CHARACTERIZATION OF THE DEFORMATION AND FRACTURE BEHAVIOR OF POLYMERS IN MONOTONIC TORSION AND COMBINED TENSION/TORSION EXPERIMENTS

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ABSTRACT

While the deformation behavior of engineering polymers is frequently characterized under torsion over a wide temperature range with small scale oscillatory deformations, hardly any data exist for monotonic deformations and for large strains. Similarly, fracture toughness values for mode I are available for a number of polymers but there are no data for the ubiquitous mode III loading mode. Tension and torsion tests were carried out on various thermoplastic polymeric materials using unnotched and notched round bar specimens in this study. Modulus and yield stress values were determined by using the unnotched specimens and fracture toughness values were derived in terms of K_{Ic}, K_{IIIc} and J_{Ic}^P and J_{IIIc}^P by using the notched round bar specimens. Special emphasis was devoted to the proper conduction of torsion tests with various control modes. The polymers investigated were compared based on the fracture toughness values and on the appearance of fracture surfaces.

KEYWORDS

torsion loading, unnotched and notched round bar specimens, mode III fracture toughness.

INTRODUCTION

While the deformation behavior of engineering polymers is well acknowledged and extensively characterized under tension and bending loading conditions and the fracture behavior is widely characterized under crack tip opening (mode I) loading over a wide temperature and loading rate range, hardly any data exist both for monotonic torsion deformation over a wide deformation range and for fracture mode III. This is, in spite of the fact, that the torsion loading is the simplest and most reasonable experiment to produce simple shear even under large strain conditions and to realize mode III loading conditions in the crack tip. Hence, the main objectives of this paper are: (1) to develop and implement adequate test methods and data reduction schemes to characterize the large scale deformation behavior of engineering polymers under monotonic torsion loading and under complex tension/torsion loading conditions and (2) to characterize the mode III fracture behavior of several thermoplastic polymers.

EXPERIMENTAL

The deformation and fracture tests were run on an axial/torsional servohydraulic test system (MTS System GmBH, Berlin, D) equipped with a hydraulic grip. The maximum force capacity of the machine is 25 kN, the stroke is 50 mm, the maximum torque is 250 Nm and the twist can be varied ±135 °. Five various thermoplastic polymers (Polyetherimide, PEI, Polyoxymethylene, POM, polyphenylensulphone or polyarylsulphone, PPSE polypropylene, βPP(H) and polytetrafluorethylene, PTFE) were used in this study. The materials were previously used in other research projects for different purposes and were available as well controlled compression molded plaques with nominal thickness of 14 mm. The tensile modulus values were ranged from 800 MPa to 3300 MPa for these engineering polymers. Cylindrical round bar specimen configuration with nominal diameter of 10 mm was used for the deformation analysis and various notched specimen configurations with 2 mm radial notch length for the fracture analysis in this study. The various round bar specimen configurations are shown in Fig. 1.

