Characterization and modeling of the deformation and damage of an aluminum sheet for crash

F. Andrieux[1]*, S. Klitschke[1], W. Böhme[1] and D.-Z. Sun[1]

[1] Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany
** Corresponding author (email: florence.andrieux@iwm.fraunhofer.de)*

Abstract

In this work an aluminum sheet was characterized under static and crash relevant loading conditions. Tension, biaxial and shear tests were performed. The parameters of isotropic and anisotropic material models in combination with a failure model were determined through the simulation of the different tests. The applicability of the used material models was verified by comparing experimental and calculated results of fracture mechanics tests, namely Kahn-specimen tests.

Keywords: *Al-Alloy, Anisotropy, Failure, Strain Rate Sensitivity, Crash*

1. Introduction

For car manufacturer the lightening of vehicle is an important goal, aluminum alloys are good candidates for the production of lightweight cars. Strain hardening Al-Mg alloys are used for the structural parts of the body-in-white because they offer an excellent combination of weldability, strength and crash resistance. AlMg3.5Mn also presents a good resistance against corrosion. Al-Mg alloys are known to exhibit, in certain range of temperature and strain rate, negative strain rate sensitivity (SRS) that gives rise to the Portevin-Le Chatetelier phenomenom (PLC) which manifests by a serrated flow due to the interactions between solute and dislocations referred as dynamic strain aging (DSA). Also the ductility of the material is affected by the PLC effect.
In this work the alloys AlMg3.5MnH111 (AA5042) was characterized under different loading situations (stress state, orientation, strain rate). Reliable modeling of the material behavior is necessary for the assessment of crash safety. The von Mises isotropic model and two variants of an anisotropic material model according to Barlat were used. Since fracture strains of aluminum are relatively low, damage modeling has to be included and the deformation models were used in combination with a failure criterion. The model parameters were determined by modeling specimen tests. In order to investigate the effect of strain gradients and to verify of the numerical method fracture mechanics tests were performed and simulated.
All specimens were cut from a sheet with a thickness of 1.5mm. The FE-code LS-DYNA was used for all simulations. In vehicle simulations shell elements have to be used due to computer capacity and the parameter were determined for shell elements.

2. Characterization and modeling

2.1 Material characterization

Orientation:
The orientation dependence of the stress vs. strain curves was characterized with smooth tension specimens cut in three orientations. The measured engineering stress vs. engineering strain curves of specimens in three orientations under static loading are compared in Figure 2. Both flow stress and fracture strain depend on specimen orientation. While the specimen in longitudinal direction shows the largest flow stress and ultimate strength and the smallest fracture strain. The jerky flow on Figure 2 also shows that a PLC effect is present under the investigated strain rate and temperature conditions.

Triaxiality:
To study the influence of triaxiality, defined as the ratio of the mean stress σ_m to the von Mises stress σ_e, torsion tests, shear tension tests, smooth and notched tension tests and biaxial tension tests were performed under static loading.

Strain rate:
In order to investigate the effect of strain rate, tensile tests with a speed of 0.014 and 1.4 m/s corresponding to a nominal strain rate of respectively 1 and 100 /s were performed. Shear tensile tests and tensile tests on notched specimens were also performed with a speed of 1.4 m/s.

