The Effect of Strain Rate and Heat Developed During Deformation on the Stress-Strain Curve of Plastics

Temperature rise developed during deformation can have significant effects on the stress–strain relationship. Four hard plastics are tested at various strain rates, and temperature changes are measured during deformation of the specimen

by S. C. Chou, K. D. Robertson and J. H. Rainey

ABSTRACT—Polymethylmethacrylate, cellulose acetate butyrate, polypropylene and nylon 6-6 have been characterized in compression at various strain rates from 10^{-4} s^{-1} to 10^3 s^{-1} at room temperature. A medium strain-rate machine and a split-Hopkinson-bar apparatus are used in conducting the experiments. The temperature rise developed during deformation is also measured by using a thermocouple. All four materials tested definitely show a viscous effect at the beginning of the deformation and a plastic flow follows thereafter. Test results also indicate that the temperature rise developed during deformation cannot be neglected in determining the dynamic response of those materials investigated in this study.

Introduction

It is well known that polymeric materials are very sensitive to strain rate and temperature. In the past two decades, many polymeric materials have been characterized. However, most studies concern the determination of mechanical properties of plastics under tensile testing. The testing of plastics in compression is a neglected field. Percy and Meikle[1] made a thorough survey of the work regarding the properties of plastics in compression. A summary of all the work from 1949 to 1969 cited by Percy and Meikle is given in Table 1. By examining the work listed in the table, it is noticed that only a few studies give results of plastic in compression at medium strain rates (say, from 0.5 to 50 s^{-1}); there is even less work reported in the range of strain rates for medium to high (50 to 10^3 s^{-1}) covered in the same investigation.

When a specimen is formed other than elastically, some of the work done in producing the deformation will appear as heat. Although this statement is true for all metallic and nonmetallic materials, the temperature rise in metals during the deformation is, in general, neglected in analyzing the data due to their relative insensitivity to these temperature changes. On the other hand, since polymeric materials are much more sensitive to the temperature change than metals in the region of interest in this study, it is expected that the heat developed during deformation will affect the stress-strain curve. Hall[16] has made a theoretical study of the temperature rise developed during extension of a filament by employing the first law of thermodynamics. No work has been reported on measuring the temperature rise and comparing with the theoretical value.

In this study, two amorphous polymers, namely, polymethymethacrylate (PMMA) and cellulose acetate butyrate (CAB), and two semicrystalline polymers, polypropylene, and nylon 6-6 have been systematically studied. A specially designed "medium strain-rate" machine[17] is used for strain rates from 10^{-4} s^{-1} to 50 s^{-1}, and a split-Hopkinson-bar apparatus[18] is used for strain rates from 50 s^{-1} to 5000 s^{-1}. The temperature rise developed during deformation was measured by a thermocouple embedded in the specimen. The results will be presented, and the effect of heat developed during deformation on the stress-strain curve will be discussed.

Experimental Test Techniques

The Medium Strain-Rate Machine (MSRM)

DESCRIPTION OF MACHINE—This specially designed machine, Fig. 1, (for details see Ref. 17) has two

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TABLE 1—SUMMARY OF WORK DONE IN COMPRESSION OF PLASTICS (FROM PERCY AND MEIKLE)[1]

Investigator	Date	Materials	Strain Rate s⁻¹	Temp °K
Kolsky[2]	1949	polyethylene	1,900-7,500	293
		PMMA	575	292
		natural rubber	5,000	290
Back, Campbell[3]	1957	phenol formaldehyde	500	Room
		phenol formaldehyde composite	500	
Ripperger[4]	1958	polyethylene	2,200;5,700	210;300;340
		PTFE	2,200	300
		nylon	2,200	300
		CAB (Tenite M)	2,200	300
		CAB (Tenite H)	2,200	300
		polystyrene	2,200	300
		polyvinylidene chloride	2,200	300
Volterra, Barton[5]	1958	natural rubber	41	274;294
		hard rubber	25	
		polychloroprene (Neoprene GNA)	33	
Ely[6]	1963	polyethylene	0.4-16	233-323
		ethyl cellulose	0.4-7.4	
		CAB	0.4-4.3	
Tardif, Marquis[7]	1963	PMMA	150-590	Room
		polycarbonate	327-1028	
		nylon	500;860	
		polyacetal	450;670	
		PTFE	570-1,420	
		epoxy	150-690	
Davies, Hunter[8]	1963	PMMA	1,550;5,600	Room
		nylon 6	2,000;8,000	
		polyethylene	1,270;3,700	
		PTFE	1,430	
		PVC	1,250	
Lindholm[9]	1964	epoxy	930	Room
Hoge[10]	1965	polypropylene	0.6-1,610	Room
Maiden, Green[11, 12]	1966	PMMA	0.005-1,210	Room
Hold[13]	1968	PMMA	10^{-5}-1,000	273-388
Dao[14]	1969	polyethylene nylon 6-6	0.00033-33	77-450
Meikle[15]	1969	PMMA	0.07-33	200-360

operating modes: the servo-controlled closed-loop mode covers the strain rate from 10^{-4} to 10^{-1} s⁻¹, and the open-loop mode covers the strain rate from 1 s⁻¹ to 50 s⁻¹. In other words, the machine uses the principle of open-loop which was used by Clark and Wood,[19] Campbell and Marsh,[20] and Maiden and Green[11,12] in conjunction with the conventional servo-controlled hydraulic-testing technique. The interchange of operating modes from either oil to gas, or gas to oil is accomplished by utilizing an automatic purging sequence. The MSRM was designed to have a load capability of 140,000 lb. Additionally, the loading frame was designed to be sufficiently rigid so that the maximum load would produce no more than 0.005-in. total machine stretch.

For the servo-controlled closed-loop mode, there are three feed-back systems incorporated with a function generator; namely, the load, displacement,

and gaged specimen so that various constant rates of load, displacement and strain can be achieved. For example, strain rates from 10^{-4} s⁻¹ to 10^{-1} s⁻¹ can be attained in closed-loop operation.

For the open-loop mode, the principle of operation and analytical study of piston motion can be found in Refs. 12 and 17. Briefly, the system consists of two fast-acting valves equipped with an adjustable plate which has various orifice sizes ranging from 0.125 in. to 1.0 in. By adjusting the size of orifice, the pressure in the cylinder, and the length of stroke of the piston, a desired nominal displacement rate can be obtained for a given material. A computer program[12] is used to estimate a set of parameters, i.e., orifice size, gas pressure, and stroke which will give the desired rate of displacement. A strain rate of 50 s⁻¹ is attainable without any difficulty. Higher strain rates may be obtained with MSRM, but the inertia effect must be

considered in the analysis.

METHOD OF DATA RECORDING AND REDUCTION—In order to eliminate any possibility of changes of properties caused by the adhesives used in strain-gage application, the strain is calculated by measuring the piston-head movement for all tests. For strain rates from 10^{-4} s^{-1} to 10^{-2} s^{-1}, the load-cell output and the output from a dual-film potentiometer located inside the piston are recorded vs. time on a X-Y-Y′ recorder. These recorded time histories are then converted to load time and pistonhead-displacement time histories by using the calibration factors which are obtained before every test. A constant displacement rate is admittedly not a constant strain rate. The deviation will be the difference between the engineering strain and true strain divided by the time and can be estimated as follows: The relationship between the engineering and true strains is given by

$$e = \ln (1 + \epsilon)$$
$$= \epsilon - 1/2\epsilon^2 + 1/3\epsilon^3 - \dots \qquad (1)$$
$$\text{or} \quad e - \epsilon = - 1/2\epsilon^2 + 1/3\epsilon^3 - \dots$$

where e = true strain

ϵ = engineering strain (compressive strain is considered as a negative quality).

For a maximum engineering strain of 20 percent, the difference will be 2 percent with respect to the total strain which is negligible in the study of strain-rate effect.

