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Plastics Extrusion Technology Handbook

by

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PLASTICS EXTRUSION TECHNOLOGY HANDBOOK—**FIRST PRINTING**

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PREFACE

The art of plastics extrusion has developed over the last century from one using crude presses and questionable materials to a highly sophisticated process for manufacturing a wide variety of important products. The advances in the art range from better materials to an understanding of the flow characteristics of high polymers. Better machinery and control systems have made possible closer control of the process and the manufacture of product with precise dimensions and good material characteristics.

The subject has been covered extensively in the literature from the characteristics of screws to the rheology of materials. This text draws on the extensive literature for background. It is directed to the technology of the process—the machines, dies, and auxiliaries used to manufacture product. It provides an introduction to the mechanisms whereby extruders work and how plastics flow through dies. Its primary purpose is to provide the information needed to design, install, and operate plastics extrusion systems to make product. While extruders are used in other plastics processes such as injection molding, blow molding, and compounding, these subjects are not covered since the extruder acts only as a melt-generating unit in those processes.

It is hoped that this presentation on the technology of plastics extrusion will provide a useful guide to those working in the field. The extensive literature references will enable those with a need for more detailed information to go to other sources to supplement this handbook.

INTRODUCTION

Plastics extrusion is one of the most important processes used in the plastics industry. Fully 60% of all plastics material passes through an extruder on its way to conversion to a product. Some of this processing is to pelletize, compound, and color raw materials, but the bulk of the processing is for conversion to finished product or semifinished stock shapes. An examination of some classes of products made by extrusion will give an idea of the scope of the process.

Products made by extrusion range from simple shapes such as sheet and film to rod, pipe, and tubing and complex profiles, which are used for both industrial and commercial applications. Gaskets, house siding, structural furniture parts, decorative moldings, and window and door tracks are some examples of widely used profile extrusions. A variation of straight extrusion called crosshead covering is used to make insulated wire, decorative foil moldings, and plastics-covered towel bars. The coextrusion of several different materials to make laminated sheet and dual durometer parts is another extension of the process capability. The text will discuss these and many other applications for the plastics extrusion process.

The wide range of products results from a fundamentally simple technique that consists of heating a plastics material to melt it, forcing the melted material through a shaping die, and subsequently cooling it while holding the shape. In some instances a post die-forming process is included, which extends the scope of the product capabilities. From rather simple and crude beginnings as an adaptation of the rubber and clay products extrusion equipment, the process has become more sophisticated and complex. This resulted from the need to process new and more difficult materials, and the need for better process control. The improved process control is necessary for precision in dimensional control and control of the physical properties of the extrusions.

The text will cover equipment and process as well as the theory of operation of both machines and tooling. The process control techniques for shape control and uniformity essential to successful operation are discussed in detail. The productivity of specific equipment used on a wide variety of products is described so that appropriate plant equipment and tooling can be selected to make a product at the desired rates. Plant design and operation is described to provide the plant designer or the plant operator with sufficient information to understand the manufacturing methods and the limitations of the extrusion process.

Important subjects to be discussed are (1) design of screws and barrels for the extrusion machine; (2) heating and cooling systems for the extruder, the dies, and the cooling equipment; (3) shape-holding equipment such as cooled rollers, vacuum sizers, and similar devices; (4) machine drives; (5) pullers; and (6) special equipment for specific products including dies. Each of these has a bearing on product quality, productivity, and costs. The diversity of ways in which each of these operations can be done lends great flexibility to the plant design but requires studied decisions as to the most appropriate devices to be used.

In a general text such as this, it is impossible to cover all of the relevant extrusion process technology. The intent is to present material which will lead to a reasonable understanding of the process. This will be amplified by examples of specific production lines used to make a number of widely used products. The philosophy of design involved will give guidance to the plant designer and operator when faced with extensions of the techniques to new materials and new products. The operations will be described with some of the typical problems associated with them to indicate how such operational situations can be analyzed and corrected.

Materials will be discussed with respect to the way in which they process and what properties are required for successful extrusion of certain products. Not all plastics materials can be used in making all extruded shapes. The selection of materials and their interaction with product specifications and processing requirements is a major activity involved in plant design and operation.

