Thickness effects in split Hopkinson pressure bar tests

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(Received 25 February 1993)

Results are presented for the high strain rate behaviour of a medium and high density polyethylene, polycarbonate and poly(ether ether ketone) in compression for strain rates up to $10^4\,s^{-1}$ obtained using a split Hopkinson pressure bar apparatus. It is shown that the choice of specimen thickness in these tests significantly affects the measured flow stresses at high strain rates, with the thicker specimens showing an apparent enhancement of flow stress at high rates. Comparison of the present results with published work suggests that some high strain rate data in the literature could be erroneous due to an inappropriate choice of specimen dimensions.

(Keywords: compression; strain rate; specimen dimensions)

INTRODUCTION

The increasing use of polymers in applications where they are subjected to rapid loading ranges from the use of polycarbonate as shields[1] to the use of polyethylene in pipelines for the distribution of fuel gas[2] where, in the event of an accidental impact, pipes can fail catastrophically by propagation of a fast-running crack. Since axial rapid crack propagation can destroy hundreds of metres of pipe within a few seconds, the economic and safety implications are very serious.

There is therefore a great need for data on the properties of polymers at high strain rates. In spite of this there are few published works[3–8] on the behaviour of polymers at strain rates above $10^3\,s^{-1}$, all of which involve experiments using split Hopkinson pressure bar apparatus. Walley *et al.*[3,4] and Briscoe and Nosker[5,6] achieved high strain rates by testing very thin specimens, typically less than 2 mm. On the other hand, Rietsch and Bouette[7] and Chou *et al.*[8] used rather thick specimens, typically greater than 8 mm, and achieved high strain rates by employing successively higher impact velocities.

Briscoe and Nosker[5,6] concluded from their tests on high density polyethylene that the strain rate sensitivity of this material could be described by an Eyring model for strain rates up to $10^4\,s^{-1}$. Walley *et al.*[3,4] also arrived at a similar conclusion for most of the polymers tested, although in some cases they reported a drop in measured flow stresses at strain rates in excess of $10^3\,s^{-1}$, which they attributed to thermal processes. However, results obtained by Rietsch and Bouette[7] and Chou *et al.*[8] showed an increase in the measured flow stresses at high strain rates for all the materials tested, thereby suggesting an increase in strain rate sensitivity at strain rates above $10^3\,s^{-1}$. Rietsch and Bouette[7] went further and explained this behaviour in terms of a difference in relaxation modes at high and low strain rates. The present workers, however, believe that this observed increase in strain rate sensitivity reported by some authors at high strain rates is related to specimen thickness.

The objectives of the work described here were: (1) to carry out an investigation on the effect of specimen thickness in split Hopkinson pressure bar tests at strain rates above $10^3\,s^{-1}$; and (2) to alleviate the paucity of high strain rate data on polymers. In order to achieve this, tests on four polymers were carried out at low (10^{-4}–$10^{-1}\,s^{-1}$), intermediate (10^{-1}–$10^2\,s^{-1}$) and high (10^2–$10^4\,s^{-1}$) strain rates and for various specimen thicknesses.

EXPERIMENTAL

Materials

The strain rate sensitivity of four thermoplastics has been studied: medium density polyethylene (MDPE; Rigidex 002/50, from BP Chemicals); a modified high density polyethylene (HDPE; Soltex TUB 125, from Solvay); polycarbonate (PC, Lexan, from General Electric); and poly(ether ether ketone) (PEEK; Victrex, from ICI). All the materials were supplied in the form of compression-moulded sheets. The samples were machined into 12.7 mm diameter discs of thickness 4.4 mm or 1.5 mm. Before testing, each specimen was coated with a thin layer of petroleum jelly, which has been shown to be a good lubricant for testing polymers at high strain rates[3–5].

Tests

The low and intermediate rate tests were carried out on an Instron and a Mayes machine, respectively. Due to the small specimen thicknesses used, a linear voltage differential transducer (LVDT) was used to monitor specimen deformation. Strain rate was calculated from the LVDT readings and checked against the chosen crosshead velocity of the machine.