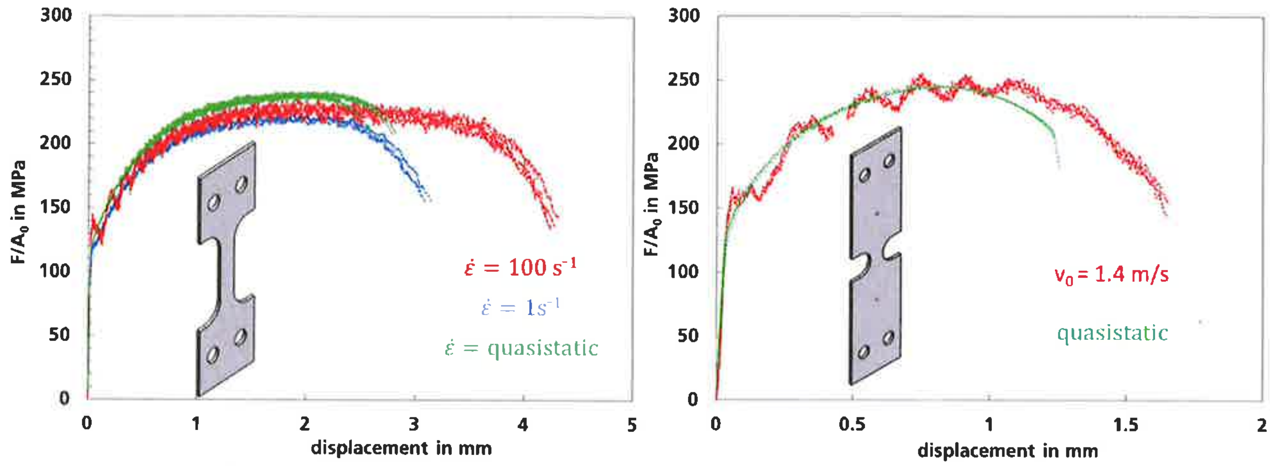

Figure 1: Nominal stress-strain curves of tensile tests under quasi-static loading and at 1/s and 100/s (left) Nominal stress-displacement curves of tensile tests on notched specimens under quasi-static loading and with a speed of 1.4 m/s (right)

Figure 1 shows a non-monotone effect of the strain rate. The dynamic curves lie below the static ones but between 1 and 100/s a strain rate hardening is observed. The strain rate has a great effect on deformation at failure with the minimal value obtained at quasi-static loading condition and the maximal at 100/s.

2.2 Material models for deformation and failure

Deformation models:
The isotropic von Mises model and an anisotropic material model according to Barlat [1] for anisotropic sheet under plane stress conditions also referred to as Barlat-3-parameter were used. This model is implemented in LS-DYNA [2], the user has to define the 3 parameters of the yield function a, h and p and the stress-strain curve in the reference direction. Alternatively it is possible to give instead of the 3 yield parameters, the 3 Lankford parameters r_0, r_{45} and r_{90}, in this case the yield parameters are internally determined using the flow rule. In LS-DYNA several extensions of the Barlat-3-parameter model are proposed. One consists of defining three stress-strain curves for three directions and the three Lankford parameters. This leads to a non-associated formulation with anisotropic hardening.

Failure model:
In LS-DYNA it is possible to add to each constitutive model failure criteria. In this work we use this feature and choose the GISSMO option. It is based on a Johnson-Cook type damage model [3]. The fracture strain is always defined as a function of the stress triaxiality but the input is given by tabulated data to allow a large flexibility for describing the form of damage curves. A detailed description of this model was given by Neukamm et al. [4]. Because the number of points in this curve is limited by the number of experiments we also used an empirical model to construct the failure curve, namely the bi-failure model described in [8]. In this model the fracture strain vs. triaxiality curve is divided into two regions for dimple rupture at high triaxialities and shear failure at low triaxialities. An exponential

function proposed by Johnson-Cook is used for high triaxiality and an empirical polynomial curve is used for the low triaxiality. The failure curve determined with the bi-failure model was used as input to the GISSMO damage model

Simulation of specimen tests:

In order to get a conservative solution the static stress-strain curves were retained for the material parameters simulation.

The material models according to von Mises and Barlat in combination with the GISSMO damage model were used to simulate the different specimens and determine the model parameters. The numerical simulations of different specimen tests were performed using shell elements with length element 0.5 mm. For each deformation models (von Mises, Barlat, and Barlat with non-associated formulation and anisotropic hardening (Barlat NA)) a corresponding failure strain curve was defined. Figure 2 shows that the Barlat model can well predict the orientation dependence of the deformation behavior. The results of the von Mises model were obtained using the stress vs. strain curve in longitudinal direction. The strain measured at fracture depends on orientation which cannot be well predicted with the isotropic GISSMO failure model. With the non-associated version of the Barlat model with anisotropic hardening, the nominal stress vs. strain curves of tension tests for the three orientations are exactly calculated because they are input of the models. As a consequence the orientation dependent fracture strain can be well predicted using the isotropic failure model.

