THE STRENGTH OF GEOMETRY CHANGES IN PLASTIC PRODUCTS

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Objective of the research is to develop a model, that can be applied to predict the load carrying limits of plastics products with geometry changes. Therefore tensile and three-point bending tests on PMMA specimens with a drilled hole have been carried out. The stress and strain fields at fracture have been studied, using a linear-elastic; plastic constitutive model.

From FEM-analyses and fracture surface morphologies, it is concluded, that at PMMA geometry changes the maximum principal stress is the controlling fracture parameter. Two types of mirror zones, can be found on fracture surfaces of geometry changes. However, they are concerned with crack growth and do not necessarily have a direct relation with the strength of PMMA geometry changes.

INTRODUCTION

In general, geometry changes act as stress raisers and (even in the case of quasi-static loading) one cannot always rely on the mechanism of redistribution of stresses. Essential elements of a model, which predicts the strength limits of plastics products with geometry changes are 1) a useful constitutive model and 2) a quantitative fracture criterion.

A linear-elastic; plastic constitutive model with isotropic work hardening and a von Mises yield criterion has been adopted. A typical tensile curve has been applied for each combination of temperature and cross-head speed. Based on this, temperature and strain rate are involved in the applied constitutive model.

A local fracture criterion in terms of stresses (or strains) is the starting point of the research. A critical principal stress criterion would be preferred, rather than a mean normal stress criterion, because, as was shown earlier (Heidweiller (1)), the former is less sensitive to loading conditions. Many tests on PMMA specimens (tensile and three-point bending) have been carried out, applying several cross-head speeds and temperatures, part of which already has

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been presented in (1). Circular holes have been applied as a geometry change and the stress and strain fields at fracture were established using FEM-technique. FEM-technique is able to take into account the actual material behaviour more accurately than the analytical method of slip line fields as applied by e.g. Ishikawa et al (2). The analyses have been carried out by using the FEM code "MARC K.5", applying the 20 nodes solid element nr. 21. The following basic points have been analyzed:

- The maximum stresses near a geometry change at the moment of fracture have been compared for different stress fields using FEM-technique. Therefore tensile tests on specimens with different thicknesses and three-point bending tests have been carried out
- The fracture mechanisms have been analyzed by relating the fracture surface morphologies with the FEM-results.

EXPERIMENTAL

Specimens. Tensile tests and three-point bending tests have been carried out on compression moulded specimens at 23 °C and 29 °C for two grades of PMMA (ICI CMG 302 and Rohm 7h). All specimens have been annealed after drilling at a temperature of 90 °C during 16 hours. PMMA has been used, because it is rather brittle and therefore sensitive to stress concentrations. The tensile specimen geometry was based on ISO/R527 type 1 with a drilled hole in the middle (figure 1). The holes were drilled in water and (generally) a hole diameter of 2 mm was applied. A range of specimen thicknesses between 0.2 and 10 mm has been used, to create different stress fields.

For the three-point bending tests, a 2 mm hole was drilled at 4.5 mm from one edge and from the opposite edge a groove was milled (figure 1).

Results. It was shown, that the nominal strength (net section strength) was higher for the thin specimens, both for the tensile specimens and for the three-point bending specimens. In figure 5 the relation between the nominal strength and the specimen thickness is given for 29 °C tensile tests on Rohm 7h specimens. Especially the thin specimens exhibited a high spread in nominal strength. This was probably due to defects induced by drilling, because the low strength datapoints correspond with specimens having the crack initiation point at one of the ends of the hole. Datapoints indicated with an open circle are concerned with such defects. To minimize the influence of the drilling, we used the maximum value of each range of datapoints in the analysis. The fat line in figure 5 connects these maxima and it clearly shows the increase of nominal strength related to the decrease of specimen thickness, which of course in fact is a plane stress - plane strain transition. The 1 mm thick specimens even show notch strengthening, with 0.91 as minimum notch factor (i.e. tensile strength of smooth specimen over net section strength). As was mentioned above, the other test conditions also showed a transition, however, not so pronounced.

MAXIMUM PRINCIPAL STRESS AT FRACTURE

As is shown in figure 5, a maximum strength of 58.5 MPa was obtained from the experiments on the specimens with 4 mm thickness. Starting from this datapoint, the FEM analysis arrived at a maximum principal stress of 101 MPa. Local strains of more than 35 % were calculated for the 1 mm thick specimens, so orientation hardening can be expected (2). This explains why in the FEM analysis of the specimens with 1 mm thickness the peak stress arrived at 101 MPa, while the loading did not reach the nominal strength of 75.7 MPa.