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0032-3861/93/204230-05

All high rate tests were carried out in a split Hopkinson pressure bar apparatus. In its compressive configuration this consists of two long elastic bars, an input and output, with the disc-shaped specimen sandwiched in between. Both the input and output bars are made from 15.8 mm diameter high strength aluminium (HE15) bars. The free end of the input bar is subjected to an axial impact by a projectile made from the bar stock. This generates a compressive loading pulse which travels along the input bar towards the specimen. Due to a difference in mechanical impedance between the bars and the specimen, interaction of the incident pulse and the specimen results in stress waves being reflected back into the input bar and also being transmitted through the specimen into the output bar. Having recorded the incident, reflected and transmitted strain pulses at fixed points in the bar (denoted by $\varepsilon_I(t)$, $\varepsilon_R(t)$ and $\varepsilon_T(t)$), the displacement conditions at the specimen–bar interfaces can be established. The variation of stress and strain in the sample are conventionally obtained from the following expressions[9]:

$$\varepsilon_s(t) = \frac{-2C_b}{l}\int_0^t \varepsilon_R(t)\,\mathrm{d}t \tag{1}$$

$$\sigma_s(t) = E\left(\frac{A}{A_s}\right)\varepsilon_T(t) \tag{2}$$

$$\dot{\varepsilon}_s(t) = \frac{-2C_b}{l}\varepsilon_R(t) \tag{3}$$

where $\varepsilon_s(t)$, $\sigma_s(t)$ and $\dot{\varepsilon}_s(t)$ are the variation of strain, stress and strain rate, respectively, in the specimen with time. E and C_b are the Young's modulus and elastic wave speed in the bars, respectively, while l is the initial length of the specimen and A/A_s is the area ratio between the bars and the specimen. The strain pulses are shifted in time so as to be coincident at the specimen. The stress–strain relation of the material being measured can then be obtained by eliminating time, t, between equations (1) and (2), and the strain rate directly from equation (3).

RESULTS AND DISCUSSION

Wherever possible, results such as those shown in *Figures 1* to *4* are presented in the form of yield stress against the logarithmic strain rate in order to assess the strain rate sensitivity of the material under investigation. This was only possible for PC, since it is the only material tested that exhibits a yield point in compression. For the other materials, plots of flow stress at specific values of strain were produced instead (*Figures 7* to *12*).

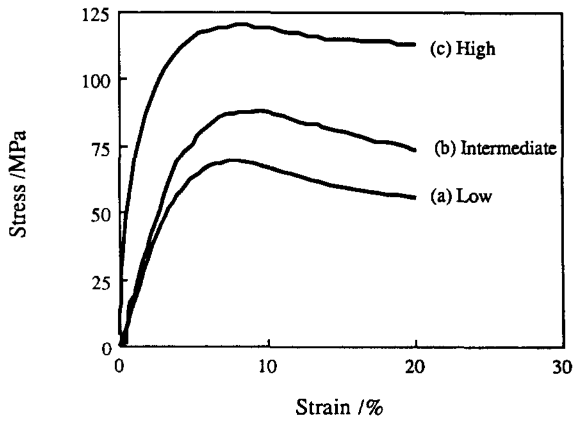

Figure 1 Typical stress–strain curves for PC at 23°C for various strain rates showing a definite yield point. Curves (a), (b) and (c) correspond to average strain rates of 0.000368 s^{-1}, 8.43 s^{-1} and 6000 s^{-1}, respectively

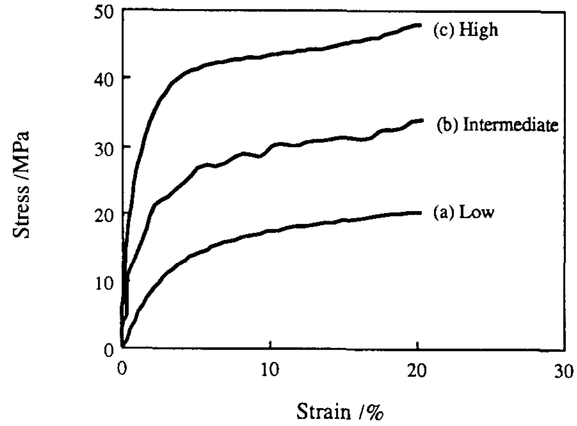

Figure 2 Typical stress–strain curves for MDPE at 23°C for various strain rates. Curves (a), (b) and (c) correspond to average strain rates of 0.00037 s^{-1}, 9.35 s^{-1} and 3910 s^{-1}, respectively