For strain rates from 10^{-1} s^{-1} to 50 s^{-1}, the output from load cell and displacement potentiometer are recorded by a Tektronix 564B oscilloscope. Figure 2(a) shows a typical Polaroid camera record obtained from a test on polypropylene at a strain rate of 2 × 10^{-1} s^{-1}. The upper trace is proportional to specimen load, and the lower trace is proportional to the displacement of piston rod. These Polaroid records are then converted to load vs. time and pistonhead displacement vs. time by using the calibration factors of the oscilloscope. The calibration is done each day before tests are carried out.

The Split-Hopkinson-bar Apparatus

SUMMARY OF TECHNIQUE—A split-Hopkinson-bar apparatus has been used to conduct tests at strain rates higher than those obtained with the medium strain-rate machine. The range of strain rate achievable with such a device is from about 50 s^{-1} to 10^4 s^{-1}.

The principle of this method is to accelerate a striker down a launch tube by compressed gas and impact an input bar with a constant velocity. A short cylindrical specimen is sandwiched between the input and output bars of the same diameter. The resulting stress wave from the impact travels down the input bar with part of the wave being reflected at the specimen and part being transmitted into an output bar. The response of the bars, which remains elastic, is measured by strain gages mounted on the bars. The recorded wave shapes are then analyzed to obtain a
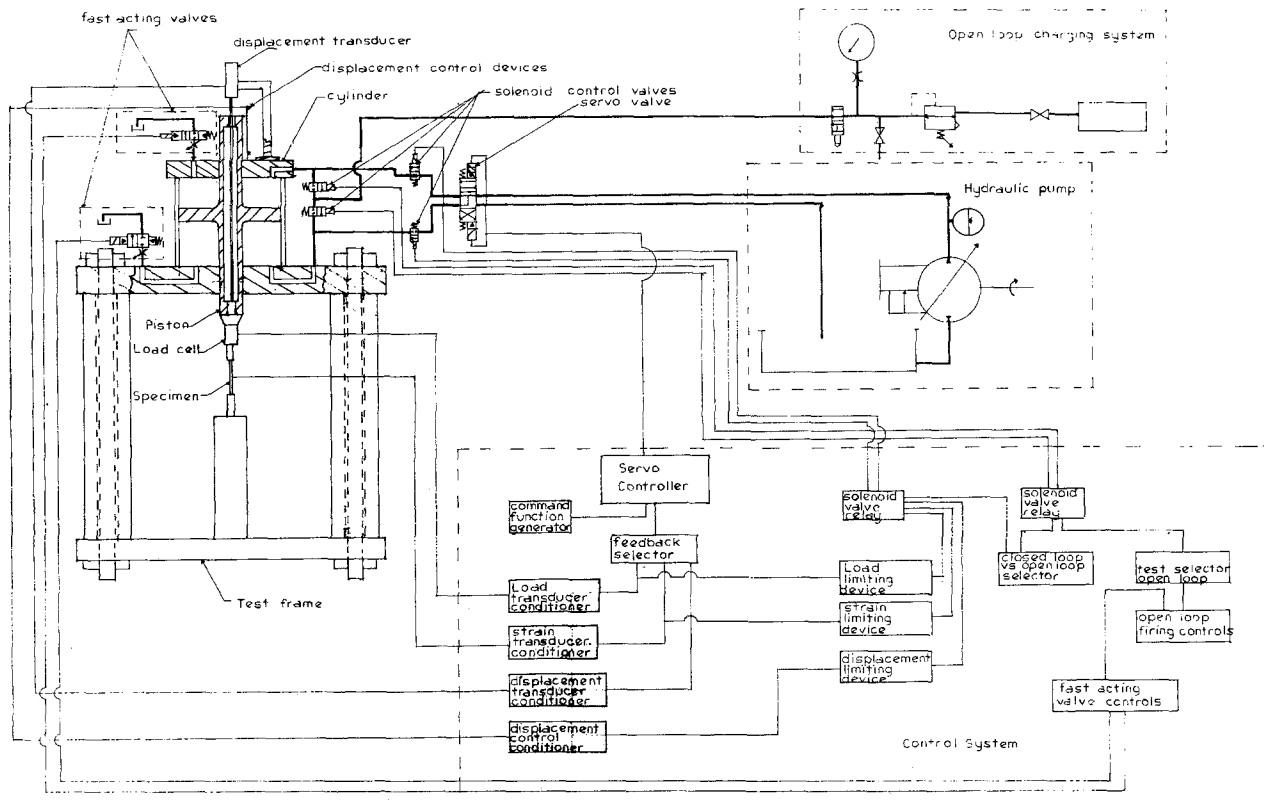

Fig. 1—Schematic of controls for the medium strain-rate test machine

stress-strain and strain-rate curve for the test material by assuming that the theory of one-dimensional wave propagation holds. Details of the operation and analysis of test results are given in Ref. 18.

DESCRIPTION OF DATA REDUCTION—Figure 3 shows two typical Polaroid records obtained from a test of PMMA. Figure 3(a) gives the incident wave while the top trace of Fig. 3(b) is the resultant of incident and reflected wave, and the bottom trace is the transmitted wave. Polaroid records as such are converted to digital representations by using a telereader. This digital representation is then changed to stress vs. time by using the proper scale factors. Once these stress–time curves are obtained, a stress–strain strain-rate relationship of the test material is obtained by averaging the values for the two specimen faces.

Temperature Measurement

Temperature rise developed during deformation is measured by a thermocouple embedded in the specimen. The thermocouple is made by welding together into a bead, copper and constantan wires with diameters of 0.010 in. The final size of the bead is about 0.030 to 0.040 in. A hole with approximately the same size as the bead is drilled radially into the cylindrical specimen to its center. The bead of the thermocouple is then forced into the hole, so that an intimate contact between the thermocouple and the surrounding specimen material is obtained particularly when the specimen is under compression. The voltage output of the thermocouple is essentially linearly proportional to the temperature rise up to $600°$ F with a ratio of 0.025 mV/$°$F. The thermocouple is directly connected to an oscilloscope through a Tektronix 3A3 differential plug-in with a smallest scale of 0.1 mV/division for tests with strain rates above 10^{-1} s^{-1}. For tests with strain rates 10^{-4} s^{-1} to 10^{-2} s^{-1}, the temperature rise is recorded by an
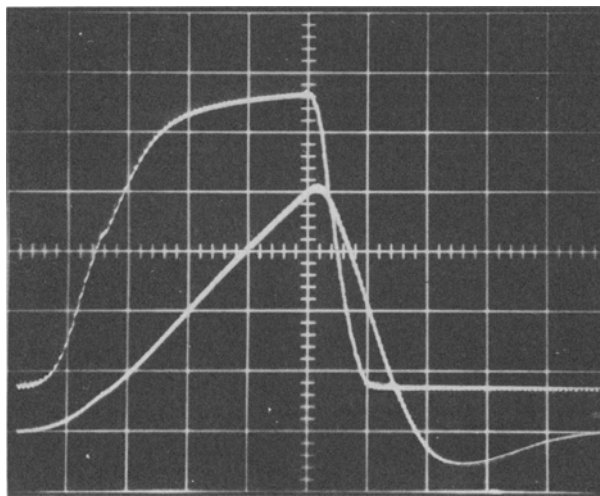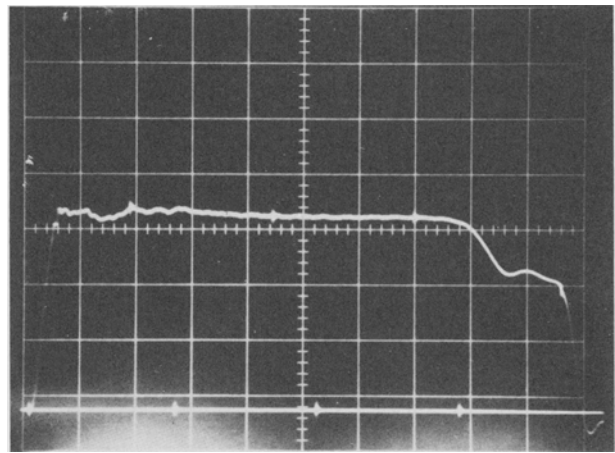