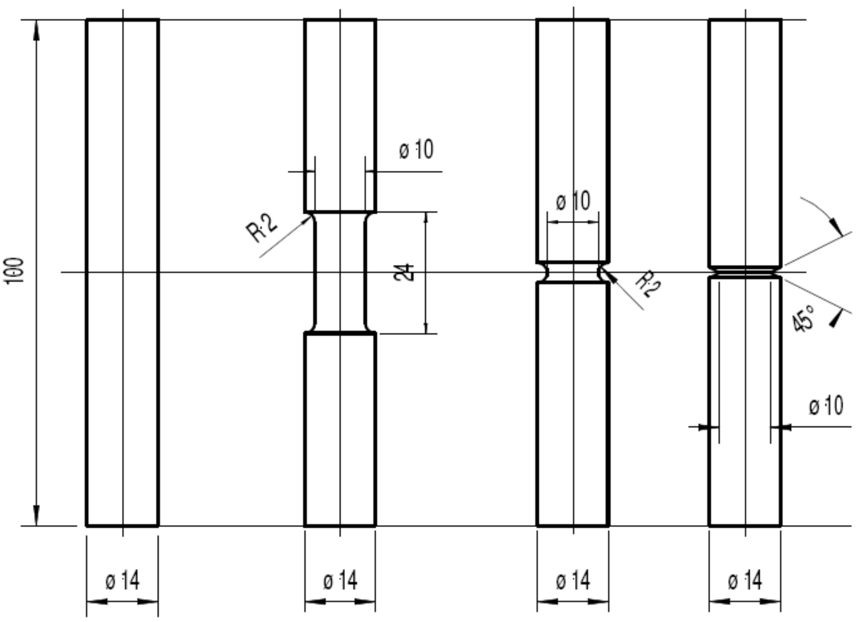


Fig. 1: Round bar specimen configurations

The testing rate in axial direction was varied between 0.1 and 10 mm/s, the angular test velocity was 0.1 to 10 degree/s in the torsion experiments. In all tests both the axial load-displacement data and the torque-angle data were measured and recorded. While the monotonic tensile test were carried out under displacement control, the monotonic torsion tests were performed under angular displacement control and simultaneously the axial deformation was controlled both by the axial load (load control, F_{ax}=0 N) and the axial displacement (displacement control, s_{ax}=0 mm). The specimen was placed in the hydraulic grip and subsequently loaded up to 270 ° twist angle. The specimen twisted and a schematic representation of the process is shown in Fig. 2.

The mode I stress intensity factor was calculated as in [1]:

$$K_I = \frac{P\sqrt{\pi a}}{\pi R^2} f\left(a/R\right) \tag{1}$$

Where P is the axial force, a is the crack length R is the half diameter of the round bar specimen and f(a/W) is the geometry factor defined as follows:

$$f\left(a/W\right) = \left(1 - a/R\right)^{-3/2} \left(0.8 + 3.2\left(a/R\right)\right)^{-1/2} \tag{2}$$

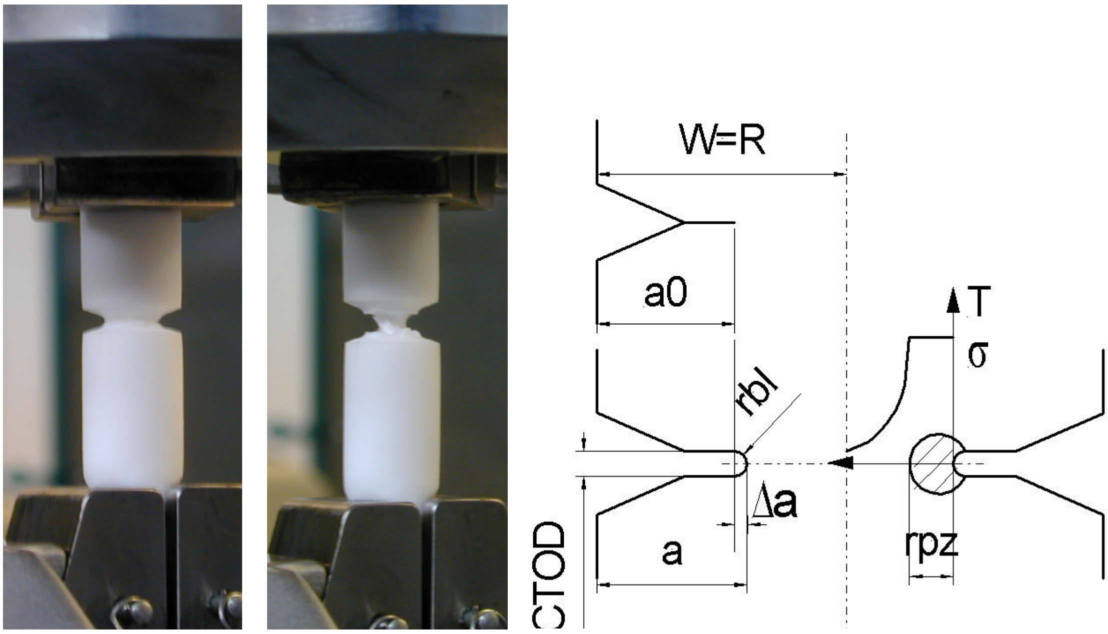


Fig. 2: Twisted round bar specimens and the schematic representation of the crack tip deformation process.

