

The Effect of Strain Rate on the Stress-Strain Curve of Oriented Polymers. I. Presentation of Experimental Results

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Synopsis

The stress-strain curves of viscose, nylon 6.6, poly(ethylene terephthalate), polyacrylonitrile, and polypropylene have been determined at a large number of different strain rates between 10^{-4} and 330 sec.^{-1} . The shape of these stress-strain curves and its change with strain rate is shown to depend upon whether the material is tested above or below its glass temperature. The stress-strain curves of materials tested below their glass temperature consists of an initial straight portion followed by a yield point at a few per cent strain. The breaking strain is only slightly affected by strain rate, and the energy to rupture increases with increasing rate. For materials tested above their glass temperature the initial portion of the stress-strain curves is nonlinear, and the yield strain is much higher than for the other materials. There is a small range of strain rate, in which the breaking strain falls sharply to the yield strain with increasing rate, and the energy to rupture also decreases. Outside this range the energy to rupture increases with increasing rate.

Introduction

It is well known that the mechanical properties of polymeric materials are dependent upon the rate of deformation. However, whereas creep, stress relaxation, and dynamic moduli have been studied extensively at very small strains, information on the variation of mechanical properties with rate of extension at finite strains is scanty.

Meredith¹ has measured the stress-strain curve at constant strain rate for several rates covering a fairly wide range, but the highest rate he used was about two decades below that available with modern instrumentation, and some materials of current interest were not included in his study. The present author² has reported the properties of a large number of different textile fibers at strain rates of 330 and $8.3 \times 10^{-3} \text{ sec.}^{-1}$. In the present paper these results are supplemented by measurement of the stress-strain curves of five of the fibers at a large number of rates between 330 and $10^{-4} \text{ sec.}^{-1}$.

The results will be presented and their major features analyzed in this paper. The effect of heat developed during extension will be discussed in Part II. The investigation was performed primarily for the purpose of

studying methods of viscoelastic analysis at finite strain. This part of the work will be published separately.

The results on one of the materials (polypropylene) have already been published.³ Those parts of the results which are necessary to make the present papers complete in themselves will, however, be reproduced here.

Experimental

The object of the present work was to supplement with measurements at intermediate rates earlier experiments, in which the stress-strain curves of a large number of different fibers were measured at one high strain rate and one low strain rate. Since such a project involves a great deal of experimental work, only a few different fibers could be studied, and so one sample was chosen from each of the five chemical bases from which most commercial fibers are derived.

Details of these materials are given in Table I. All were in the form of

TABLE I
Specifications of Materials

Mfr.'s desig.	Chemical base	No. of Filaments	Nominal linear density, ^a tex	Mfr.
Standard rayon ^b	Cellulose	50	27.8	Courtaulds Ltd.
Nylon 100 ^c	Nylon 6.6	34	7.8	B.N.S. Ltd.
Terylene Dull M.T.	Poly(ethylene terephthalate)	48	11.1	I.C.I. Ltd.
Courtelle	Polyacrylonitrile	50 (approx)	11.5	Courtaulds Ltd.
Reevon	Polypropylene	1	8.1	Reeves Bros. Inc.

^a A tex is weight in grams of 1000 m. of yarn.

^b Called "viscose" in this text.

^c Called "nylon" in this text.

continuous filament yarn and, except for the polyacrylonitrile, were taken from standard commercial production. With the exception of polypropylene they were multifilament yarns and were tested with a twist of about 2 turns/cm. This was sufficient to hold the individual fibers together but insufficient to affect their mechanical properties.

It was desired to cover the range of strain rate by using as few different pieces of apparatus as possible, and to this end two testing machines were specially developed, both of which have been described elsewhere.^{3,4} With one machine a range of strain rate from 10^{-4} to 1 sec.^{-1} could be covered; with the other, a range from 30 to 330 sec.^{-1} .

