CHARACTERIZATION OF POLYMER MATERIALS BY ELASTIC-PLASTIC CRACK GROWTH RESISTANCE CURVES

E. Reese[1], K.-H. Schwalbe[1], and K. Friedrich[2]

Three polymers, one of which having 30wt% short glass fibers, were machined into compact and center cracked tensile specimens varying in thickness, width and precracked length ratio. Applying the multiple specimen method, displacement controlled fracture mechanics tests were performed, the J-integral and the δ_5 type crack tip opening displacement were determined. The results showed that the elastic-plastic crack growth resistance curve methodology, the details of which were developed for metallic materials, could successfully be applied to polymeric materials. Furthermore, the variation of the specimen dimensions had an influence on the J-Δa-curve, whereas no effect on the δ_5-Δa-curve was observed. In addition, the CTOD δ_5 was found to correlate more stable crack growth than the J-integral.

INTRODUCTION

Engineering thermoplastics received wide spread attention because of their good mechanical properties (high strength to weight ratio, wear resistance) and low production costs. The increasing use of polymers as structural components raises the question of their reliability and service life. Fracture mechanics provides tools to characterize the fracture behavior of materials, which in turn allows predictions of the time to failure, in particular, once flaws and/or cracks have been formed.

The factors that influence the fracture behavior of a material can be expressed in terms of the crack field parameter. An important element of fracture mechanics is the crack growth resistance curve (R-curve) which correlates the crack field parameter with crack growth. For metals it was shown that the J-integral and the crack tip opening displacement (CTOD) are appropriate parameters to describe a nonlinear elastic material response (1).

The objective of this work is the determination of R-curves of polymers applying the methods which were initially developed for metals. In addition, the

1 GKSS Research Center Geesthacht GmbH, D-2054 Geesthacht, F.R.G.
2 Polymer and Composites Group, Technical University Hamburg-Harburg, D-2100 Hamburg 90, F.R.G.

effect of the specimen geometry is to be investigated to answer the question of transferability of the results obtained on laboratory samples to real structures.

EXPERIMENTAL DETAILS

Three types of materials were investigated: (i) a homopolymeric polypropylene (PP-H), (ii) a tough copolymeric polypropylene (PP-C), and (iii) a homopolymeric polypropylene with 30wt% coupled glass fibers (PP-H + 30 wt% GF). The materials were supplied as injection moulded plates of B=4mm, 6mm, and 10mm thickness. The mechanical properties, listed in Table 1, were obtained from tensile tests according to the German standards DIN 53455 and DIN 53457.

TABLE 1- Mechanical Properties.

Material	σ_{YS} [MPa]	σ_{TS} [MPa]	ε_{YS} [%]	ε_{TS} [%]	E [MPa]
PP-H	30.2	33.1	17.3	872	1610
PP-C	20.5	26.2	12.2	937	1490
PP-H + 30 wt% GF	41.0	41.0	14.4	14.4	4400

For the fracture mechanics experiments the multiple specimen technique was applied. CT- (compact tension) and CCT- (center cracked tension) specimens (Figure 1) were machined with the dimensions listed in Table 2.

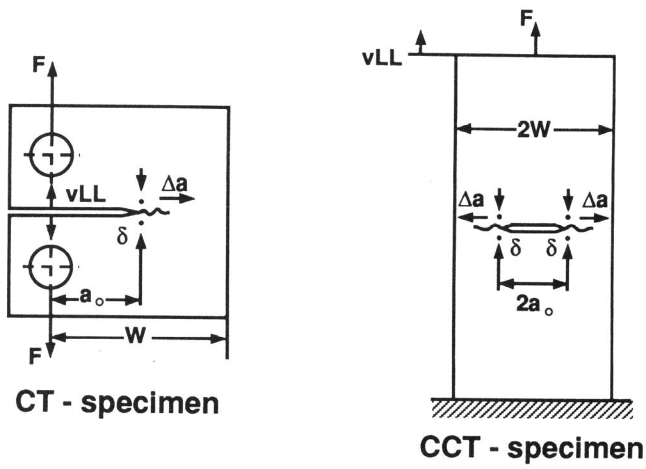


Figure 1. Specimen geometries for fracture mechanics experiments

TABLE 2 - Specimen dimensions.

Specimen type	a/W = 0.3	a/W = 0.5	a/W = 0.6	a/W = 0.7
CT	-----	W = 100 mm	W = 50 mm	W = 100 mm
CCT	W = 50 mm	W = 25 mm	W = 50 mm	-----

With metals, a natural crack is initiated by fatigue precracking. In many polymeric materials a sufficiently sharp crack may be induced by a razor blade cut (2).

