a critical pressure point which varied with the viscosity of the melt, the die pressure and the die geometry. As the last factor was the only one which could be modified without causing a loss of output, the effect of the inlet geometry, and land length, of dies were considered. The theoretical aspects of melt fracture have been studied by Schulken and Boy (9) and applied to the development of a method of calculating the die entrance geometry. Tordella called melt fracture a critical pressure, and Schulken and

Boy called it a critical shear rate which is dependent principally on the die entry geometry and viscosity.

**a. Entry geometry**

The importance of entry geometry is not confined to melt fracture problems. Melt expansion caused by elastic recovery of the melt as it leaves the die is important in establishing die design. By calculating the volume of the taper and dividing it by the flow rate, the melt residence time can be obtained. When this is compared with the relaxation rate of the melt, will indicate whether expansion on leaving the die is likely to occur, and whether draw-down for thickness control is called for.

The importance of die entry geometry and confirmation of its influence on extrudate quality has also been given by Metzner et al (10) in a study of the steady-rate flow properties of molten polymers. It is also proved that a longer-capillary die appreciably increases the stress at which a deterioration of quality commences.

**B. PROFILE PELLET DIES**

It is not only the die which determines the shape of an extrudate but also the operating conditions. There are two general categories of dies used for profiles in terms of general construction. These are plate dies and streamline dies as in Figures 14 and 15.

Figure 14 shows that the shaping orifice is in a flat plate attached to a die holder. It is evident that there is a great deal of stagnation in the region behind the die. Thermally sensitive materials such as PVC cannot be run for any significant length of time in plate dies. What happens is that the degraded material which forms in the stagnation regions will start to release stained and decomposed resin and the result will be an unusable product.

Figure 15 illustrates a streamlined die which has a transition section that matches the flow from the extruder head diameter to the product shape. This type of tool construction is used to prevent stagnation of material in the die.

This project is primarily concerned with profile extrusion and in particular to dies for bilobal and trilobal pellets. Profiles are all extruded articles having a cross-sectional shape that differs from that of a circle, an annulus, or a very wide and thin rectangle (flat film or sheet). Cross-sectional shapes are usually more complex, which in terms of solving the flow problem in profile dies , means complex boundary conditions. Furthermore profile dies are of nonuniform thickness, raising the possibility of transverse pressure drops and flow rates, making the prediction of extrudate swelling for viscoelastic fluids very difficult. For these reasons profile dies are built today on a " trial-and-error " basis, and final product shape is achieved with " sizing " devices that act on the extrudate after it leaves the profile die.

The original die was designed by Dr. Keith T. O'Brien and Mr T.L. Jan (16). The die was made and later developed at NJIT. Experimentation with different die inserts was performed and the inserts were designated as A201, A203 and A301. The first digit indicates the number of lobes in the die channel. These dies are illustrated Figures 18-21.

## C. ANALYSIS OF THE FLOW THROUGH THE DIE :

As indicated earlier designing a profile die is difficult due to the complex boundary conditions.

Let us consider the square tube flow patterns calculated by Rothmeyer (11) for a power law fluid of n = 0.5 ( as shown in Figure 17 ). Although the velocity profiles are symmetric, they still are $\theta$ dependent, $\theta$ being the angle in the cross-sectional plane. It is further evident that the velocity gradient $dv_z/dr$ where r is an " effective radius " coordinate, also depends on the angle $\theta$ . Therefore in each quadrant, for every value of the angle $\theta$ , there is a different velocity gradient variation with r. At $\theta = 0$ and $\theta = \pi/2$ the velocity gradients are high , since r = H where H is the channel depth ; while at $\theta = \pi/4$ , where $r = \sqrt{2H}$ , the velocity gradients are small. It follows then that if a polymer melt were flowing in a channel of square cross-section, the extrudate would swell more at the vicinity of the center of its sides, because of high prevailing shear rates. The resulting extrudate shape would then show a " bulge " outward at the sides.

Therefore the shape of the extrudate would never be like the cross-sectional sectional shape of the die. This is very evident in the photographs (Figures 21 to 28) comparing the die inserts to the extrudate shapes.

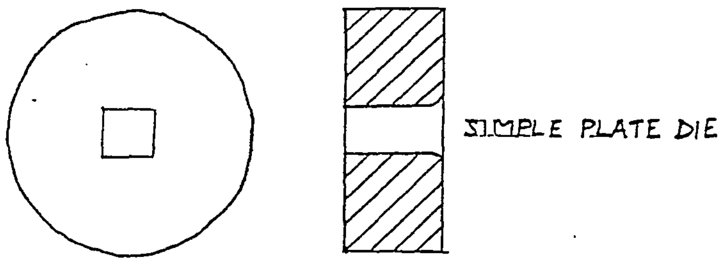
Extrudate swelling refers to the phenomenon observed with polymer melts and solutions that when extruded , emerge with cross-sectional dimensions apprecibly larger than those of the flow conduit. The ratio of the final jet diameter to that of the capillary, $D/D_o$ , for Newtonian fluids varies only from 1.12 at low shear rates to 0.87 at high rates (4). Experimentally $D/D_o$ depends on:

the shear stress at the wall (a flow variable).

the molecular weight distribution (a structural variable), and

the length-to-diameter ratio of the capillary (a geometric variable).

Based on these three variables the die swell can be accomodated.




SOURCE :- 'PLASTICS EXTRUSION TECHNOLOGY HANDBOOK' By SIDNEY LEVY PAGE 90 & 91

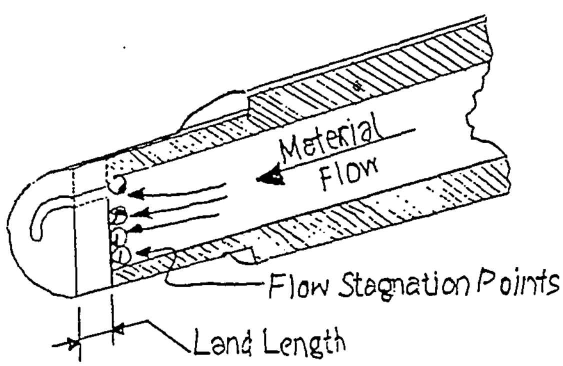
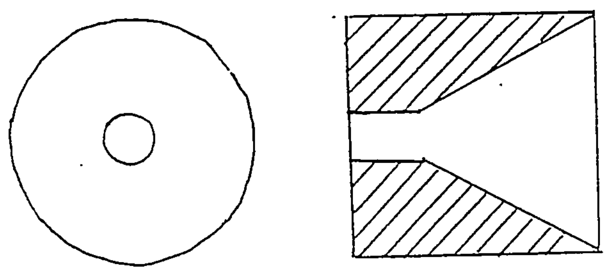



PLATE DIE

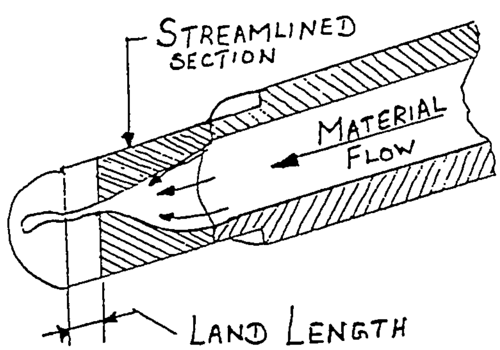
FIGURE 14



STREAMLINE APPROACH DIE
APPROACH ANGLE 60° INC.