(a) Time: 200 ms/div
    Load: 2 mV/div (~200 lb/div)
    Displacement: 50 mV/div (~0.036 in./div)
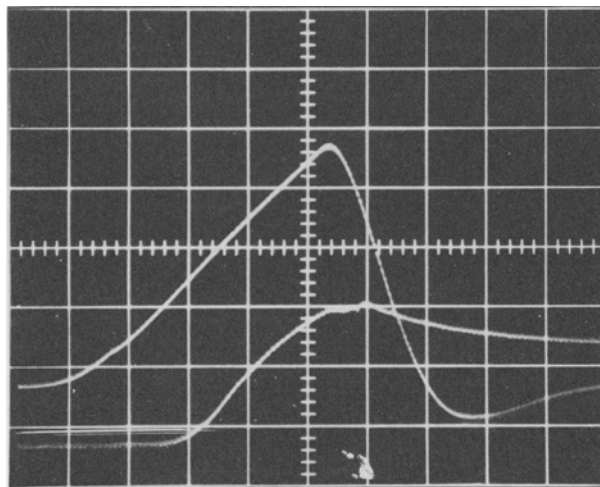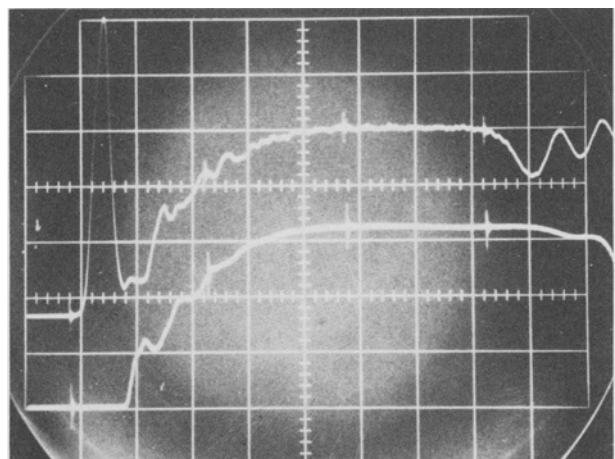

(b) Time: 200 ms/div
    Displacement: 50 mV/div (~0.036 in./div)
    Temperature: 0.1 mV/div (~4° F/div)

Fig. 2—Typical Polaroid record from medium strain-rate machine of compression test on polypropylene (0.375-in. diameter × 0.500-in. long)
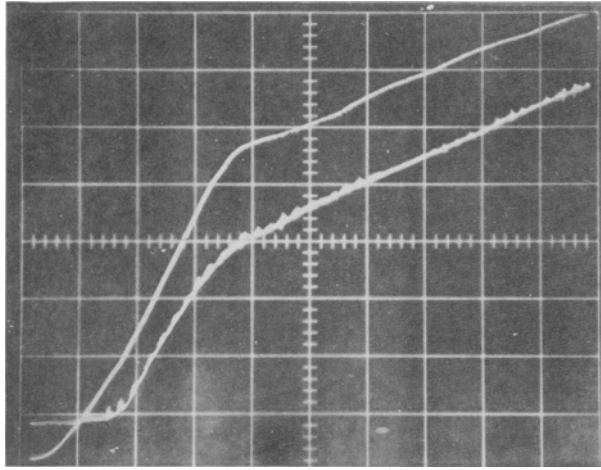

(a) Incident wave–time: 20 ms/cm
    Stress: .2 V/cm

(b) Resultant of incident and reflected wave (top); transmitted wave (bottom).
    Time: 20 ms/cm
    Stress: .2 V/cm

Fig. 3—Polaroid records from modified Hopkinson-bar compression test on PMMA .375 × .500-in. long

Time: 5 ms/div
Displacement: 50 mV/div (~0.036 in./div)
Temperature: 0.1 mV/div (~4° F/div)

Fig. 4—Displacement and temperature-time record from medium strain-rate machine of compression; test on polycarbonate 0.375-in. diameter × 0.500-in. long

Fig. 5—Stress–strain and strain–temperature-rise curves for PMMA (Rohm and Haas Plexiglas II) at various strain rates in compression at 72°F

X-Y recorder.

The response time of the thermocouple may be calculated by using the following expression:[21]

$$\tau = \frac{V\rho C_p}{hA} \qquad (2)$$

where τ is the response time, V designates the volume of a thermocouple, ρ the density, C_p the specific heat, A the surface area and h the coefficient of heat transfer. However, the parameter h which characterizes the interface between the thermocouple and the solid cannot be determined easily. In this study, the response time of the thermocouple is estimated experimentally. A specimen is compressed to a large percentage of strain at a rate which yields an adiabatic deformation (details will be discussed later), and the specimen is held at constant strain for a period of time. The temperature developed during deformation and during dwell is measured by the thermocouple. The idea is that, under an adiabatic-deformation condition, the temperature rise may be assumed to be linearly related to the strain after the specimen has yielded. Should the response time of the thermocouple be too slow in measuring the temperature rise, the output of the thermocouple would lag behind; consequently, a temperature rise would be indicated after a maximum strain is obtained. Figure 4 shows the results of this experiment on CAB. The top trace gives the pistonhead-displacement history, and the bottom trace is the output of a thermocouple embedded in the specimen. The strain rate is approximately 20 s^{-1}. It is noticed that, at the beginning, the temperature rise is very small. This is due to the viscous behavior of material (see next section for detailed discussion). After the displacement reaches a value corresponding to 8- to 10-percent engineering strain in the specimen, the rate of temperature rise increases significantly and is linearly proportional to the displacement rate as it was assumed. Although in this
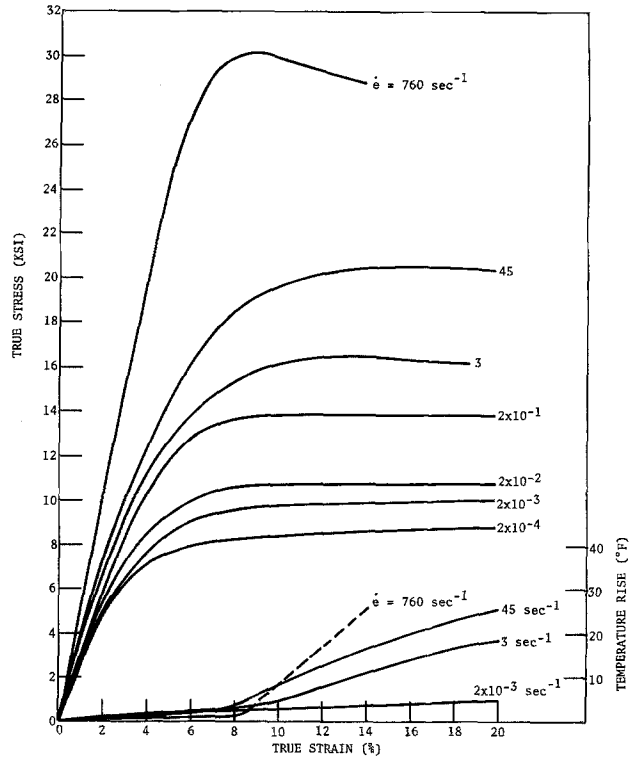
test the displacement was not held constant (equivalent to a zero displacement rate) after the specimen had been deformed to 30-percent engineering strain, the change of displacement rate was sufficiently large to serve the purpose of estimating the response time of a thermocouple. If the backward extrapolation method in determining the yield stress is applied on both traces here, it is found that there is practically no time lag between the two curves. Based on this observation, it is concluded that the response of the copper-constantan thermocouple with the size of bead of 0.03 to 0.040 in. is fast enough to be used in this study.

A typical test result of temperature rise is shown in Fig. 2(b). The top trace is the displacement-time history, and the bottom trace is the temperature-rise-time history. They are cross plotted to obtain the strain vs. temperature-rise curve.

