Improved Plasticity and Failure models for Extruded Mg-Profiles in Crash Simulations

Authors:

Gernot Oberhofer (Sp), Harry Dell, Dmitri Dell, Helmut Gese
MATFEM Partnerschaft Dr. Gese & Oberhofer
Horst Lanzerath, Jürgen Wesemann
Ford Forschungszentrum Aachen
Elke Hombergsmeier
EADS Corporate Research Center, München

Correspondence:

Gernot Oberhofer
MATFEM Partnerschaft Dr. Gese & Oberhofer
Nederlingerstr. 1
D-80638 München
Germany

Tel: +49-(0)89-1598979-0
Fax: +49-(0)89-1598979-9
e-mail: gernot.oberhofer@matfem.de

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ABSTRACT

The Crash Simulation of Magnesium Structures with Finite Element Methods demands the use of suitable material and failure models. An associated plasticity model describing the complex asymmetric yield behaviour in tension and compression of Mg extrusions has been developed during the InMaK-project (Innovative Magnesium Compound Structures for Automobile Frames) supported by the German Federal Ministry for Education and Research (BMBF). Differences to the material model 124 in LS-DYNA are exposed. In order to describe the failure behaviour of Mg extrusions under multiaxial loading in FEM crash simulation this constitutive model has been combined with a fracture model for ductile and shear fracture. The fracture model has been added to the user defined constitutive magnesium model in LS-DYNA. The experimental investigations carried out on model components are compared with numerical derived results. Experimental methods for fracture parameter evaluation are shown and general aspects of metal failure due to fracture as well as different modelling techniques are discussed.

INTRODUCTION

The aim of reducing the CO_2 emission of vehicles has started an intensive development of new light weight structures. In this contents magnesium offers promising properties like low density, good weldability, good mechanical damping etc. Whereas the application of casted components is widely spread the use of formed and extruded profiles is actually very limited but shows additional weight saving potential compared to steel and aluminum [1].

However the effective use of new materials requires a complete description of material behavior under all loading conditions in vehicles life. So weak points can be detected at an early design state and optimization steps can be performed by the developing engineer. At this state the development process can be supported by computer simulation if suited material models are available.

MATERIAL CHARACTERISATION

FUNDAMENTALS

Yield locus and strain hardening

The material characterization for forming and crash simulation of metals is accompanied by large displacements as well as elastoplastic material behavior and failure. Therefore several material models with different yield loci (v. Mises, Barlat, asymmetric model 124, etc) are available in LS-DYNA 9.60. An ongoing development step was made during the InMak-project by developing a new material model for magnesium alloys that strictly obeys the associatied flow rule and includes models for the specific, strain rate dependent hardening behavior as well as materials failure due to fracture.

In order to give an overview about some fundamentals Figure 1 shows a yield locus (cross section of yield locus for τ_{xy}=0) for the 2D-stress space for a general asymmetric, anisotropic behavior. The yield locus cuts the axis σ_x, σ_x at the yield points for uniaxial loading in relation to materials yield orthotropy. In case of associated flow, when the derivatives of the yield surface are equivalent to the derivatives of the plastic potential surfaces, the normals to the yield locus at the points of uniaxial loading describe the behavior of plastic flow in plane to plastic flow in thickness direction (R-value). For isotropic behavior this ratio becomes equal to 1.

