ON THE SIMULATION OF DUCTILE CRACK EXTENSION IN AN AL/SIC METAL MATRIX COMPOSITE USING DAMAGE MODELS

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In a metal matrix composite made of aluminium A 6061 T6 and 20 vol% SiC particles, ductile crack extension only occurs in the ductile Al phase, whereas cracks of the rigid SiC inclusions and decohesion of the Al/SiC interfaces were not observed experimentally. The SiC particles lead to locally different constraints on the micro scale, resulting in a zig-zag shaped crack path. The failure process in the Al phase consists of the nucleation of voids resulting from rigid second-phase inclusions, the growth and coalescence of voids up to final failure. The ductile Al matrix is modelled by using Gurson´s constitutive model, whereas the SiC particles are assumed to be elastic. The observed crack path is in good agreement with the numerically predicted crack path.

INTRODUCTION

Metals used in engineering constructions usually contain rigid second phase particles in order to increase mechanical properties such as yield strength and ultimate tensile strength. An A6061 T6 aluminium reinforced by 20vol% SiC is used e.g. for racks in aircrafts or various components in automobile and motorcycle engines (Harrigan (1)). In some foregoing investigations, this metal matrix composite (MMC) was investigated numerically by using different damage models and experimentally by performing 3 point bending (3PB) fracture mechanics experiments (Wulf (2) and Schmauder et al. (3)). The specimens with the dimensions of 100mm x 10mm x 20mm were initially manufactured with a Chevron notch. After performing the 3PB experiments, the specimens were grinded to the half of their initial thickness. Fig. 1 was taken from some SEM investigations showing that the crack path follows a zig-zag depending on the local distribution of the SiC inclusions, but the crack extension occurs only in the ductile Al phase, whereas cracking of the rigid SiC inclusion was not observed (2). The failure mechanism in the ductile Al phase consists of the

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nucleation of voids, starting from rigid second phase inclusions in the Al phase, the growth and coalescence of voids (2,3). It was the aim in the present investigation to predict the shape of the crack path in the microstructure by numerical modeling.

CONSTITUTIVE EQUATIONS

As engineering metals are ductile and contain rigid inclusions or second-phase particles, a debonding process occurs at the interfaces between the inclusions and the ductile matrix which causes damage represented by voids. A further loading in the plastic regime results in growth and coalescence of voids. Constitutive equations taking the micromechanical process of ductile void growth into account base on considerations for a spherical cavity in a perfectly plastic matrix with the yield stress σ_m. Gurson (4) introduced a yield condition, where yielding even occurs, if only the hydrostatic part $tr\,\underline{T}$ of the stress tensor $\underline{T}$ is active:

$$\Phi(\underline{T}', tr\underline{T}, f, \sigma_m) = \frac{3\, \underline{T}' \cdot\cdot\, \underline{T}'}{2\sigma_m^2} + 2\, f \cosh\left(\frac{tr\underline{T}}{2\sigma_m}\right) - 1 - f^2 \quad . \tag{1}$$

The deviatoric part of the stress tensor is denoted $\underline{T}'$, the void volume fraction f is defined as the ratio of the void volume to the whole volume of a unit cell. Gurson´s yield condition was modified by Needleman and Tvergaard (5), who introduced an empirical parameter q, which takes account to the fact that failure of a unit cell does not occur, if the void volume fraction f takes its ultimate value 1, but much earlier:

$$\Phi(\underline{T}', tr\underline{T}, f, \sigma_m) = \frac{3\, \underline{T}' \cdot\cdot\, \underline{T}'}{2\sigma_m^2} + 2\, q\, f^* \cosh\left(\frac{tr\underline{T}}{2\sigma_m}\right) - 1 - (qf^*)^2 \quad . \tag{2}$$

A typical value for ductile steels is q=1.5 (5). Additionally, Needleman and Needleman (5) introduced the modified void volume fraction f^* as

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + K\,(f - f_c) & \text{for } f > f_c \qquad \text{with } K = \dfrac{f_u^* - f_c}{f_f - f_c} \end{cases} \tag{3}$$

considering the coalescence of adjacent voids due to slip planes which occur during the failure process after a critical void volume fraction f_c has been achieved. The crack appears, if the final void volume fraction f_f is reached, where the material looses its stress carrying capacity and where the modified void volume fraction f^* achieves its ultimate value f_u^*. Additionally, strain controlled void nucleation is considered as introduced by Chu and Needleman (6).

FINITE ELEMENT MODEL

The initial topology of the microstructure from Fig. 1, where the crack path was experimentally observed, and the respective finite element mesh are given in Fig. 2. The material properties of the integration points in the inner domain of Fig. 2 are associated with the elastic properties of the SiC or the Gurson properties of the Al material in the way as it was given by the photograph, Fig. 1, which is scanned in Fig. 2 into the finite element mesh (3). As ductile crack extension is mainly affected by the local constraint situation, it is sufficient to model the main features of the microstructure by assigning the properties of the respective material to the integration points, whereas a more detailed modeling, e.g. by modelling every SiC inclusion, seems to be not necessary. The application of the modified Gurson model is justified as the failure mechanism in the Al exhibits the stages nucleation, growth and coalescence of voids up to final failure. The material properties of the outer domain are elastic-plastic and averaged over the composite. As the experimentally observed crack path was taken from the centre of the specimen, plane strain conditions are assumed for the numerical simulation. In total, 3052 triangular elements with quadratic interpolation functions were used (Reusch (7)).