Experimental Results and Discussions

Four commonly used plastics, namely, polymethylmethacrylate, cellulose acetate butyrate, polypropylene, and nylon 6-6, have been tested in compression for six strain rates ranging from 10^{-4} s^{-1} to 2 × 10^3 s^{-1} at 72° F (room temperature). The specimens are made from either a single plate or block to eliminate the wide variation of material properties. Their configuration is a short cylinder of 3/8-in. diameter and 1/2-in. length, which is compatible with both testing machines. The ends of each specimen were lubricated with Molykote before testing. The recorded load-time and displacement-time histories are cross plotted
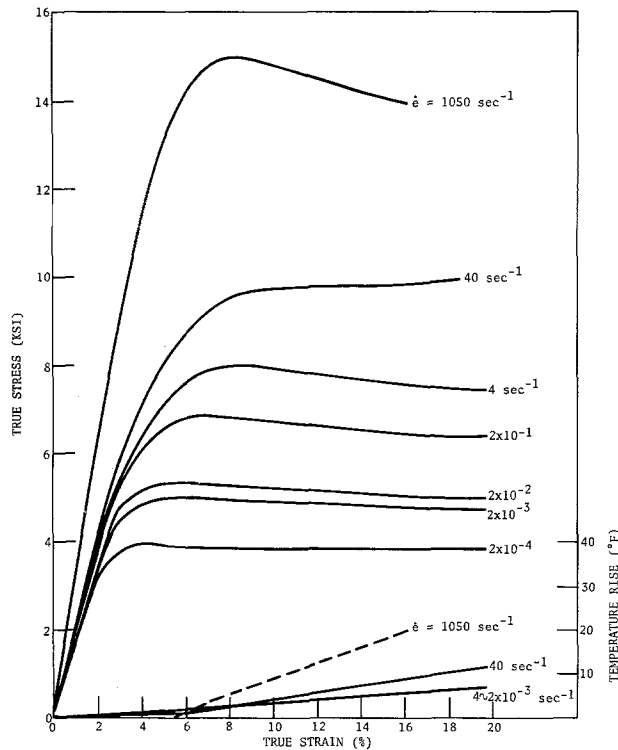
Fig. 6—Stress–strain and strain–temperature-rise curves for cellulose acetate butyrate (Kodak Tenite Butyrate) at various strain rates in compression at 72° F
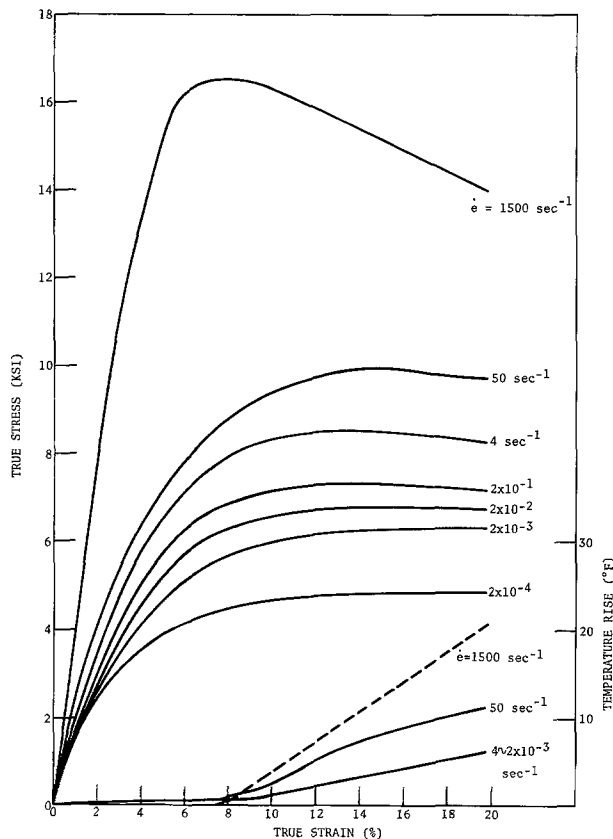

Fig. 7—Stress–strain and strain–temperature-rise curves for polypropylene at various strain rates in compresion at 72° F
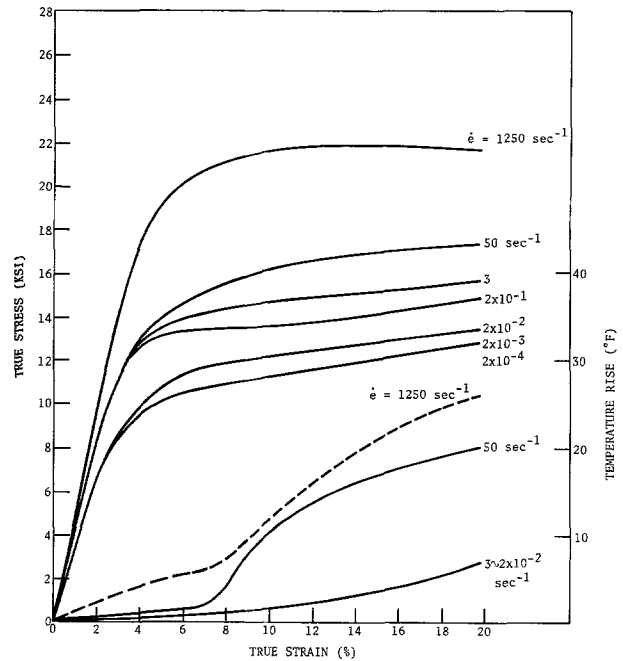

Fig. 8—Stress–strain and strain–temperature-rise curves for nylon 6-6 at various strain rates in compression at 72° F

with respect to the time to obtain stress-strain strain-rate curves. The temperature rise developed during deformation is measured until an engineering strain of 20 percent is reached. For such large strain, it will be more meaningful to use true strain and stress instead of engineering stress and strain in the data reduction. The relation between the true strain and engineering strain is given by eq (1). The true stress, S, is related to engineering stress, σ, in the following manner:

$$S = \sigma(1 + \epsilon) \tag{3}$$

This relationship is derived from a fact, which has been recognized by the investigators (e.g., Ref. 22) in the field of polymer science, that the volume of a specimen of materials used in this study remains essentially constant under uniaxial-stress conditions.

In this study, even though all specimen ends were lubricated with Molykote, a small barreling was observed at large strains beyond 10 percent of strain. This effect of the end constraint on the results due to friction is estimated at less than 3 percent at the maximum strain of 20 percent. Stress-strain curves shown in the study are the average values of two or three tests. The deviation from the average value is less than ± 3 percent which is considered satisfactory in view of variation of materials and the effect of environment such as temperature and humidity on material properties and measuring system of the medium strain-rate machine and the split-Hopkinson-bar apparatus.

Figures 5 through 8 show, respectively, the true stress and strain curves at various strain rates for PMMA, CAB, polypropylene, and nylon 6-6 in compression at 72° F. The temperature rise vs. strain at various strain rates is also plotted on the same figure

for each material. It is noticed that both amorphous and semicrystalline polymers studied show a viscous effect at the beginning of the deformation and a plastic flow follows thereafter (details will be discussed later). The effect of heat developed during deformation on mechanical properties of materials investigated is quite evident, particularly at the highest strain rate where the stress in the materials decreases while the strain is increasing. These results suggest that, in many studies such as structural vibrations, impact, cold forming, etc., the effect of temperature rise during deformation must be taken into consideration.

Figures 9 through 12 give the relationships between the stress and the log strain rate at various strains for four materials under investigation. The data points are obtained directly from the stress-strain curves at various strain rates shown in Figs. 5 through 8. A curve is fitted through the points with an error band of $\pm$ 3 percent. For PMMA, Fig. 9, a linear relationship exists between the stress and log strain rate up to a strain rate of 45 s^{-1} at 4 percent of strain. Above 4 percent, there is practically no simple relation existing between the stress and log strain rate. At all percentages of strain considered, the strain rate sensitivity increases rapidly beyond $\dot{e}$ = 100 s^{-1}. CAB, another amorphous polymer, shows the

same trend as that of PMMA. Here again, for small percentages of strains such as 3 percent and 5 percent (see Fig. 10), a linear relationship can be found between the stress and log strain rate. The strain-rate sensitivity also increases significantly beyond $\dot{e}$ = 100 s^{-1}. The crossover of curves for strains of 5 percent to 9 percent is an indication of the effect of temperature rise developed during deformation which causes the stress to decrease as the strain increases.