The mode III stress intensity factor was calculated according to the equations below [2]:

$$K_{III} = F S_g \sqrt{\pi a} \tag{3}$$

$$S_g = \frac{2T}{R^3 \pi} \tag{4}$$

Where T is the torque and F(a/R) is the geometry factor

$$F = \frac{3}{8\beta^{2.5}} \left[1 + \tfrac{1}{2}\beta + \frac{3}{8}\beta^2 - \tfrac{5}{16}\beta^3 + \tfrac{35}{128}\beta^4 + 0.208\beta^5 \right] \tag{5}$$

Where

$\alpha = a/R, \beta = 1 - \alpha$ and *F=1.00 (a/R<0.09)*

Energy based fracture toughness parameters were also calculated for both tension and torsion loading. The J integral was calculated for the tensile (mode I) loading according to the simplified equation which is a reasonable approximation for 0.45<a/R<0.65.

$$J = \frac{U}{2\pi R^2 \left(1 - a/R\right)^2} \tag{6}$$

Where U is the strain energy and was calculated by using the force-displacement curve.

Similarly to this, strain energy release rate for torsion loading condition was calculated using the following equation [3]:

$$G = \frac{\mu\phi^2}{2h(R-a)}(R-a)^3 \tag{7}$$

Where the strain energy in torsion, U was calculated according to

$$U = \frac{1}{2}M\phi = \frac{1}{2}K\phi^2 \tag{8}$$

Where M is the torque and K is the torsion stiffness of the specimen and μ is the shear modulus.

RESULTS AND DISCUSSION

To determine modulus and yield stress values, tensile tests were performed applying unnotched (RBT) and notched (CRB) specimens and the corresponding load displacement curves are shown in Fig.3.

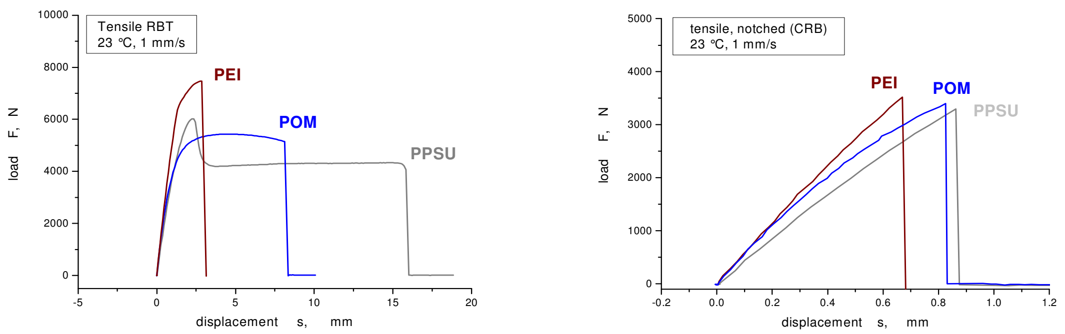


Fig. 3: Load-displacement curves for unnotched (RBT) and notched (CRB) round bar tensile specimens for 3 polymers investigated.

PPSU revealed the highest and PEI the lowest ductility during the unnotched tensile tests, all 3 materials has shown a rather brittle behaviour during the notched tensile tests.

Furthermore, torsion tests were carried out applying the same round bar specimens. The corresponding torque-twist angle curves are shown in Fig. 4. For simplicity, only the results of the axial force controlled (F_{ax}=0) experiments are shown in this study.

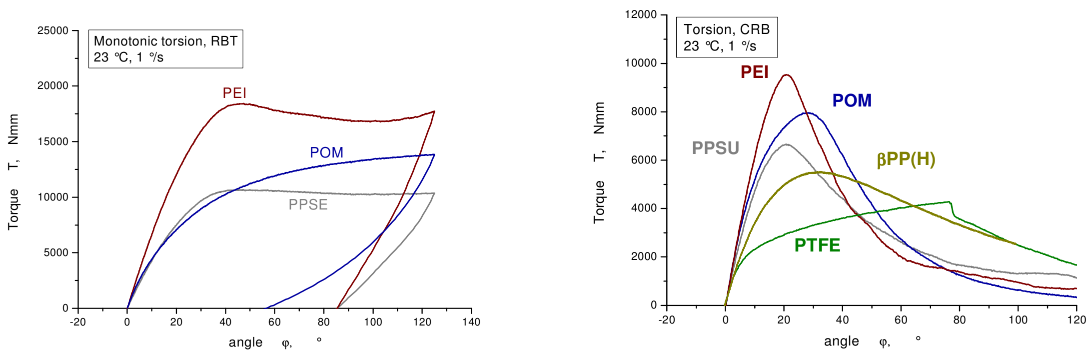


Fig. 4: Torque-twist angle curves for unnotched (RBT) and notched (CRB) round bar tensile specimens for the polymers investigated.