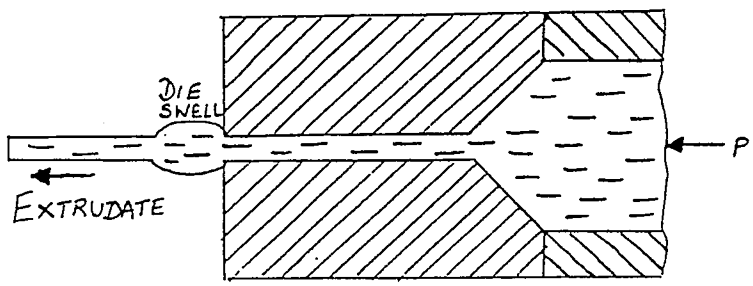
STREAMLINE APPROACH FOR ROD DIE

SOURCE :- 'PLASTICS EXTRUSION TECHNOLOGY HANDBOOK' BY SIDNEY LEVY PAGES 90 & 91




STREAMLINE PROFILE EXTRUSION DIE

FIGURE 15




SCHEMATIC OF DIE SWELL IN THE FLOW OF PLASTICS

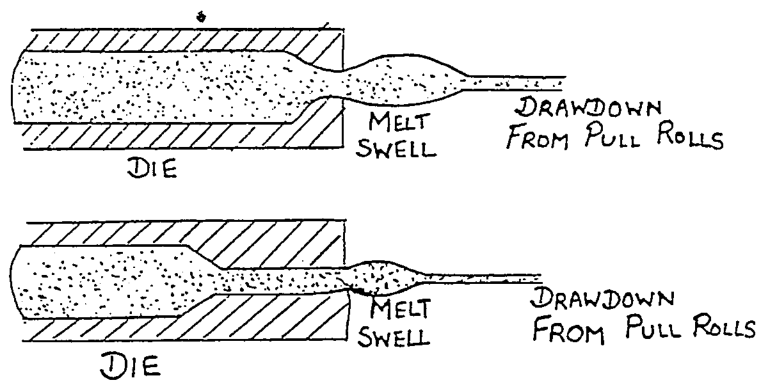
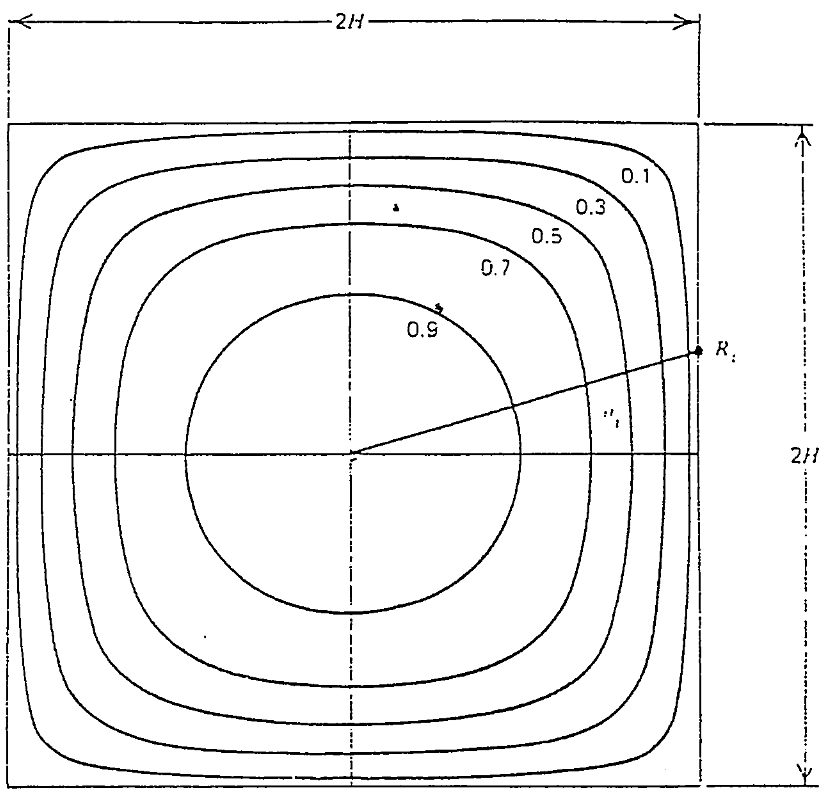



DIAGRAM SHOWING EFFECT OF LAND LENGTH ON DIE SWELL

FIGURE .16

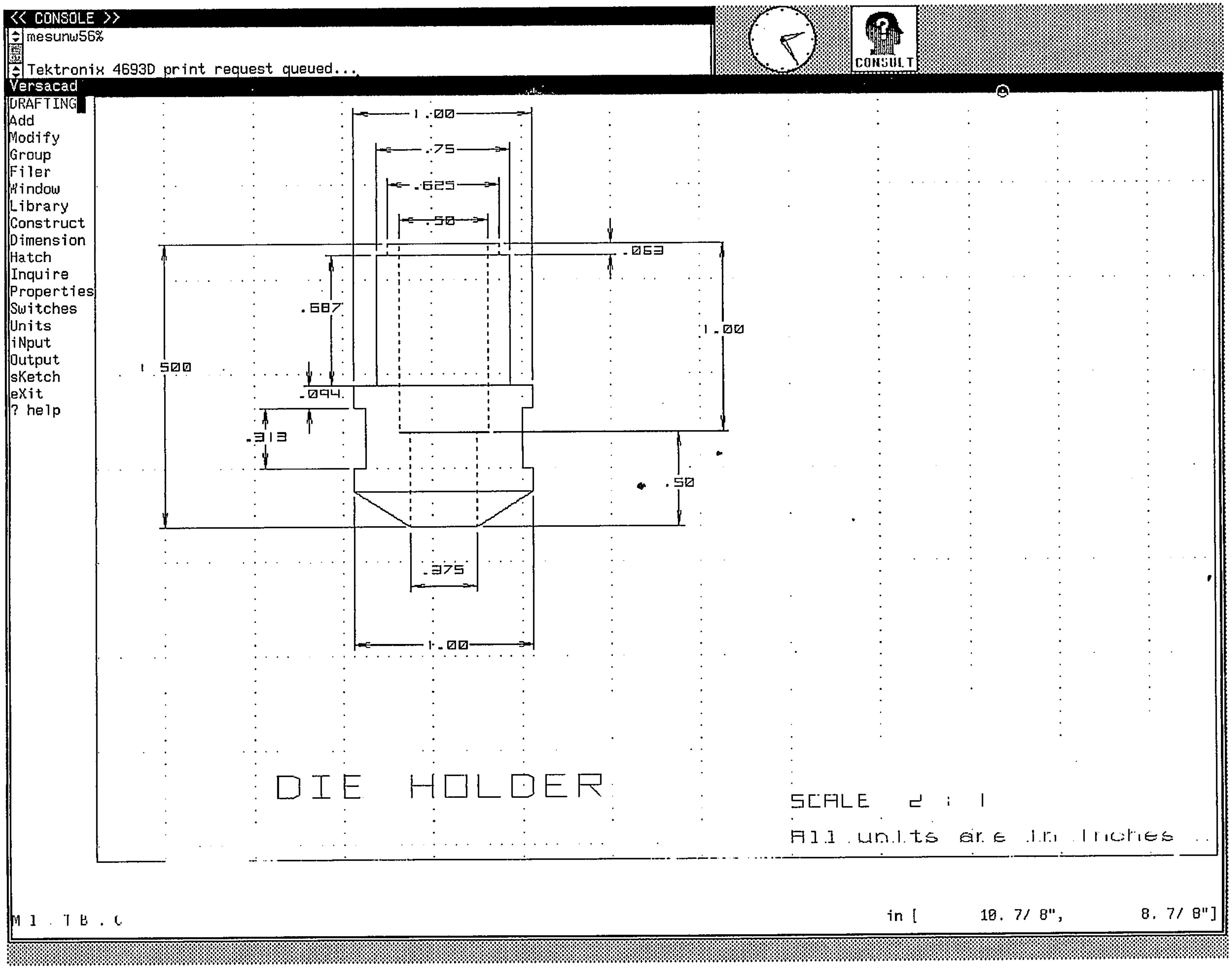
SOURCE :- 'PLASTICS EXTRUSION TECHNOLOGY HANDBOOK' – BY SIDNEY LEVY PAGE 101




ISOVELOCITY CONTOURS $v/V_0$ OF A POWER LAW FLUID FLOWING IN A SQUARE CHANNEL OF $n = 0.5$

SOURCE :- FROM F. RÖTHEMEYER, KUNSTSTOFFE, 59, 333 (1969)

FIGURE 17



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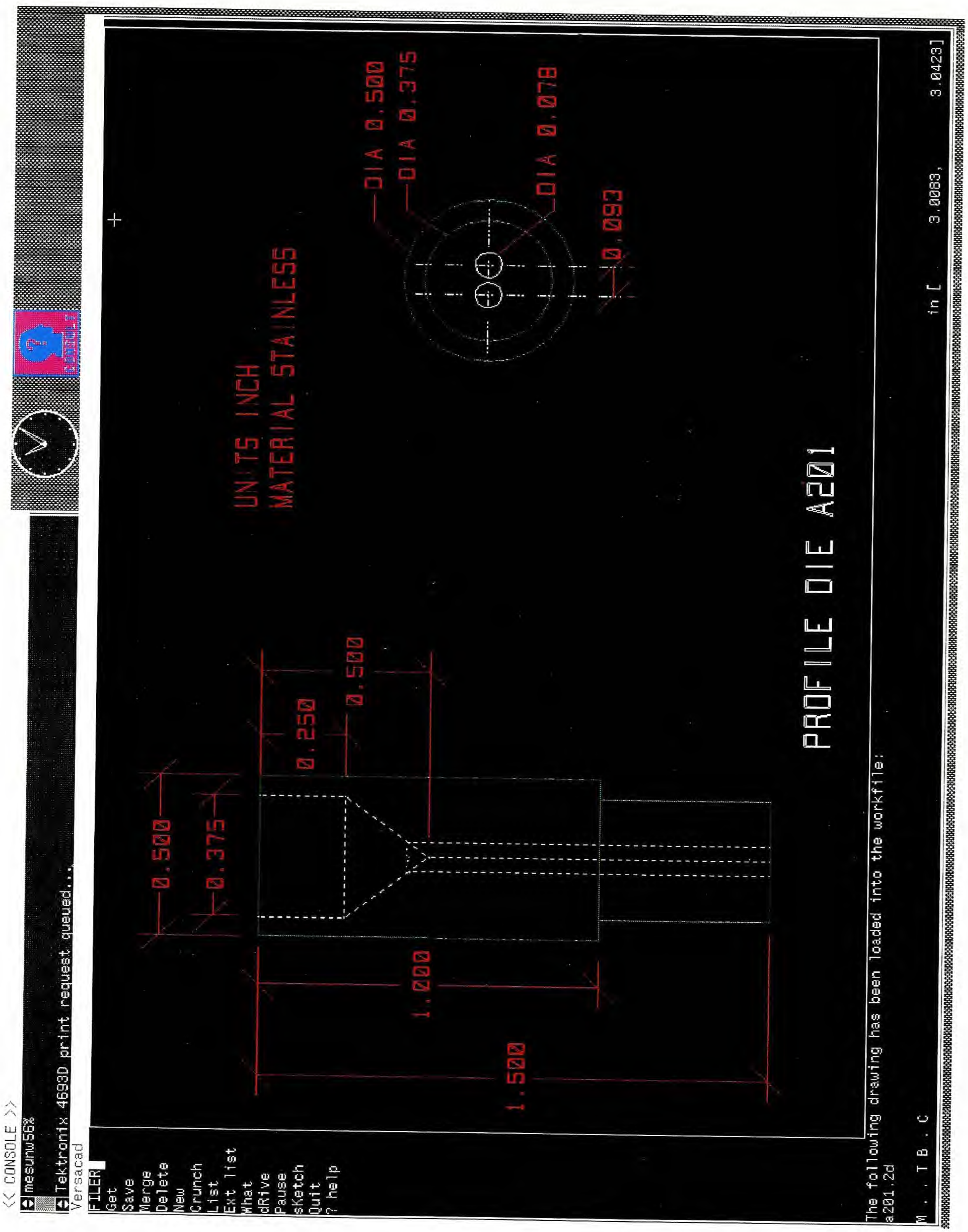
Output
sKetch
eXit
? help
CONSULT
1.00
.75
.625
.50
.063
.687
1.00
1.500
.094
.313
.50
.375
1.00
DIE HOLDER
SCALE 2 : 1
All units are in inches
in [ 10. 7/ 8", 8. 7/ 8"]