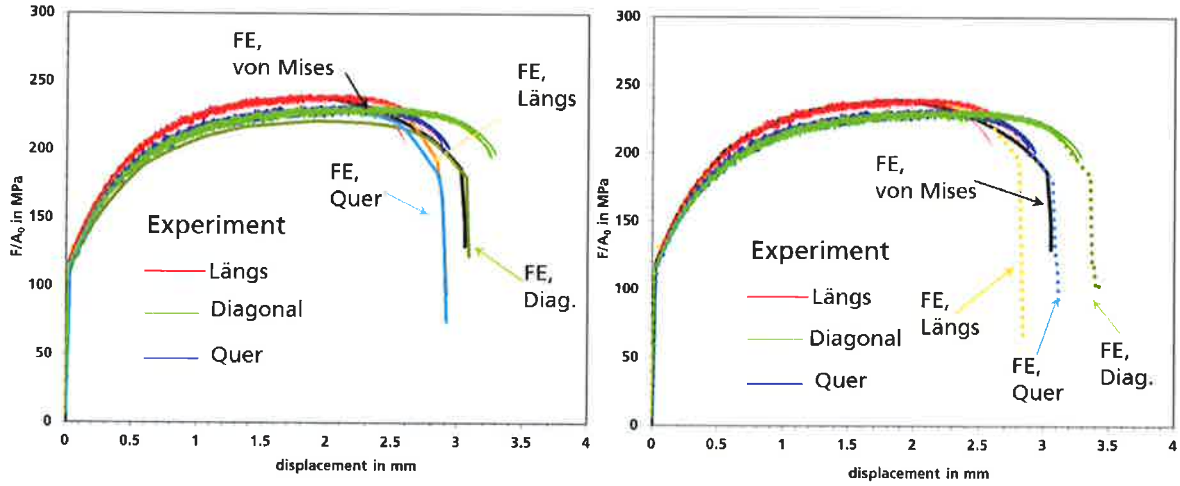

Figure 2: Measured and calculated nominal stress vs. strain curves of tension tests for three orientations. The von Mises model is compared with the Barlat model (left) and with the non-associated Barlat model with anisotropic hardening (Barlat NA) (right).

Shear tensile tests, tensile tests on notched specimens and punch tests were also simulated using the three models. The von Mises yield function overestimates the yield stresses of shear and notched tension tests in contrast to the Barlat model which leads to a good prediction. However in these cases the use of the standard Barlat model or the non-associated version with anisotropic hardening only leads to slightly different results.

2.3 Validation

In order to validate the material models and to verify the transferability of the material parameters, fracture mechanic tests on Kahn specimens were performed and simulated with the three material models. Figure 3 shows the load vs. displacement curves. Two specimen geometries with two notch radii were used to investigate the effect of the notch size, in the simulation because of the element size of 0.5 mm it was not possible to take the notch into account.

Figure 3 shows that the three models give a realistic description of the test. In this case the von Mises model leads to the best agreement with experiment. However because of the simplification of the FE-model due to the shell description and the coarse element length, this test is not a way to determine which model is better. However it can validate the three models with their parameters.

