THE LOAD CARRYING-ABILITY OF PMMA FLEXURAL SPECIMENS WITH BLUNT NOTCHES

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ABSTRACT

The effect of blunt notches on the load carrying-ability of poly(methyl methacrylate) flexural specimens was investigated. A large number of three-point bending tests were carried out on specimens with various notch radii and notch depths. Four different loading rates were applied. The results were analyzed in terms of nominal strength. Furthermore, apparent blunt notch values for critical strain energy release rate G_b and critical stress intensity factor K_b were determined. The latter approach was applicable to the relatively deeply notched specimen. The reduction of the load carrying-ability of the specimens with shallow notches and notch radii greater than 0.1 mm followed the stress concentration factor quite well.

KEYWORDS

Blunt notch, PMMA, strain energy release rate, stress intensity factor, stress concentration factor.

INTRODUCTION

Geometry transitions often are weak parts of products due to a local appearance of peak stress combined with a tri-axial stress state. It was tried to model the effect of stress concentrations with the concept of notch factors [1]. A notch factor is defined as the ratio between the load carrying ability of a component with a geometry transition and without a geometry transition. However, the relation between notch factors and geometrical stress concentration factors could not be described by simple parameters and besides, this relation depends on temperature and loading rate as well [2].

Models based on a critical stress were also proposed. E.g., a maximum principal stress was proposed in [3] and in [4] was concluded from the results of plane strain tests and an analytical analysis based on the theory of slip line fields, that craze formation in glassy polymers could be described on the basis of a critical value for the mean normal stress. In general, polymer products have thin walls and therefore geometry transitions often are not in plane strain conditions, but finite element method techniques might be applied to evaluate the maximum mean stress. Plati and Williams [5] applied the concept of fracture mechanics to specimens with blunt notches. There method was based on Linear Elastic fracture Mechanics (LEFM). They assumed, a critical value of the (Dugdale) plastic zone size, whether or not the plastic zone was caused by a crack or a blunt notch. For deep blunt notches a simple relation was derived between the notch radius, the critical plastic zone size and the critical strain energy release rate of blunt notches (G_{BI}) or cracks (G_{CI}). Their tests

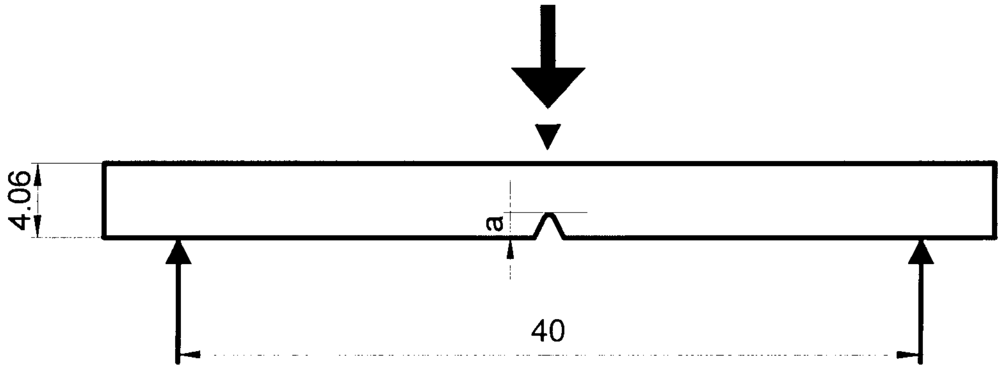

Figure 1: three-point bending set up

showed good correspondence between theory and experimental results in the range of notch radii between 0.2 and 1 mm.

The present study is part of our research concerning the effect of geometry changes on the load carrying ability of plastic products. The method of [5] is applied to study the effect of blunt notches in flexural specimens of PMMA. The effect of loading rates also was studied.