Earlier work³ had indicated that with this apparatus a test piece had slipped in its clamp during extension, and so a procedure was used which allowed a correction to be determined and applied to the gauge length.⁴

This involved testing specimens with gauge lengths of 2.5, 5, and 10 cm., each gauge length being tested at a different extension velocity but at the same strain rate. Five test pieces of each gauge length were tested. There was considerable statistical variability in the materials, and this resulted in a large probable error in the gauge-length correction. It was therefore assumed that this was independent of the strain rate, and the mean value for a piece of apparatus and material was determined.

The results were then recalculated with the corrected gauge length, and the mean stress-strain curve for a given strain rate was determined.

The stresses, as is customary with textile materials, are expressed as forces per unit of linear density in the unstrained state. The unit of force was the gram-weight and that of linear density was the tex (the weight in grams of 1000 m. of yarn). The linear density was determined individually for each test piece by measuring its weight and length.

The mechanical properties of all textile materials are sensitive to the temperature at which they are determined, and those of some are sensitive to the relative humidity of the surrounding atmosphere. Consequently, all experiments were performed in a laboratory in which the temperature was controlled at $21 \pm 1^\circ\text{C}$. and the relative humidity at $65 \pm 4\%$.

Results and Discussion

A selection of the stress-strain curves for each material at a number of strain rates are shown in Figures 1-5. These curves terminate at the fracture strain. The materials may be classified into two groups according to the shape of the stress-strain curve. The first group comprises viscose,

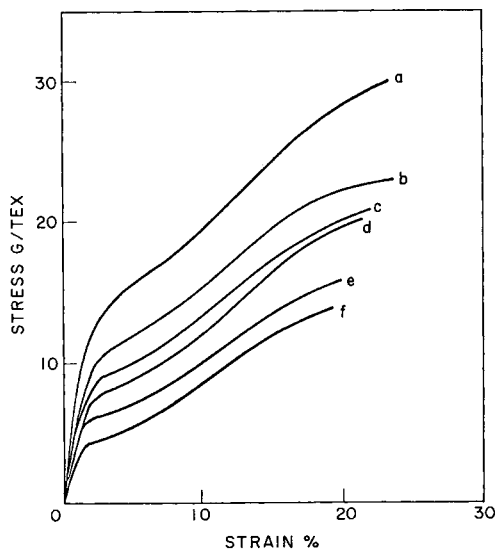


Fig. 1. Stress-strain curves of viscose at strain rates (sec^{-1}): (a) 320; (b) 8.4; (c) 6.3×10^{-1} ; (d) 4.0×10^{-2} ; (e) 1.6×10^{-3} ; (f) 1.0×10^{-4} .

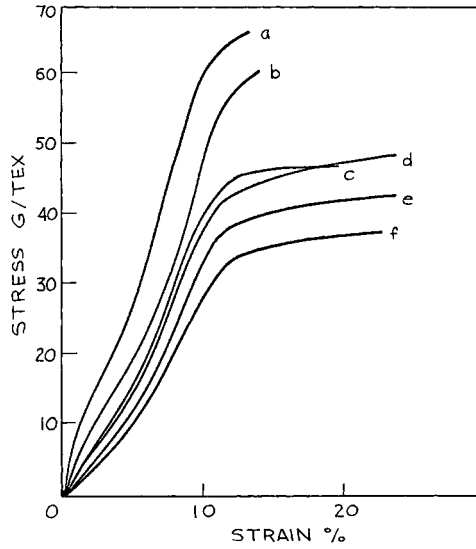


Fig. 2. Stress-strain curves of nylon at strain rates (sec.^{-1}): (a) 300; (b) 4.1; (c) 3.2×10^{-1} ; (d) 4.9×10^{-2} ; (e) 3.2×10^{-3} ; (f) 1.8×10^{-4} .