This volume should be a useful guide to tooling and manufacturing engineers, equipment designers, plant operators, and product designers who need knowledge of the plastics extrusion process in their work. The material covered is broad enough to supply each of these interests with the basics of the process and the references cited will enable the reader to extend his or her knowledge in specific areas. Extrusion personnel can use the book to understand, design, and operate the extrusion systems for efficient production and to upgrade the plant performance by the use of the best available technology.

Plastics Extrusion Technology Handbook

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Chapter One

Fundamentals of the Extrusion Process

Plastics extrusion is a process for producing a plasticized mass of polymer compound, forcing it under pressure through a shaping die orifice, and subsequently setting the shape by means of a cooling and shaping system. The shaping process in the die, which is analogous to squeezing toothpaste from a tube, is the key part of the process and will be discussed first.

Figure 1-1 shows an idealized extruder orifice with the material passing through. It is assumed that the material has been completely plasticized or melted and that the die orifice is at a temperature that will not cause cooling of the material. What is of interest is how much material will flow through the orifice in response to an applied pressure and how uniform the flow will be in various parts of the orifice. The first factor will determine the throughput and the second will determine the effectiveness of the orifice as a shaping device. Both of these factors are controlled by the material rheology.

The rheology of a material is the manner in which it deforms in response to an applied stress. In the case of plastics in the melt condition, the stress applied is pressure, and the response is continuous deformation and flow. The flow is dependent on the shear characteristics of the material, and this response can be of several types, as illustrated in Fig. 1-2. If the material has a constant viscosity, i.e., constant ratio between shear stress and shear rate, it is called a Newtonian fluid. The shear stress and shear rate can be defined in conjunction with the illustration in Fig. 1-3 which shows a material being sheared between two parallel plates:

$$\text{shear stress} = \frac{\text{shear force}}{\text{shear area}} = \frac{F}{A}$$

$$\text{shear rate} = \frac{dv}{dh} = \frac{V}{h}\,\text{(for a Newtonian fluid)}$$

$$\text{Newtonian viscosity } \mu_N = \frac{\text{shear stress}}{\text{shear rate}} = \frac{F/A}{V/h}$$

$$\text{general viscosity } \mu = \frac{F/A}{dv/dh}$$

Most plastics are non-Newtonian in their characteristics. This is to be expected from the fact that they are made up of long-chain high-polymer materials. The viscosity of the materials will change with the amount and

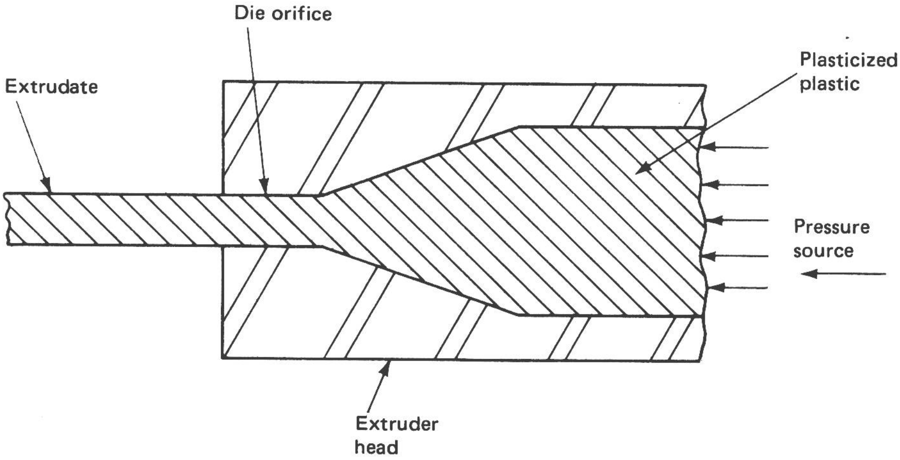

Fig. 1-1. Idealized extrusion scheme for plastics.

