LOADING RATE DEPENDENCE OF FRACTURE PROPERTIES FOR ENGINEERING PLASTICS

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To characterize the time dependent fracture behaviour of high density poly(ethylene) (PE-HD) and poly(oxy-methylene) (POM), instrumented impact tests were performed with a servohydraulic test system using various specimens under bending and tensile loading. The objectives of this study were to develop and implement a test methodology and a data recording and reduction scheme for various test speeds and impact rates (0.0001 to 8 m/s), and to determine the effect of the impact rate on the fracture toughness of PE-HD and POM. The data reduction to determine dynamic fracture toughness values was carried out according to different procedures taking account of the various impact rates and the specific deformation behaviour of the materials tested.

INTRODUCTION

For many engineering applications, impact fracture behavior is of prime practical importance. While impact properties of plastics are usually characterized in terms of notched or unnotched impact fracture energies, there has been an increasing tendency to also apply fracture mechanics techniques over the last decade (1, 2). However, due to dynamic effects several special problems are encountered in high rate fracture testing (1, 3, 4). While the control of dynamic effects at impact rates up to 1 m/s frequently makes use of mechanical damping in the load transmission by placing a soft pad between the striker and the specimen, for intermediate impact rates above 1 m/s to 10 m/s, dynamic techniques (1, 3), may be applied. Furthermore, for this impact rate range, a modified tensile type specimen geometry together with damping elements has been suggested by other investigators to determine fracture toughness values with the conventional force based method (4). The objective of this study was to develop, implement and compare different test methodologies and data recording and reduction schemes to determine impact rate dependent fracture toughness values for two semicrystalline polymers. Included in the investigations were bending and tensile specimens which were exposed to impact rates from 0.0001 to 8 m/s using a servohydraulic test system instrumented for high rate testing.

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EXPERIMENTAL

Materials and Specimens

Two polymeric materials, commercial grade poly(oxymethylene) (POM) (Hostaform C 2552, Hoechst AG, Frankfurt/Main, D) and commercial grade poly(ethylene) (PE-HD) (Daplen 3964, PCD Polymere, Linz, A), were used in this study. The POM was supplied as extruded sheets with a nominal thickness of 10 to 12 mm. The PE-HD was compression moulded to plaques with a nominal thickness of 10 mm. Single edge notched bending (SENB) and compact type (CT) specimens according to a configuration defined in (1), and single edge notched tensile (SENT) specimens according to a configuration defined in (5) were machined from the sheets and plaques, respectively, and subsequently notched razor blade precracked and side grooved. The side grooving for SENT specimen was 20 % of the nominal thickness. The normalized crack length, a/W (a being the crack length and W the specimen width), ranged from 0.45 to 0.55.

Testing and Data Acquisition

A fully digitized servohydraulic test machine (MTS 831.59 Polymer Test System, MTS Corp., Minneapolis, USA) was used to perform all of the tests. The striker for the SENB specimens and the fixture for the CT and SENT specimens was equipped with a piezo load cell (Kistler 9041A). The load-point displacement associated with the striker movement was determined from an LVDT signal of the piston. For impact rates above 1 m/s some specimens were also instrumented. In several test series, strain gages (CEA-06-032UW-120, CEA -06-062UW-350, Measurements Group Inc. Raleigh, USA) were applied to the specimen near the crack tip.

Data Reduction

Typical examples of force/load-point displacement curves of SENB specimens for impact rates of 0.1 m/s, 1 m/s and 3.3 m/s are shown in Fig. 1 for POM and PE-HD. While the recorded non-damped signal at 0.1 m/s is of sufficient quality to directly determine the fracture force, F_Q, significant force oscillations are visible in the non-damped signal at 1 m/s. An equivalent diagram for a loading rate of 1 m/s with a plasticene damping material placed at the striker tip is also shown in Fig. 1a and compared to the non-damped case. Force oscillations are seen to be significantly reduced, thus allowing again for a direct determination of F_Q. For a loading rate of 3.3 m/s the inertial forces apparently overshadow the true mechanical response of the specimen. Hence, a force based analysis is not possible in this case.

For POM loaded at impact rates up to 1 m/s in case of the SENB specimens and up to 8 m/s in case of the CT specimens, fracture toughness values, K_{Ic}, were calculated as follows:

$$K_{Ic} = \frac{F_Q}{BW^{1/2}} f(a/W) \tag{1}$$

where F_Q is the fracture force, B is the specimen thickness, W is the specimen width, and a is the crack length.