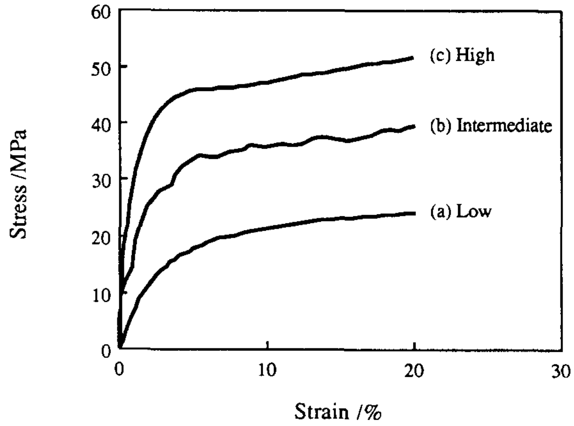

Figure 3 Typical stress–strain curves for HDPE at 23°C for various strain rates. Curves (a), (b) and (c) correspond to average strain rates of 0.00039 s^{-1}, 9.58 s^{-1} and 4450 s^{-1}, respectively

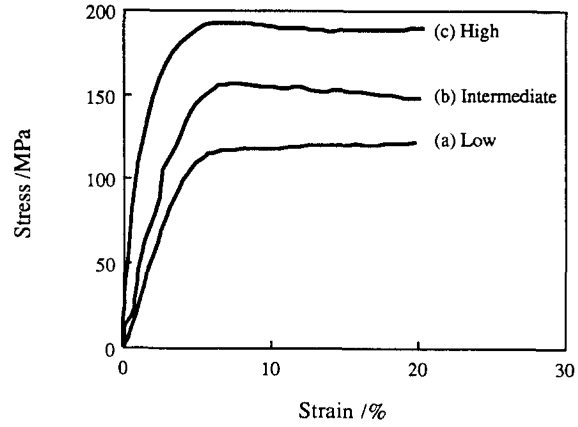

Figure 4 Typical stress–strain curves for PEEK at 23°C for various strain rates. Curves (a), (b) and (c) correspond to average strain rates of 0.000375 s^{-1}, 8.44 s^{-1} and 5520 s^{-1}, respectively

Whereas at intermediate strain rates there is good agreement between the measured flow stresses for both specimen thicknesses, at high strain rates the measured

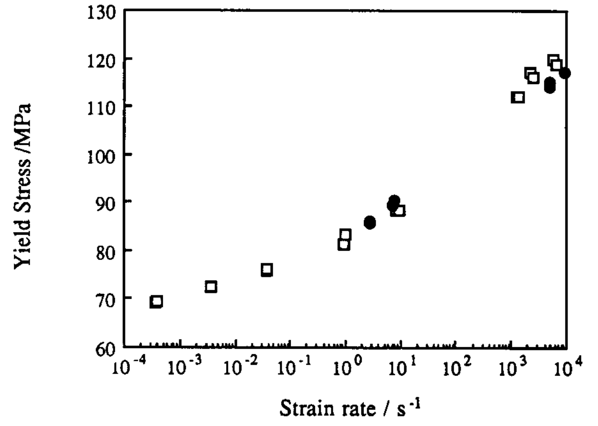

Figure 5 Measured yield stress as a function of logarithmic strain rate for PC at 23°C. Symbols: □, 4.4 mm thick specimen; ●, 1.5 mm thick specimen