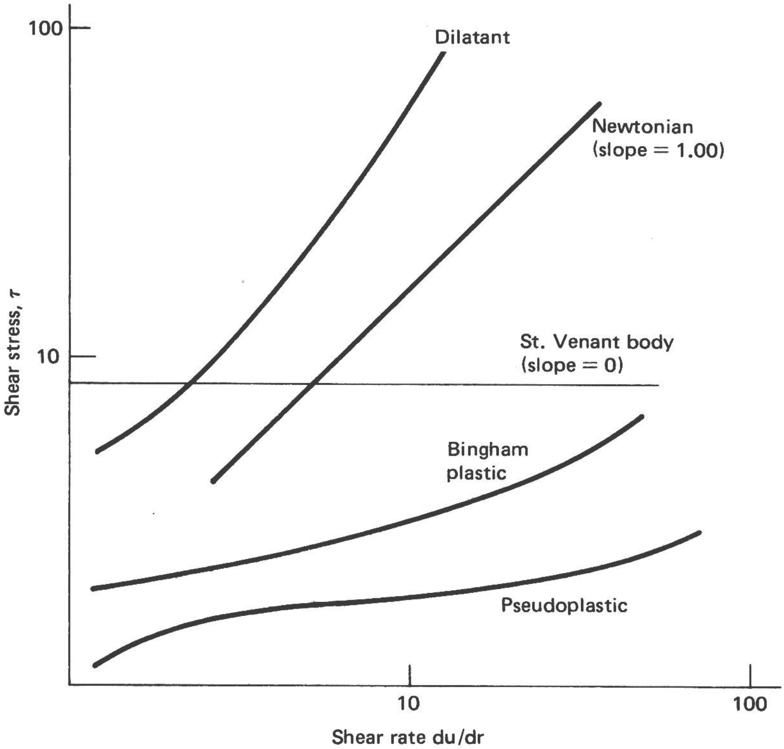

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Fig. 1-2. Flow curves for materials with different rheological characteristics.

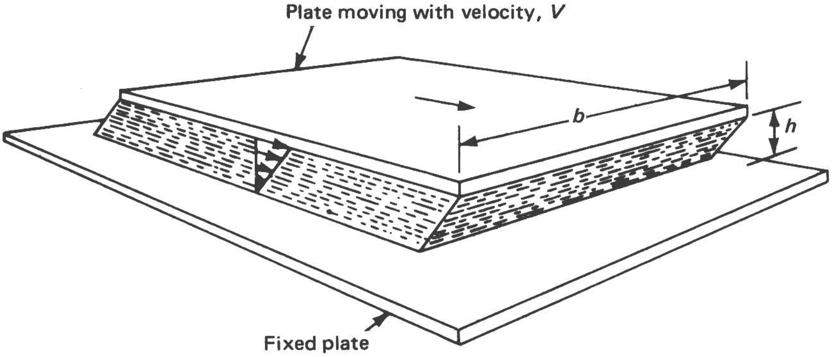

Fig. 1-3. Diagram for simple shear for a Newtonian fluid between parallel plates.

duration of the shearing forces, which have a tendency to align the polymer molecules in the flow direction and hence reduce the resistance to flow. As a result, the flow of the polymers through the die orifices is quite complex and requires analysis to determine the true shaping effects.

Data on the response of plastics materials to flow are generally reported in the literature in the form shown in Figs. 1-4 and 1-5. These are, respectively, the shear rate/shear stress curve and the shear rate/

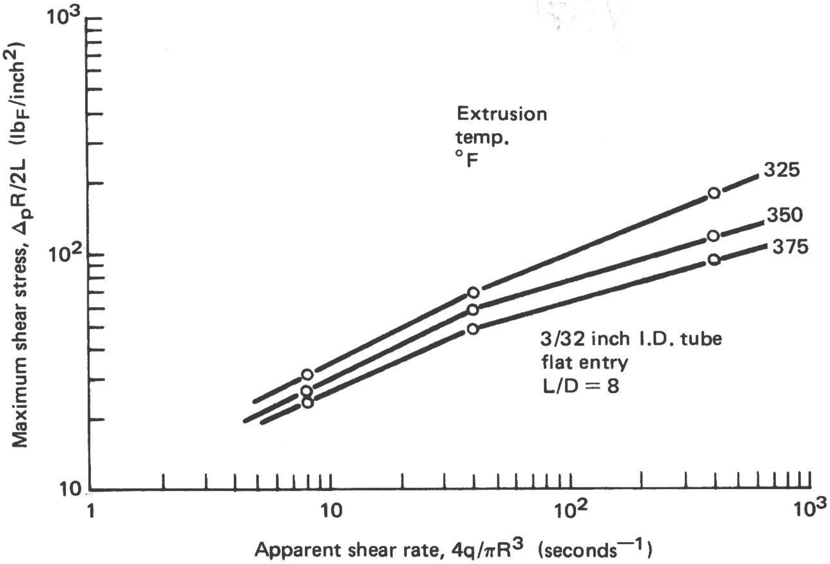

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Fig. 1-4. Plot of relationship between shear rate and shear stress.