EXPERIMENTAL

Three point bending tests on injection molded poly (methyl methacrylate) (PMMA) specimens were carried out. The test set up is shown in figure 1. The specimen width was about 4.06 mm and the thickness about 6.1 mm. To correct for the small spread of the dimensions, the cross section of all specimens was measured. Specimens were notched applying 5 notch radii (see table 1). The notch depths varied from about 0.1 mm till about 2.5 mm. The cracks (notch radius of 0 mm) were formed by a razor blade, which was hit by a falling weight. The blunt notches were formed with a special notch device. Repeatedly a thin layer of the specimen was scraped away by a steel bar with the appropriate profile till the desired notch depth was reached. The blunt notch depth could be determined from the notch device. The depth of the razor blade notch was determined from the fracture surface using a microscope. Smooth specimens also were tested.

Four tup velocities were applied. The velocity of 0.1 m/s is missing for the razor blade notches and the velocity of 0.001 m/s for the smooth specimens. The test temperature was 23 °C. The tests were performed on a hydraulic set up. Both the displacement (LVDT) and the force (piëzo element) were measured as a function of time during the test. From this the load – displacement relation was established. The number of tests was between 20 and 40 for each combination of notch radius and tup velocity.

TABLE 1
NOTCH RADII AND TUP VELOCITY OF TEST SERIES

radius	tup velocity			
[mm]	10^{-4} m/s	10^{-2} m/s	10^{-1} m/s	1 m/s
0	x	x	x	
0.01	x	x	x	x
0.1	x	x	x	x
0.3	x	x	x	x
1	x	x	x	x
smooth		x	x	x