All polymers revealed ductile behavior under torsion loading conditions. In spite of this fact, however, the torque-twist angle curves indicate some differences, which can also clearly be recognized in the fracture surfaces. Light microscopy images of the fracture surfaces are shown in Fig. 5 for PEI, POM and PPSU. The surfaces are very rough (ductile) and clearly show twisted lines between the center of the specimen and the circumferential notch. The different roughness observed is associated with the different microstructure and different local plastic deformation mechanisms of the polymers.

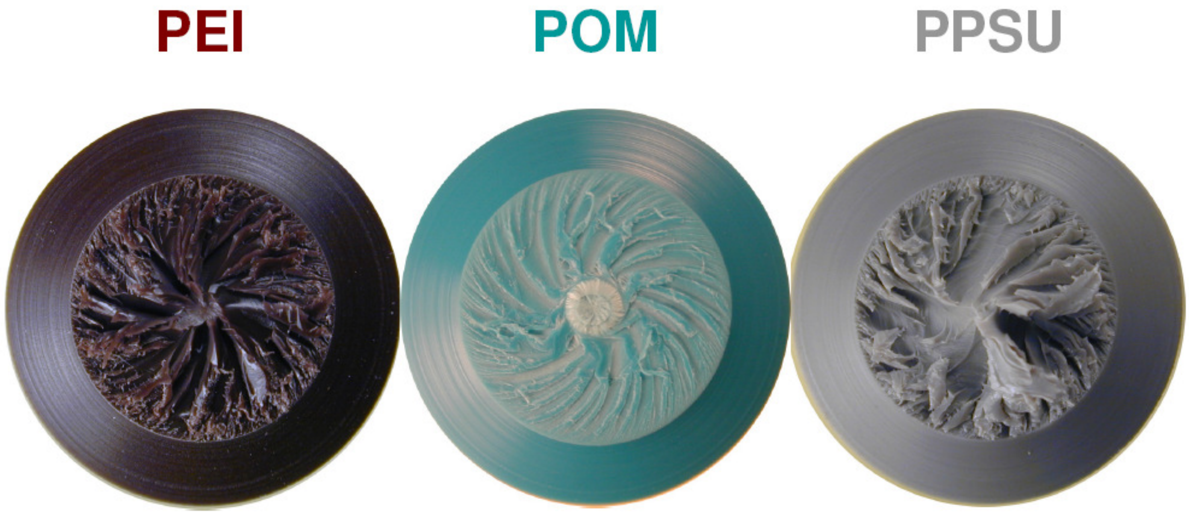


Fig. 5: Fracture surfaces of CRB specimens for three polymers investigated; (a) PEI, (b) POM and (c) PPSU.

To gain more insight into these differences scanning electron microscopy images were also made and examples are shown in Fig. 6 for PTFE. The twisted torn regions are also recognized in the SEM images. In addition, between these regions fibrils were developed and stretched during the twisting. It is assumed that this fibril formation provides a sufficient contribution to the ductility of the PTFE. It must be noted here, that while 3 polymers (POM, PPSU and βPP(H)) can be processed by injection moulding, PEI and PTFE typically manufactured by sintering and reveal a significantly different microstructure and thermo mechanical behaviour.