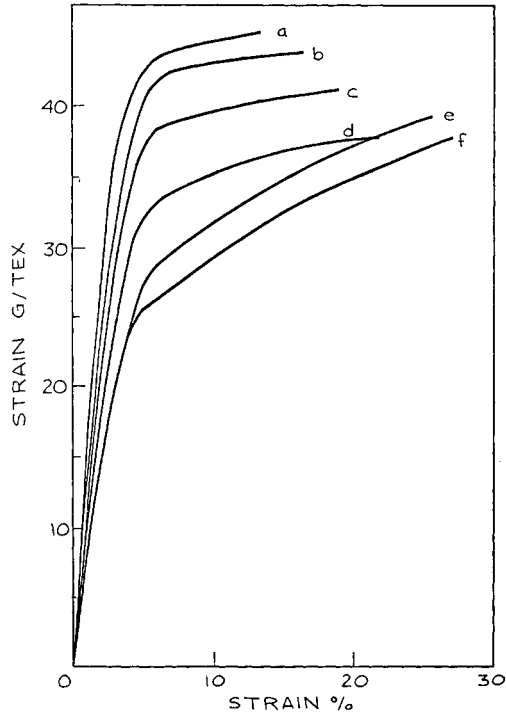


Fig. 3. Stress-strain curves of poly(ethylene terephthalate) at strain rates (sec.^{-1}): (a) 230; (b) 64; (c) 18; (d) 1.2; (e) 1.3×10^{-2} ; (f) 1.8×10^{-4} .

poly(ethylene terephthalate), PET, and polyacrylonitrile, PAN (Figs. 1, 3, and 4, respectively). For these the initial portion of the stress-strain curve is linear up to a few per cent strain, at which there is a yield point. The second group comprises nylon and polypropylene, PP (Figs. 2 and 5, re-

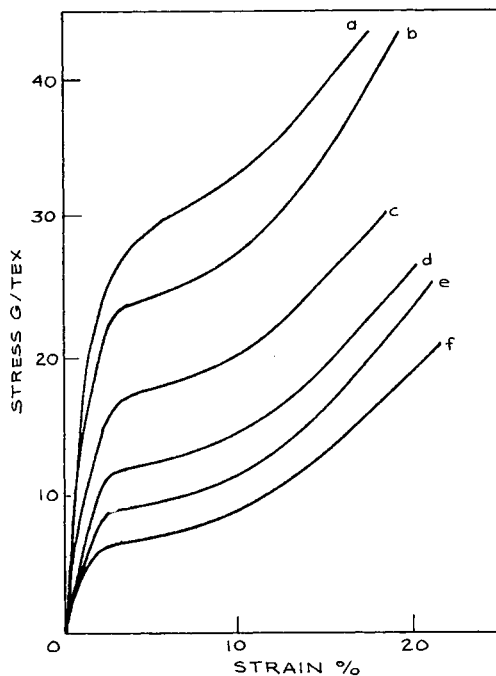


Fig. 4. Stress-strain curves of polyacrylonitrile at strain rates (sec.^{-1}): (a) 600; (b) 75; (c) 4.2; (d) 7.7×10^{-2} ; (e) 9.9×10^{-3} ; (f) 1.0×10^{-4} .

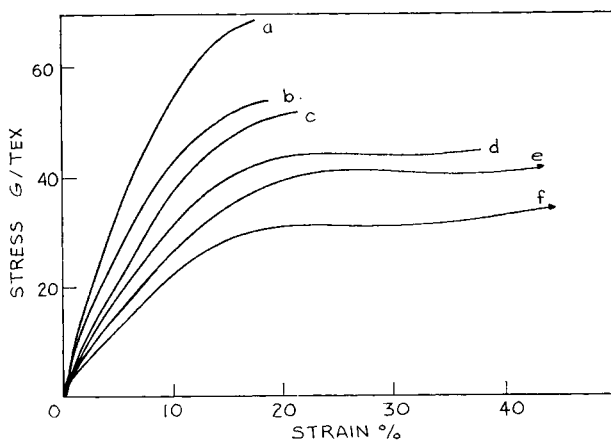


Fig. 5. Stress-strain curves of polypropylene at strain rates (sec.^{-1}): (a) 490; (b) 63; (c) 2.9; (d) 3.3×10^{-2} ; (e) 4.2×10^{-3} , 60%, 45 g./tex; (f) 3.5×10^{-4} , 58%, 38 g./tex.