FIGURE 18



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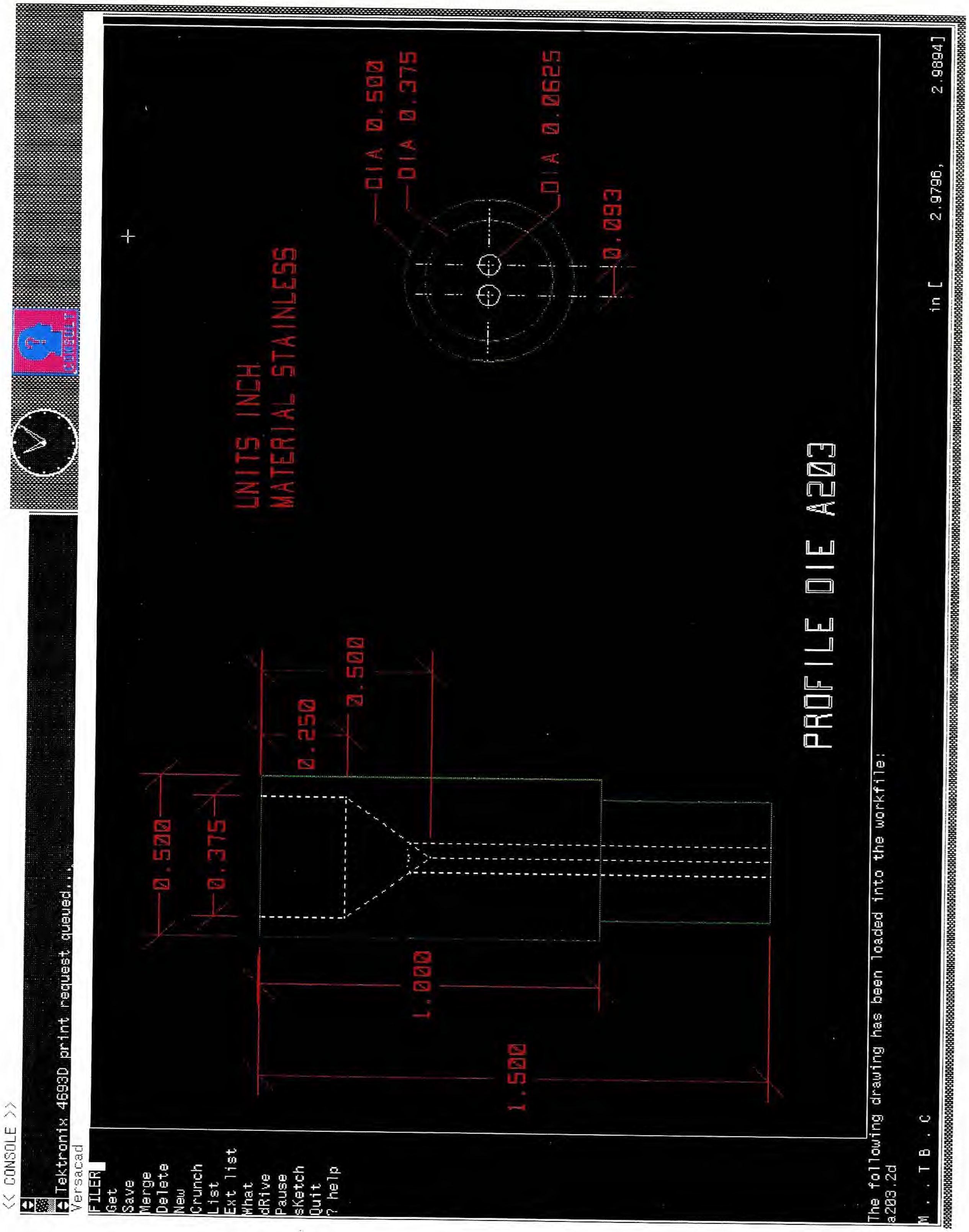
UNITS INCH
MATERIAL STAINLESS
DIA 0.500
DIA 0.375
DIA 0.078
0.093
0.500
0.375
0.250
0.500
1.000
1.500
PROFILE DIE A201
The following drawing has been loaded into the workfile:
a201.2d
M . . T B . C
in [ 3.0083, 3.0423]


FIGURE 19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Ext list
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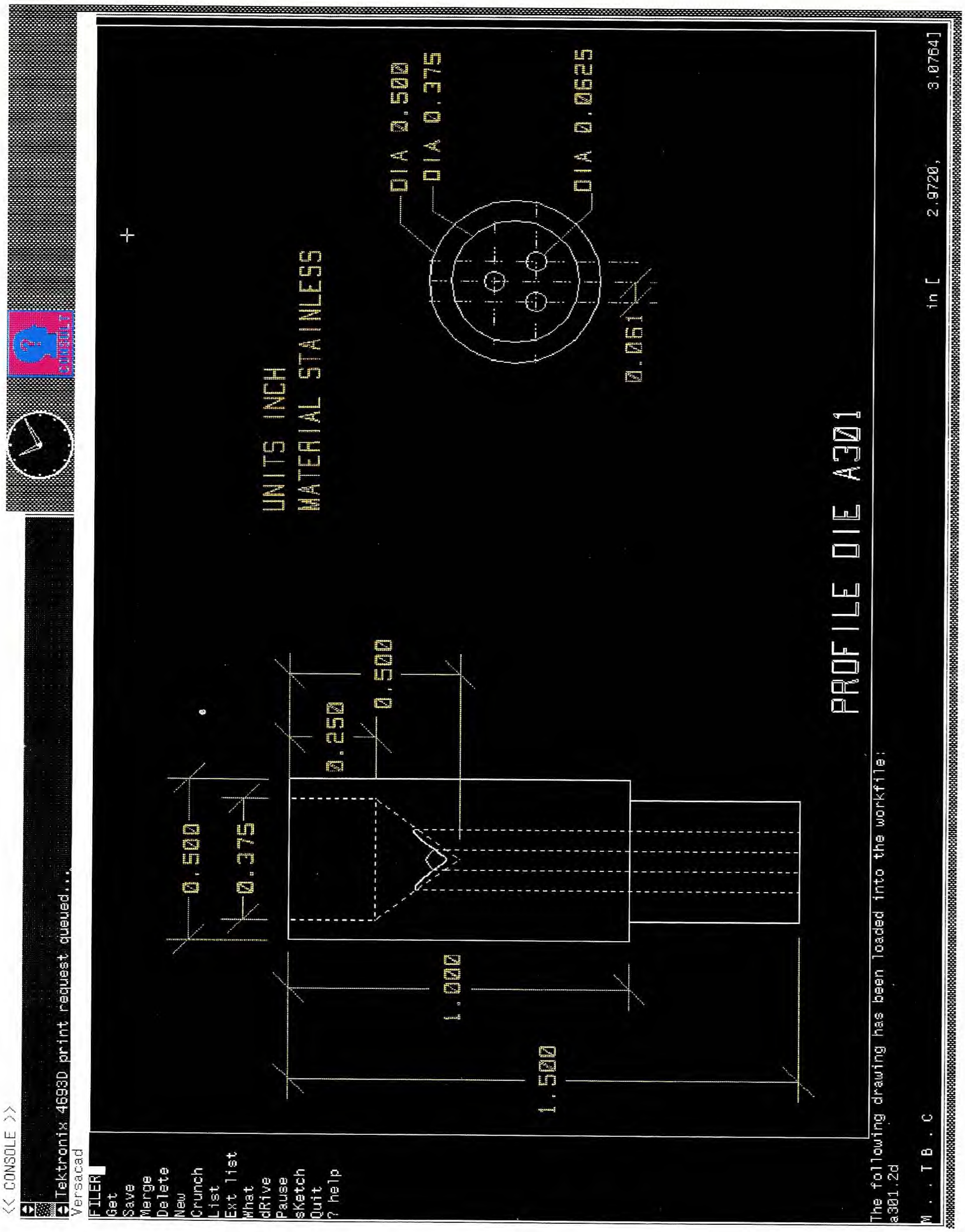
dRive
Pause
sKetch
Quit
? help
0.500
0.375
1.000
1.500
0.250
0.500
UNITS INCH
MATERIAL STAINLESS
DIA 0.500
DIA 0.375
DIA 0.0625
0.093
PROFILE DIE A203
The following drawing has been loaded into the workfile:
a203.2d
M . . T B . C
in [ 2.9796, 2.9894]

FIGURE 20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FILER
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Delete
New
Crunch
List
Ext list
What
dRive
Pause
sKetch
Quit
? help
0.500
0.375
1.000
1.500
0.250
0.500
PROFILE DIE A301
UNITS INCH
MATERIAL STAINLESS
DIA 0.500
DIA 0.375
DIA 0.0625
0.061
The following drawing has been loaded into the workfile:
a301.2d
M . . T B . C
in [ 2.9720, 3.0764]

FIGURE 21

## CHAPTER IV

## TEST EQUIPMENT

The extruder that was used for manufacturing the pellets is a single screw extruder made by Wayne Machine & Die Company located at Totowa in New Jersey. The extruder used has a 1" diameter screw and is driven by a 220 volt, 3 phase motor.