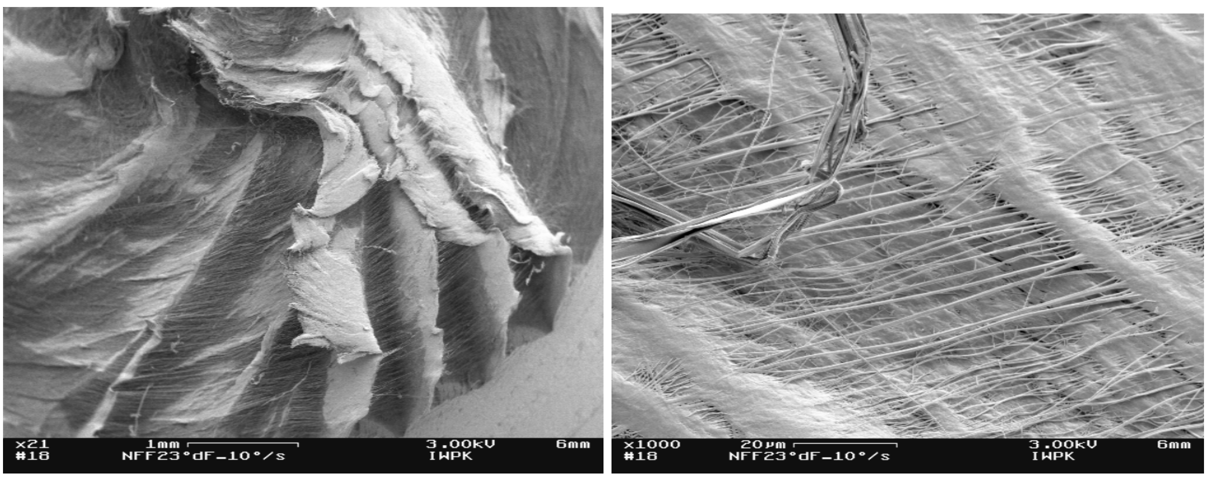
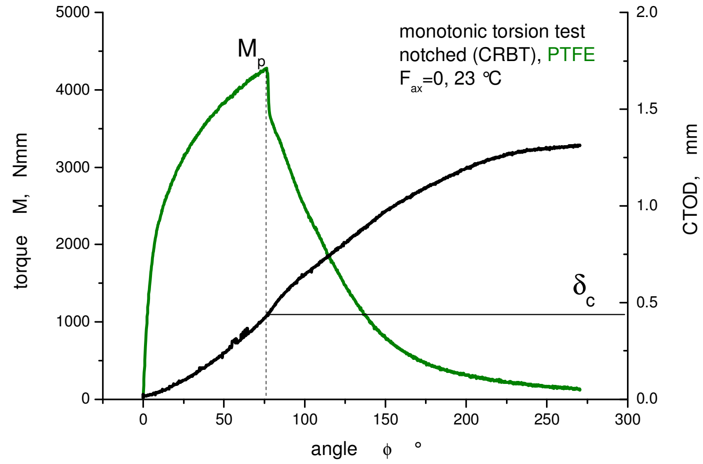
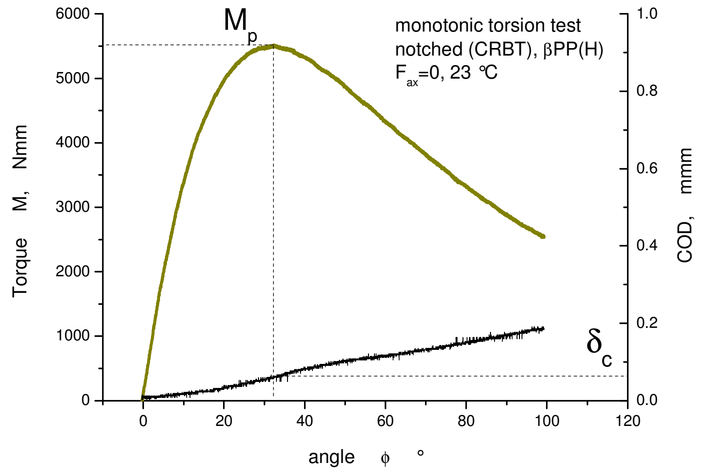


Fig. 6: SEM images of fracture surfaces of CRB specimens for PTFE.