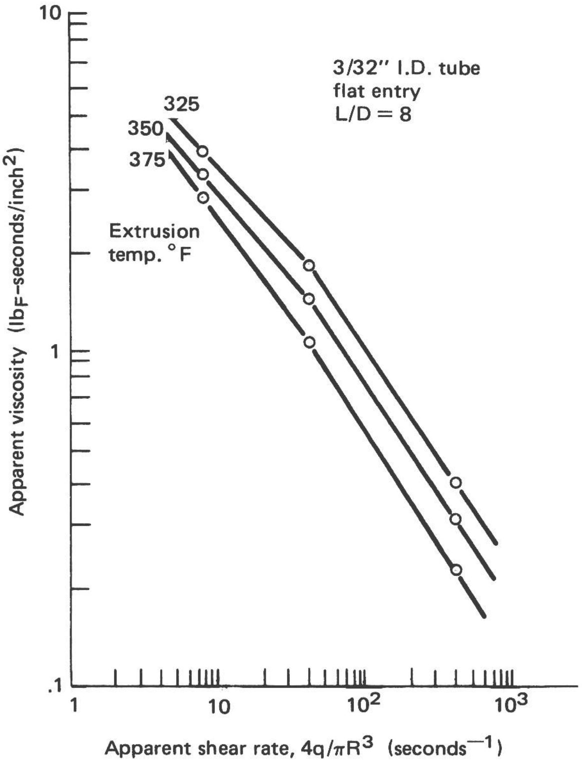

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Fig. 1-5. Plot of apparent viscosity versus shear rate.

PVC

viscosity curve for polyvinyl chloride, a material which is widely used. An examination of the curves reveals that, indeed, the viscosity is lower for high shear rates and the shear stress is lower for higher shear rates. The effect is to modify the flow through the die orifice. [illegible]

The flow modification caused by shear-dependent viscosity is shown clearly in Fig. 1-6. A Newtonian fluid would have a velocity profile flowing through the die as shown in Fig. 1-6a since the viscosity is independent of shear rate. With a material that has a viscosity dependent on the shear rate, this may be the initial shape of the velocity profile, but it will be modified rapidly since the material in the vicinity of the walls is sheared at a much higher rate than the material in the center of the extrudate stream. The ultimate velocity profile may be the one shown in Figs. 1-6 b, c, or d, or in the limit e. This results from higher dependence of viscosity on shear rate and the development of lower viscosity flows

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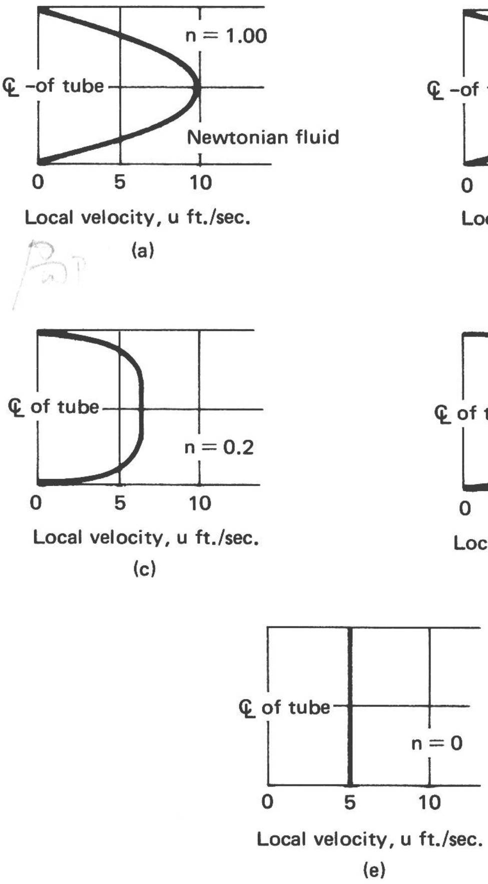

(a) (b) (c) (d) (e)

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Fig. 1-6. Velocity profiles of power-law fluids flowing inside round tubes in laminar flow.

near the orifice walls. The more dependent the viscosity is on the shear rate, the more closely the velocity profile will conform to Fig. 1-6e, a condition described as plug flow.