The control panel has three temperature controllers regulating the temperature of the screw at the front end, middle end and at the die end. It records temperature variations from $0^{o}$ to $800^{o}$ Fahrenheit. An ammeter records the load fluctuations and an RPM meter records the speed of the extruder. This is illustrated in Figure 22. The views of the profile die, die inserts and the die holders along with the profiled pellets are shown in Figures 23 to 26.

Figure 22

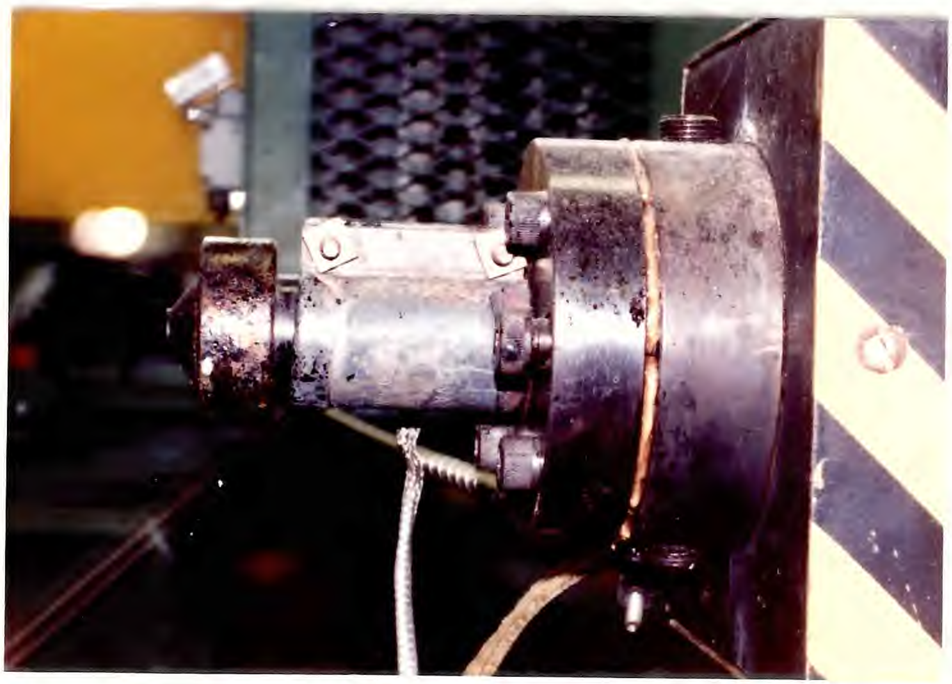

Figure 23

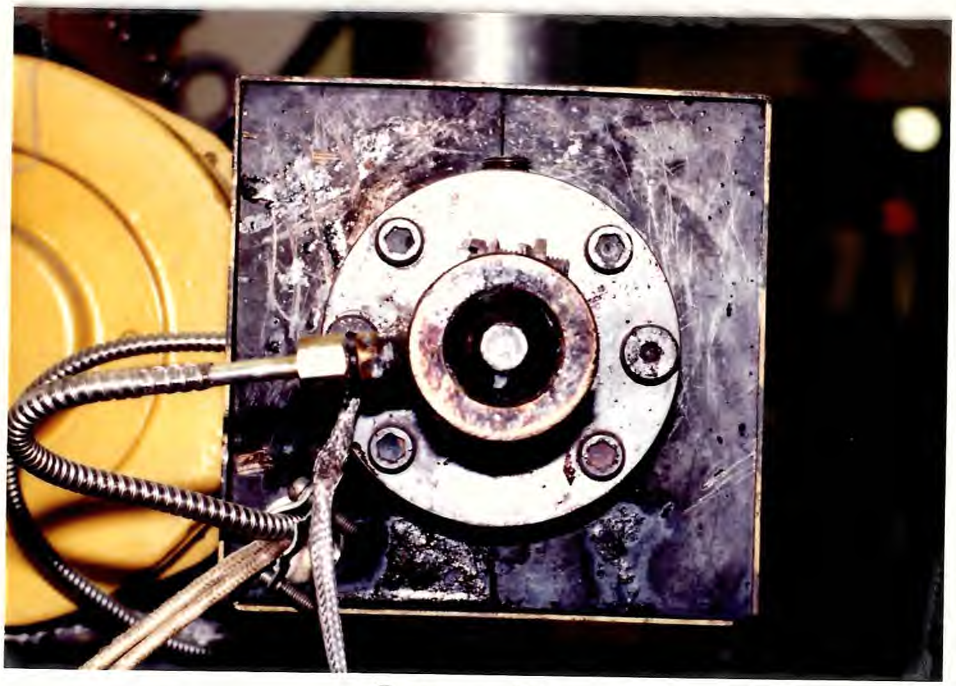

Figure 24

Figure 25

Figure 26

CHAPTER V

# MATERIALS FOR MANUFACTURING PROFILED PELLETS

## Moisture content

The percentage of moisture in a material for extrusion is a very important factor. If this figure exceeds certain low limits then the product will suffer from many obscure faults which are difficult to diagnose. In the worst cases obvious steam bubbles will actually form and burst in the extrusion as it leaves the die. In materials of lower moisture content, the moisture may show itself as lines of minute bubbles to give an unevenly matt surface; and in transparent extrusion, this will cause cloudiness among other defects, Occasionally, an erratic surging effect may also be caused by a high moisture content figure.

For this reason all test materials were dried in accordance with the recommendations of the manufacturer.

The different test resins and grades used for the manufacture of bilobal and trilobal pellets are presented in Table 2.

The materials for manufacture of the pellets have been taken from several base reins, ranging from soft to hard, that is low modulus to high modulus. The low modulus materials tend to deform under pressure in contrast to that of the high modulus as illustrated in Figure 29. Therefore some of these materials contain fillers and reinforcements, to represent the industrial situation. Table I (which appears on page 5 and is duplicated here for reference), gives us the per annum usage of the production of plastics for extrusion purposes.

**Table I**

| **Sl. No.** | **Material** | **Market** | **Million Lbs 1988** | **1989** |
|---|---|---|---|---|
| 1 | Low-Density Polyethylene | Extrusion | 7760 | 7311 |
| 2 | Polypropylene | Extrusion | 2735 | 2850 |
| 3 | Polystyrene | Extrusion | 2179 | 2156 |
| 4 | High-Density Polyethylene | Extrusion | 1769 | 1795 |
| 5 | Polyesters Thermoplastic (PET and PBT) | Extrusion | 510 | 520 |
| 6 | Acrylonitrile Butadiene Styrene (ABS) | Extrusion | 420 | 445 |
| 7 | Acrylics | Molding & Extrusion Compounds | 200 | 220 |
| 8 | Nylons | Extrusion | 148 | 151 |
| 9 | Cellulosics | Extruded film & sheet | 17 | 17 |

Source: Modern Plastics, January 1990, Pages 100-104

**Materials for the Manufacture of Profiled Pellets**

**Table 2**

| Sl No. | Code No. | Material | Manufacturer | Grade |
|---|---|---|---|---|
| 1. | PP001 | Polypropylene | Soltex | P4D 0326-61 Soft |
| 2. | PS001 | Polystyrene | Hoechst Celanese | Clear |
| 3. | N0001 | Nylon | Plaskon | 917 XPN Clear |
| 4. | A0001 | Acrylonitrile Butadiene Styrene (ABS) | UNK | White |
| 5. | N0002 | Nylon | UNK | Black |
| 6. | N0003 | Natural Nylon | Hoechst Celanese | 1503-2 |
| 7. | N0004 | Natural Nylon | Hoechst Celanese | 7520-2 Tough |
| 8. | CE001 | Celanex (Thermoplastic Polyester) | Hoechst Celanese | CX-2000 |
| 9. | CE002 | Celanex (Thermoplastic Polyester) | Hoechst Celanese | CX-3300 D Black |
| 10. | CC001 | Celcon (Acetal Copolymer) | Hoechst Celanese | U10-11 |
| 11. | CC002 | Celcon (Acetal Copolymer) | Hoechst Celanese | M-25 |
| 12. | CC003 | Celcon (Acetal Copolymer) | Hoechst Celanese | M-90 |

| | | | | |
|---|---|---|---|---|
| 13. | CC004 | Celcon (Acetal Copolymer) | Hoechst Celanese | M-270 |
| 14. | CC005 | Celcon (Acetal Copolymer) | Hoechst Celanese | M-450 |