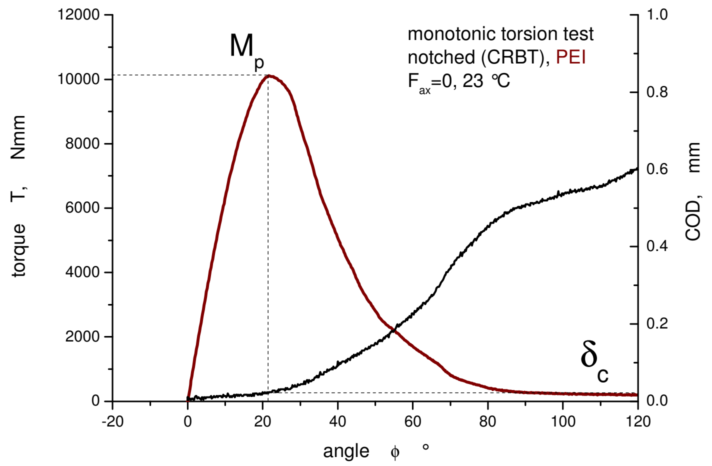
For more detailed fracture mechanics analysis 3 materials were selected and the torque-twist angle-COD curves for these polymers are shown in Fig. 7 for comparison.



(a)



(b)



(c)

Fig. 7: Torque-twist angle-crack opening displacement (COD) curves for three polymers investigated; (a) PTFE, (b) βPP(H) and (c) PEI.

As expected, based on the tensile behavior (i.e-, stress-strain curves and modulus values) significantly different torque-twist angle curves were observed for these polymers with peak torque values ranged from 4500 Nmm (PTFE) to 10000 Nmm (PEI). While a short crack instability was observed for PTFE after the peak torque the two other materials revealed stable crack growth although in different manner. The post-peak curve is stable (tearing) for βPP(H) and curved for PEI (softening). Furthermore, as the axial force was controlled during these experiments and was kept as 0, a significant axial displacement rise was observed during the torsion loading. This displacement act as crack opening during the torsion loading and was at the peak torque about 0.03 mm for PEI, 0.07 for βPP(H) and 0.4 mm for PTFE. These COD curves were also different, for βPP(H) linear and highly non-linear for PTFE and PEI.

SUMMARY AND CONCLUSIONS

The material parameters determined in the experiments are listed in Table 1 for all polymeric materials investigated.

Polymers	**Tensile modulus, E, MPa**	**Shear modulus, G, MPa**	**Yield stress, σ_y, MPa**	**Mode I fracture toughness K_{Ic}, $MPm^{1/2}$**	**Mode III fracture toughness K_{IIIc}, $MPm^{1/2}$**	**Mode I J_{Ic}^P, kJm^{-2}**	**Mode III J_{IIIc}^P kJm^{-2}**
PEI	3312	1325	105	2.5	3.6*	8.3	14.1
POM	3052	1106	60	2.3	2.9*	10.7	18
PPSU	2530	950	72	2.2	2.3*	10	10.2
PTFE	880	312	18	1.1	1.6*	3.8	29.2
βPP(H)	1400	508	25	1.6	2*	6.5	14.8

Table 1: The deformation and fracture parameters for the polymers investigated.

*) due to the ductile behavior the values are only apparent toughness values

Tension and torsion tests were performed on various polymeric materials in these experiments. The polymers investigated reveals significantly different modulus and yield stress values in tensile tests. Furthermore, the fracture behavior of these polymers was observed as brittle or semi-brittle in notched fracture tests with mode I fracture toughness values varied form 1.1 to 2.5 $MPam^{1/2}$. These values are in good agreement with fracture toughness values determined in [4] for βPP(H) and for a similar POM grade. In contrary to this, ductile fracture behavior was observed under torsion (mode III) in our experiments. Due to the experimental limitations torsion tests can be performed over a rather limited loading rate range (up to about 50 °/s) and only at RT. Despite, the question is arisen whether brittle fracture behavior of engineering polymers can be achieved in torsion experiments. The apparent mode III fracture toughness values are higher than the mode I values and are in the range of 1.6 to 3.6 $MPam^{1/2}$. Critical J integral values at the peak load were also calculated both for mode I and for mode III loading. The mode I J_{Ic}^P values are from 3.8 (PTFE) to 10.7 kJm^{-2} (POM) which are common values for engineering polymers [4]. Significantly higher J_{IIIc}^P values were determined under torsion loading conditions ranged from 10.2 (PPSU) up to 29.2 kJm^{-2} (PTFE). While PPSU revealed the less difference between J_{Ic}^P and J_{IIIc}^P values (practically no difference), a significant difference, nearly 10 times higher J_{IIIc}^P values were observed for PTFE. Latter is associated with the unique microstructure of the PTFE and the fibril formation during the shearing fracture and it will be described in a future paper.

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