Compressive Behavior of Worked Plastics

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Synopsis

The effect of temperature and loading history on the compressive stress–strain properties of two plastics is described. Polypropylene and nylon cylindrical specimens were reduced in height by 20%, 40%, 60%, and 80%, at room temperature and 25°F below the melt point and at two different deformation rates. Test specimens were cut from these worked billets along two directions, axially and radially. Subsequent compressive stress–strain tests were run using an Instron tester. Results of these tests are presented and compared with the stress–strain curve of the virgin material.

INTRODUCTION

With increased interest in the solid-phase forming of plastics (forming below the crystalline melting point), many papers have appeared in the literature describing the effect of working on the mechanical properties of plastics.[1-5] The purpose of this paper is to describe the effect of several forming variables, such as the amount of deformation, the billet temperature, and the rate of deformation (forming speed) on the compressive stress–strain of two plastics, polypropylene and nylon 6.

EXPERIMENTAL

Materials

Two materials were used for this study, polypropylene and nylon. Specimens were obtained from commercial-grade extruded (isostatic) polypropylene rod of an average density of 0.911 g/cm³. Nylon specimens were obtained from cast nylon 6 rod with a density of 1.148 g/cm³. Details of materials are shown in Table I.

Procedure

A simple upsetting operation was used to work the plastics. In this forming operation, a cylindrical billet is reduced in height by a certain amount. The billet size used was 1.5 in. long and 1.5 in. in diameter, as shown in Figure 1. Four different height reductions were produced: 20%, 40%, 60%, and 80%. Two billet temperatures were used, room temperature and an elevated temperature which was about 25°F below the melting

TABLE I

Characterization of Plastics

Manufacturer	Room temp. density, g/cc	Viscosity-average molecular weight[a]	Degree of crystal-linity,[b] %
Polypropylene, Cadillac Plastics (isostatic, extruded rod)	0.911	0.8[c]	71
Polyamide (nylon 6), Cadillac Plastics (cast and annealed)	1.148	3.21[d]	37

[a] The intrinsic viscosity was measured by dissolving in a solvent and using a viscometer, and then extrapolating to zero dilution.

[b] Obtained from density measurement only.

[c] At 293°F with phenyl ether as solvent.   An Ubbelohde viscometer was used.

[d] At 86°F with m-cresol as solvent.   A Cannon-Feuske viscometer was used.
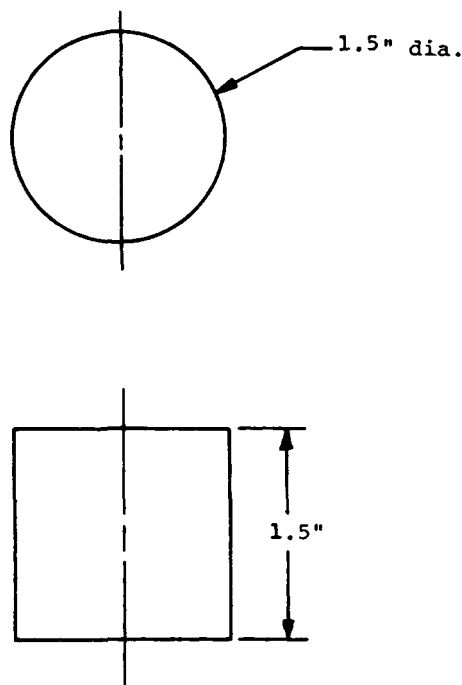

Fig. 1. Schematic diagram of upset billet.

point of the plastic.   When forming at the elevated temperature, the billets were preheated for 1 hr in an oven at 300°F for polypropylene and 400°F for nylon 6.