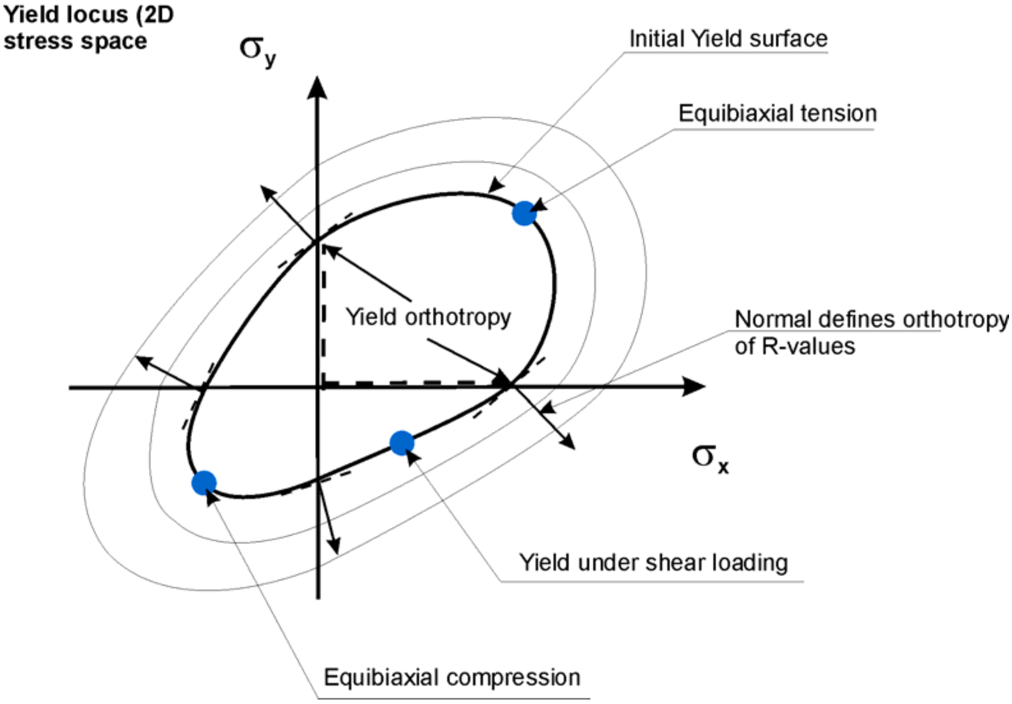


Figure 1 Fundamentals for the development of a yield locus for magnesium alloys; orthotropic yield locus (τ_{xy}=const.)

For elasto-plastic material it is necessary to describe the evolution of the yield surface with increasing plastic strain after initial yielding (hardening/softening behavior) in addition to the yield locus. In case of crash analysis strain rate dependent effects have to be taken into consideration.

Fracture

For metals the equivalent strain at fracture shows a significant relation to the type of loading. Usually the type of loading is defined through stress triaxiality η, which describes the relation between hydrostatic stress and v. Mises equivalent stress. With growing stress triaxiality ductile fracture, which is characterized through void nucleation, void growth and void accumulation to a fracture plane, is dominant. In the fracture plane the preceding voids are visible as a honeycomb structure. Another failure mechanism named shear fracture appears in cases of shear and pressure loading. In these cases the fracture plane is comparatively smooth. The transition point of stress triaxiality between shear fracture and ductile fracture is material dependent. Figure 2 shows a schematic representation of the ductile fracture and shear fracture limit curves of a metal with overview over specimens for the experimental evaluation of the fracture strain.