Figure 6 shows the FEM-analysis results of the 23 °C tensile tests on ICI CMG 302 material at a cross head speed of 5 mm/min. The maximum principal stress near the hole (denoted as peak stress) is presented as a function of the net section stress for 1.6 and 4 mm thick specimens. The two indicated points in each line represent respectively the mean and the maximum value of the set of datapoints. From the two maxima, we can conclude that the peak stresses are rather close (95.4 and 98.4 MPa respectively), especially when compared to the tensile strength of smooth specimens (72.3 MPa). As was shown in figure 5, the thin specimens are more sensitive to defects induced by drilling and this can explain the relatively low specimen strength.

The fat arrow in figure 6 shows the peak stress calculated for three-point bending notched specimens with a thickness of 8 mm. These specimens are loaded in the middle with a cross head speed of 1.4 mm/min, which in order of magnitude causes the same elastic strains as a cross head speed of 5 mm/min on the smooth tensile specimens. It can be seen, that the bending peak stress of 98.0 MPa corresponds rather well with the tensile peak stress.

The results mentioned above showed that a critical principal stress can be used as fracture criterion.

FRACTURE MECHANISM

Initiation point. The crack origin is located in the centre of the mirror zone (highly reflective zone at the fracture surface) and it can easily be detected. Often the crack origin is located inside the material at some distance from the hole as can be seen in figure 2. The radial lines denotes the direction of crack propagation. The distances between hole and crack initiation point have been measured for a number of specimens at different cross-head speeds. It was shown that these values correspond well with the location of the maximum principal stress as obtained by FEM-analysis (1). This shows, that the applied constitutive model provides a good description of the fracture mechanism and also that fracture at a PMMA geometry change is controlled by the local maximum principal stress. It also supports the suggestion of Fraser and Ward (3), that crack initiation or craze breakdown control fracture of (blunt) PMMA geometry changes.

Fracture mechanism. The specimens showed two types of mirror zones, as was discussed earlier by Zwet (3). By optical microscopy it is easy to distinguish between both types of mirror zones, because the difference in morphology is clear and consistent. We will not discuss the characteristic features here, but the first type was already mentioned before (figure 2). In our opinion this type is typical for failure of PMMA geometry changes. The second type (figure 3) is the mirror zone of smooth specimens and also of (sharply) notched specimens.

Obviously the difference in mirror zone is caused by a difference in crack growth mechanism, which simply might be a consequence of the triaxial stress state at the crack initiation point of the geometry change. This explanation corresponds with the fact, that the distance between the hole and the crack initiation point of the typical geometry change morphology of figure 2 corresponds well with the location of the maximum principle stress (1).

The crack initiation point of the second type (figure 3) is commonly located at the circumference of the hole and then probably is connected with defects induced by drilling. However, some of the 1 mm thick specimens of figure 4 with a relatively high strength show a mirror zone which is located inside the material, but nevertheless is of the "smooth specimen" type (figure 4). This corresponds with the fact, that the stress state of these specimens was relatively close to plane stress. However, as was mentioned before, the strength of these specimens still corresponds (or is even higher due to orientation hardening) with the strength of specimens with 4 mm thickness, established on the basis of a critical principal stress.

CONCLUSIONS

Although the research still is going on, we may conclude, that the maximum principal stress is the controlling factor of the strength of PMMA geometry changes under the applied loading conditions. This explains the location of fracture initiation, as well as the change in nominal strength as a function of specimen thickness. The three-point bending tests also show a good correspondence in maximum principal stress. The difference in mirror zone morphology implies a difference in crack growth mechanism, and do not necessarily have a direct relation with the strength of PMMA geometry changes.

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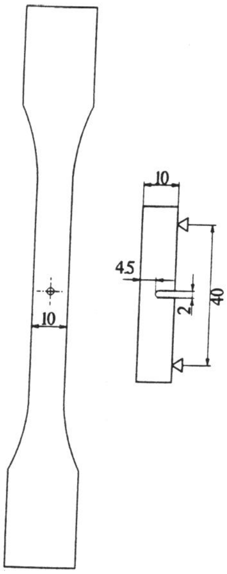

Fig. 1 Specimens used for tensile tests and for three-point bending tests.

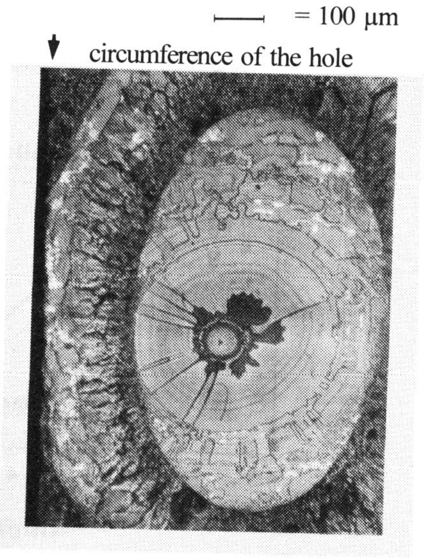

Fig. 2 Typical mirror zone of geometry changes (hole starts at the left).

