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Damage and fracture of the optimized X0-specimen

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The paper deals with numerical and experimental results of the gradient based optimized biaxial X0-specimen. The original, engineering based design has been optimized under producibility restrictions for two different loading conditions to gain a distinct (high or low) stress triaxiality maintaining a sufficiently homogeneous distribution in the notched regions of the specimen. Specimens with the initial and the two load case dependent optimized geometries have been fabricated of aluminum alloy sheets and biaxially tested. Here the corresponding results with respect to biaxial tension loading are presented and the numerical results clearly indicate the higher stress triaxialities and the experimental results demonstrate elevated void growth as leading damage mechanism.

1 Introduction

In several engineering applications ductile sheet metals improve the lightweight design and the utilization factor. Consequently the damage and fracture behavior is of special interest and has to be characterized by experiments covering a wide range of stress states. In this context new biaxial specimens have been proposed [2] and successfully applied. The material modeling can be realized by the phenomenological continuum damage model presented by Brünig [1] in an efficient way. The damage condition (Eq. (1a)) as well as the damage law (Eq. (1b)) are stress state dependent and reflect the different deterioration processes like nucleation of voids as well as its growth and coalescence at high and the formation of micro-shear-cracks at low or negative stress triaxialities, defined as the ratio of the mean normal stress and the von Mises equivalent stress. Especially the damage mode parameters α and β and the kinematic parameters $\bar{\alpha}$ and $\bar{\beta}$ correspond to these different mechanisms

$$f^{\mathrm{da}} = \alpha I_1 + \beta\sqrt{J_2} - \sigma = 0 \quad \text{(a)} \qquad \text{and} \qquad \dot{\mathbf{H}}^{\mathrm{da}} = \dot{\mu}\left(\bar{\alpha}\frac{1}{\sqrt{3}}\mathbf{1} + \bar{\beta}\mathbf{N}\right) \quad \text{(b)}\,. \tag{1}$$

Here, I_1 and J_2 are invariants of the Kirchhoff stress tensor and σ reflects the damage threshold. $\mathbf{N}$ is the normalized deviatoric stress tensor while μ represents the equivalent damage strain measure.

2 Optimized X0-specimen

The original, engineering based design of the X0-specimen (Fig. 1a) can be applied to study the damage behavior [3], whereas higher stress triaxialities are needed to study damage and fracture under these conditions. In addition, geometry optimization can improve the applicability of the specimen [5]. Consequently, besides the need for distinct stress states, a rather homogeneous distribution of stress triaxiality and the Lode parameter are required, which have been set as objectives by the optimization of the geometry [4]. These modifications have to be realized under producibility and experimental restrictions, i.e. milling of the grooves and the application of digital image technique should be possible. The optimization process resulted for the tension/tension (1/1) load-case (Fig. 1b) in sharper notches in thickness direction and outer direction whereas for the tension/compression (1/-1) load-case (Fig. 1c) in wider notches and a reduced penetration depth of the notch in thickness direction by maintaining the cross sectional area.

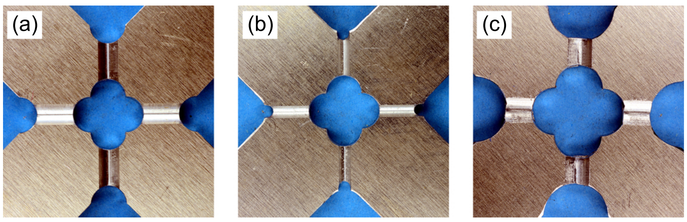

Fig. 1: Photographs of X0-specimens: (a) Initial geometry, (b) Optimized geometry V1 for load case 1/1, (c) Optimized geometry V2 for load case 1/-1

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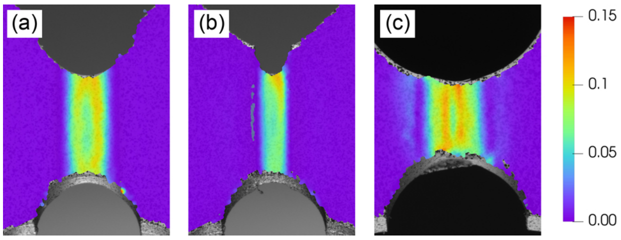

Fig. 2: First principal strains reported by digital image correlation (DIC): (a) initial geometry, (b) V1 geometry, (c) V2 geometry

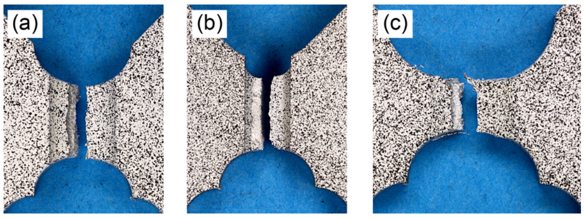

Fig. 3: Fractured specimens: (a) initial geometry, (b) V1 geometry, (c) V2 geometry

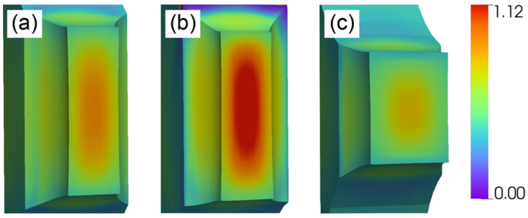

Fig. 4: Stress triaxiality: (a) initial geometry, (b) V1 geometry, (c) V2 geometry

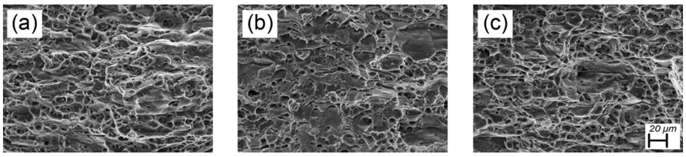

Fig. 5: Scanning electron microscopy images at the center of the fracture surface: (a) initial geometry, (b) V1 geometry, (c) V2 geometry

3 Experimental results

The deformation behavior of the specimen surfaces has been monitored by digital image correlation (DIC) and the reported first principal strains are displayed in Fig. 2 before fracture occurrence and the photos given in Fig. 3 display one fractured notch. The sharp notch in thickness direction of the V1 geometry leads to a reduced area of elevated strains and consequently less overall deformation before fracture. The fracture surfaces have been analyzed by scanning electron microscopy (SEM) and representative pictures are given in Fig. 5. All fracture surfaces indicate failure due to void nucleation, growth and coalescence which corresponds to the indicated tension dominated stress state (Fig 4). But the V1 geometry indicates significantly higher stress triaxialities and consequently remarkably larger voids and a more brittle behavior.

4 Conclusions

The experiments with the optimized X0-specimens confirmed the results of the optimization process and the corresponding numerically predicted results. For the presented tension/tension load-case the increased stress triaxiality of the V1 geometry indicated micro-pores with elevated diameter and a less ductile behavior. These first promising results mark the onset of shape optimization with respect to biaxial specimens to study the damage and fracture behavior of ductile metals. In future investigations, shape optimization problems with respect to other loading condition needs to be studied and if possible standardized geometries for certain loading conditions can be proposed.

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