Fracture Mechanics Experiments

All tests were performed in laboratory atmosphere at room temperature. The experiments were conducted on a universal testing machine (type ZWICK) with displacement control to ensure stable crack growth during the loading process as long as possible. After the test, the specimen was cooled in liquid nitrogen to ensure brittle fracture and then broken open. The crack length which had been marked by a liquid penetrant was measured on the fracture surface by means of an optical travelling microscope.

There are several formulae available to calculate the fracture resistance J from the P-v_{LL}-record. The ones given here are considered most appropriate for the multiple specimen technique. For the CT-geometry, J is calculated for each specimen using the relationship

$$J = \frac{U}{B\,(W-a)}\,\eta(a/W) \tag{1}$$

where U is the area under the load versus load-point displacement record and η is a geometry correction factor depending on the a/W-ratio. For the CCT-geometry, J is determined from

$$J = \frac{K^2}{E} + \frac{U^*}{B\,(W-a)} \tag{2}$$

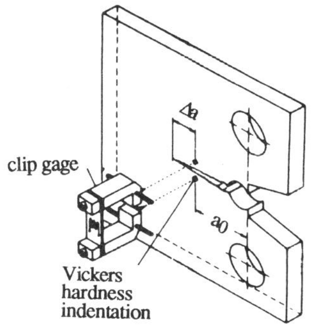
where K is the stress intensity factor according to

$$K = \frac{P}{2BW}\sqrt{\pi a}\sqrt{\sec\frac{\pi a}{2B}} \tag{3}$$

The energy term U^* represents the plastic component of the P-v_{LL}-curve.

The δ_5 type crack tip opening displacement (1) was measured as depicted in Figure 2. The δ_5 clip gage was held in its position by a small device which is not shown in the schematic picture.

The values for J and δ_5 are used to construct the plot of fracture resistance against crack growth.



Courtesy: D.Hellmann

Figure 2. Test set up for the determination of the crack tip opening displacement δ_5

RESULTS

Force-displacement-curves

Figure 3 depicts the force-displacement-curves for the three material systems tested. The PP-copolymer shows a very ductile behavior, the curve is strongly non-linear. Only stable crack growth was observed. The homopolymer exhibited a mainly elastic response accompanied by small amounts of stable crack growth and failed catastrophically upon reaching maximum load. Reinforcing the homopolymer with 30 wt% short glass fibers turned the notch sensitive PP-H matrix into a "tough" material which tolerated stable crack propagation almost throughout the entire ligament while conserving dimensional stability.

In the following we will focus our attention on the PP-C because this material showed a clear elastic-plastic response during the fracture mechanics tests.

R-curves

The metals standards for elastic-plastic fracture testing were applied to polymer materials and crack growth resistance curves on the basis of the J-integral and the crack tip opening displacement δ_5 were determined (Figure 4 and 5). The R-curves were defined to be independent of specimen geometry when the deviation of the J-Δa- and δ_5-Δa-curves due to specimen variation amounted to less than 5%.

For the PP-C, no effect of the specimen thickness, varying from 4mm to 10mm, on the crack growth resistance curves were found. It is assumed that the constraint effect in the crack tip region because of an increase in specimen thickness causing a transition from plane stress (as in the 4mm thick sample) to plane strain conditions (as expected for the 10mm thick samples) did not effectively take place.

Comparing the J-Δa-curves of two CCT-geometries with 2W=50mm (W-a=12.5mm) and 2W=100mm (W-a=35mm) a slight influence of the specimen width was observed beyond stable crack growth of $\Delta a \sim 1$mm. The large difference in the ligament causes a deviation of the J-Δa-curve of the smaller sample which was not found with the δ_5-R-curve.

A distinct geometry effect occurred due to different specimen types, such that the J-Δa-curves of the CCT-specimens were significantly higher than those for the CT-specimens, whereas, again, this effect was not found with the δ_5-Δa-curve. Hence, under tensile loading the J-integral correlates more crack growth than under bending; and under bending conditions the CTOD correlates more stable crack growth than the J-integral.

Comparison of J and δ_5

A comparison of J and δ_5, as depicted in Figure 6, shows that a unique relationship between the J-integral and the crack tip opening displacement δ_5 exists, independent of the specimen type and specimen dimensions. Thus, the CTOD δ_5 can be used as a crack field parameter characterizing the situation at the crack tip in a one parametric way.

CONCLUSIONS

1) The metals concepts of elastic-plastic fracture mechanics can be applied to polymer materials.