Those polymers that exhibit this property to a high degree are most readily extruded to the shape of the die orifice. The property is called thixotropy, and the polyvinyl chloride resin (whose rheology curves are shown in Figs. 1-5 and 1-6) is one that is easy to shape. In addition to the shear, the effect of temperature on the viscosity must be taken into account in order to understand flow through the orifices. Die swell, which is a result of the viscoelastic nature of the polymer melt, is another

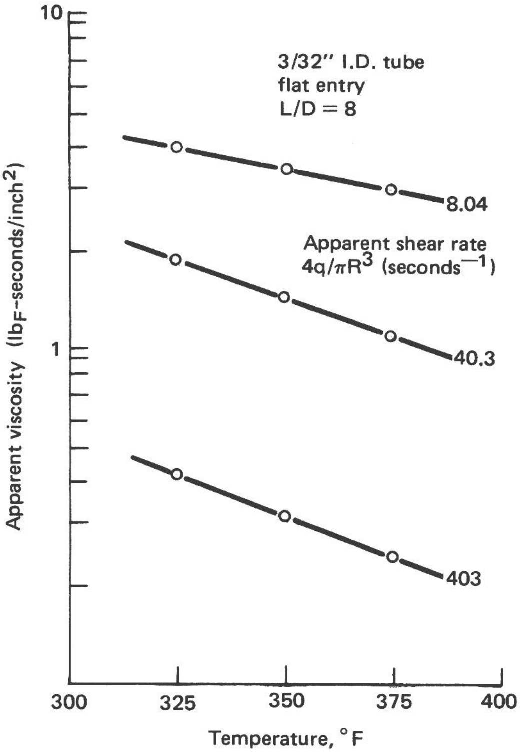

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Fig. 1-7. Effect of temperature on apparent viscosity.

variable. Energy, stored as pressure in the material going through the die orifice, is released on exiting and exhibited as an increase in the cross-sectional area of the extrudate. These effects are shown graphically in Figs. 1-7 and 1-8.

The reduced viscosity resulting from elevated temperature increases the average flow rate at constant pressure. In some cases the control of melt temperature can be used to balance and control the output from various areas of the die orifice by changing the local temperatures. One complication results from the temperature–viscosity dependence because the shearing effects are heat generating. Where there is a high shear rate, the material will heat up and reduce the viscosity. This adds to the viscosity reduction caused by the shear alignment of the polymers and will accentuate the transformation from parabolic to plug flow. It can also cause localized degradation of heat-sensitive polymers. [illegible]塞流动

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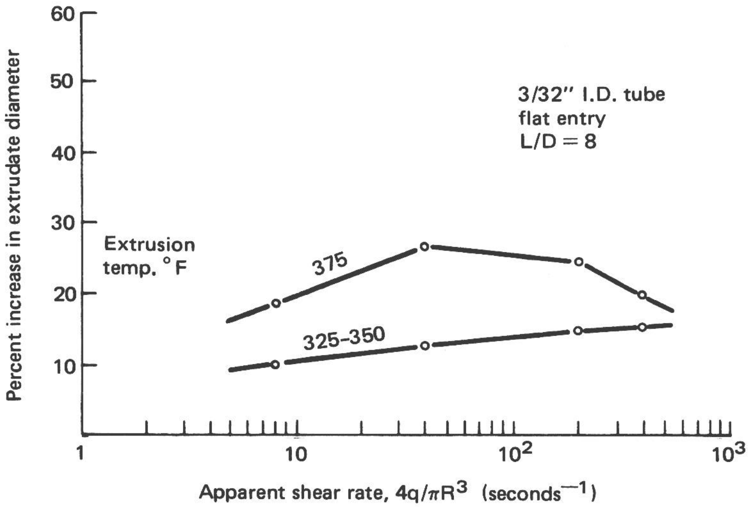

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Fig. 1-8. Effect of shear rate on die swell for two temperatures.