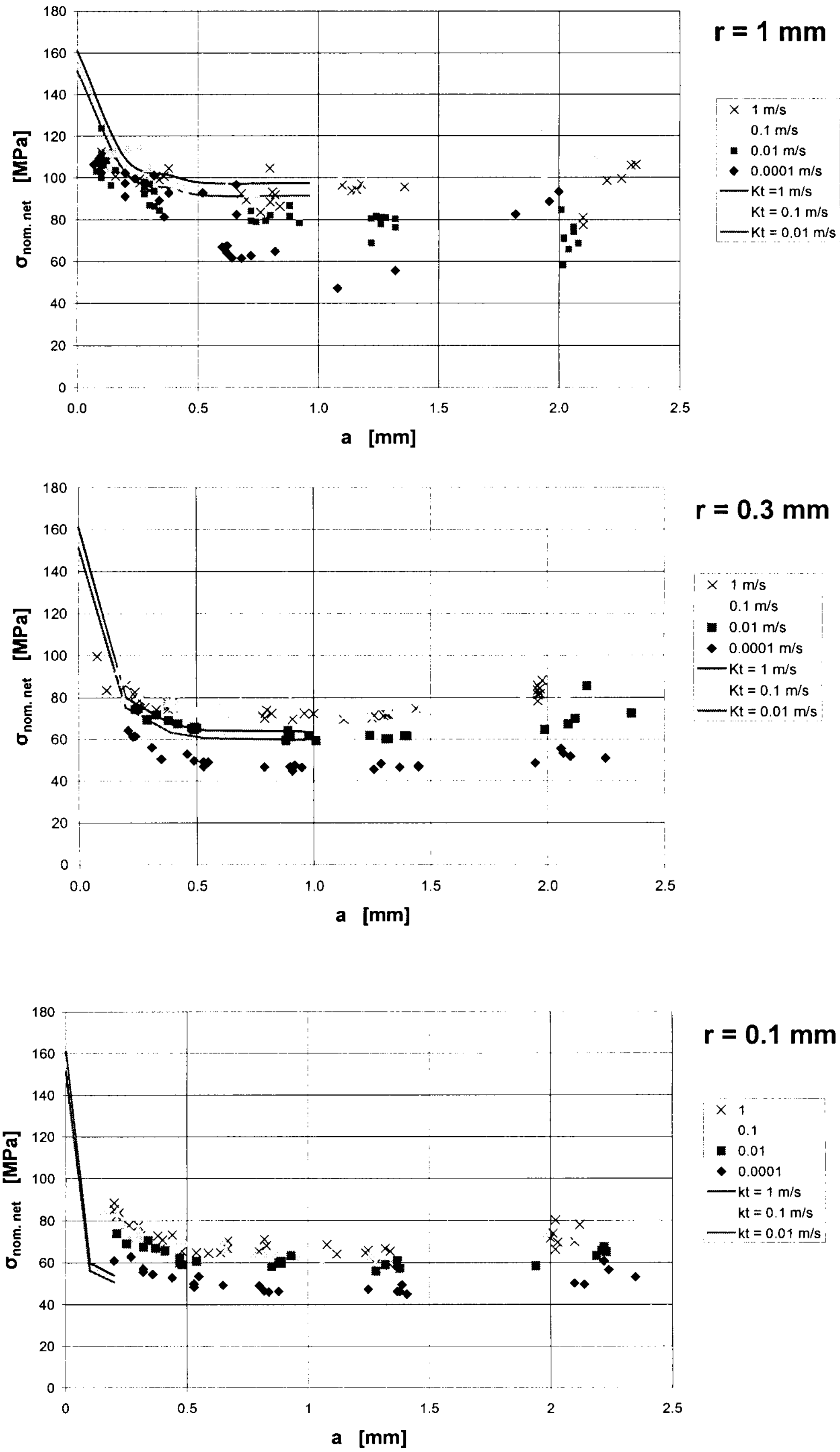

Figure 2: Nominal strength related to notch depth for three (out of the series of five) notch radii. The results of all four tup velocities are indicated in each diagram. The lines indicate the ratios of nominal smooth specimen strength over stress concentration factor K_t for tup velocities of (in order of decreasing nominal strength) 1 m/s, 0.1 m/s and 0.01 m/s.

RESULTS AND ANALYSIS

Nominal strength

The nominal strength, $\sigma_{nom.\ net}$ was defined as the maximum stress working on the net-section according to linear-elastic theory, but leaving out the effect of stress concentrations. It holds:

$$\sigma_{nom.\ net} = M_{max} / (1/6 * B * (D-a)^2) = 60F_{max} / (B*(D-a)^2) \quad (1)$$

Where M_{max} is maximum moment in specimen, B is specimen thickness, D is specimen width, a is notch depth and F_{max} is maximum force during the test. In figure 2 the nominal strength related to the notch depth a is shown for notch radii of 1, 0.3 and 1 m/s. Additionally, the ratio of nominal smooth specimen strength over the stress concentration factor is indicated for shallow notches in the graphs. This ratio can be considered as a prediction of nominal strength based on linear elastic theory. The stress concentration factors were taken from [6].

The following could be concluded from the nominal strength results:

- The shallow blunt notches caused a considerable reduction in nominal strength. The graphs of notch radii 1 and 0.3 mm show, that the strength reduction for notch depths smaller than the notch radius could be described by the stress concentration factor.
- The spread in nominal net stress sometimes was very high. E.g. for deep notches with radius 1 mm.
- The tup velocity is positively correlated with the nominal strength as well as for notched as for smooth specimens.
- The increase of the nominal stress for notch depths greater than 2 mm probably was due to some plastic hinge effect.

Analysis based on LEFM

From the load – displacement curves apparent values for both the critical strain energy release rate, G_B and the critical stress intensity factor, K_B were established for all tested specimens. The subscript B indicates that these parameters refer to blunt notches. The values of K_B were determined from the maximum load during the tests. The values of G_B were determined from the work performed to fracture as was proposed by [5]:

$$G_{IC} \text{ or } G_{IB} = W / (B * D * \varphi) \quad (2)$$

Where W is the area under load deflection curve (work performed to fracture) and φ is a geometrical factor, which was determined using an approximation of the geometry factor Y, supplied by [7]. G_B was estimated from the slope of the straight line fit of W related to $BD\varphi$. K_B was estimated from the slope of the straight