Figure 11 shows the relationship between the stress and strain rate at various strains for polypropylene. It is evident that a linear relation exists at all strain levels up to 9 percent for strain rates less than 100 s^{-1}. Above 100 s^{-1}, the rate sensitivity increases as it does for the other materials.

Nylon 6-6 is one of the semicrystalline polymers, other than polypropylene, investigated in this study. Figure 12 shows that a sigmoidal curve will fit the data points of the stress vs. the logarithm of strain rate at strains less than 10 percent and strain rates below 100 s^{-1}. However, for strains at 10 percent, there is a linear relation between the stress and the logarithm of strain rate. The rate sensitivity also increases significantly above $\dot{e}$ = 100 s^{-1} up to the strain rate attainable by using the split-Hopkinson-bar apparatus.
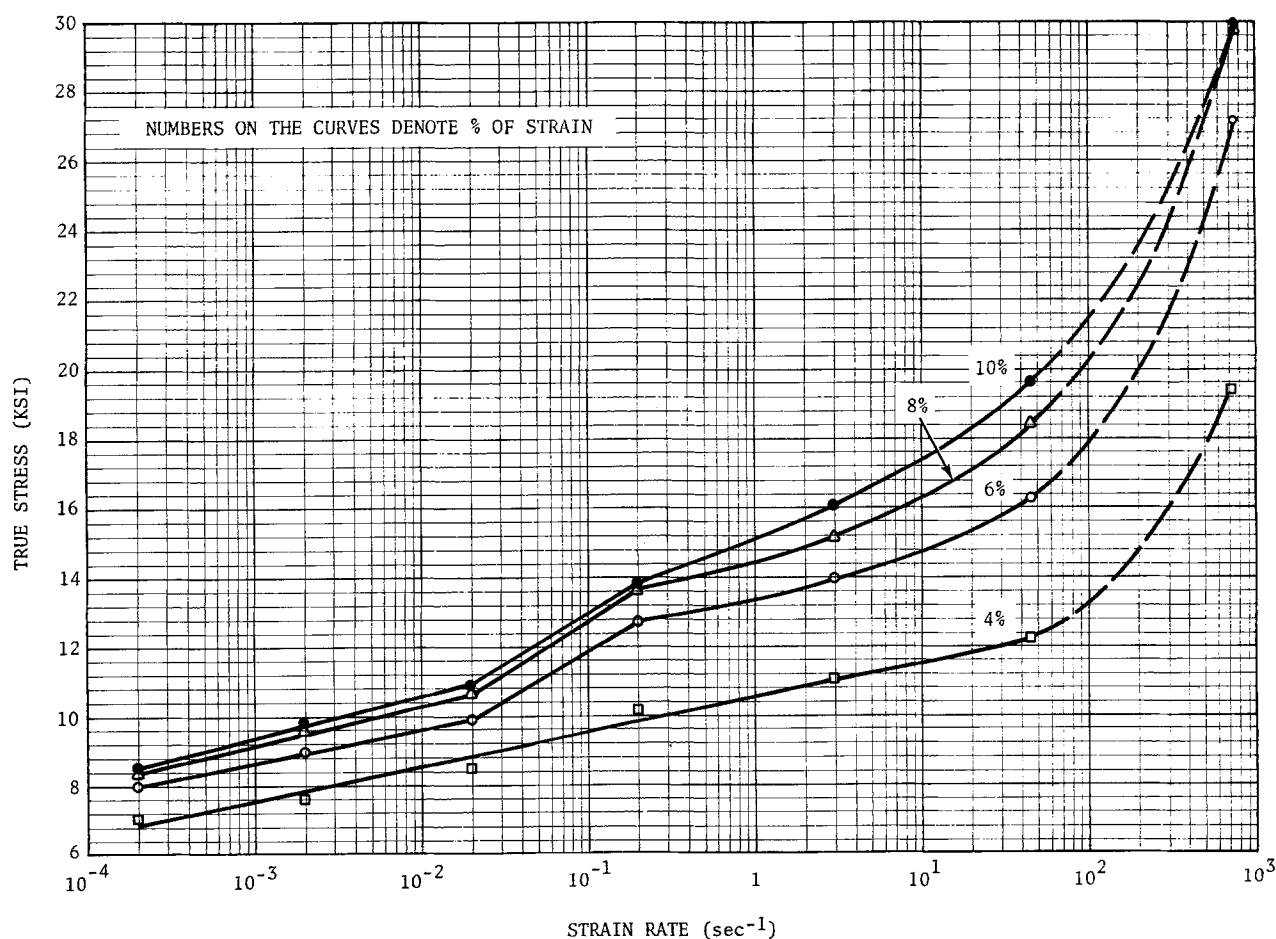

Fig. 9—Stress vs. strain at various strains for PMMA in compression at 72° F

The linear relationship between the stress and the logarithm of strain rate at constant strain obtained empirically for $e < 100$ s^{-1} can be expressed as follows:

$$S(e) = A(e) + B(e) \ln (\dot{e}) \qquad (4)$$

Equation (4) is very similar to an expression given by Seeger[23] for metals based on the thermally activated motion of dislocations over local and long-range energy barriers. According to Seeger, the strain rate is given by

$$\dot{e} = N \exp \left(\frac{\Delta H - \nu S}{kT} \right)$$

which may be written as

$$\begin{aligned}
S &= \frac{\Delta H}{\nu} + \frac{kT}{\nu} \ln \left(\frac{\dot{e}}{N} \right) \\
&= \left(\frac{\Delta H}{\nu} - \frac{kT}{\nu} \ln N \right) + \frac{kT}{\nu} \ln (\dot{e})
\end{aligned} \qquad (5)$$

where N is the structure factor, ΔH is the activation enthalpy, ν is the apparent activation volume, T is the absolute temperature, and k is the Boltzmann's constant.

By equating eqs (4) and (5), the constants A and B in eq (4) may be related to certain dislocation motions. A further experimental investigation is needed to provide a better understanding in this area.

Hall[16] has employed the first law of thermodynamics to derive an expression for the temperature rise developed during extension of a filament. Following the same procedure, the expression for a cylindrical specimen is obtained and given as follows:

$$\Delta T(e_1) = \int_0^{e_1} \left[\frac{0.027}{\rho C_v} S - \left(\frac{\partial U}{\partial L} \right) TV \frac{L}{C_v} \right]$$

$$\mathrm{Exp} \left[-\frac{2(L\, h_1 + r\, h_2)}{\rho\, C_v\, r\, \dot{e}\, L} (e_1 - e) \right] de \qquad (6)$$

where

ρ = density, lb/cu in.
U = internal energy, cal/lb
L = length of a specimen, in.
C_v = heat capacity at constant volume, cal/lb-°C
h_1 and h_2 = heat-conduction coefficients, cal/in.^{2}-°C-s
r = radius of a cylindrical specimen, in., and the subscripts are the state variables which remain constant when the partial differentiation is carried out.

