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Anisotropic plastic Deformation and Damage in commercial Al 2198 T8 Sheet Metal

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Abstract. Deformation anisotropy of sheet aluminium alloy 2198 (Al-Cu-Li) has been investigated by means of mechanical testing of notched specimens and Kahn-type fracture specimens, loaded in the rolling direction (L) or in the transverse direction (T). Contributions to failure are identified as growth of initial voids accompanied by a significant nucleation of a second population of cavities and transgranular failure. A model based on the Gurson-Tvergaard-Needleman (GTN) approach of porous metal plasticity incorporating isotropic voids, direction-dependent void growth, void nucleation at a second population of inclusions and triaxiality-dependent void coalescence has been used to predict the mechanical response of test samples. The model has been successfully used to describe and predict the direction-dependent deformation behaviour, crack propagation and, in particular, toughness anisotropy.

Introduction

Characterisation of alloys with respect to resistance against ductile crack extension has become an essential part of a damage-tolerance concept, which acknowledges the existence of cracks and structural damage. Damage mechanics provides a unified approach of combining constitutive equations for anisotropic deformation with equations describing the degradation of the material, taking full advantage of the potential of the local approach. Ductile damage is usually approached by using isotropic damage models, in which voids are assumed to be spherical while the matrix material is assumed to be isotropic. Assuming plastic isotropy of the matrix only, many authors have investigated the influence of the void geometry on the homogenised response of the material. Apparently, there is a coupling between anisotropy and void growth due to the constraint added in the vicinity of the void. In order to account for this effect in a general way, a homogenisation procedure has to be accomplished, which finally leads to a set of constitutive equations comprising plastic potential, flow rule and an evolution equation for the porosity. For the sake of simplicity, porosity is commonly expressed as a scalar quantity; its evolution is therefore assumed to be isotropic. To the contrary, evolution equations for non-isotropic voids require at least a non-scalar damage measure, e.g. for the modelling of ellipsoidal voids [1-3] or general anisotropic damage [4-6]. For orthotropic material like rolled sheets, various yield criteria are available. Anisotropy is expressed by using a structural tensor, which is based on the axes of orthotropy. In damage models this framework may be used together with the assumption that effects caused by matrix anisotropy and void shape are independent [7].

The material considered in the present study is a new member of the Al-Cu family. These alloys are specifically designed to have good mechanical properties in order to use them for structural components in aircrafts. It has superior yield strength than the well established alloy Al 2024.

Constitutive Model

For commercial aluminium alloys, non-quadratic yield criteria are recommended. In a previous investigation [8], it was proven that the Bron model [9] based on an anisotropic yield surface is able to predict the direction-dependent deformation response of different types of flat specimens machined from rolled sheets. This particular constitutive model has been extended in order to incorporate the effect of hydrostatic pressure on the growth of micro-voids. This was done by replacing the (von Mises) equivalent stress usually used in the yield function of a voided aggregate by the respective definition of the anisotropic deformation model, $\bar{\sigma}$:

$$\frac{\bar{\sigma}^2}{R^2(p)} + 2q_1 f^* \cosh\left(q_2 \frac{3\sigma_h}{2R(p)} \right) - 1 - \left(q_1 f^* \right)^2 = 0 . \tag{1}$$

For the nucleation term different functions have been proposed. Following the popular assumption to link nucleation rate to plastic equivalent strain, a constant nucleation rate starting at a threshold value of the plastic equivalent strain is used in the present contribution,

$$\dot{f}_{nuc} = A\, H\left(p - \varepsilon_0 \right), \tag{2}$$

with H being the Heaviside function and A and ε_0 model parameters. This was chosen to support void nucleation at high plastic strains on a phenomenological basis. Hardening and damage evolution are assumed to be isotropic, expressed by the plastic equivalent strain, p, and the void volume fraction, f. The mathematical model has been realised in the object-oriented FE code Zébulon [10]. It has been linked via the material library Z-Mat to the commercial finite element program ABAQUS/Standard, which is used to perform the simulations in the present contribution.