The die swell shown in Fig. 1-9 is a consequence of two mechanisms, both related to the properties of the polymer melt. Because of the viscoelastic nature of the polymer materials, pressure energy is stored as omnidirectional strain in the melt. This is converted to stresses perpendicular to the flow direction in the orifice. When the resin exits from the orifice, the stresses produce the strain exhibited as die swell. The other mechanism involved in die swell is a frictional one. This is exhibited by polymers which have a high coefficient of friction against the material of which the die orifice is made. By restricting flow of the boundary layer of the melt stream, the effect is to restrain flow at the die/material interface

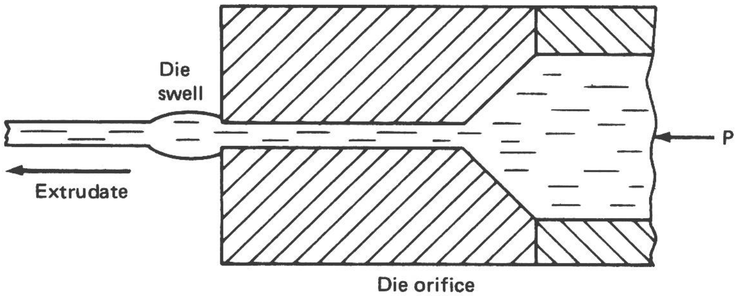

Fig. 1-9. Schematic of die swell in the flow of plastics.

while the bulk of the stream flows more freely. As a result, the extrudate will swell or bloom. This effect is more evident with materials like polyurethane which have high friction coefficients. It is almost nonexistent with materials such as polyethylene which are low-friction-coefficient materials against most die materials. The magnitude of the die swell can exceed 100% of the die orifice dimensions. This can be reduced by changes in material temperature, lubricant levels in the polymer melt, die land-length changes, and changes in the entry angle into the die orifice. Changes in the surface coatings on the die orifice change the swell ratio. It will also change the rate for the onset of melt fracture, a related phenomenon.

The phenomenon of melt fracture or melt instability is one in which the material coming out of a die orifice becomes so irregular or rough that the product is unusable. Melt fracture material is shown in Fig. 1-10, and the curve in Fig. 1-11 indicates that at some shear rates the effect will occur. It usually occurs at a high swell ratio, and it is a specific characteristic of a particular plastics formulation and die configuration. The initiation of melt fracture will also depend on such factors as temperature, lubricant levels, land length, entry angle, and surface quality in the die orifice. The appearance of melt fracture is the

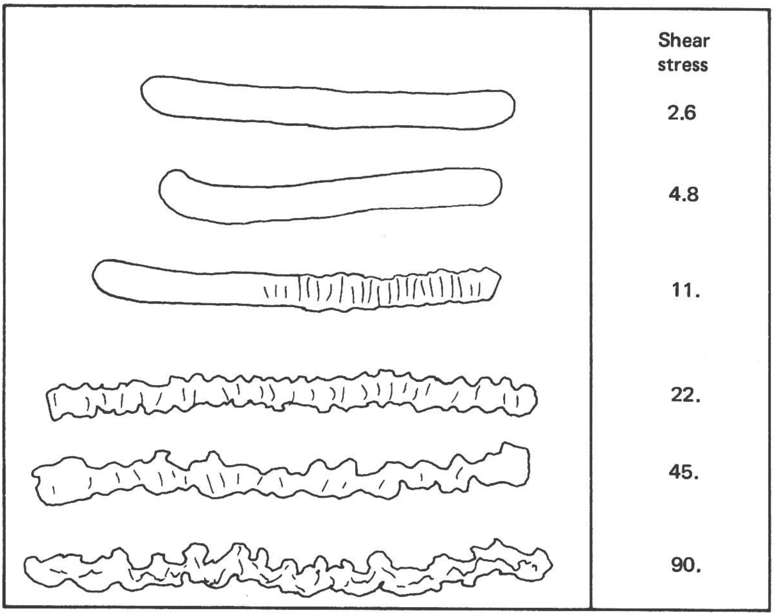

Fig. 1-10. Appearance of melt fracture in plastics.