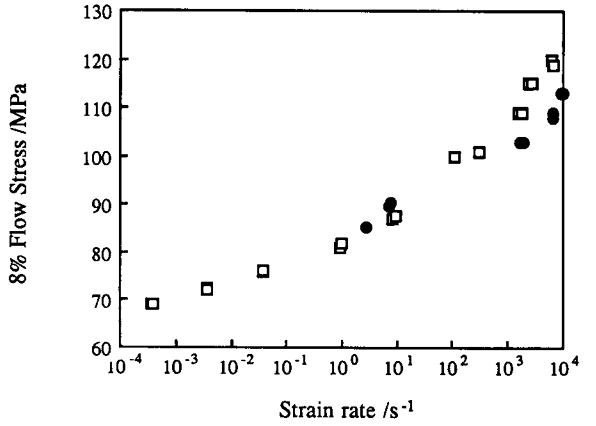

Figure 6 Measured 8% flow stress as a function of logarithmic strain rate for PC at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

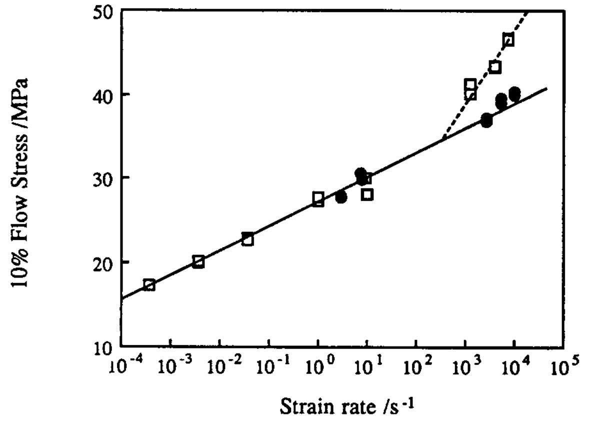

Figure 7 Measured 10% flow stress as a function of logarithmic strain rate for MDPE at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

flow stresses for the thinner specimens are significantly lower for all the materials tested. The behaviour of the MDPE and HDPE at room temperature can be described by the Eyring model if the high rate data for the thinner specimens are used. Using the data for the thicker specimens at high strain rates would lead to the conclusion that the strain rate sensitivity of each material increases suddenly at high strain rates. However, even results for thinner specimens suggest that the simple Eyring model cannot adequately describe the behaviour of PC and PEEK at room temperature between the strain rates of 10^{-4} and $10^{4}\ \mathrm{s}^{-1}$.

The results obtained for HDPE (*Figures 9* and *10*) are in agreement with those reported by Briscoe and Nosker[6]. The present work suggests that the simple Eyring model, which has been shown to describe closely the behaviour of PC at low strain rates[10], is inadequate at high strain

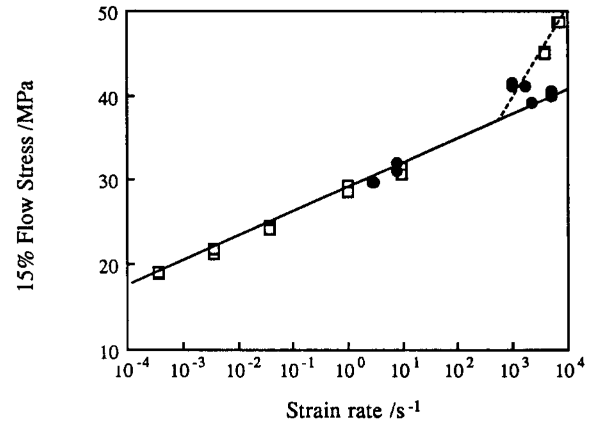

Figure 8 Measured 15% flow stress as a function of logarithmic strain rate for MDPE at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

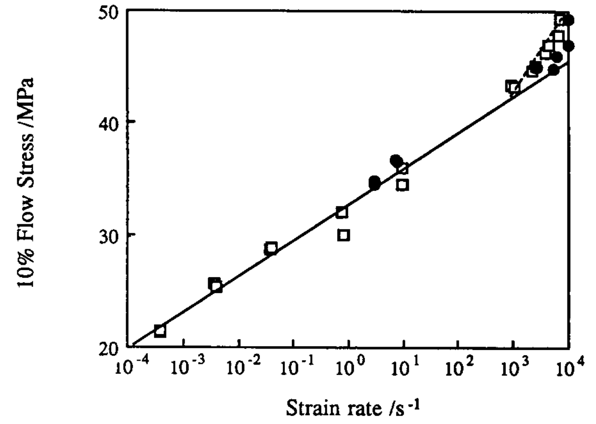

Figure 9 Measured 10% flow stress as a function of logarithmic strain rate for HDPE at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