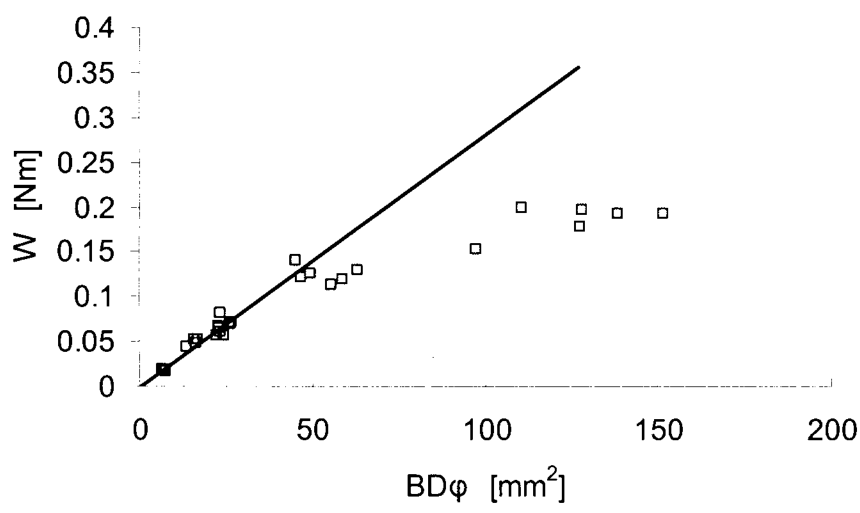

Figure 3: Typical diagram for determining G_B (notch radius 1 mm and tup velocity 1 m/s)