In sharp contrast to POM, PE-HD reveals distinct non-linear load-displacement characteristics with an F_{max}/F_Q ratio larger than 1.1 (see Fig. 1b). However, once F_{max} is reached, unstable crack propagation in a quasi-brittle fracture mode occurs. As expected, the degree of non-linearity decreases with increasing test speed; simultaneously the maximum force is also slightly reduced up to 3 m/s. As the methodology of linear elastic fracture mechanics (LEFM) to determine K_{Ic} is not applicable for the high degree of non-linearity observed, a data reduction scheme based on critical value of the J-integral up to F_{max} was applied. Accordingly, critical values for J_c and K_{Jc} were determined as follows (5):

$$J_c = \frac{\eta_{el} U_{elcorr}}{B(W-a)} + \frac{\eta_{pl} U_{plcorr}}{B(W-a)} \tag{2}$$

$$K_{Jc} = \sqrt{\frac{J_c E}{(1-\nu^2)}} \tag{3}$$

where J_c is the critical J-integral value and K_{Jc} is the apparent fracture toughness accounting for the non-linear load-displacement response. As to the the other terms in eqs. (2) and (3), U_{elcorr} and U_{plcorr}, respectively, are the elastic and plastic energies up to F_{max} with indentation correction, η_{el} and η_{pl}, respectively are the elastic and plastic geometry factors for the SENT specimen geometry (6), ν is Poisson's ratio, and E is Young's modulus. The proper time dependent E values were determined with different techniques described elsewhere (7).

Examples of force/load-point displacement curves for the tensile loading mode specimens of the CT and SENT type are shown in Fig. 2 for POM and PE-HD for impact rates of 0.1 m/s, 1 m/s, and 3.7 m/s. In contrast to the results with bending specimens (i.e., SENB) in Fig.1, which indicate a limit of about 1 m/s for a data reduction scheme based on load-displacement records, the load-displacement results of the tensile load specimens in Fig. 2 apparently are of sufficient quality to determine fracture force values even at loading speeds above 1 m/s. It is also interesting to note, that the tensile mode SENT specimens of PE-HD reveal a much reduced non-linearity in the load-displacement trace when compared to the corresponding result of SENB specimens (compare Figs. 1b and 2b). The improved signal quality of the tensile mode CT and SENT specimens over the bending type SENB specimens is a result of the higher specimen and contact stiffness associated with the former specimen configurations as well as the more effective damping situation in the loading unit.

To characterise the real material response of POM with SENB specimens at impact rates above 1 m/s, specimens were instrumented with crack tip strain gages (Fig. 3). Fig. 3a shows a typical example of corresponding striker force and the strain gage signals. To determine accurate values for time-to-fracture, t_f, both signals are required.

While the striker signal is more accurate in defining the point of initial load implementation, the strain gage signal reveals a delayed load implementation response. On the other hand, the striker signal reveals no indication of where fracture initiation occurs, a point which can clearly be deduced from the strain gage signal. Based on the crack tip strain gage signal, K_{Ic} values may be determined according to various methods (3, 7).

RESULTS AND DISCUSSION

Experimental results for the effect of the strain rate on K_{Ic} and K_{Jc} for POM and PE-HD, respectively, are shown in Fig. 4 for various specimen geometries, including also side grooved specimens of PE-HD to enhance the constraint at the crack tip upon loading and to favour the tendency for brittle fracture. The testing rates in these experiments covered the range from 0.0001 to 8 m/s (approximately five decades). Based on the testing rates, local crack tip loading rate values (dK/dt), were obtained according to a procedure described in (1). In general, for both materials good agreement is found in the results for various specimen configurations.

For POM (Fig. 4a) K_{Ic} is seen to continuously decrease with increasing loading rate up to about $5x10^3$ $MPam^{1/2}s^{-1}$. Above this loading rate rate, the results with CT specimens and instrumented SENB specimens indicate a knee in the K_{Ic}-strain rate dependence with a stronger drop-off in fracture toughness. The comparison with the results of non-instrumented SENB specimens indicates that this technique is limited to local crack tip loading rates up to about $5x10^3$ $MPam^{1/2}s^{-1}$ (corresponds to impact rates of up to about 1 m/s). Using these K_{Ic} results together with strain rate dependent yield stress values of the POM material investigated, it could be shown that the plain strain fracture toughness concept is applicable (7).

Compared to the results for POM, the apparent fracture toughness K_{Jc} of PE-HD (see Fig. 4b) reveals a much more pronounced crack tip loading rate dependence in the range from 10^{-1} up to $5x10^3$ $MPam^{1/2}s^{-1}$, with K_{Jc} values dropping from about 10 $MPam^{1/2}$ to 3 $MPam^{1/2}$. At $5x10^3$ $MPam^{1/2}s^{-1}$ apparently a minimum in the K_{Jc}-dK/dt rate dependence occurs, an explanation of which needs further investigations.

SUMMARY AND CONCLUSIONS

To characterize the dynamic fracture behaviour of POM and PE-HD, instrumented impact tests were performed in the testing rate range from 0.0001 to 8 m/s with a servohydraulic test system using various fracture mechanical specimens and data reduction methods. In general, good agreement was found in the results obtained by different methods for each of the materials, revealing a reduction in the characteristic fracture toughness values, K_{Ic} and K_{Jc} for POM and PE-HD, respectively, with increasing impact rate up to at least about 5 m/s. In agreement with previous considerations (8), this fracture toughness decrease is thought to be a result of the viscoelastic nature of these materials revealing an increase in yield stress with increasing strain rate and the corresponding reduction in crack tip plastic zone size.