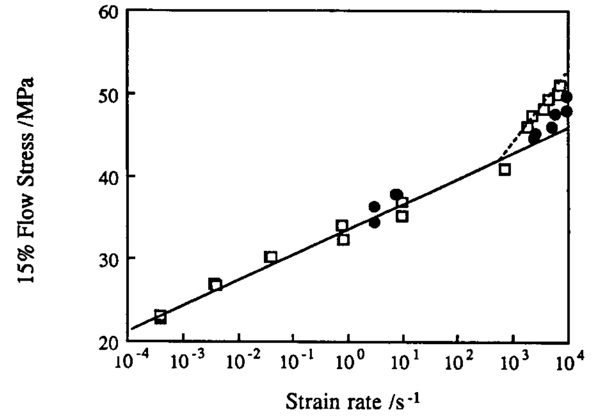

Figure 10 Measured 15% flow stress as a function of logarithmic strain rate for HDPE at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

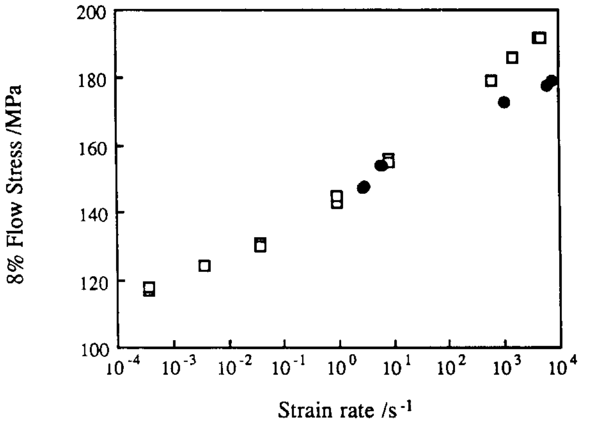

Figure 11 Measured 8% flow stress as a function of logarithmic strain rate for PEEK at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

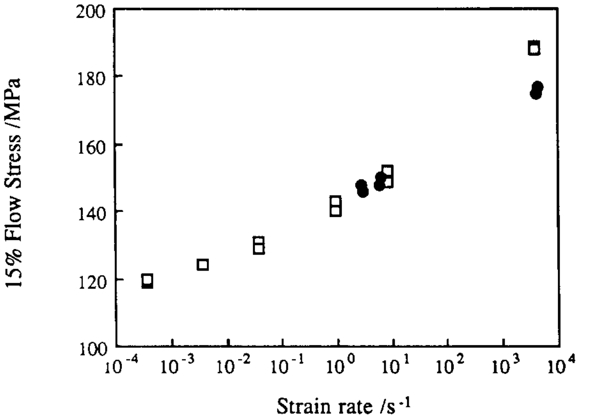

Figure 12 Measured 15% flow stress as a function of logarithmic strain rate for PEEK at 23°C. Specimen thickness: □, 4.4 mm; ●, 1.5 mm

rates, towards which a gentle increase in strain rate sensitivity emerges (*Figures 5* and *6*). The results presented in these figures also show that if the specimen thickness is chosen carefully, the sudden increase in the strain rate sensitivity of PC at high strain rates, reported by Rietsch and Bouette[7] (*Figure 13*), does not appear. This suggests that the sudden increase in strain rate sensitivity of a range of polymers at strain rates above $10^3\,s^{-1}$, observed by Chou *et al.*[8] (*Figure 14*) for specimen thicknesses of 9.5 mm, might also disappear for an appropriate choice of thickness. No comparisons can be made for PEEK as data at strain rates above $250\,s^{-1}$ are not available in the literature.

A sharp increase in the strain rate sensitivity of most metals has also been reported at high strain rates; there is still some controversy as to the underlying explanation. In the past, this behaviour was generally interpreted as a transition from one or more of a series of thermally activated flow mechanisms at low rates to a flow process dominated by viscous drag at high rates. However, recent work by Follansbee and Kocks[11] suggests that this observed behaviour can be more accurately interpreted as a change in the way the structure evolves with strain. By considering deformation velocity, friction and inertia in these high rate tests, Gorham[12] argues by a process of elimination that inertial resistance to longitudinal and radial deformation may be responsible. By compiling experimental data for copper obtained by various authors, he shows that the strain rate at which this sharp increase in strain rate sensitivity occurs is influenced by the specimen geometry.