The exponential term in eq (6) describes a thermal condition under which the deformation occurs. For example, if $\dot{e}$ is sufficiently small, the exponential term will approach zero, in which case ΔT also ap-
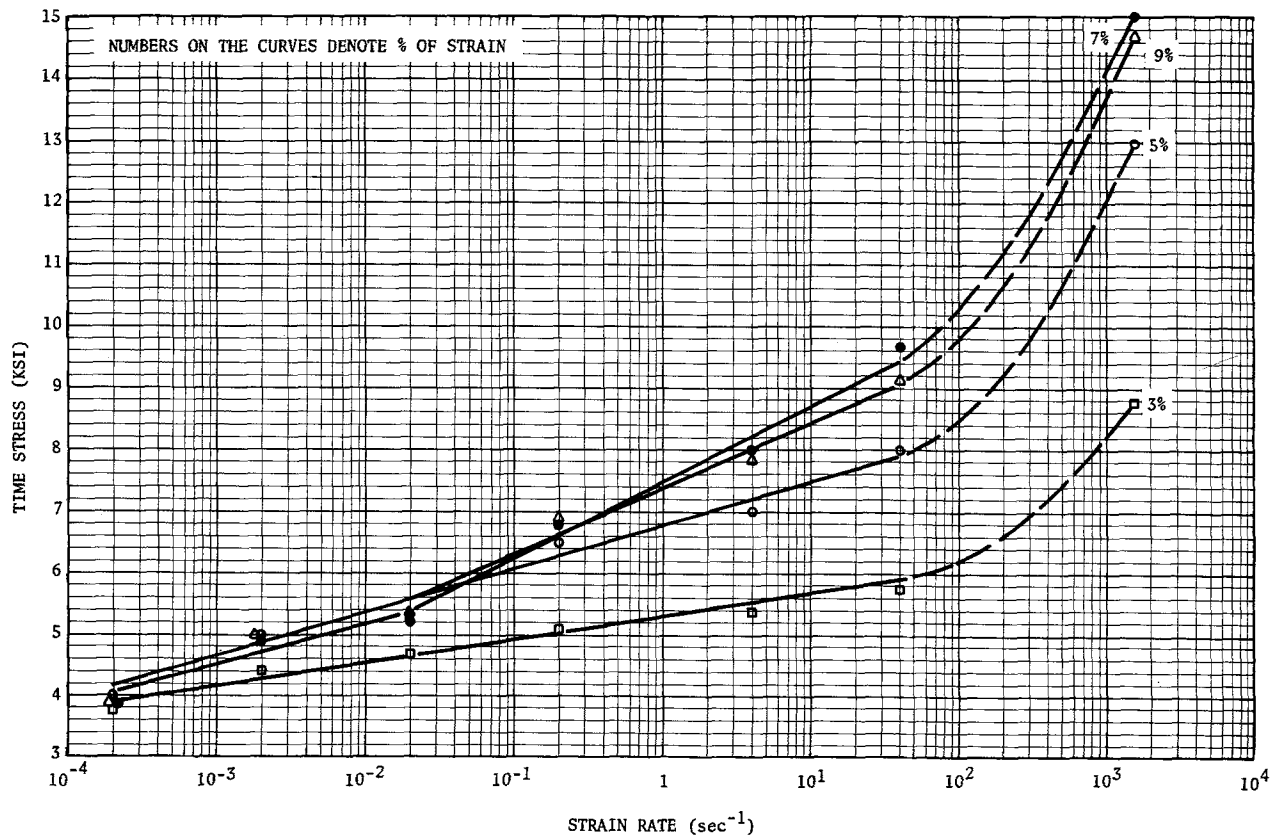

Fig. 10—Stress vs. strain rate at various strains for cellulose acetate butyrate (Kodak Tenite Butyrate) in compression at 72° F
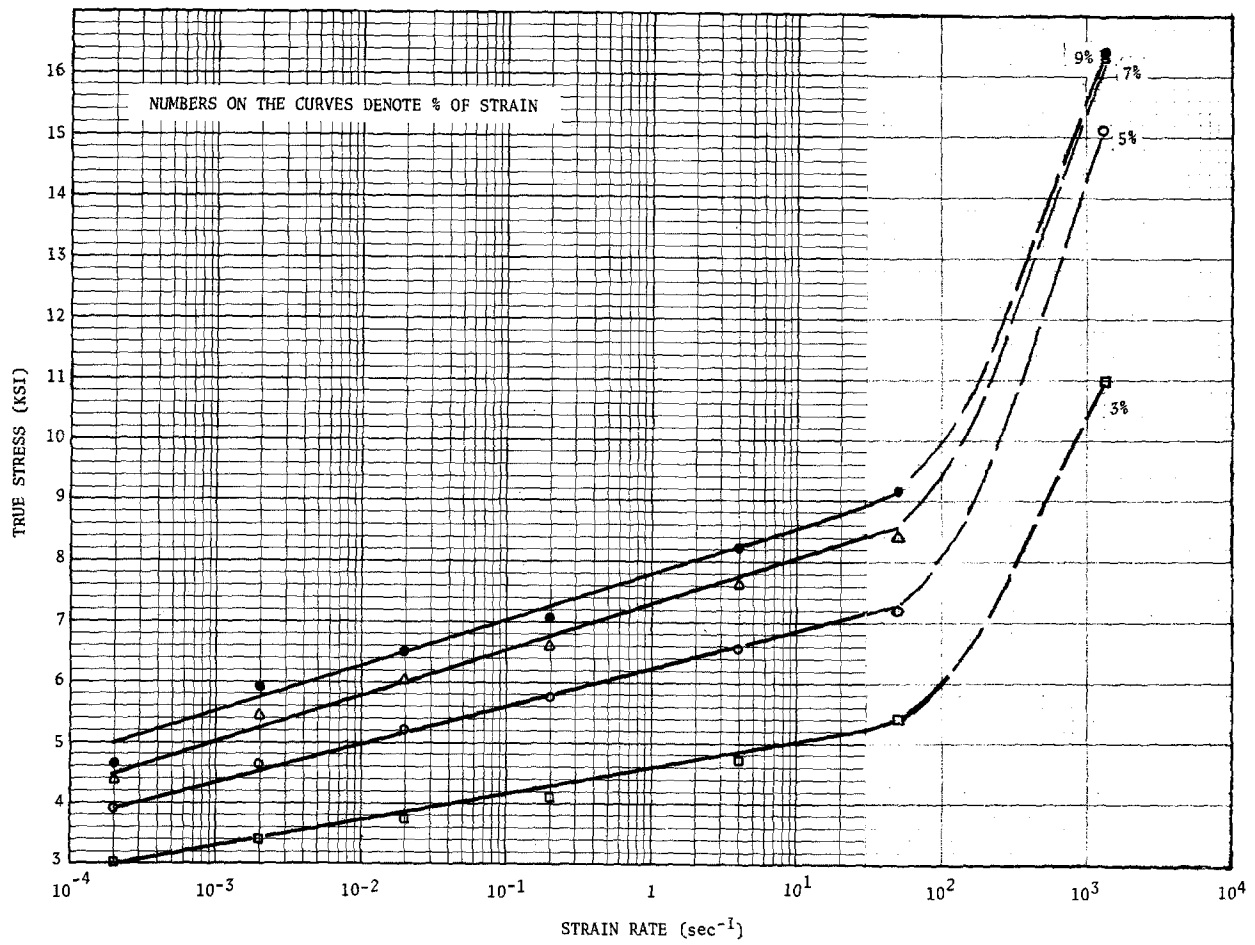
Fig. 11—Stress vs. strain rate at various strains for polypropylene in compression at 72° F
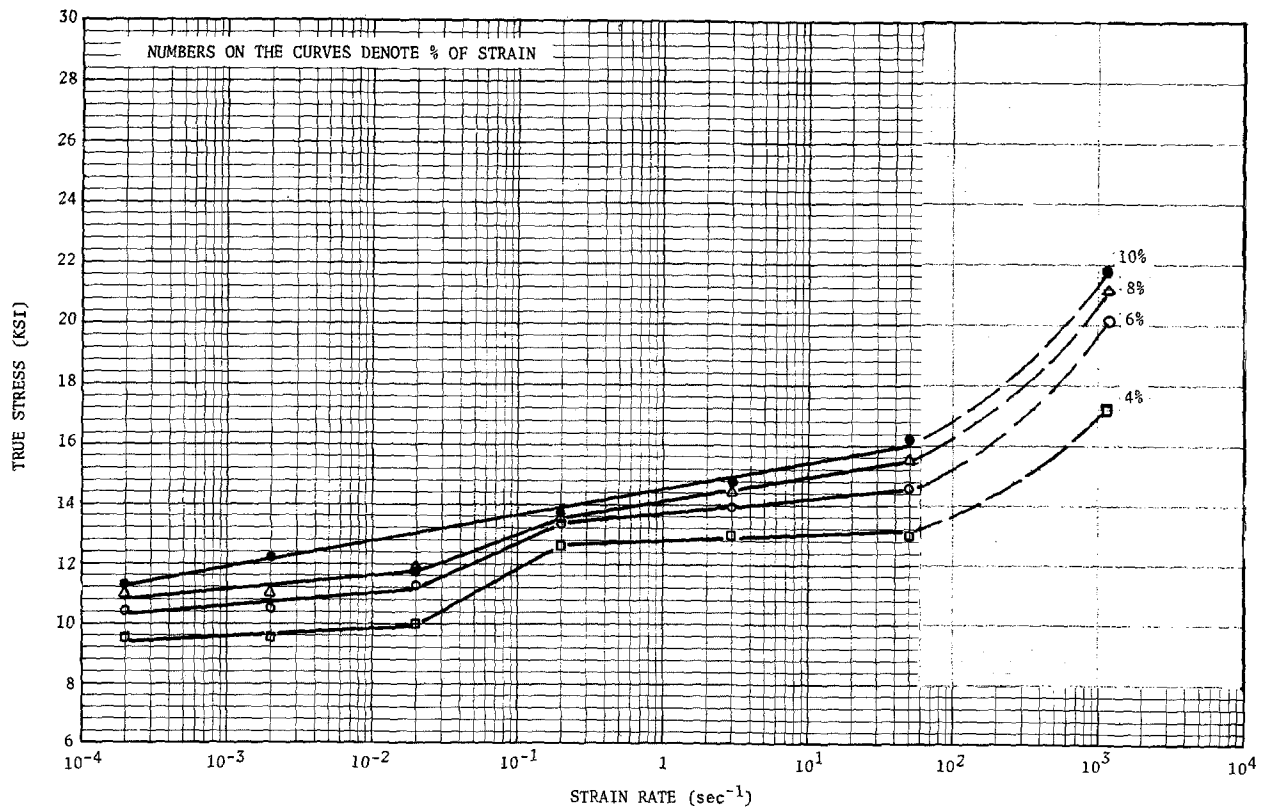