2) A variation of the specimen width and specimen type had an influence on the J-Δa-curve, whereas no effect on the δ_5-Δa-curve was observed. No influence of the specimen thickness on the crack growth resistance curves, neither in terms of J nor δ_5 was found.

3) Under tensile conditions, the J-integral correlates more crack growth than under bending.

4) The CTOD δ_5 correlates more crack growth than the J-integral, under tension as well as under bending conditions.

ACKNOWLEGDEMENT

The authors gratefully acknowledge the material supply by the Imperial Chemical Industries PLC, England.

ADDITIONAL SYMBOLS

U = work done
η = eta factor (relating work done to J-integral)

REFERENCES

(1) Hellmann, D. and Schwalbe, K.-H., "Geometry and Size Effect on J-R and δ-R Curves under Plane Stress Conditions," Fracture Mechanics: Fifteenth Symposium, ASTM STP 833, R.J.Sanford, Ed., American Society for Testing and Materials, Philadelphia, 1984, pp.577-605.

(2) Williams, J.G. and Cawood, M.J., "European Group on Fracture: K_c and G_c Methods for Polymers," Polymer Testing 9 (1990) 15-26

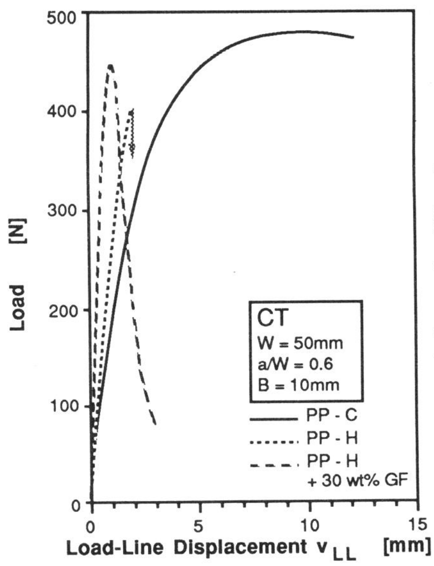


Figure 3. P-v_{LL}-diagramm

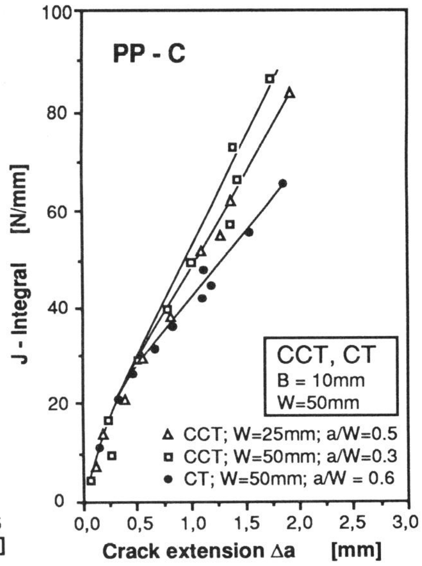


Figure 4. J-R curve

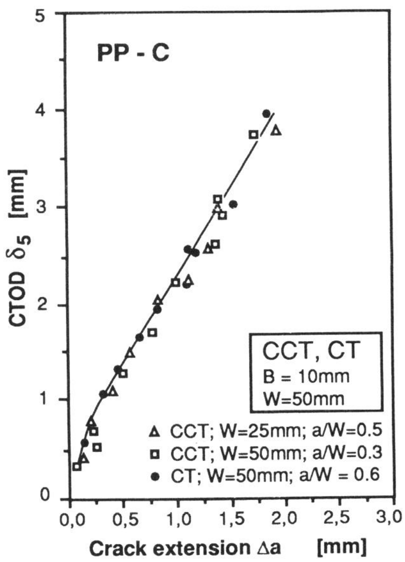


Figure 5. δ_5-R curve

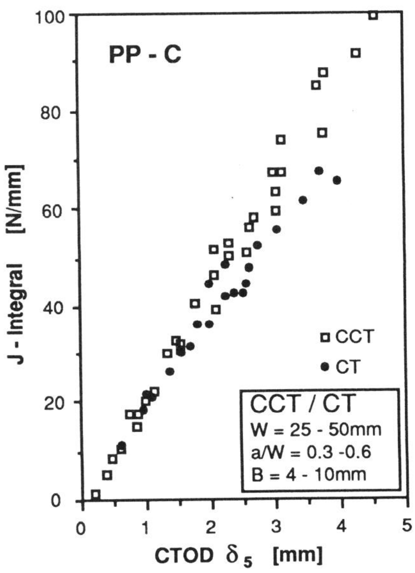


Figure 6. Comparison of J and δ_5