From the evidence presented, it is apparent that if results obtained at high strain rates are to be relied upon, then they must be shown to be independent of geometry, in particular specimen thickness.

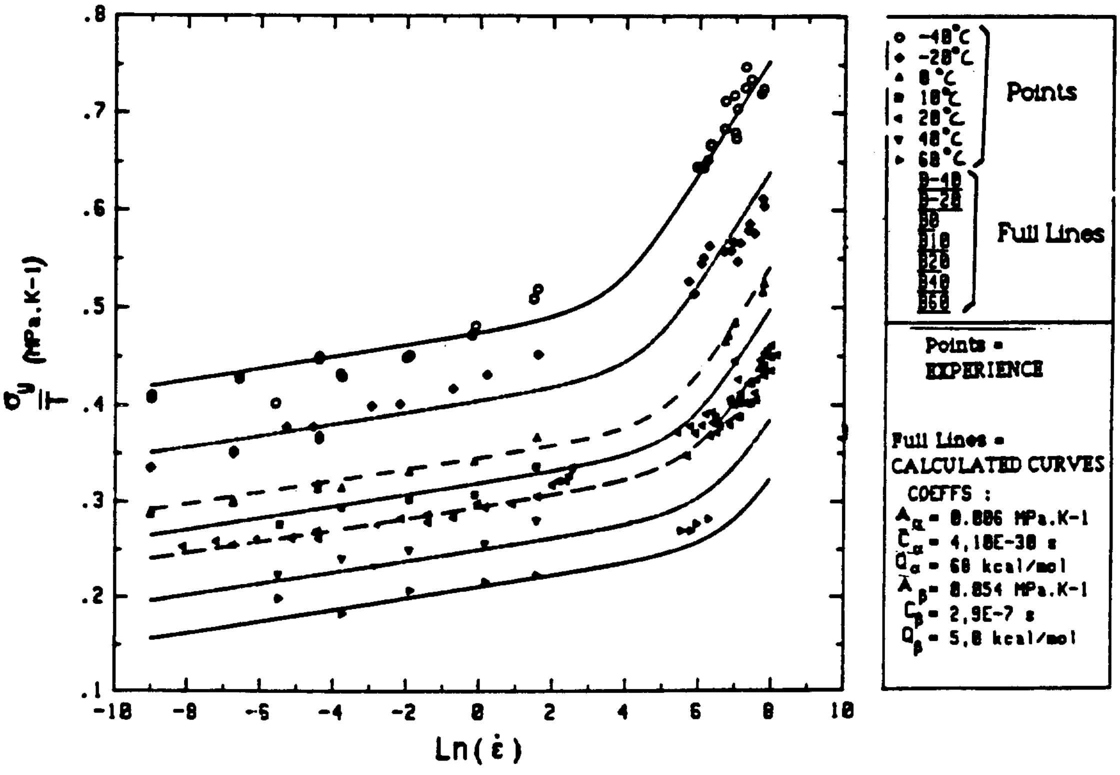

Figure 13 Measured ratio of yield stress as a function of logarithmic strain rate for PC. After Rietsch and Bouette[7]