The billets were upset in a gas-operated high strain-rate machine where ram speeds up to 60 in./sec can be obtained.   This machine (Fig. 2) was developed at General Motors for testing tubular-shaped specimens in biaxial stress.[6,7]   A modification (Fig. 3) was made to the compression load-
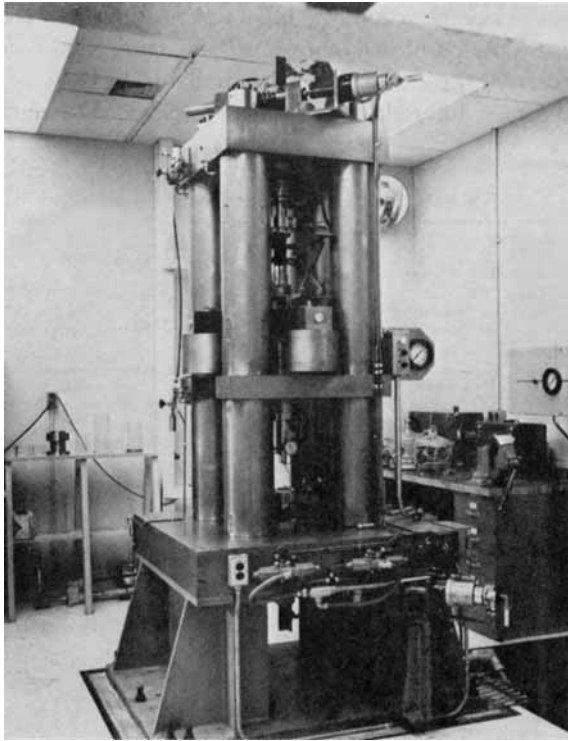
Fig. 2. Photograph of high strain rate machine.

ing center ram–lower platen area to accept the cylindrical compression specimens reported here. The 12.5-in.-diameter titanium loading piston achieves a nearly constant velocity after the charging gas from the lower reservoir has exhausted through the fast-acting valve. Prior to this, both the upper and lower reservoirs are charged with either air, nitrogen, or helium to equal pressures. The combination of pressure magnitude, orifice size on the fast-acting valve, and type of gas controls the velocity attained by the piston.

During the upsetting operation, deformation of the specimen was measured with a slide-wire potentiometer, and the load was measured by a load cell connected to the ram. Both parameters were recorded on magnetic tape and played back through analog-to-digital converters to a computer for data reduction.

Two different ram speeds were used, 0.18 in./sec and 18 in./sec. A 30-sec dwell time, defined as the time interval between the deformation reaching a maximum and the removal of external load from the formed part, was used for all the upset tests. A schematic diagram of the load and deformation history of the upset plastic is shown in Figure 4. The matrix of upsetting tests is summarized in Table II.

After the upsetting operation, the billets were allowed to recover at room temperature for a period of one month. Then, compression test specimens were machined from these billets, both radially and axially. Although the specimen dimensions differed for each test condition, the length-to-diameter

TABLE II
Matrix of Upset Tests

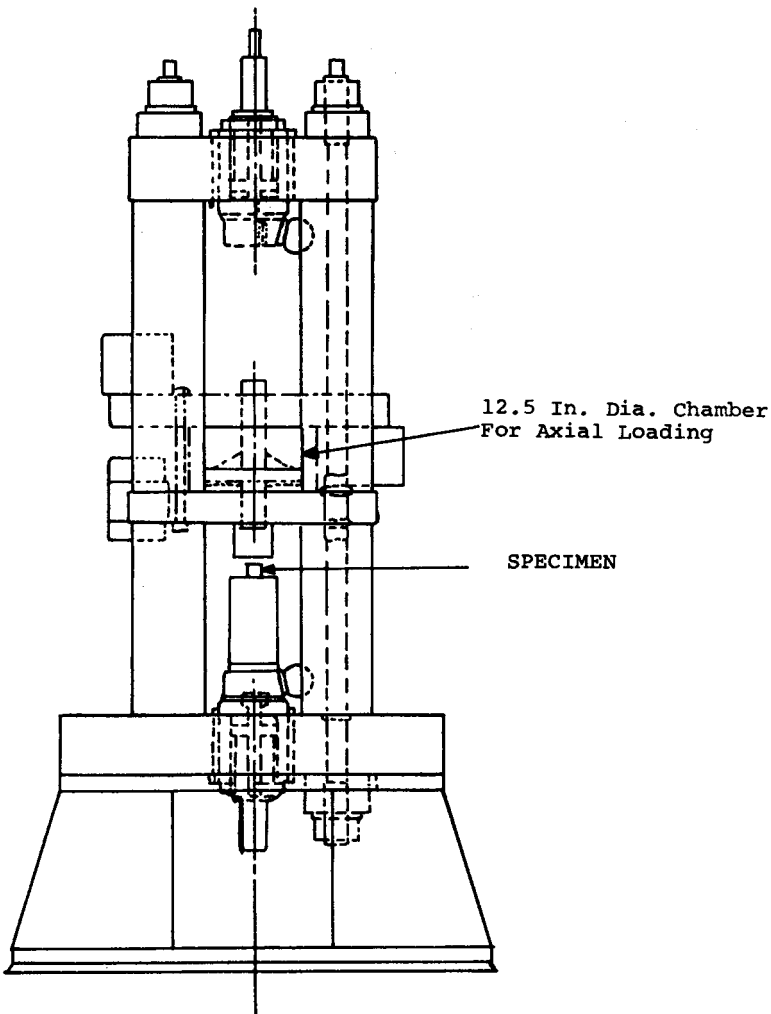| Height reduction, %	20	40	60	80
Deformation rate, in./sec	18	18		
Billet temperature, °F	73	25		
		Below melt		
Dwell time, sec	30			