**SOME OF THE CHARACTERISTICS OF THE ABOVE MATERIALS**

| CODE NO | CHEMICAL DESCRIPTION | MELTING POINT (in degrees Kelvin ) | SPECIFIC GRAVITY |
|---|---|---|---|
| CE001 | Unreinforced thermoplastic polyester resin | 442 | 1.31 |
| CE002 | 30 % glass reinforced | 442 | 1.54 |
| CC001 | Crystalline acetal copolymer based on trioxane | 345 | |
| CC002 | Crystalline acetal copolymer based on trioxane | 329 | 1.41 |
| CC003 | Crystalline acetal copolymer based on trioxane | 335 | |

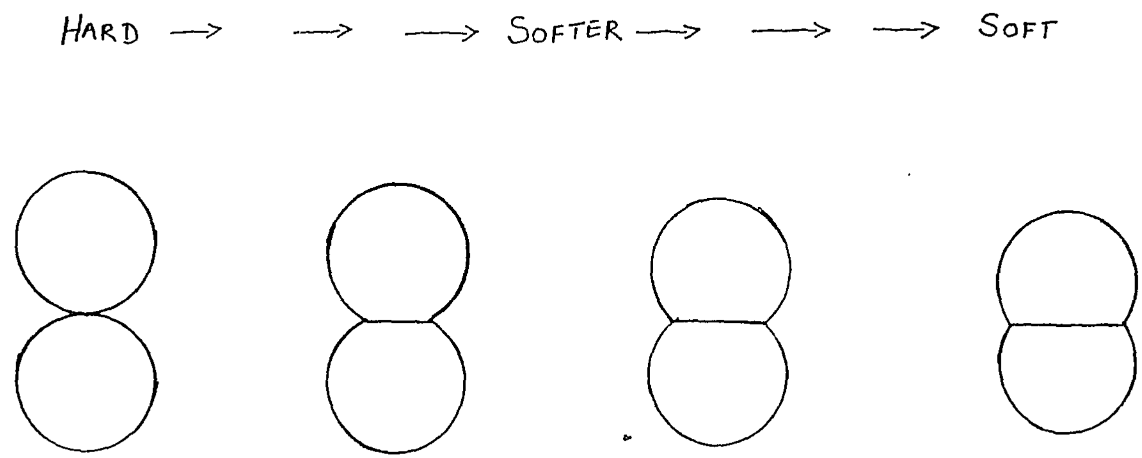


FIGURE 29

SIGNIFICANCE OF LOW MODULUS TO HIGH MODULUS WHEN PRESSURE IS ACTED UPON THEM.

CHAPTER VI

# TEST RESULTS

## A. Test Procedure

The die inserts illustrated in Figures 18 to 21 were mounted sequentially on a 1" diameter Wayne extruder (Figure 22). The extruder was operated under several sets of operating conditions. The temperature profile was held constant for each resin system, in accordance with the recommendation of the raw material suppliers, and the screw speed was stepwise varied from 10 RPM to 50 RPM.

## B. The shear rate equation for flow in the die

The starting point of the analysis is the component of the momentum equation for a steady, isothermal, laminar, fully developed pressure flow of an incompressible power law model fluid in a horizontal tube,

$$\frac{dP}{dz} = -\frac{1}{r}\frac{d}{dr}\left(r\,\tau_{rz}\right) \qquad \text{---1.}$$

where P is the pressure and r the radial coordinate in cylindrical coordinates.

Integrating equation 1. we obtain

$$\tau_{rz} = -\tau_{w}\left(\frac{r}{R}\right) \qquad \text{---2.}$$

where R is the radius of the tube and $\tau_\omega$ is the shear stress at "wall"
( r = R ) which can be experimentally evaluated.

By assuming that the polymer melt is viscous and time independent, without specifying the viscosity function, we can apply the ' Generalized Newtonian Fluid ( GNF ) ' equation for capillary flow at the wall (4).

$$\tau_\omega = -\eta \dot{\gamma}_{rz}\Big|_{r=R} \equiv \eta \dot{\gamma}_\omega \qquad ---3.$$

Equation 3. suggests that if, in some way $\dot{\gamma}_\omega$ could be evaluated experimentally, the viscosity function could be determined. This is indeed possible through the measurement of the volumetric flow rate Q , which can be expressed independently of any constitutive equation as follows

$$Q = 2\pi \int_0^R r v_z(r)\, dr = 2\pi \left[ \left( \frac{r^2 v_z(r)}{2} \right)\Big|_0^R - \int_0^R \frac{r^2}{2}\, dv_z \right] \qquad ---4.$$

Assuming no slip at the wall of the capillary, we note that the first term on the right hand side of equation 4 is zero, hence it can be re-written as

$$Q = -\pi \int_0^R r^2 \left( \frac{dv_z}{dr} \right) dr \qquad \text{---5.}$$

From equation 2, $r = \tilde{\tau}_{rz} R / \tilde{\tau}_\omega$, a relationship that can be utilized to change the integration variable in the previous equation. Therefore ;

$$Q = \frac{-\pi R^3}{\tau^3_\omega} \int_0^{\tau_\omega} \left( \frac{dv_z}{dr} \right) \tilde{\tau}_{rz}^2 \; d\tilde{\tau}_{rz} \qquad \text{---6.}$$

Next, equation 6 is differentiated with respect to $\tilde{\tau}_\omega$ to give

$$\frac{1}{\pi R^3} \left[ \tau^3_\omega \frac{dQ}{d\tau_\omega} + 3 \tau^2_\omega Q \right] = - \left( \frac{dv_z}{dr} \right)_{r=R} \tilde{\tau}^2_\omega \qquad \text{---7.}$$

Equation (7) can be written as

$$-\left( \frac{dv_z}{dr} \right)_{r=R} = \dot{\gamma}_\omega = \frac{3T}{4} + \frac{\tilde{\tau}_\omega}{4} \frac{dT}{d\tilde{\tau}_\omega} \qquad \text{---8.}$$

where T is the Newtonian shear rate at the wall, that is

$$T = 4 Q / \pi R^3 \qquad \text{---9.}$$

which is the equation used for the calculation of the shear rate at the wall.

## C. Measurements

Below are the observations made while making pellets of bilobal shape for the following materials :-
The die used for all the materials were A201 and A203.

**Table 3**

Material: N0002

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 482 | 491 | 509 | 518 | 536 |
| Middle Temperature | 500 | 500 | 509 | 518 | 545 |
| Die Temperature | 338 | 347 | 338 | 347 | 356 |
| | 9 | 9 | 9 | 10 | 10 |
| | Cutter Speed in RPM | | | | |

**Table 4**

Material: N0001

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 550 | 540 | 545 | - | - |
| Middle Temperature | 550 | 560 | 550 | - | - |
| Die Temperature | 350 | 340 | 345 | - | - |
| | 14 | 17 | 16 | - | - |
| | Cutter Speed in RPM | | | | |

**Table 5**

Material: PE001

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 460 | 465 | 460 | 465 | 460 |
| Middle Temperature | 480 | 495 | 500 | 495 | 495 |
| Die Temperature | 350 | 345 | 350 | 345 | 350 |
| | 8 | 10 | 13 | 16 | 18 |
| | Cutter speed in RPM | | | | |

**Table 6**

Material: PS001

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 482 | 482 | 482 | 473 | 473 |
| Middle Temperature | 500 | 500 | 509 | 500 | 491 |
| Die Temperature | 338 | 338 | 347 | 347 | 338 |

**Table 7**

Material: PP001

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 473 | 482 | 473 | 482 | 482 |
| Middle Temperature | 482 | 482 | 500 | 491 | 500 |
| Die Temperature | 338 | 338 | 347 | 347 | 338 |

**Table 8**

Material: CC002

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 450 | 445 | - | - | - |
| Middle Temperature | 455 | 460 | - | - | - |
| Die Temperature | 295 | 300 | - | - | - |
| | 10 | 16 | - | - | - |
| | Cutter Speed in RPM | | | | |

**Table 9**

Material: CC003

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 435 | 435 | 430 | - | - |
| Middle Temperature | 440 | 440 | 440 | - | - |
| Die Temperature | 260 | 260 | 260 | - | - |
| | 19 | 21 | 24 | - | - |
| | Cutter Speed in RPM | | | | |

**Table 10**

Material: CC004

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 400 | 400 | - | - | - |
| Middle Temperature | 410 | 410 | - | - | - |
| Die Temperature | 280 | 280 | - | - | - |
| | 12 | 23 | - | - | - |
| | Cutter Speed in RPM | | | | |

**Table 11**

Material: CC005

| Temperature in Fahrenheit | Screw speeds in RPM | | | | |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 |
| Front Temperature | 430 | 430 | - | - | - |
| Middle Temperature | 450 | 450 | - | - | - |
| Die Temperature | 285 | 285 | - | - | - |
| | 30 | 36 | - | - | - |
| | Cutter Speed in RPM | | | | |

The area of the pellet cross section $A_e$, was measured and compared to the area of the die cross section, $A_d$ by using the ratio, $A_e/A_d$ which is the expansion ratio. The die length L and the effective radius $R_e$, were also compared through the ratio $L/R_e$, the aspect ratio. These are presented in Figures 30 to 35.

**Shear Rate Calculations**
(using the shear rate equation)

**Table 12**

| Material | Die | Screw speeds (in rpm) | | | | |
|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 |
| N0001 | A201 | 258.9 | 522.7 | 681.1 | * | * |
| N0002 | A201 | * | * | 374.4 | 574.3 | 1030.3 |
| PP001 | A203 | 585.9 | 1150.5 | 1470.6 | 1586.8 | 1788.5 |
| PS001 | A203 | 538.8 | 1086.6 | 1649.7 | 2133.9 | 2659.5 |
| A0001 | A203 | 453.1 | 1036.9 | 1483.9 | 1953.3 | 2653.4 |

Given below is the ratio of A (extr) / A (die) for different materials at varying screw speeds.