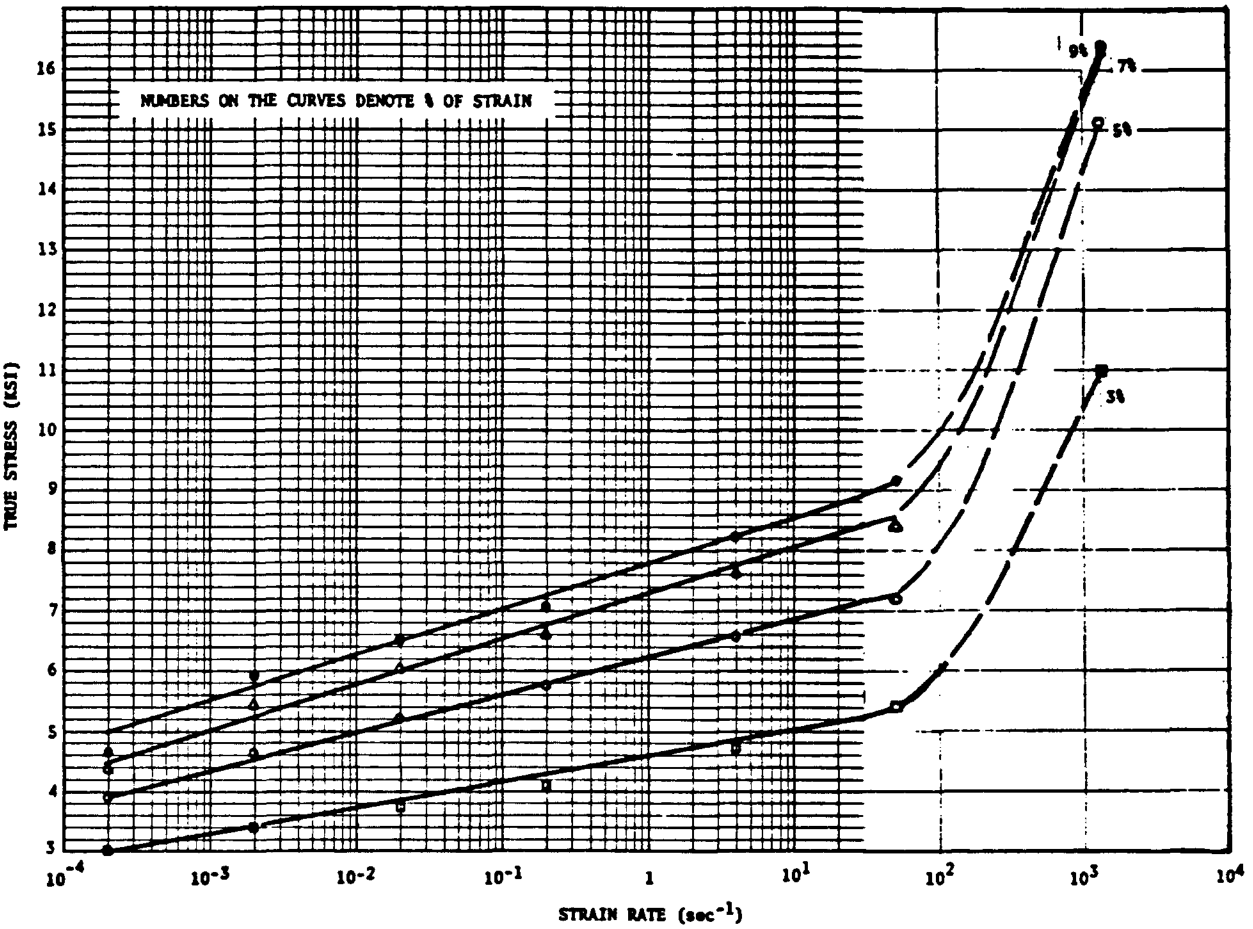

Figure 14 Measured flow stress as a function of logarithmic strain rate for polypropylene. After Chou *et al.*[8]

CONCLUSION

Results have been presented for the high strain rate behaviour of MDPE, HDPE, PC and PEEK at room temperature for strain rates up to $10^4\,s^{-1}$. The effect of specimen geometry on these results at intermediate and high strain rates has also been investigated. At intermediate strain rates, good agreement is obtained between the measured flow stresses for both specimen thicknesses. At high rates, however, the measured flow stresses for the thinner specimens are significantly lower for all the materials tested. The results are shown to be consistent with those in the literature. This suggests that some results available in the literature may be erroneous due to an inappropriate choice of specimen dimensions, undermining conclusions made about the inherent behaviour of the materials under investigation.

ACKNOWLEDGEMENTS

The authors are grateful to the Quantum Chemical Corporation for providing the financial support necessary during the course of the work, and to Stewarts and Lloyds Plastics and ICI Plastics for providing polymer samples.

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