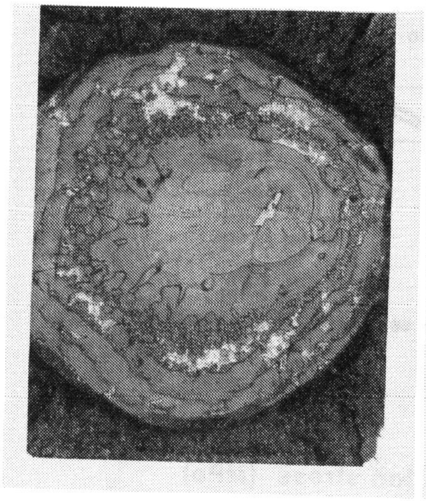

Fig. 3 Typical mirror zone of smooth PMMA specimens.

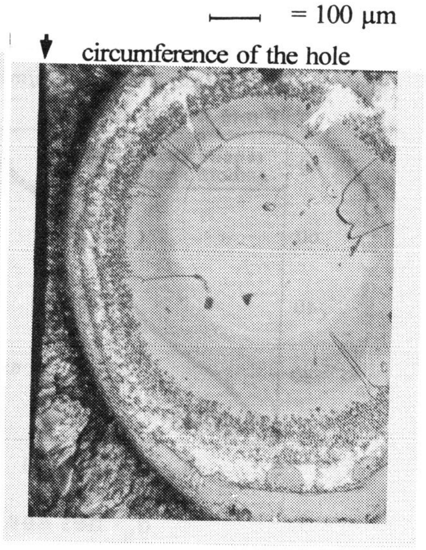

Fig. 4 Typical mirror zone of geometry changes in thin spec. (hole at the left).

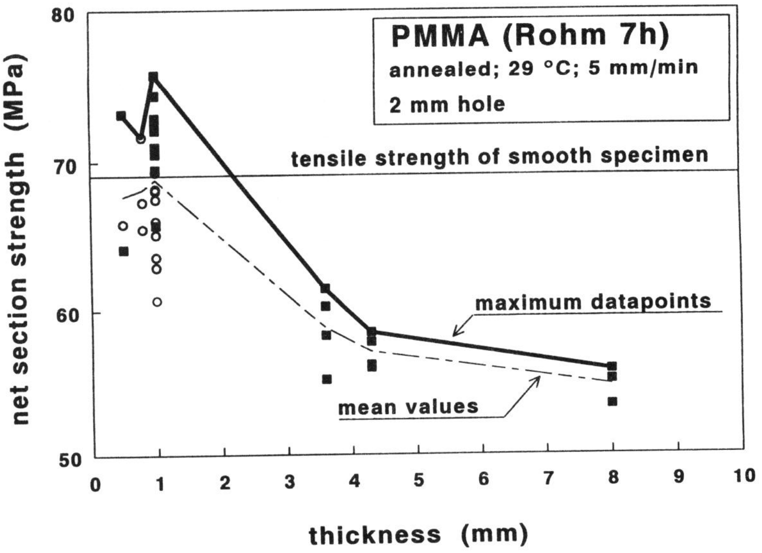

Fig. 5 Nominal strength (net section strength) of tensile specimens related to the specimen thickness.

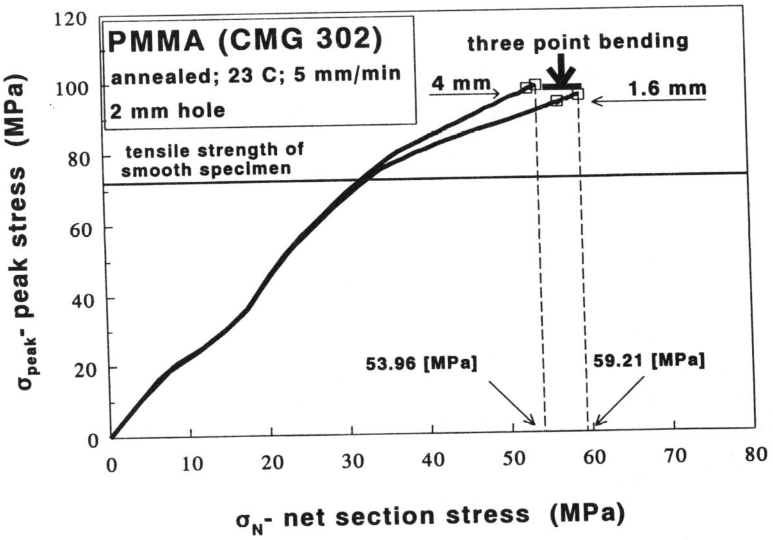

Fig. 6 maximum principal stress (peak stress) related to the net section stress for tensile specimens (1.6 and 4 mm thick) and for three-point bending specimens.