THE EFFECT OF GEOMETRY CHANGES IN PLASTIC PRODUCTS

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Objective of the research is to describe a local fracture criterion, which can be applied to predict the load carrying capacity of plastic products with geometry changes. Therefore, tensile test experiments using several combinations of temperature and cross-head speed have been carried out on PMMA specimens with different thicknesses and with a drilled hole. The results have been analyzed, using FEM-technique, applying an isotropic work-hardening material model. It appears that such a model is able to predict the location of crack initiation rather well. Furthermore, the peak stress at fracture has been evaluated.

INTRODUCTION

The objective of the research program is to develop a model that can be applied to predict the load carrying capacity of plastic products. Geometry changes are, in general, part of plastic products and they often act as stress raisers. As a result they determine the load carrying capacity.

A useful model should be based on (1) the constitutive behavior and (2) a suitable fracture criterion. Especially the former point is not simply to satisfy, because of the influence of temperature and strain rate on the mechanical behavior. Up to now, the usefulness of nonlinear visco-elastic models is small due to the complexity of these models. Therefore, an isotropic work-hardening elastic plastic (Prandtl-Reuss) model has been used.

The following procedure has been applied.

- Extensive tensile tests on PMMA specimens at different temperatures and elongation rates have been carried out. The applied stress raisers were holes (both drilled and injection molded) and V-shaped edge notches with different notch tip radii. Tensile tests as well as three point bending tests have been carried out.

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- The location of the mirror zone center, which coincides with the location of crack initiation, has been measured on the fracture surface of the specimens.
- The stress and strain fields of different geometry changes under the ultimate loading condition, are compared to each other, by using the finite element method-technique (3D-solid elements). Different values of specimen thickness have been applied.

PMMA has been used, because it is rather brittle and therefore sensitive to stress concentrations. It was proposed by Fraser and Ward (1), that the strength of PMMA specimens with blunt notches is controlled by the forming of an initial craze and crack. Consequently, once the crack is formed there will be always sufficient energy for fracture. In a separate paper of Van der Zwet (2) the relation of this proposal to the fracture surface morphology will be explained. In common practice blunt geometry changes are more important than cracks, especially, in the case of injection molded products. Therefore round holes have been applied as a geometry change.

The effect of injection molding as well as the parameter study will be presented in separate papers (2) and (3). In the present paper we will focus on the local (one parameter) fracture criterion, applying nonlinear constitutive behavior. From the experiments mentioned under the first item above, we know, that even in the case of a brittle material like PMMA the strength is underestimated considerably when linear elastic theory is applied (Heidweiller (4)).

EXPERIMENTAL

Two types of PMMA material have been used, namely Röhm 7H and ICI CMG 302. The tensile tests have been carried out on smooth specimens and on specimens with a drilled hole (in water). The ICI specimens were annealed after drilling at a temperature of 90 °C during 16 hours. The test temperature was 23 °C. The Röhm specimens were loaded at 29 °C and not annealed, which favor a more ductile behavior. Three cross-head speeds have been applied, namely 5, 50 and 500 mm/min. The applied specimen geometry corresponds to ISO/R 527 type 1, with a cross section of 4 * 10 mm², except that also smaller thicknesses have been applied to the compression molded specimens.

Röhm material was used for manufacturing injection molded smooth specimens. Drilled holes of a diameter of 2, respectively 3 mm have been applied. Between five and ten tests have been used for each data point.

Both materials have been applied to manufacture compression molded specimens. The specimen thickness has been varied between 1 mm and 4 mm. The application of thicker (plane strain) specimens of course offers advantages, but up to recently the restrictions of our mould did not allow that.

The three-point bending tests have been carried out on injection molded as well as on compression molded specimens, but the analysis of the test results has not been finished.

MATERIAL MODELLING AND FEA

The analysis has been carried out using the FEM system MARC, applying 3D-solid nr.21. The mean tensile strength of the specimens was used as the loading.

The constitutive behavior has been modelled as linear-elastic / plastic with isotropic piecewise linear work-hardening. At least ten tensile tests on smooth specimens have been used for each combination of temperature and cross-head speed. The tensile curve with the highest (or with a relative high) tensile strength has been adopted for the FEA. After annealing, the tensile curves of the compression molded specimens do not deviate from the course of the injection molded specimens, but the latter reach a higher strength. Therefore, in that case, the injection molded tensile curve has been used for both specimen types. Without annealing, the compression molded specimens have a higher strength, due to the applied slow cooling rate during processing. After reaching the maximum strength, an ideally plastic behavior has been adopted.

RESULTS

Fracture surface morphology

The origin of the crack can easily be detected on the fracture surface, as the center of the mirror zone. As is schematically indicated in figure 1, the origin of the crack is often located on some distance from the hole surface. The FEA shows, that after a certain loading level has been reached, the peak stress (i.e. the maximum principal stress σ_{xx}) moves from the surface of the hole, inside the material. The same applies to the maximum mean normal stress.

The distance between the surface of the hole and the crack origin was measured, by using an optical stereo microscope. The coefficient of variation varied from 10 % to 39 %. In table 1 the mean values of this distance are compared with the distances of the peak stress location. Having in mind the rather high spread in the location of crack origin, it can be concluded, starting from a

TABLE 1 - Distance to the surface of the hole of (injection molded specimens)
1) the peak stress as follows from the FEA;
2) the crack origin as measured on the fracture surface.