The model parameters have been identified sequentially. The strain hardening function in terms of true stress and true (logarithmic) plastic strain was taken from a tensile test in L-direction up to the load maximum and extrapolated using a power-law function

$$\sigma = 468\ [\text{MPa}]\ (1 + 40.95\, p)^{0.1202} \tag{3}$$

The shape parameters of the yield surface a, b_1, b_2 and α as well as parameters describing the orthotropy c_{ik} were calibrated based on force-elongation and reduction of width signal taken from smooth and notched samples [8]. The model is used in the following to determine parameters associated to damage and to predict the mechanical behaviour of notched tensile specimens and Kahn-specimens. The void volume fraction at the beginning of coalescence has been derived form 3D-unit-cell calculations and found to be dependent on stress triaxiality, T. An exponential decay functions have been used for the respective main loading directions.

U-notch tensile specimens and Kahn specimens

Two different kinds of notched specimens were used: specimens with notch radius of 1 mm and notch radius of 2 mm. Specimens were machined in three directions with respect to the rolling direction of the sheet:

- along the rolling direction, L “Longitudinal”, three specimens each radius,
- perpendicular to the rolling direction, T “Transversal”, three specimens each radius,
- 45° to the rolling direction, D “Diagonal”, three specimens each radius.

Despite the fact that the specimen thickness is comparably small, 3D discretisation has to be used for the simulations to properly capture the void evolution.

Kahn specimens were machined in two directions with respect to the rolling direction of the sheet:

- along the rolling direction, L "Longitudinal",
- perpendicular to the rolling direction, T "Transversal".

For the FE-model of the specimen, one fourth of the specimen is modelled due to the twofold symmetry. The complete specimen was constructed with 3D quadratic solid elements with reduced integration.

Figure 1 displays the experimental results obtained from the notched specimens in the three directions and the corresponding simulation results. The maximum force of the specimen oriented in T-direction is highest for notch radii of 1 mm and 2 mm, while D-orientation shows a significantly lower force level. The elongation at failure observed in the experiments is sorted in increasing order L, T, D for both notch geometries. While L and T-orientation differ only slightly, D shows a significantly higher failure strain. This effect correlates well with the fracture surface appearance, where the amount of dimples is significantly higher on D-oriented specimens compared to L and T orientation revealing an increased ductility.

Figure 2 displays the experimental results of the two representative Kahn-type specimens and the corresponding simulation results. One can see from the simulation results that slight differences in specimen's "pre-fracture" deformation behaviour between L- and T-orientation exist. The simulations under predict the maximum force, but meet the decreasing part of the load-CMOD curve. This implies that the stable crack extension phase is not exactly met by the simulations, whereas the mixed-mechanism-phase is. This goes back on the calibration of the nucleation function used, eqn. (2), which is based on the sudden load decrease obtained from the notched samples originating from a turn to a slanted failure mode. Consequently, the use of the strong nucleation rate aims rather on an assessment of the slanted failure mode instead of meeting the stable crack extension correctly.