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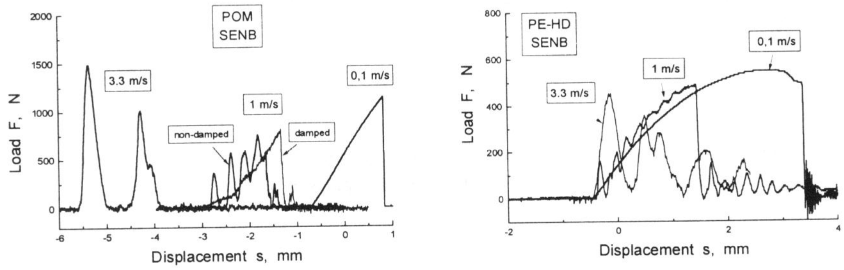
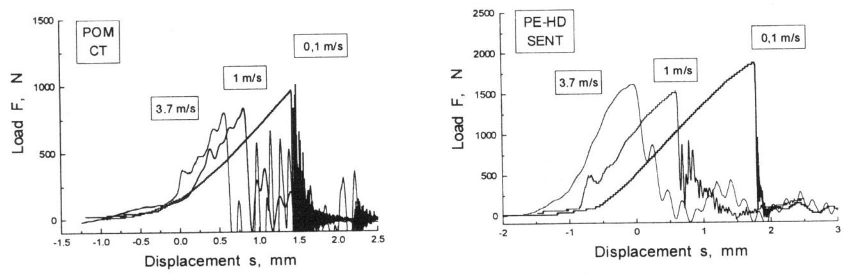


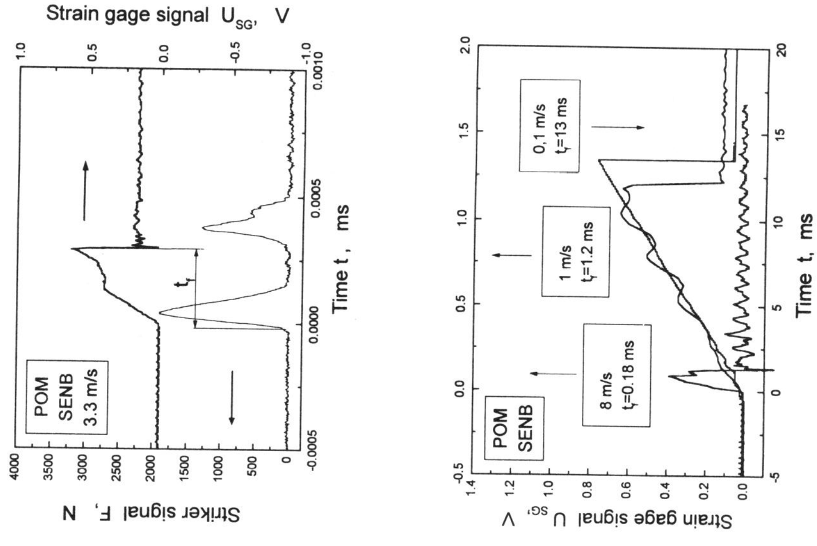
(a) (b)

Figure 1: Load/Displacement records for SENB specimens of POM and PE-HD at impact rates of 0.1 m/s, 1 m/s and 3.3 m/s



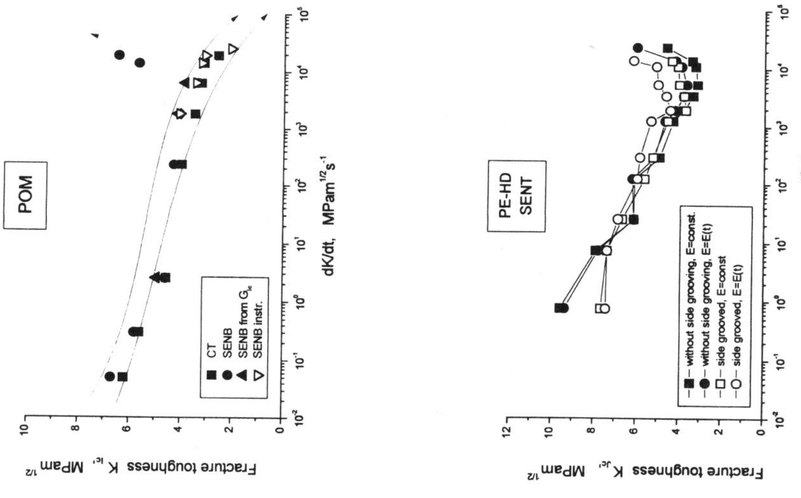
(a) (b)

Figure 2: Load/Displacement records for CT and SENT specimens of POM and PE-HD at impact rates of 0.1 m/s, 1 m/s and 3.7 m/s



(a) (b)

Figure 3: Striker force and strain gage signal (Fig. 3a) and strain gage signals at various testing rates (Fig. 3b) for POM (specimen type: SENB)



(a) (b)

Figure 4: Effect of loading rate on K_{Ic} and K_{Jc} for POM and PE-HD, respectively, using various specimen geometries