Fig. 3. Schematic of compression loading modification of high strain rate machine.
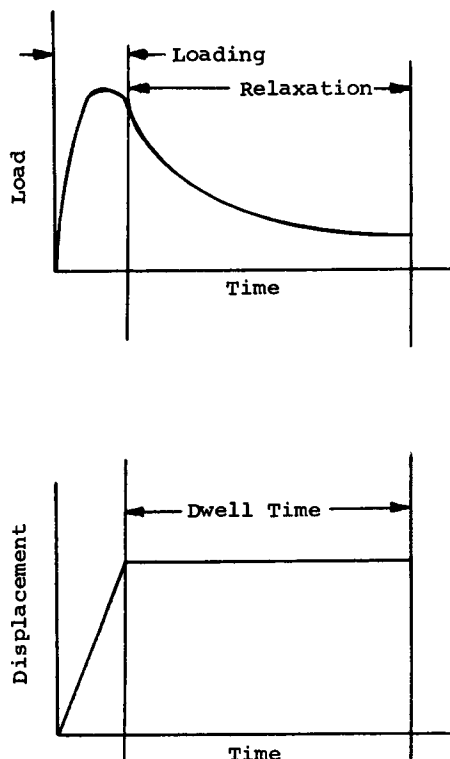
Fig. 4. Schematic diagram showing load and displacement on the plastic during upsetting operation.

ratio of the specimens was kept constant at 4/3. The subsequent stress–strain tests were run on an Instron tester using a strain rate of 0.1/in./in./min.

RESULTS AND DISCUSSION

During the initial upsetting operation, the time required to achieve the required amount of height reduction was very short because of the speed of deformation at both strain rates. Consequently, very small amounts of heat were conducted away to the atmosphere and surroundings. Hence, the upsetting tests can be considered to be adiabatic. However, the upsetting temperatures stated should be considered as initial temperatures only since the plastic would tend to heat due to plastic work.