RESULTS

The evaluation of the crack path under loading for the inner domain from Fig. 2 is given in Figs. 3a-d, where ε denotes the overall strain in loading direction. Elements, where at least one integration point achieved the final void volume fraction f_f, are omitted. The curved path of the crack front is predicted in the right way by Gurson´s model compared to the original photograph, Fig. 1. The zig-zag of the crack path is caused by the local distribution of the SiC particles, which strongly influence the local constraint. It is remarkable that in the beginning of the process, Fig. 3b, cracks start from two points where various SiC particles are located close together resulting in a high constraint and thus leading to an early failure. Only in a later stage, both cracks are growing together, Fig. 3d. It is a quite natural feature of pressure dependent plasticity models such as the Gurson model that the hydrostatic part of the stress tensor is incorporated and therefore the local constraint situation is considered resulting in a realistic modeling of crack shapes.

CONCLUSIONS

Ductile crack extension in an Al/SiC (20 vol%) MMC strongly depends on the local distribution of the SiC particles resulting in a zig-zag shaped crack front. As the ductile Al matrix exhibits the typical failure of metals containing second phase particles, e.g. nucleation, growth and coalescence of voids, Gurson´s model in the formulation of Tvergaard and Needleman was used to predict the shape of the crack front compared to experimental results. It turned out that the predictions obtained by FE simulations are in good agreement with the experimental observations. As the overall behaviour of specimens strongly depend on the micro structure of the material, the method is suited to be used for the design and optimization of materials, e.g. optimizing of sizes, population and shapes of rigid inclusions.

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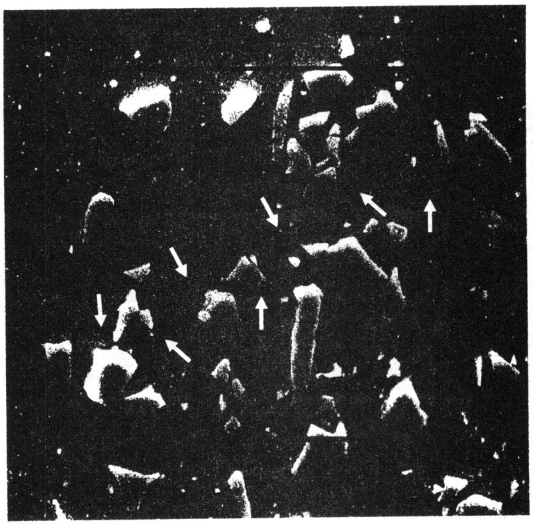

Figure 1: Crack path of an Al/SiC(20vol%) MMC used for simulation (Crack approaches from the right to the left hand side; arrows indicate the crack path)

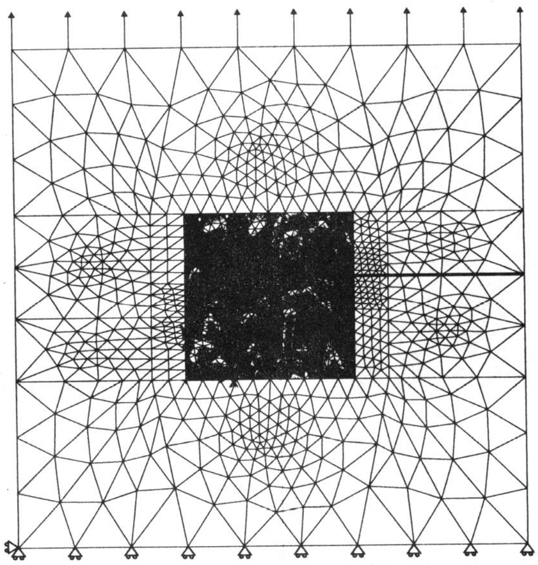

Figure 2: Finite Element model with the modelled part of the micro structure

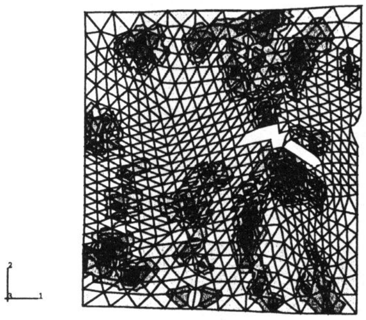

Fig. 3a : $\varepsilon = 2.54$ %

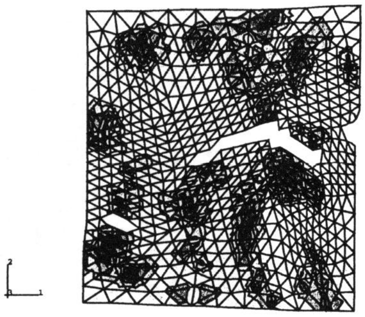

Fig. 3b : $\varepsilon = 2.83$ %

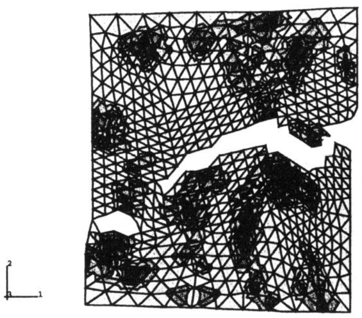

Fig. 3c : $\varepsilon = 3.77$ %

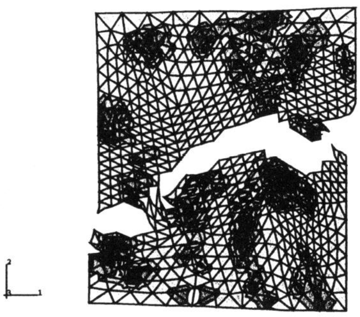

Fig. 3d : $\varepsilon = 5.17$ %

Figures 3: Crack extensions at different load levels with increasing load from Fig. 3a to Fig. 3d