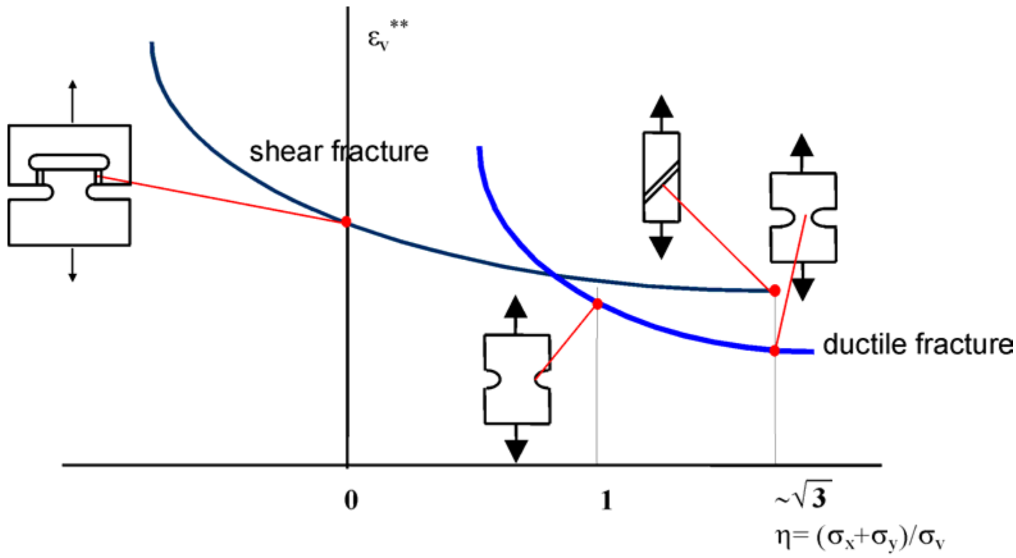


Figure 2 Schematic representation of ductile fracture and shear fracture limit curves of a metal with overview over specimens for the experimental evaluation of fracture strains

EXPERIMENTAL INVESTIGATIONS

From literary studies and experimental tests on AZ61 and AM50 magnesium extrusions the plastic behavior can be characterized in general through

- a strong asymmetry between yield strength in compression and tension,
- different hardening behavior in compression and tension,
- significant strain rate dependency for strain rates above 10 s^{-1} - different for compression and tension,
- anisotropy with regards to extrusion direction.

In Figure 3a the experimental tensile hardening curves are displayed for different extrusion directions (0°, 45°,90° according to extrusion direction). In Figure 3b the hardening curves for tension and compression are compared. The complex hardening behavior of magnesium extrusions shows additionally a significant strain rate sensitivity as shown in Figure 3b.

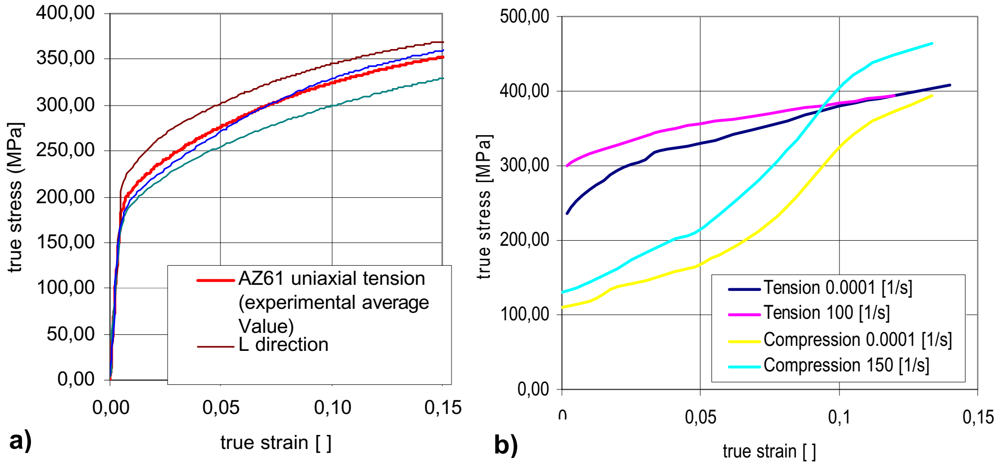


Figure 3 a) averaged experimental results from different directions according to the extrusion direction; b) Tensile and compression curves for different strain rates;. Material AZ61 (Experimental results on Magnesium extrusion AZ61 from EADS Cooperate Research Center München in the framework of the InMak-project)

In Figure 4 the fracture strain versus $\alpha = \varphi_2 / \varphi_1$ ($\alpha = \dot{\varphi}_2 / \dot{\varphi}_1$ for nonlinear strain pathes) is shown for Mg extrusions from different experimental tests. As all experimental tests showed shear fracture as the relevant failure mechanism, ductile fracture is not considered in the following investigations. Here the equivalent shear fracture strain shows a significant dependence upon the type of loading. It is assumed that for linear deformation history the maximal shear fracture is linearly dependent upon stress triaxiality η. Further on it is useful to define the relation of maximum shear stress versus equivalent stress as a second parameter (ϕ) beside stress triaxiality. The shear fracture diagram is approximated in coordinates of „equivalent strain at fracture" versus a parameter θ through equation (1)

$$\varepsilon_v^* = b \exp(f\theta), \qquad (1)$$

assuming θ to be a function of η and ϕ.

