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A MODEL OF ANISOTROPIC DUCTILE DAMAGE APPLIED TO AL 2024

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Abstract. *Anisotropic fracture of an aluminium alloy is investigated using a porosity-based damage model accounting for the void aspect ratio and the relative void spacing. A model of the microstructure based on microstructural investigations is proposed, which incorporates the relevant microstructural features of aluminium 2024-T351: precipitation free zones and void nucleating particles. Using advanced characterisation tools quantitative information can be gathered for the identification of the damage model parameters. The effects of void shape and void spacing on the coalescence behaviour are elucidated by means of cell model calculations. Predictions of the ductility of D-notched bars with different notch radii loaded in different orientations are made and compared with experimental data. Based on this analysis, qualitative understanding of trends in the fracture toughness of aluminium alloys can be gained.*

INTRODUCTION

Airplane designers estimate the residual strength of fuselage components by tests on specimens and components of various sizes. These test campaigns are time consuming and expensive. The development of predictive models for ductile crack extension is thus essential for improving structural design and maintenance and accelerate the introduction of new materials or assembling methods.

Fracture mechanics based assessment methods often encounter transfer problems of fracture resistance data from small to large specimens and structures. Micro-mechanically based damage models like those by Gurson, Rousselier or Tvergaard allow for the description of size and geometry effects.. In addition, the material parameters can at least partly be identified from investigations of the microstructure. The models are commonly restricted to isotropic material behaviour with respect to both deformation and damage. Metal alloys, which have undergone extensive plastic deformation by rolling or extrusion, exhibit a significant anisotropy of mechanical properties, however. Due to the cubic symmetry of fcc and bcc metals, the yielding behaviour may still be considered as almost isotropic, while ductility shows a significant reduction, if loading is applied in the thickness direction. This effect can be considered by orientation dependent damage parameters.

In the present contribution, the model developed by Pardoen and Hutchinson based on the growth and coalescence of ellipsoidal voids embedded in a work hardening matrix material is chosen to simulate the failure of round notched bars made of Al 2024. The effect of varying model parameters is studied by cell model calculations. Special emphasis is laid on a careful characterisation of the precipitate and particle morphology. From this microstructural information, a simplified model is derived, which allows to directly evaluate model parameters for loading in S-direction. In a second step, these parameters are modified based on simple geometrical assumptions and used to predict failure in L-direction.

The particles, clusters of particles and precipitates are the sites of damage initiation. Their morphology and volume fraction thus primarily affect the global fracture properties. Intergranular fracture in Al-alloys is essentially induced by the breaking or debonding of coarsened precipitates located inside precipitate free bands, PFB. Optical microscopy, scanning electron microscopy and X-ray microtomography have been used to obtain quantitative information. A simplified model for this material incorporating the most significant parameters with respect to microstructure and fracture mechanisms has been proposed and will be applied here. It is assumed that the material is mainly composed of matrix domains surrounded by PFBs containing coarse particles representing the weak regions. Assuming a “closed package” of these matrix domains, the material’s microstructure can be idealised as an assembly of weak and strong layers, 5 μm (average thickness of the PFB) and 25 μm (average thickness of matrix domains) high, respectively. According to this model, loading in the S-direction leads to a high damage rate in the PFB. A macroscopic crack can extend throughout the material perpendicularly to the loading direction. For loading in the L-direction, damage will also start in a PFB, but a macroscopic crack will have to cross the tougher matrix material, leading to a higher ductility.

ANISOTROPIC DAMAGE MODEL

Despite the fact that big efforts in the modelling of ductile fracture by computational models incorporating the void growth process have been made, the models in use suffer from two basic limitations. One is the constraint imposed to the shape of the void to remain spherical. The second limitation is that void coalescence is only phenomenologically described by an acceleration of damage, which lacks of micromechanical foundation.

Gologanu et al. proposed a constitutive relation for a plastic continuum containing ellipsoidal voids of radii Rr and Rz,. The voids differ according to their aspect ratio, $\kappa = Rz/Rr$, namely: oblate void, $\kappa < 1$, prolate void, $\kappa > 1$, spherical void, $\kappa = 1$. Pardoen and Hutchinson extended the Gologanu model by adding a criterion for tensile localisation in the ligament between the voids according to Thomason´s approach. This criterion requires some assumption on the arrangement of voids in the matrix. Assuming that they are regularly aligned in distances of 2Lr and 2Lz, a representative volume element (RVE) is defined by the aspect ratio, $\lambda = Lz/Lr$,. Damage is thus characterised by three parameters, namely the porosity, f, the void shape parameter, κ, and the void distribution parameter, λ. The model was implemented in the commercial finite element programme ABAQUS as a user-interface UMAT.