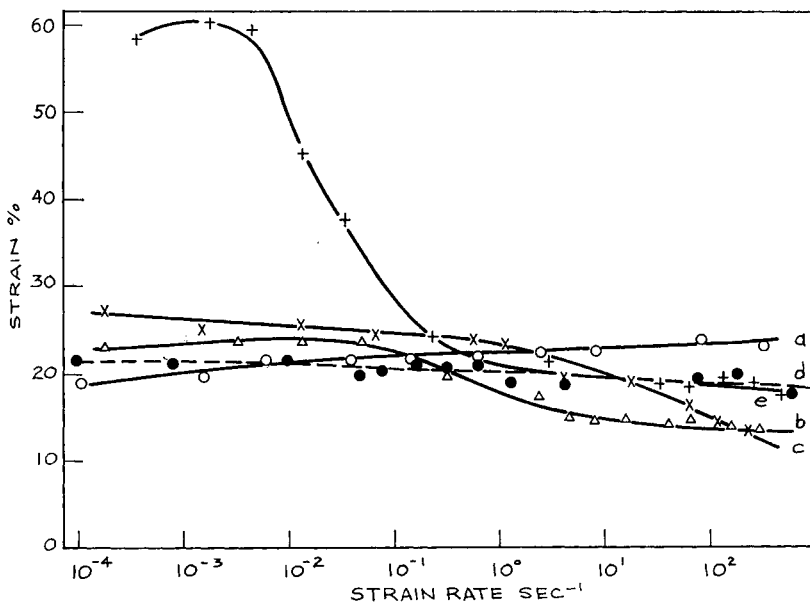


Fig. 6. Effect of strain rate on breaking strain: (a) viscose; (b) nylon; (c) poly(ethylene terephthalate); (d) polyacrylonitrile; (e) polypropylene.

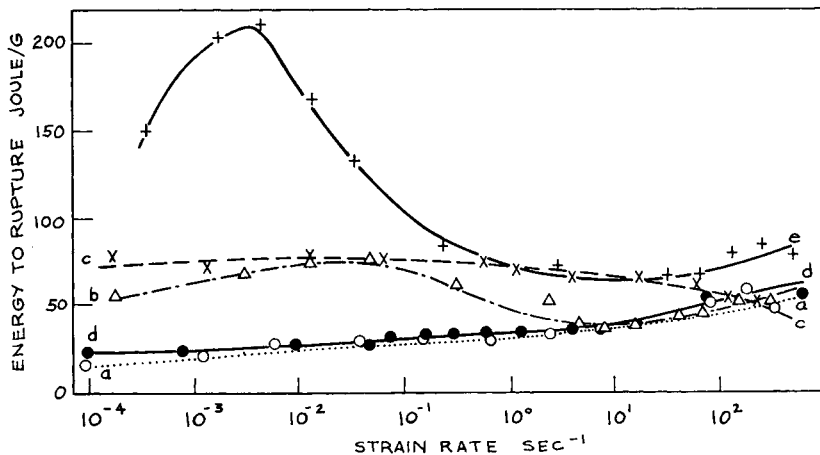


Fig. 7. Effect of strain rate on energy-to-rupture: (a) viscose; (b) nylon; (c) poly(ethylene terephthalate); (d) polyacrylonitrile; (e) polypropylene.

spectively). For these the initial portion of the stress-strain curve is non-linear, and yielding does not occur until a strain of about 15% is attained.

The change in strain at break with strain rate can also be classified according to these groups. At low strain rates the materials in the second group fracture at a strain considerably greater than the yield strain, but at high strain rates they fracture at the yield point. The transition between the two types of fracture occurs over a range of about two decades (Fig. 6).

The materials in the first group fracture after yielding, even at the highest strain rates. Indeed (from Fig. 6) it will be seen that the breaking strain of viscose increases with strain rate throughout the range investigated, and for PAN it falls only slightly.