**Expansion Ratios**

**Table 13**

| Material | Die | Screw speeds (in rpm) | | | | |
|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 |
| N0001 | A201 | 1.71 | 1.21 | 0.78 | * | * |
| N0002 | A201 | * | * | 2.86 | 2.21 | 1.77 |
| PP001 | A203 | 1.26 | 1.30 | 1.26 | 1.45 | 1.26 |
| PS001 | A203 | 1.30 | 1.73 | 1.78 | 1.86 | 2.18 |
| A0001 | A203 | 1.31 | 1.35 | 1.27 | 1.29 | 1.33 |

(* indicates that the material could not be extruded at that speed)

Figure 27

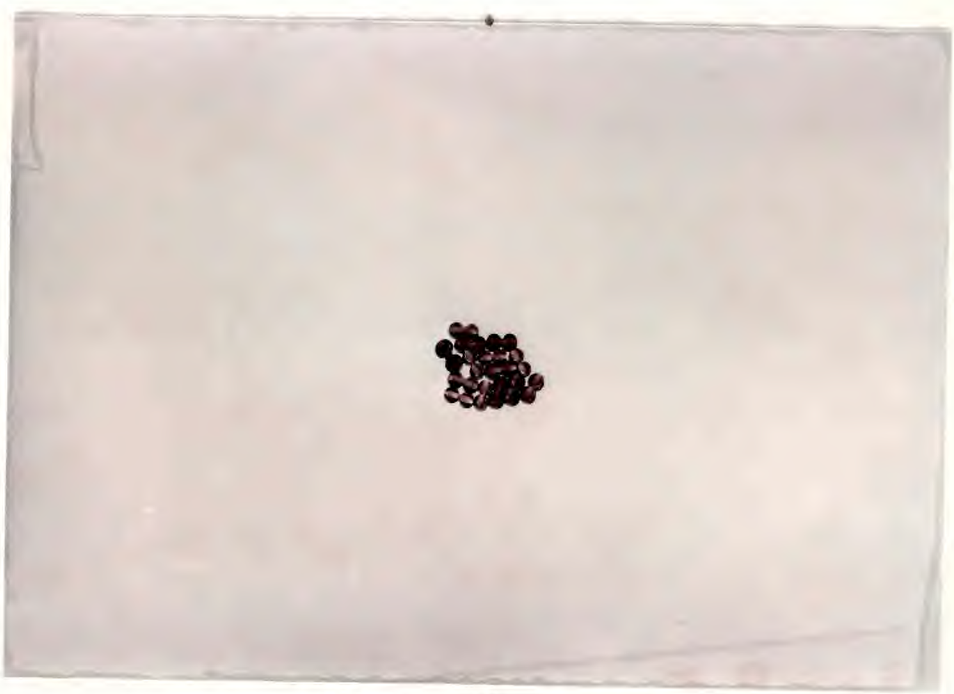

Figure 28

Material : N0001

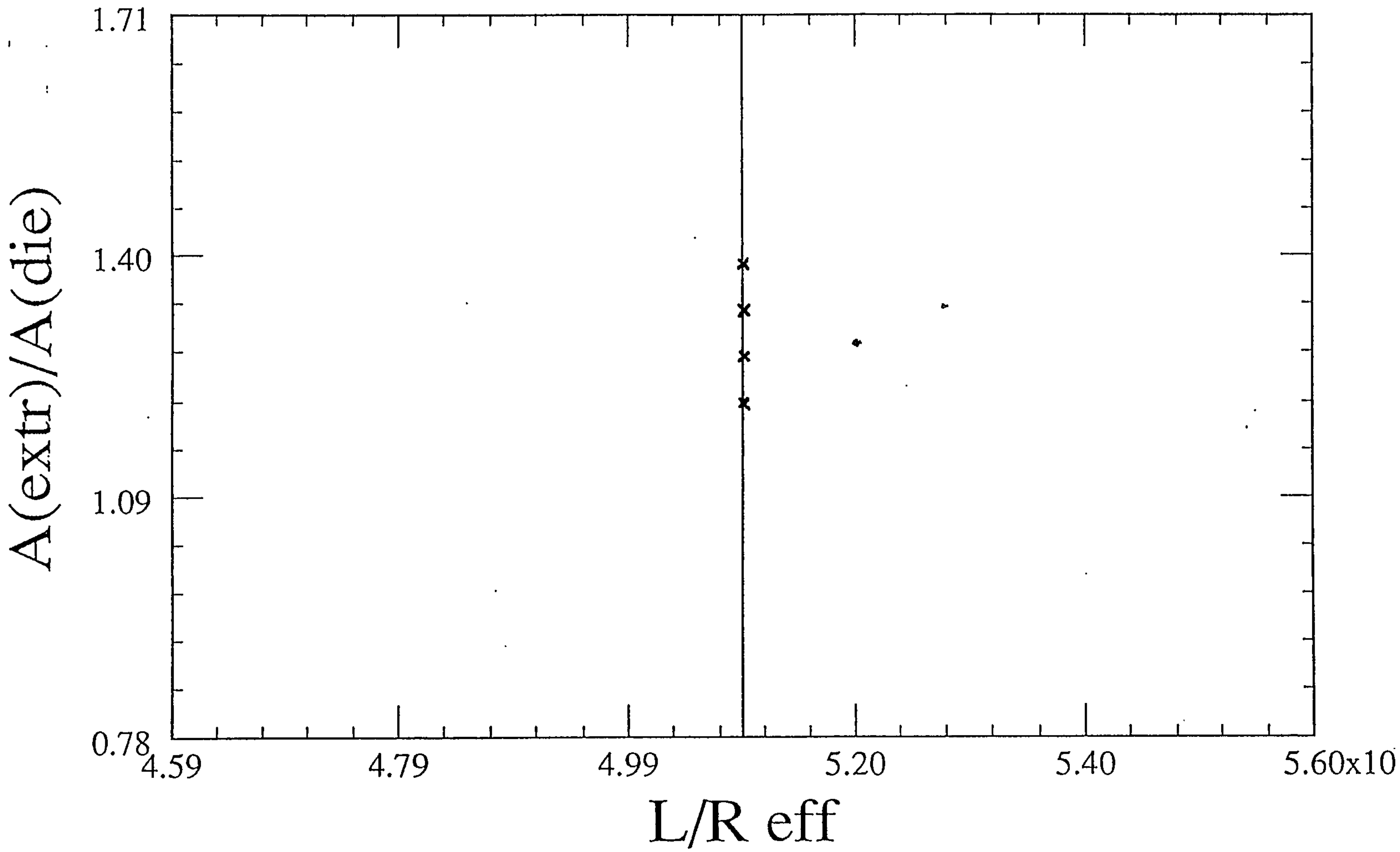


FIGURE 30

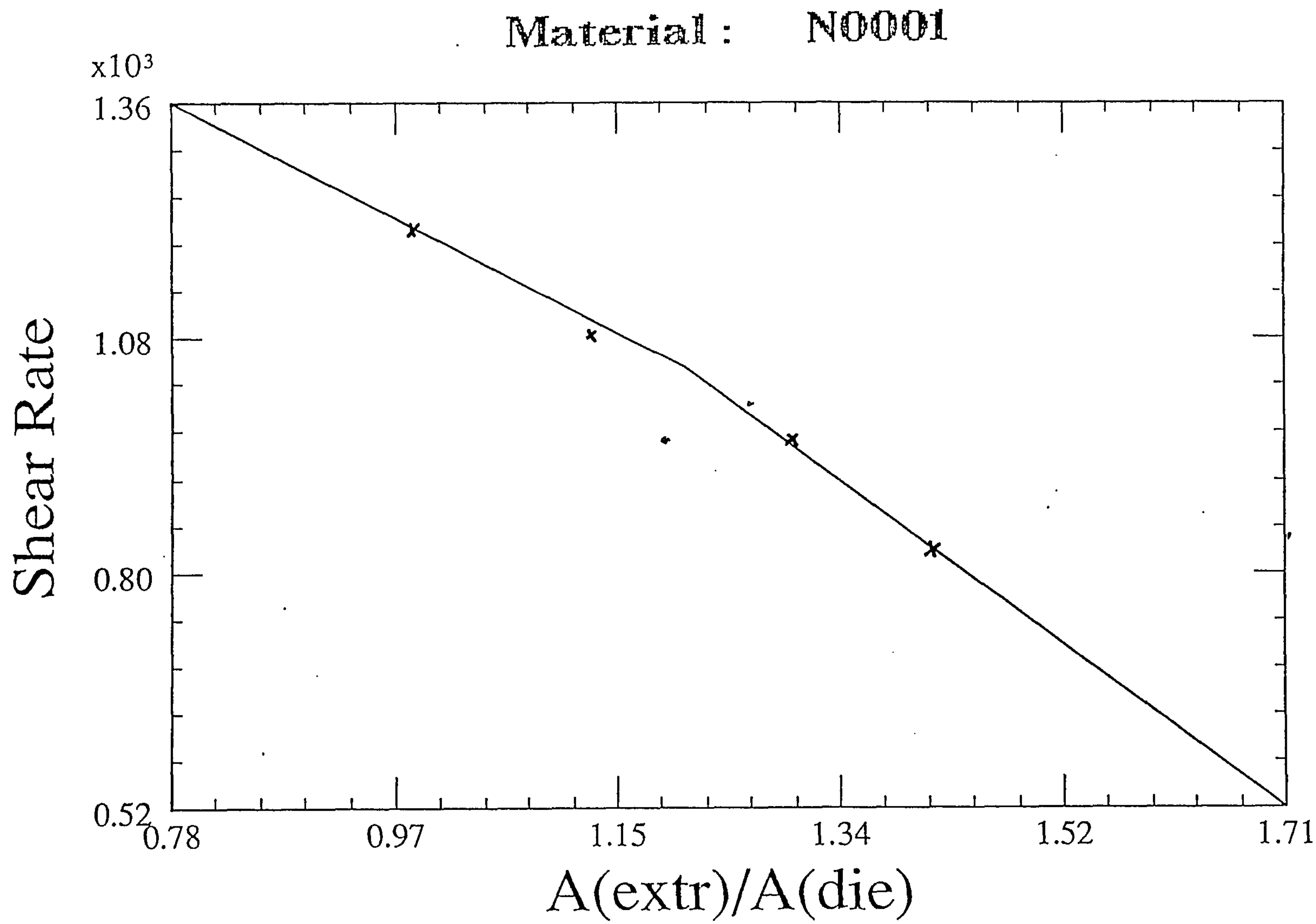
Material : N0001
x10³
1.36
1.08
0.80
0.52
Shear Rate
0.78
0.97
1.15
1.34
1.52
1.71
A(extr)/A(die)