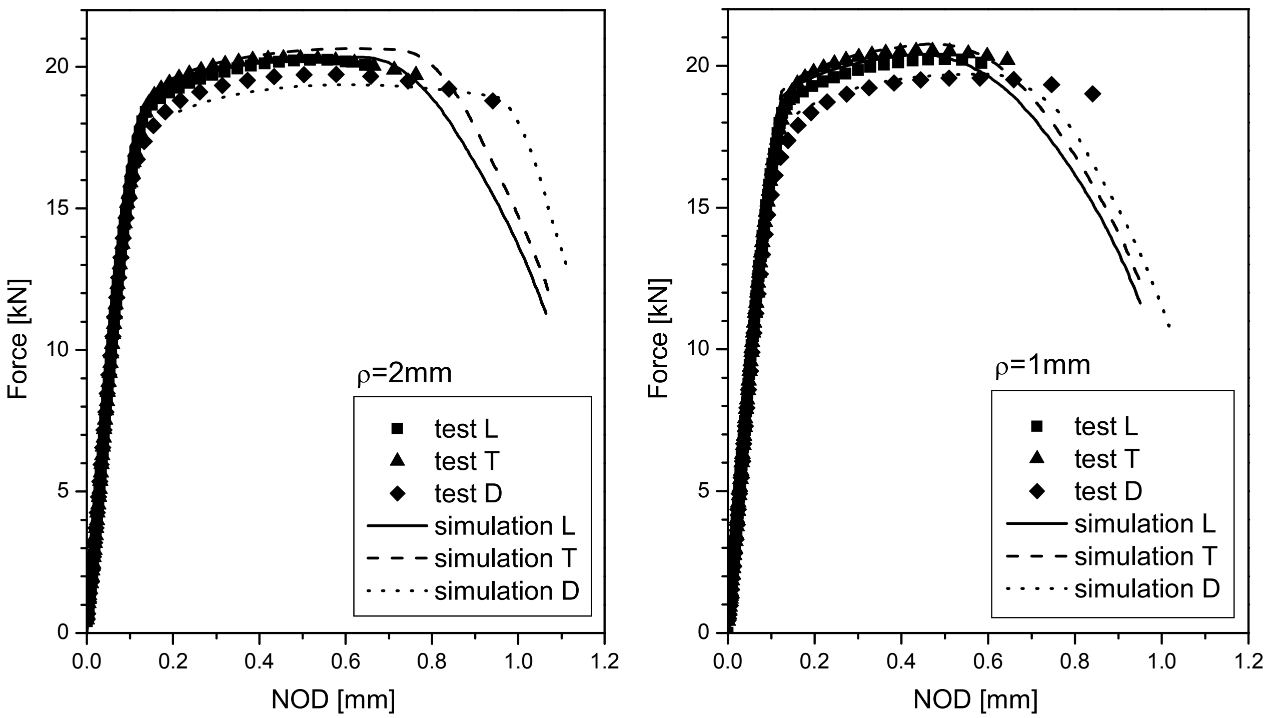

Figure 1: Response of the U-notched samples ρ=2 mm (a) and ρ=1 mm (b) – experiment and simulation using the damage model

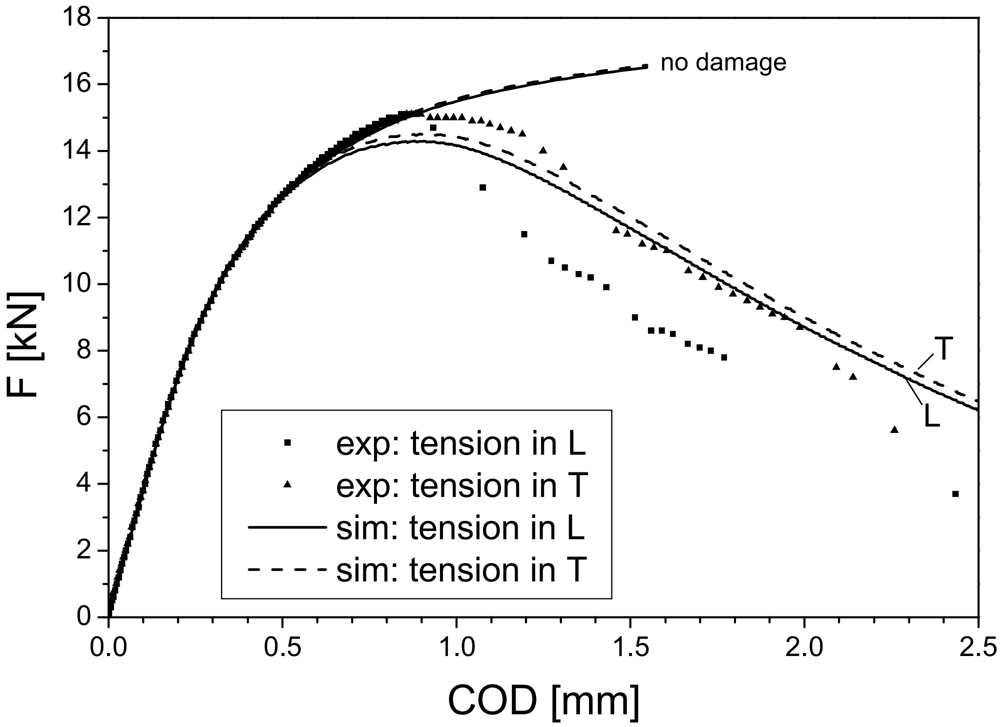

Figure 2: Results of the FE-simulations of the Kahn tear tests in comparison with experimental data

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