Fig. 12—Stress vs. strain rate at various strains for nylon 6-6 in compression at 72° F

proaches zero, and the deformation will be essentially isothermal. For sufficiently large values of the strain rate, $\dot{e}$, this exponential term will approach unity, then the deformation occurs adiabatically. In this case, if we further assume that the term containing $(\partial U/\partial L)TV$ can be neglected compared with the term containing S, eq (6) reduces to

$$\Delta T = \int_0^{e_1} \frac{0.027}{\rho C_v} S \, de \qquad (7)$$

Equation (7) implies that all mechanical work done on a specimen is converted to heat regardless of the level of strain e_1.

In this study, a comparison is made between the computed temperature rise from eq (7) under adiabatic conditions and the measured value vs. true strain at various strain rates for all materials investigated. Figures 13 and 14 show typical comparison from PMMA and polypropylene. It is noticed that at low strain rates, 4 s^{-1} for polypropylene and 3 s^{-1} for PMMA, the measured temperature rise is less than the value computed from eq (7). This suggests that, at low strain rates, a portion of the heat developed during deformation is conducted into the surroundings such as the platens of the piston and the base plate and the air. The remainder of the heat causes the temperature rise. This result is also predictable by the exponential term in eq (6). At the higher strain rates, 45 s^{-1} for PMMA and 50 s^{-1} for polypropylene, there is very little temperature rise at strains below 8 percent. In the region between 8-percent to 12-percent strain, the temperature in the

specimen has a sharp rise. For strains greater than 12 percent, the measured temperature rise is essentially equal to the value calculated from eq (7). This indicates that materials investigated behave in a viscoplastic manner under the test condition. The reason is given as follows.

A viscous material always exhibits stress relaxation during the process of deformation. For a given material, the two most important parameters which control the relaxation mechanism are time and temperature. To demonstrate the effect of the relaxation mechanism on the material response, let us examine a hypothetical case where a specimen is deformed first a prescribed displacement at a constant strain rate and room temperature, and then the displacement is held constant. The strain-time history and a probable stress-time history are shown in Fig. 15. If all mechanical work done during the test is stored in the specimen as the strain energy without any dissipation, the stress must remain constant while the strain is held constant. However, due to the relaxation mechanism, the stress decreases as the time elapses. This portion of the dissipated energy will appear as heat. The rate of dissipation is related to the characteristic relaxation time of the material investigated. In this study, although the strain was not held constant, the process of relaxation occurs continuously during the deformation. The little temperature rise at strains below 8 percent indicates that at strain rates 45 s^{-1} for PMMA and 50 s^{-1} for polypropylene, the time required to deform the specimen is relatively short in comparison with the characteristic relaxation time of materials investigated. Be-
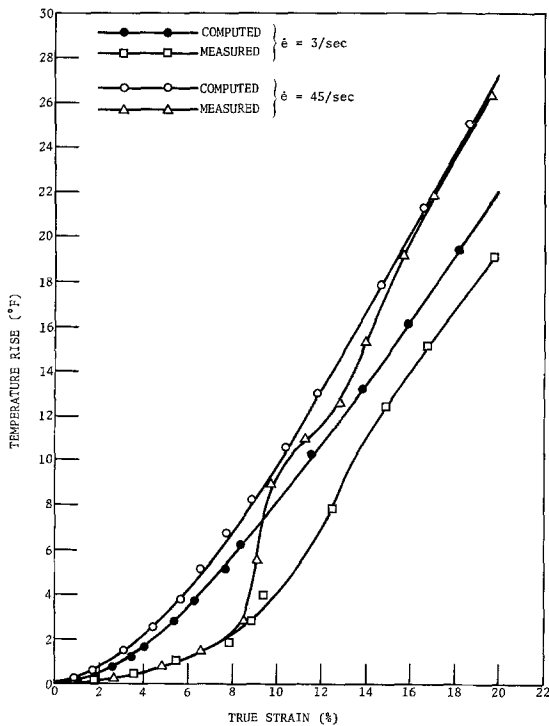

Fig. 13—Computed and meaured temperature rise vs. true strain for PMMA in compression at strain rates of $3^{-1}s$ and $45^{-1}s$
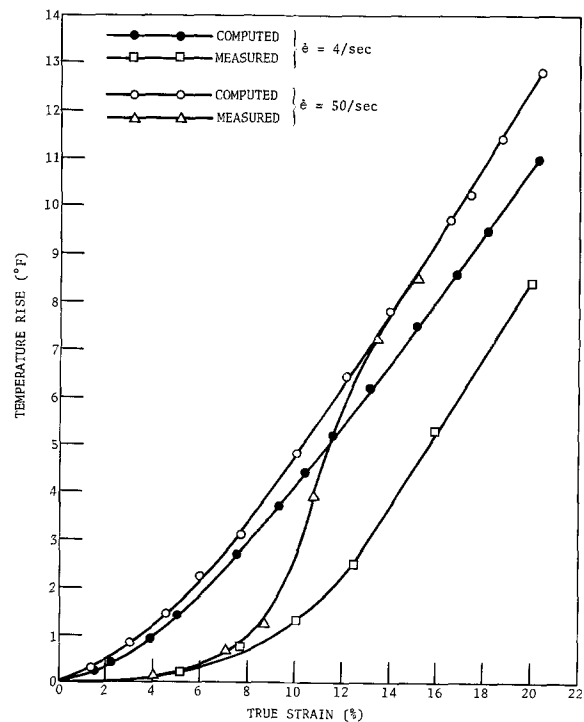

Fig. 14—Computed and measured temperature rise vs. true strain for polypropylene in compression at strain rates of $4^{-1}s$ and $50^{-1}s$
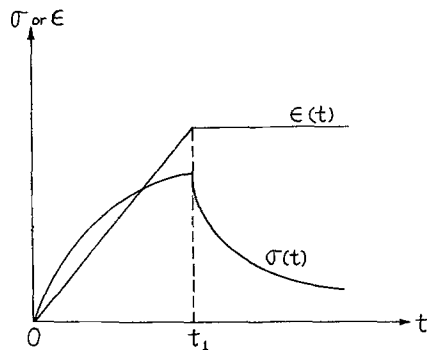
Fig. 15—Stress–time and strain–time
histories of a typical thermoplastic

tween 8-percent to 12-percent strain, both plastic flow
and relaxation mechanism begin taking place; con-
sequently, a sharp temperature rise occurs in the
specimen. For strains greater than 12 percent till the
completion of the test, the time is still sufficiently
short for the heat developed during the test not to
be conducted away. This is the reason that the mea-
sured temperature rise is essentially equal to the
value calculated from eq (7).