Figure 5 shows stress–strain curves of polypropylene which had been upset at 300°F, at a rate of 18 in./sec and by 20%, 40%, 60%, and 80% reduction in height. The curves show a drop in the elastic modulus with increased percentage reduction in height, but show an increase in the post-yield compressive strength compared to the virgin plastic. Strain hardening increases with increase in height reduction. The stress–strain curves
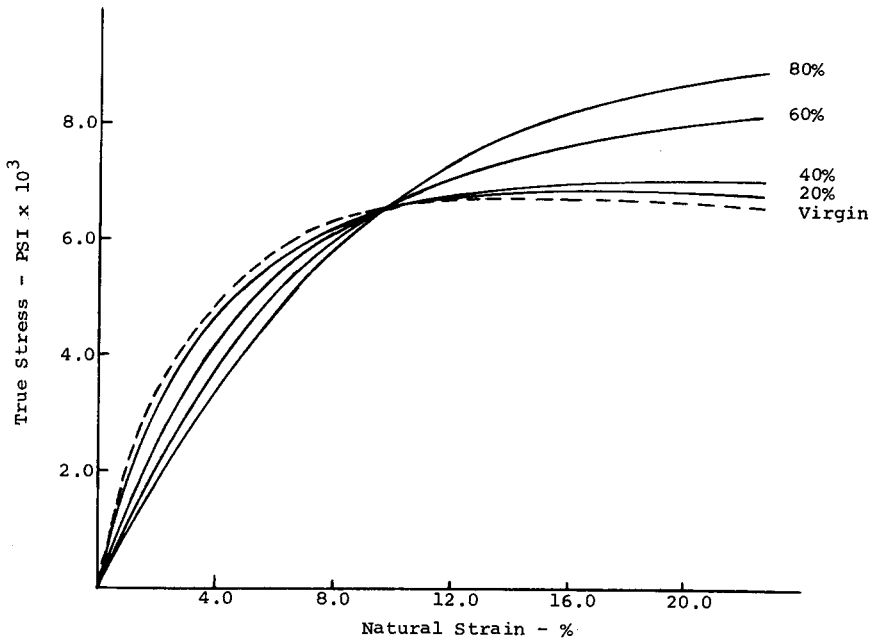
Fig. 5. Subsequent compressive stress–strain curves for polypropylene specimens cut along the axial direction from billets that had been upset at 300°F, 18 in./sec, and by 20%, 40%, 60%, and 80% reduction in height.

of polypropylene which had been upset at a rate of 0.18 in./sec show very little difference from those of Figure 5 and are not shown. Figure 6 shows stress–strain curves of polypropylene upset at room temperature. These show a more pronounced decrease in the elastic modulus and a drop in compressive strength. The postyield strength decreases with increase in height reduction. Nylon shows similar behavior to that of polypropylene, and only results of tests on billets that had been upset at 400°F are shown in Figure 7.

Dilation must occur during the upsetting operation, and it is more massive for the higher percent reduction specimens. Dilation occurs apparently as a result of packing the plastic in a less favorable form so that its density decreases during the initial compression. Thus, the subsequent stress–strain behavior is of a plastic of lower density than the virgin material and, consequently, the elastic modulus is slightly lower for the worked plastic than for the higher-density virgin sample.

The results of Figures 5 and 7 which show a marked increase in the postyield compressive strength of polypropylene and nylon worked at elevated temperatures suggest a high degree of molecular orientation perpendicular to the axis of the billet. This is shown schematically in Figure 8. The subsequent postyield compressive stress–strain behavior of a specimen cut along the axial direction must involve applying higher stresses than in the case of the virgin material, because the already radially oriented and packed
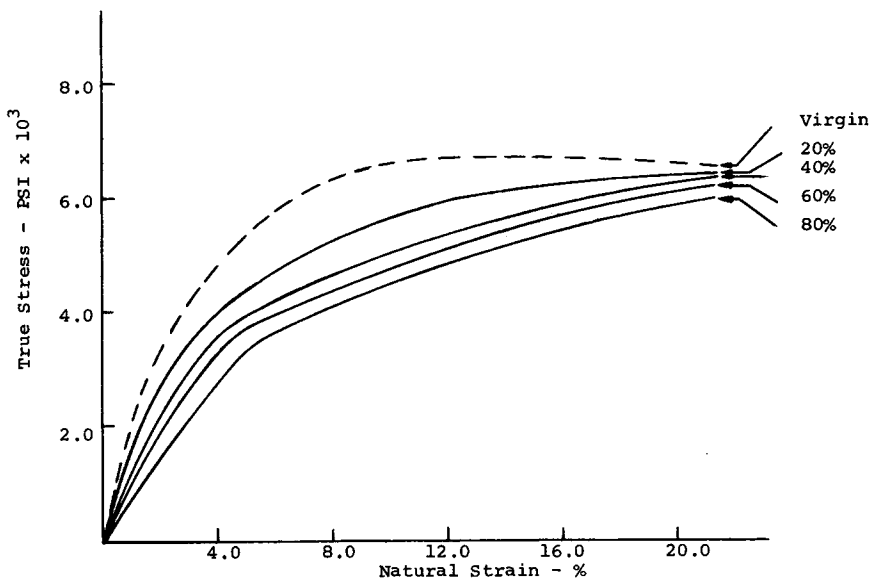
Fig. 6. Subsequent compressive stress–strain curves for polypropylene specimens cut along the axial direction from billets that had been upset at 73°F, 18 in./sec, and by 20%, 40%, 60%, and 80% reduction in height.