	5 mm/min		50 mm/min		500 mm/min	
	FEM [mm]	origin [mm]	FEM [mm]	origin [mm]	FEM [mm]	origin [mm]
ϕ 2 mm	0.47	0.38	0.23	0.17	0.02	0.07
ϕ 3 mm	-	0.62	0.26	0.25	0.0	0.05

critical peak stress criterion, that the constitutive model at least qualitatively gives a good prediction of the fracture process. However, there is tendency in overestimating the calculated distances. The overestimation can be caused by the effect of secondary stress concentrations at the hole surface due to the drilling, but also by the effect of crazing (starting at lower loading levels).

Table 1 also shows, that the crack initiates closer to the hole surface, when the cross-head speed increases, due to a more brittle material behavior. This also holds when the temperature is decreased (as has been showed already by Ishikawa et al. (5)) or when the specimens were annealed.

Local fracture criterion

Injection molded specimens. In contrary to the stresses, the strain maxima remain at the hole surface. This shows, that this type of fracture essentially is controlled by the stress and not by the strain. Figure 2 shows the peak stress value and the maximum mean normal value for the injection molded specimens having a hole of 2 mm. The influence of the loading rate on the peak stress, appears to be rather small; the influence on the mean normal stress seems to be higher. Figure 2 also shows the results of some annealed specimens loaded at 23 °C (2 mm hole spec., and double sided notch spec. with radius 1 mm and notch depth 0.3 mm).

With respect to the maximum mean normal stress in figure 2 we refer to (5), where a higher value of roughly 60 to 70 MPa was found as a criterion for craze initiation in PMMA at 23 °C, starting from ideally plastic behavior. The critical principal stress of 150 MPa suggested by Fraser en Ward (1) is much higher than the peak stress values in figure 2, but they start from linear elastic theory.

In table 2 the peak stresses and maximum mean normal stresses are shown for the CMG 302 specimens. Both types of stress maxima appear to arrive at a higher value for the 4 mm specimens then for the 1.6 mm specimens. In figure 3 the peak stress is presented as a function of the net section stress. The FEA was continued after the specimen strength had been reached. It can be seen, that the

TABLE 2 - Results of FEM analyses for compression molded specimens (ICI CMG 302). The first column yields the net section strength σ_r.

	5 mm/min max. σ_{TS} = 72.2 MPa			500 mm/min max. σ_{TS} = 96.07 MPa		
thickness spec. [mm]	σ_r [MPa]	σ_{peak} [MPa]	$\sigma_{mn, max}$ [MPa]	σ_r [MPa]	σ_{peak} [MPa]	$\sigma_{mn, max}$ [MPa]
4	53.42	97.9	50.7	57.80	117.7	56.2
1.6	54.08	91.8	43.7	59.13	113.1	49.1

1.6 mm specimen need to resist a substantial higher loading before the 4 mm peak stress will be reached. In case of the 1 mm Röhm specimens this theoretical loading point was even situated above the net section yield strength.

CONCLUSIONS

The applied constitutive model allows at least qualitatively a good description of the fracture mechanism. This follows from the comparison of the FEA results and the fracture surface morphology. The analysis shows, that the stress and not the strain controls the fracture process.

However, comparison of the peak stress and mean normal stress maxima for the specimens which differ in thickness seem to point out the fact, that stress is not the only important factor. More understanding of this matter will be obtained after analyzing the three point bending test results.

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SYMBOLS USED

σ_{TS} = tensile strength of smooth specimens

σ_r = nominal (net-section) strength of specimens

σ_N = nominal (net-section) stress

σ_{peak} = maximum principal stress σ_x near geometry change

$\sigma_{mn, max}$ = maximum mean normal stress near geometry change

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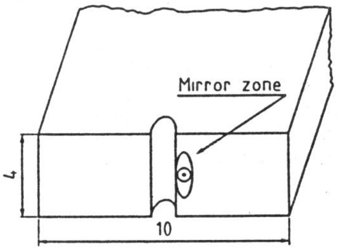

Figure 1 Schematic representation of fracture surface morphology near hole.

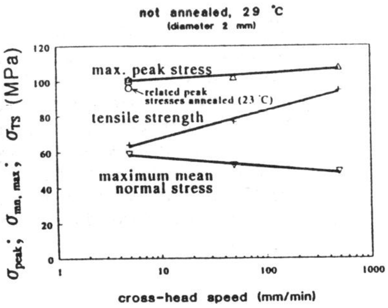

Figure 2 Max. peak stress, tens. stress mean normal stress vs. cross head sp.

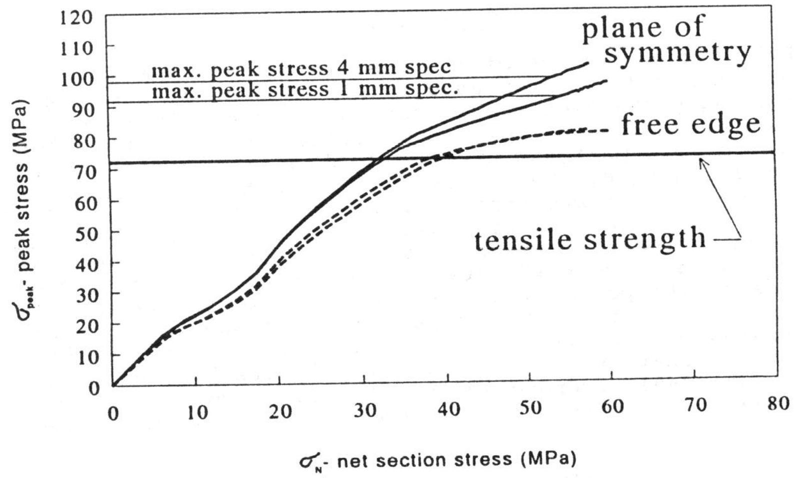

Figure 3 Peak stress related to the net section stress in the plane of symmetry and at the free edge (broken lines) for the specimens of 1.6 and 4 mm (CMG 302).