SIMULATION OF DUCTILE FAILURE

The GPH model is now applied to predict damage and fracture of round notched bars with two different notch radii of 2 mm and 4 mm. Two specimen orientations, L and S, are considered in the tests and simulations. Micromechanical parameters are taken from the quantitative microstructural analysis.

Loading in S-direction is considered first. The materials microstructure is axisymmetric, and so is the specimen. The loading axis is parallel to the axis of symmetry of the microstructure, so that the rotational symmetry of the microstructure is maintained. An adequate RVE is assumed. The aspect ratio of the (oblate) cavity can be directly taken from quantitative microstructural analysis, $\kappa_0 = 0.625$. Its shape together with the height of the PFB, $2R_{z0} = 5$ µm, determines the cavity radius, $R_{r0} = R_{z0}/\kappa_0 = 4$ µm. The initial height of the RVE, L_{z0}, can directly be related to the PFB spacing, Lz0 = 15 µm. The RVEs aspect ratio, λ_0, and the initial void volume fraction, f_0, are then determined from the area fraction of dimples on the fracture surface, $A_f = 0.28$, which is assumed to be the same as the area density of dimples in the equatorial plane of the RVE. Hence, λ_0 and f_0 can be calculated from the RVEs geometry.

Transfer of the microstructural information to the simulation of loading in L-direction is not straightforward, as the axis of symmetry of the microstructure does not coincide with the loading direction any more. Whereas the initial aspect ratio of the void is the inverse of the respective value in S-direction, $\kappa_0 = 1.6$, the choice of a respective RVE for loading in L-direction is not unique. Depending on the coalescence mechanism considered, the RVE's aspect ratio may vary between $\lambda_0 = 0.27$ (coalescence of voids bridging the matrix domains) and $\lambda_0 = 1$ (periodic arrangement of voids in the PFB). Neither of the two values predicted the ductility measured in the tests correctly, however. Small values of λ_0 delay coalescence leading to a higher ductility. Thus, gradually increasing λ_0 to meet the experimentally obtained failure point of the round notched bar with notch radius 2 mm was the only way to identify λ_0. As a result, the fitted value of λ_0 in L-direction turned out to be almost identical to that in S- direction, which was unexpected and can be construed by the primary influence of the cell´s aspect ratio on the coalescence behaviour. The values for f_0, λ_0 and κ_0 used in the simulations are summarised in Table 1.

orientation	f_0	λ_0	κ_0
S	0.031	1.98	0.625
L	0.031	2.0	1.6

Table 1. Model parameters used in the simulation of fracture of round notched bars

Eight-node isoparametric axisymmetric finite elements were used for the simulations of the tensile tests. The yielding behaviour was taken form tensile tests in L-direction and used for both L- and S-loading case, which means that texture induced plastic anisotropy is not accounted for.

the simulation results in terms of applied load vs. reduction of inner diameter, Δd, of the specimens are compared with the experimentally obtained fracture points. Four categories of specimens are included: L and S orientation, notch radius 2mm and 4 mm . Due to the higher constraint, the specimens with $r = 2$ mm show a higher maximum load. The failure point is well predicted for both specimen orientations, S and L. In the case of r = 4 mm, the simulation result obtained for S-direction meets the experiments, whereas the ductility in L-direction is still significantly overestimated by the simulation.

CONCLUSIONS

The mechanical behaviour of metal sheets exhibiting a textured microstructure generally depends on the loading direction. Whereas the yielding behaviour may still be considered as almost isotropic, ductility shows a significant reduction, if loading is applied in the thickness direction.

Morphology and volume fraction of matrix domains and particles determine the global fracture properties. An idealised axisymmetric periodic microstructure has been assumed which incorporates the most significant features relevant for the fracture mechanisms. The effects of initial porosity, stress triaxiality, void shape, and void distribution on void growth and coalescence have been studied by means of axisymmetric cells with voids of varying aspect ratios. The results have been compared with the predictions of the micromechanical GPH model, which appeared superior to the Gurson model for triaxialities $T \geq 1$.

The GPH model has been applied to simulate the failure behaviour of notched bars of an Al2024 alloy. The model parameters for loading in S-direction are directly obtained from the microstructural analysis. In a second step, these parameters were modified based on simple geometrical assumptions and used to predict failure in L-direction. Specimen failure in testing was correctly predicted for the sharply notched bar (r = 2 mm) loaded in S- and L-orientation and the bar with a notch radius of r = 4 mm in S-direction, whereas ductility in L-direction was overestimated. Simulation of the orientation-dependent ductility of rolled plates requires anisotropic damage models. In order to keep the number of model parameters as small as possible, the assumption of voids being ellipsoid of revolution is favourable but, at the same time, imposes some restrictions with respect to an adequate representation of the real microstructure.