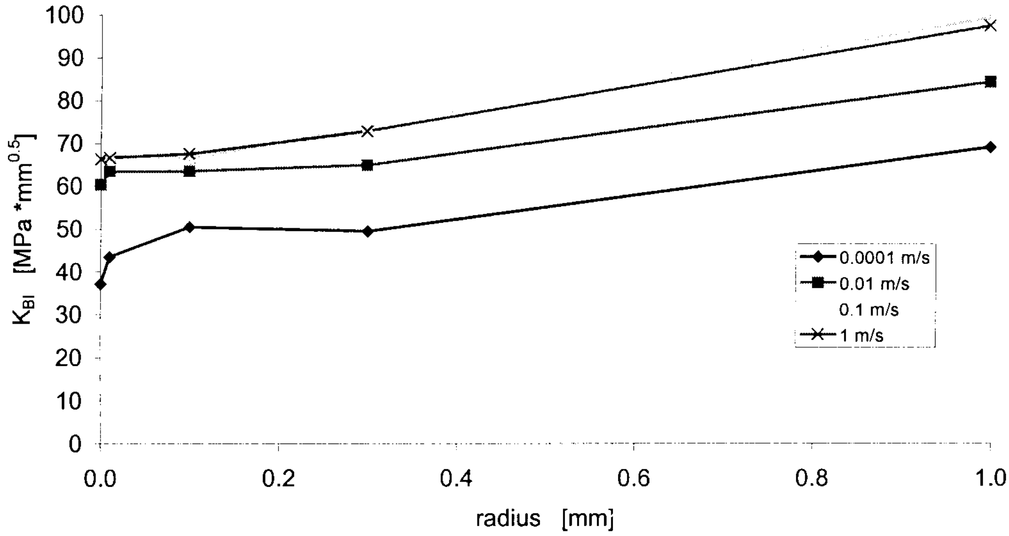

Figure 4: K_B related to notch radius at four different tup velocities

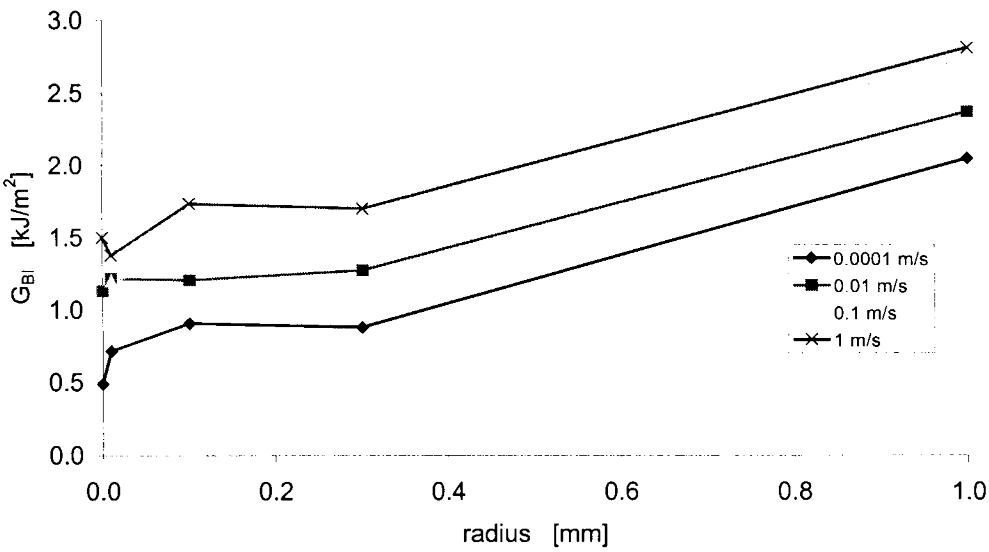

Figure 5: G_B related to notch radius at four different tup velocities

line fit of $\sigma^2 * Y^2$ related to 1/a. A typical example of this procedure is given in fig. 3 for a notch radius of 1 mm and a tup velocity of 1 m/s. Generally, the best fit to a straight line did not intersect the axis in the origin. Often a small negative or positive intercept was found. Sometimes, the line could be shifted to the origin by applying a plastic zone size correction, but not always the same plastic zone size was found for K and G_b. Therefore, we did not apply such a correction. The results were fitted to a straight line that starts from the origin. Only the results of relatively deep notches were used. For the analysis of fig. 3 only the results of notches with a depth of 0.7 mm or more were used (r = 1 mm). In case of smaller notch radii the results of smaller notch depths were used with a minimum depth of 0.3 mm. From the results of these fits was concluded, that a K_b and G_b value could be applied to deep blunt notches, where a plane strain condition was present.

Fig. 4 and 5 show K_B and G_B related to the notch radius for different tup velocities. There is a positive correlation between the notch radius and K_B or G_B. However, the differences are very small up to a notch radius of 0.3 mm. An explanation for the small differences might be the effect of blunting, but it might also be the result of crazing induced during blunt notch machining or a combined effect. The range between 0.3 and 1 mm notch radius showed a greater increase of K_B and G_B. The increase was almost the same for the four tup velocities. However, according to the above-mentioned method of [5] the increase of G_b is rather small. Application of their model resulted in relatively high plastic zone sizes r_p. The tup velocity of 10^{-4} m/s resulted in a plastic zone size $r_p = 0.06$ mm. The size increases up to $r_p = 0.19$ mm for the tup velocity of 1 m/s. According to [5] this must be caused by crazing induced during forming the blunt notches. Figure 5 and 6 show, that an increase of K_B and G_B is caused by an increase of the tup velocity. Only the graphs of 0.1 and 1 m/s were rather close, especially the graph for K_b. This could not be explained. If we take the ratio G^2/K_B as a measure of the modulus, than the modules increases with the tup velocity, except for the range from 0.1 m/s to 1 m/s, where it decreases.

CONCLUDING REMARKS

It was shown, that in case of shallow notches up to a depth of about the notch radius the stress concentration factor reasonably well described the strength reduction of the flexural specimens with the two greatest notch radii (1mm and 0.3 mm). For the deep blunt notches the concept of G_B and K_B could be used. Increase of the tup velocity caused increase of the nominal strength and K_B and also of G_B. The tests show an increase of K_B and G_B as the notch radius increases, but a higher increase was expected. The applied blunt notch forming technique probably caused more crazing than the mill technique used in [5].

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