The energy required to rupture the material is represented by the area under the stress-strain curve up to the breaking point. From Figures 1-5 the stress required to produce a given strain increases with strain rate for all materials, and this will tend to cause the energy-to-rupture to increase. On the other hand, any large reduction in the breaking strain will cancel this effect and cause a reduction in the energy-to-rupture. It will be seen that for viscose and PAN the increase in stress is the predominant effect, and the energy to rupture increases with increasing strain rate for the entire range investigated. For PET the decrease in breaking strain predominates at the highest strain rates, at which there is a gradual fall in energy-to-rupture with increasing rate. For both PP and nylon there is a large decrease in energy-to-rupture in the narrow range of rate in which the breaking strain falls sharply. Outside this range the energy-to-rupture increases with increasing rate. Thus, only the materials in the second group suffer a large drop in energy-to-rupture over a narrow range of rate. It is of interest to note that, whereas the energies needed to rupture the five materials differ greatly at low rates, at high rates the values are all very similar.

It is now necessary to inquire by what other physical property the materials can be divided into these two groups, since the behavior described is likely to be associated with such a property. The glass transition temperatures of both PAN and PAT are known to be about 100°C., i.e., well above the temperature at which these experiments were performed. On the other hand, for PP it is about 0°C., a little below the experimental temperature. Values cannot be assigned with such confidence to viscose and nylon, because these materials are hydrophylic, and the glass temperature depends on the water content. However, the literature seems to indicate that at the relative humidities used in these experiments the glass temperature of viscose is likely to be 60-70°C. and that of nylon 0-10°C. Thus the materials can be divided into these same two groupings according to whether the test temperature is above or below the glass temperature. The first group was tested below their glass temperature; the second, above it.

There is evidence with polypropylene that the change in breaking strain which is observed is associated with the glass transition. Experiments at a low strain rate and varying temperature³ showed that fracture occurred at the yield point at temperatures below the glass temperature. Detailed analysis⁵ indicated that the mechanism responsible for the change in breaking strain with increasing rate was the same as that responsible for the change with decreasing temperature. It is therefore likely that a material above its glass temperature will, if tested at a high strain rate, behave as though it was below its glass temperature.

It should be noted that if nylon and PP, when tested below their glass temperature, break without yielding, then the other three materials, which

are also below their glass temperature, might also be expected to break without yielding. The fact that they do not suggests that the mechanisms of yielding in the two groups of materials are different.

In a previous paper,² in which the stress-strain curve of a large number of fibers was studied at one low and one high strain rate, it was shown that, if the energy needed to rupture a particular fiber was less at the high strain rate than at the low, then this would be so for all chemically similar fibers. From the present and more detailed study it seems that the energy-to-rupture is likely to change with strain rate in this manner with a material tested above its glass temperature. Since the glass temperature of a fiber is determined primarily by the chemical base from which it is derived and is affected to a lesser extent by processing variables, it will have a similar value for chemically similar fibers. Hence the behavior observed previously would be expected.

Conclusions

The shape of the stress-strain curve of the five materials chosen for study and its changes with strain rate may be classified according to whether the material is above or below its glass temperature. Viscose, PET, and PAN were tested below their glass temperatures, and their stress-strain curves consist of an initial straight portion followed by a yield point at a few percent strain. The breaking strain is only slightly affected by strain rate, and the energy-to-rupture increases with increasing strain rate. The behavior of PET at high rates is an exception. At these rates there is a gradual decrease of both the breaking strain and the energy-to-rupture for this material with increasing rate.

Nylon and PP were tested above their glass temperature, and for these materials the initial portion of the stress-strain curve is nonlinear and the yield strain is much higher than for the others. There is a small range of strain rate in which the breaking strain falls sharply to the yield strain with increasing rate. This is accompanied by a sharp drop in the energy-to-rupture. Outside this range the energy-to-rupture increases with increasing rate.

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