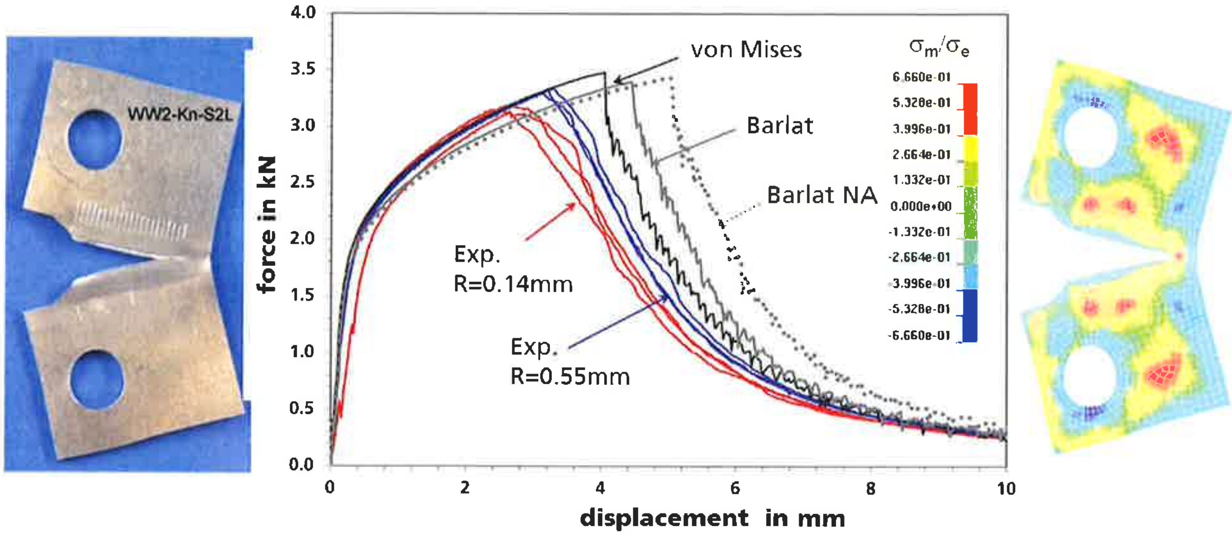

Figure 3: Measured and calculated force vs. displacement curves of Kahn-specimen tests with the specimen after test (left) and the calculated triaxiality pattern (right).
The von Mises model is compared with the Barlat model and with the non-associated Barlat model with anisotropic hardening (Barlat NA).

3. Conclusions

An Al-Mg sheet was characterized under crash relevant loading. A PLC effect was pointed out in the temperature and strain rates investigated. In order to get a conservative parameter sets the static tests were used for the parameter determination.
Von Mises isotropic and Barlat anisotropic deformation models were used in comparison always combined with an isotropic damage model based on critical failure stain. The three models were able to describe the specimen tests including failure with a good accuracy. The non-associated version of the Barlat model leads to an exact description of the tensile tests in three directions. This is attributed to the fact that in this case the 3 experimental curves in 3 direction are given in input so that the localization point can be precisely described and so the failure. The Barlat model gives better results than von Mises for all the tests but except for the tension tests the non-associated version of Barlat with anisotropic hardening is not superior to the original Barlat model.
The complex stress state of the verification test is only roughly described with coarse shell elements and the results of the corresponding simulations cannot be used to judge which model has to be used. However, all three models can be considered as a good compromise for application.
Further investigation is required to model anisotropic damage behavior of aluminum alloys.

References

[1] F. Barlat., J. Lian, *Plastic behaviour and stretchability of sheet metals, Part I: A yield function for orthotropic sheets under plane stress conditions*, Int. J. of Plasticity, **Vol.5**, pp.51-66, 1989.

[2] *LS-DYNA Keyword User's Manual*, Version 971 R6.0.0, Livermore Software Technology Corporation, February 2012.

[3] G.R. Johnson, W.H. Cook, *Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures*, Engineering Fracture Mechanics, **Vol.21**, No.1, pp.31-48, 1985.

[4] F. Neukamm, M. Feucht, A. Haufe, *Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures*, 7. LS-DYNA Anwenderforum, Bamberg, Germany, 30. Sept.-1. Oct.2008.

[5] F. Andrieux, D.-Z. Sun, *Damage modelling for simulation of process chain from forming to crash*, Int. J. Mat. Res., **Vol.101**, No.8, pp.963-971, 2010.