Since the relaxation mechanism is not taken into
consideration in the derivation of eq (6), the viscous
effect of the temperature-rise measurement cannot
be predicted by that formula. Once the material be-
gins a plastic flow, however, the temperature rise
can be estimated from eq (6).

Let us assume the following values for polypropyl-
ene:

$$h_1 = h_2 = h = 2.06 \times 10^{-2} \text{ cal/in.}^2 - {}^\circ\text{C-s}$$
$$C_v = 160 \text{ cal/lb-}{}^\circ\text{C}$$
$$\rho = 0.032 \text{ lb/in.}^3$$
$$L = 0.500 \text{ in.}$$
$$2 r = 0.375 \text{ in.}$$
$$\dot{e} = 50 \text{ s}^{-1}$$
$$e_1 = 0.20$$

and the exponential term in eq (6) has a value of

$$\text{Exp} \left[- \frac{2(L \, h_1 + r \, h_2)}{\rho \, C_v \, r \, \dot{e} \, L} (e_1 - e) \right]$$

$$= \begin{array}{ll} 0.9999 & \text{for} \quad e = 0.10 \\ 1.00 & \text{for} \quad e = 0.20 \end{array}$$

which can, for all practical purposes, be defined as
an adiabatic deformation. This agrees very well with
the experimental results.

The measured temperature rise vs. true strain at
various strain rates is also plotted in Figs. 5 through
8 together with the stress–strain curve to provide a
clear view of the effect of temperature rise on the
stress–strain relationship. The temperature rise at the
highest strain rate for each material is shown by a
dotted line because of the inconsistency in the ex-
perimental results. This inconsistency is probably a
result of many uncontrollable factors, such as the
contact interface between the thermocouple and
specimen during the deformation or fracture of spec-
imens at high strain rates. However, the comparison

of the computed and measured temperature rise at
lower strain rates as shown in Figs. 13 and 14 indi-
cates that, at highest strain rate, the deformation
takes place under adiabatic condition. This provides a
very good guideline for screening the test result. The
dotted curves in Figs. 5 through 8 are those which
have been screened by using this guideline.

Acknowledgment

References

1. Percy, J. H. and Meikle, J. B., "The Mechanical Behavior of
Polymeric Solids in Compression," Proc. of Conf. on the Sci. of
Mat., Inst. Phys. and The Phys. Soc., Univ. of Auckland, New Zea-
land (Aug. 1969).
2. Kolsky, H., "An Investigation of the Mechanical Properties of
Materials at Very High Rates of Loading," Proc. Phys. Soc. 62B:
676-700 (1949).
3. Back, P. A. A. and Campbell, J. D., "The Behavior of a
Reinforced Plastic Material under Dynamic Compression," Proc. Conf.
on Properties of Mat. at High Rates of Strain, Inst. Mech. Engineer,
Lond., 221-228 (1957).
4. Ripperger, E. A., "Stress–Strain Characteristics of Materials
at High Strain Rates," U. Texas Contract AT(29-2)-621 (for Sandia
Corp.) (1958).
5. Volterra, E. and Barton, C. S., "An Impact Testing Machine
for Plastics and Rubber-like Materials," Proc. SESA, 16 (1), 157-66
(1958).
6. Ely, R. E., "High-Speed Compression Testing of Thermo-
plastics," Symp. on Dyn. Beh. of Mat., ASTM Special Tech. Publs.
No. 336, 15-33 (1963).
7. Tardif, H. P. and Marquis, H., "Some Dynamic Properties of
Plastics," Can. Aero. J., 9, 205-13 (1963).
8. Davies, E. D. H. and Hunter, S. C., "The Dynamic Testing
of Solids by the Method of the Split Hopkinson Pressure Bar," J.
Mech. Phys. Solids, 11, 155-179 (1963).
9. Lindholm, U. S., "Some Experiments with Split Hopkinson
Pressure Bar," J. Mech. Phys. Solids, 12, 317-335 (1964).
10. Hoge, K. G., "The Effect of Strain Rate on the Mechanical
Properties of General Purpose Polypropylene," Univ. of California,
Lawrence Radiation Laboratories, Report UCRL-14316 (1965).
11. Maiden, C. J. and Green, S. J., "Compressive Strain Rate
Tests on Six Selected Materials at Strain Rates from 10^-3 to 10^4
Inch/Inch/Second," TR65-26, General Motors Corp., G. M. Defense
Research Laboratories, Santa Barbara, CA (1965).
12. Maiden, C. J. and Green, S. J., "Compressive Strain Rate Tests
on Six Selected Materials at Strain Rates from 10^-3 to 10^4 Inch/Inch/
Second," ASME Trans., Series E, J. Appl. Mech., 33, 496 (1966).
13. Holt, D. L., "The Modulus and Yield Stress of Glassy Poly-
methylmethacrylate at Strain Rates up to 10^3 Inch/Inch/Second," J.
Appl. Polym. Sci., 12, 1653-1659 (1968).
14. Dao, K. C. and Percy, J. H., "Polyethylene in Compression
at Various Strain Rates and Temperatures," Inst. Phys. and The
Phys. Soc. Conf. Sci. Mat., Auckland, New Zealand (1969).
15. Meikle, J. B., "Relaxations in Nonequilibrium Glasses," Inst.
Phys. and The Phys. Soc. Conf. Sci. Mat., Auckland, New Zealand,
152 (1969)
16. Hall, I. H., "The Effect of Strain Rate on the Stress–Strain
Curve of Oriented Polymers. II—The Influence of Heat Developed
During Extension," J. Appl. Polymer Sci., 12, 739-750 (1968).
17. Luntz, R. D., "System Control for a Hydraulic (Servo-Actu-
ated) and Pneumatic Medium Strain Rate Tensile Testing Machine,"
Dissertation for MS Degree in ME, Univ. of Utah, Salt Lake City,
UT (June 1972).
18. Robertson, K. D., Chou, S. C. and Rainey, J. H., "Design and
Operating Characteristics of a Split Hopkinson Pressure Bar Ap-
paratus," AMMRC, TR71-49 (Nov. 1971).
19. Clark, D. S. and Wood, D. S., "The Time Delay for the
Initiation of Plastic Deformation at Rapidly Applied Constant Stress,"
Proc. ASTM, 49, 717-737 (1949).
20. Campbell, J. D. and Marsh, K. J., "The Effect of Grain Size
on the Delayed Yielding of Mild Steel," Phil. Mag., 7, 933-952
(1962).
21. Jakob, M., Heat Transfer, II, Ch. 33, John Wiley and Sons,
New York (1956).
22. Green, S. J., Griffin, R. M., Black, A. D. and Langan, J. J.,
"Tri-axial Stress–Strain Response of Polypropylene to High Pressure,"
Terra Tek, Inc., Salt Lake City, UT, TR71-24 (July 1971).
23. Seeger, A., Dislocations and Mechanical Properties of Crystals,
John Wiley and Sons, New York (1956).