FIGURE 31

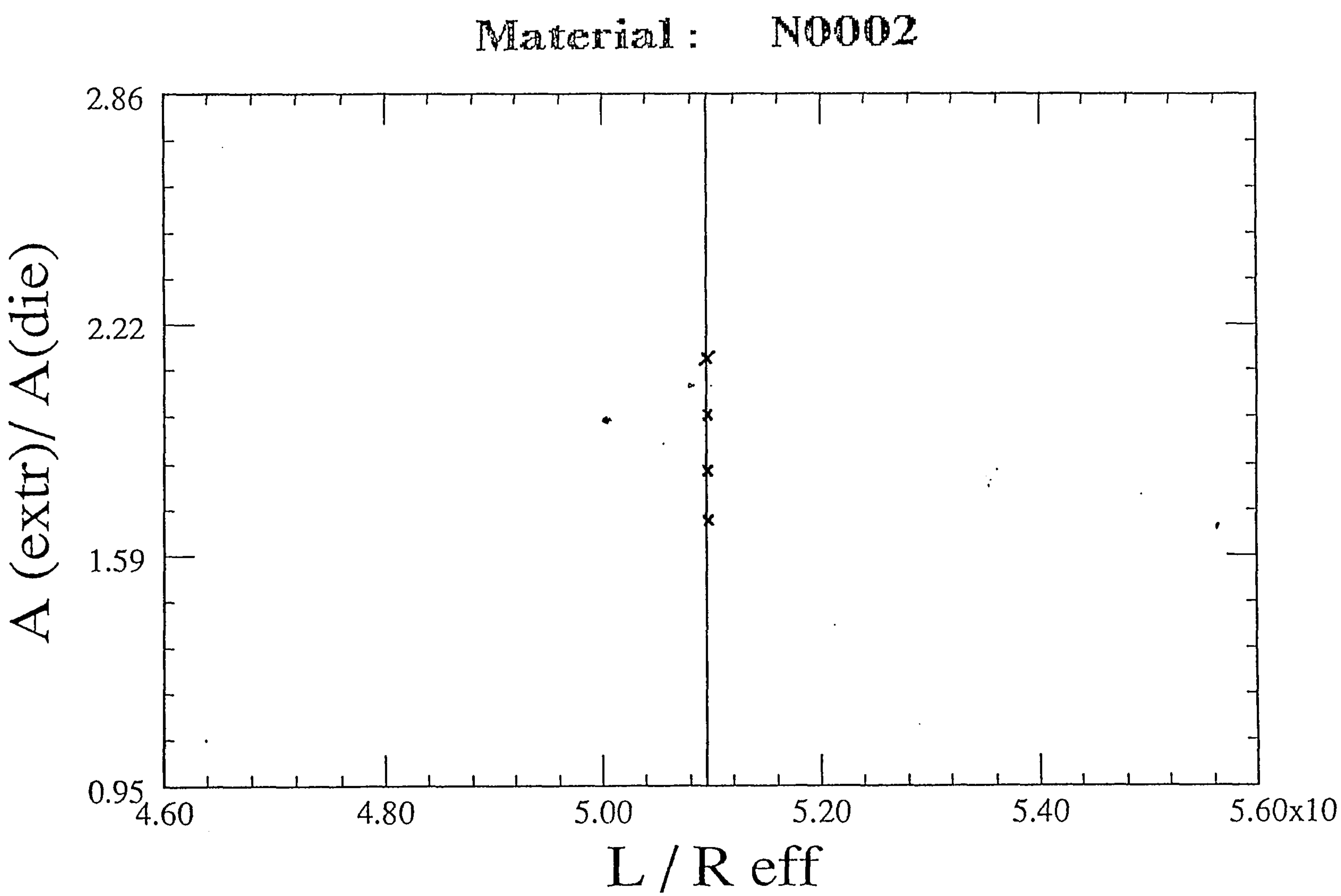
Material : N0002
2.86
2.22
1.59
0.95
A (extr)/ A(die)
4.60
4.80
5.00
5.20
5.40
5.60x10[1]
L / R eff

FIGURE 32

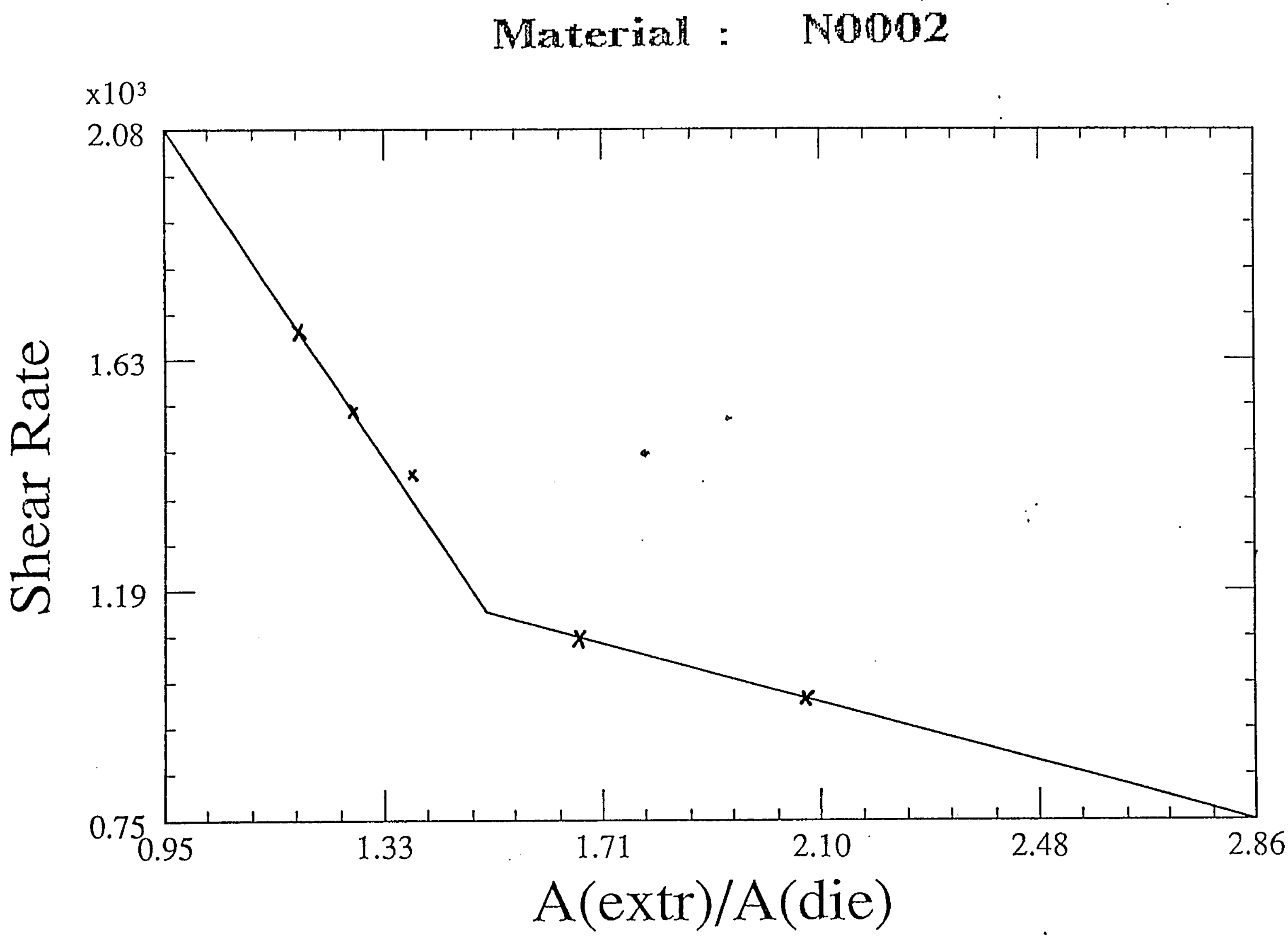
Material : N0002
x10³
2.08
1.63
1.19
0.75
Shear Rate
0.95
1.33
1.71
2.10
2.48
2.86
A(extr)/A(die)