molecular chains will be required to flow radially again owing to the Poisson effect. Since the viscous resistance to radial flow of the molecules in Figure 8b would be higher than that of the randomly oriented virgin material of Figure 8a, it should be expected that the compressive yield strength would be higher also. Thus, this orientation would make the axial direction the strong orientation direction, whereas the radial direction would be the weak orientation direction, for subsequent compressive loading. Tests on specimens cut along the radial direction from polypropylene billets upset at 300°F indicate a drop in the postyield compressive strength. This is shown in Figure 9.

To explain the drop in the postyield compressive strength of polypropylene worked at room temperature (Fig. 6), sections of the worked billets were examined for microcracks under a scanning electron microscope. The artificially induced fracture surfaces looked at were cut both parallel and perpendicular to the axis of the billet. No microcracks were observed. It was concluded that the upsetting operation at room temperature did not induce microcracks in the plastic which might have weakened it.

The mechanism of polymer deformation offers another explanation for the increased or decreased postyield compressive strength.[8] Large deformations of polymers may occur by the breaking of secondary and/or primary bonds. When secondary bonds (those which bond molecular chains together) break, the result is an unraveling of the polymer structure. The breakage of primary bonds results in the breaking of the backbone structure of the molecule. Both of these mechanisms are thermally activated, and
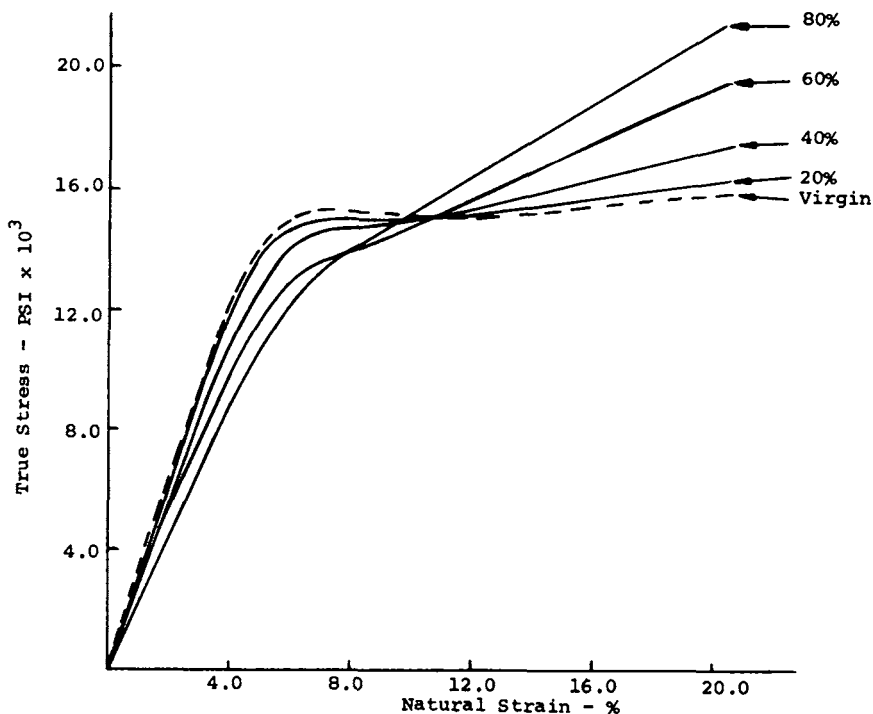
Fig. 7. Subsequent compressive stress–strain curves for nylon specimens cut along the axial direction from billets that had been upset at 400°F, 18 in./sec, and by 20%, 40%, 60%, and 80% reduction in height.
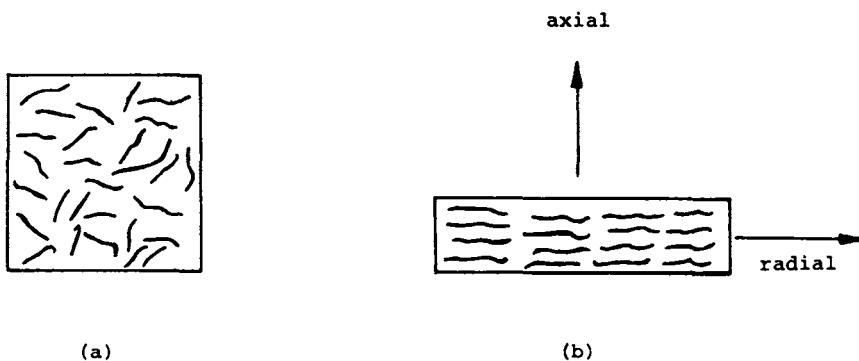

(a)   (b)

Fig. 8. Orientation of molecules in the plastic: (a) before upsetting; (b) after upsetting.

recent studies[9-11] indicate that for semicrystalline polymers at relatively low deformation temperatures, substantial backbone rupture or primary bond breakage occurs. On the other hand, deformation at higher temperatures tends to break secondary bonds. Breaking of these secondary bonds would be expected to have less effect on strength degradation than would the breaking of primary bonds.
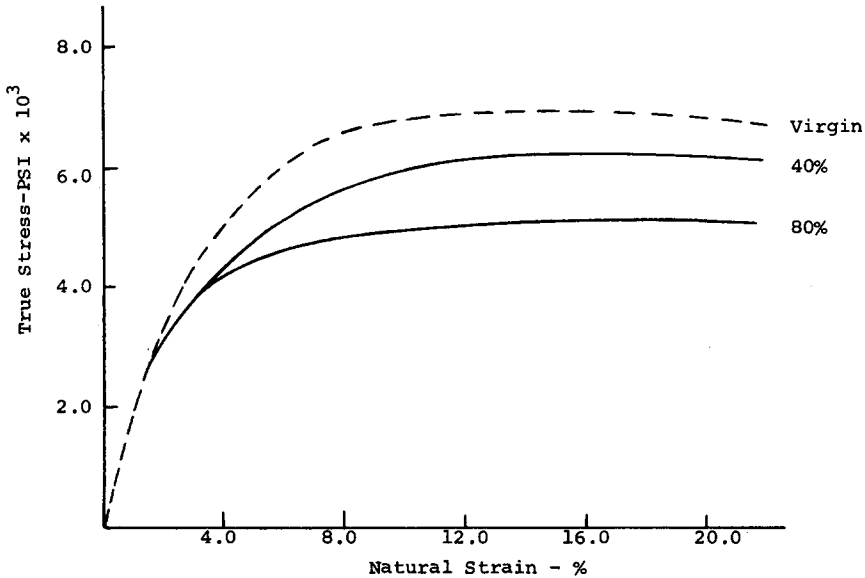
Fig. 9. Subsequent compressive stress–strain curves for polypropylene specimens cut along the radial direction from billets that had been upset at 300°F, 18 in./sec, and by 40% and 80% reduction in height.

Since the reduction in the postyield strength due to breaking of bonds during the upset loading is being offset by the competing process of work hardening due to the alignment of the molecules in the radial direction, as explained previously, the absolute value of the strength for subsequent loadings may be either increased or decreased. At high temperatures, the increase in strength due to alignment of molecular chains exceeds the decrease in strength due to the breaking of secondary bonds during the upset operation. Consequently, one observes the marked increase in the postyield compressive strength. At room temperature, however, the decrease in strength due to the breaking of backbone chains or primary bonds during the upsetting operation exceeds the increase in strength due to alignment of the molecular chains. Hence, the decrease in the postyield compressive strength is observed for the plastics upset at room temperature.

CONCLUSIONS

Mechanical working at elevated temperatures close to the crystalline melting point of plastics increases their postyield compressive strength in the direction of loading, whereas room-temperature mechanical working induces a reverse effect. The compressive strength is decreased in the direction perpendicular to the loading direction by room- and elevated-temperature working. The increase or decrease in strength is always proportional to the amount of prior deformation. The elastic modulus is decreased by both room- and elevated-temperature working.

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