FIGURE 33

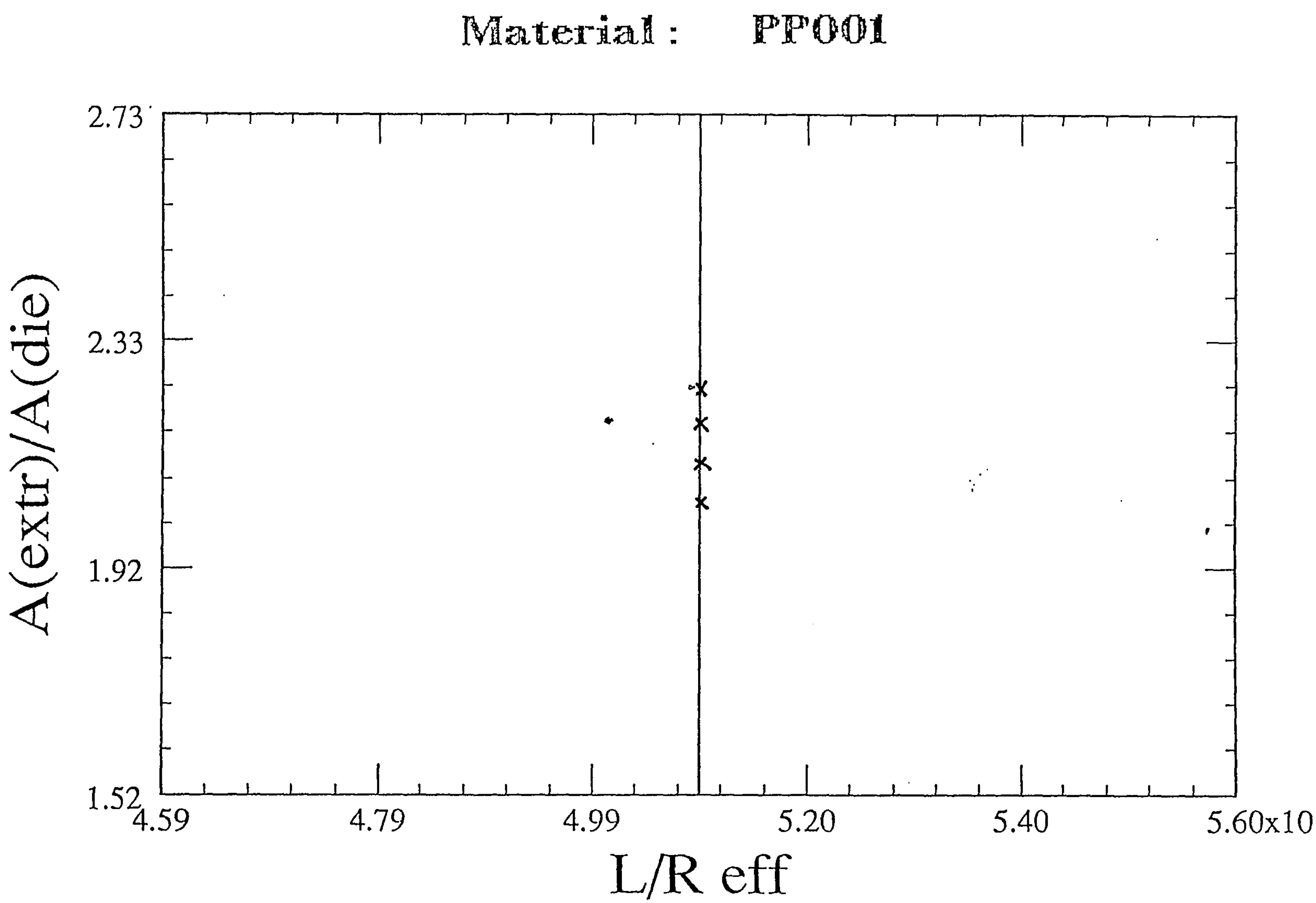
Material : PP001
A(extr)/A(die)
2.73
2.33
1.92
1.52
4.59
4.79
4.99
5.20
5.40
5.60x10¹
L/R eff

FIGURE 34

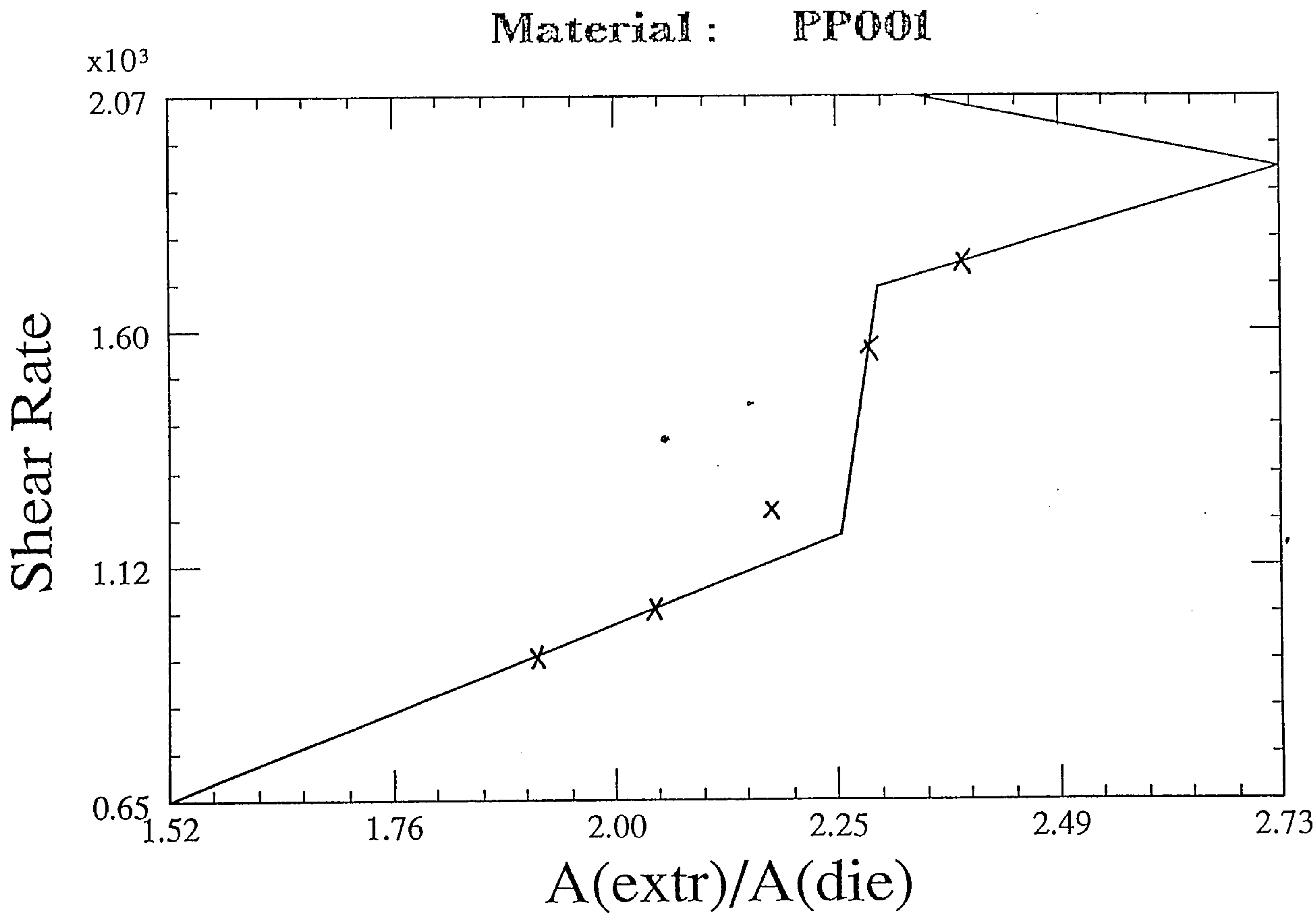
Material : PP001
x10³
2.07
1.60
1.12
0.65
Shear Rate
1.52
1.76
2.00
2.25
2.49
2.73
A(extr)/A(die)

FIGURE 35

CHAPTER VII

## CONCLUSIONS

The bilobal and trilobal pellets were successfully made to be tested for an improvement in the solids conveying in a single screw extruder.

The trial pellet cross section was found to be a function of the die cross section and the operating conditions. The pellets that were manufactured were tested in a specially built shear cell, and the interparticulate coefficient of frictions were measured (12). The hard, high modulus resins exhibited notably improved interparticulate friction coefficients compared to round pellets, whereas the results for the soft, low modulus resins were mixed (12).

The major difficulties encountered especially in the making of N0002, N0003, N0004 was the formation of bubbles in the extrudate. If the exact process temperature was not maintained, the extrudate would liquify. Occasionally, an erratic surging effect was also observed. This was rectified by oven drying the material for atleast 24 hours.

Some of the materials could not be made on account of the limitations of the extruder such as the limitations in the screw design, high temperatures for hard materials, better profile die designs for such materials.

# CHAPTER VIII

## FUTURE WORK

The trial pellets can be made in substantial quantities for field testing on an industrial extruder to determine if flow rate improvements and / or quality improvements can be achieved.

For a further extension of this study for an improvement in the interparticulate coefficient of friction and its subsequent impact on solids conveying in a single screw extruder, other profile shapes like - star, triangle with an arrow head, etc., can be made and tested. The materials which could not be manufactured into pellets on account of the design limitations of the extruder can be manufactured by redesigning the screw, redesigning the profile pellet dies which is to be run on an extruder operating at higher temperatures.

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