The experimental data have been taken to adapt the parameters of the fracture model for shear fracture according to equation (1). The corresponding shear fracture diagram (SFD) is plotted in Figure 4.

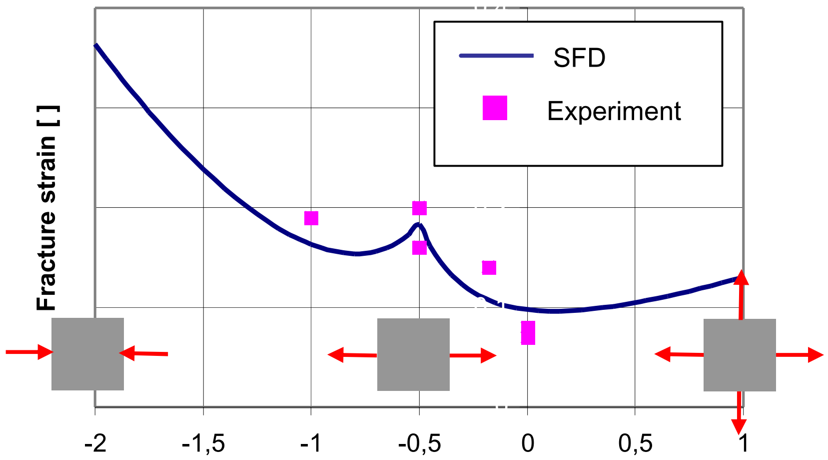


Figure 4 Fracture strain versus $\alpha = \varphi_2 / \varphi_1$ with approximated shear fracture curve (Experimental results on Magnesium extrusion AZ61 from EADS Cooperate Research Center München in the framework of the InMak-project)

MATERIAL MODEL

On basis of the experimental results mentioned above a new material model has been developed which is discussed in detail subsequently. For the InMak-project the investigations have been restricted to isotropic, asymmetric material behavior.

Yield locus [1]

As mentioned in the preceding chapter of fundamentals a yield locus for isotropic material has to fulfill the condition of the R-value isotropy (R=1) as well as the condition of yield isotropy. For the description of the yield locus the magnesium extrusion specific yield locus has been mapped onto the isotropic v. Mises yield locus through a mapping function f.

$$s_1 = \sigma_1 * f$$
$$s_2 = \sigma_2 * f \qquad (2)$$
$$s_1^2 - s_1 * s_2 + s_2^2 = \sigma_v^2$$

(σ_1, σ_2) is a stress state on the magnesium yield surface.

A mapping-function f has to be developed so that the yield locus fulfills several boundary conditions:

- continuity of the yield locus;
- continuity of the derivatives;
- convexity of the yield locus (with restriction);

- the yield locus must include the flow resistance in uniaxial compression and tension;
- the first derivatives at these point have to fulfill the isotropic/anisotropic (anisotropic –only for anisotropic yield locus) condition.

According these boundary conditions, it is assumed that

- for $\sigma_1 \geq 0, \sigma_2 \geq 0$ $f = 1$, (3)
- for $\sigma_1 \leq 0, \sigma_2 \leq 0$ $f = f_0$ (4)

is valid, where f_0 is the ratio between yield strength in uniaxial tension and compression and that for the principal stresses $\sigma_1 \geq \sigma_2$ is valid. σ_{eq} is the yield strength for uniaxial tension.

In Figure 5 an isotropic yield locus with asymmetric behavior in tension and compression is shown. From the point $\sigma_2 = 0$ to $\sigma_1 = 0$ the mapping function f=f(x) has to change from 1 to f_0 (x is a curvilinear parameter).

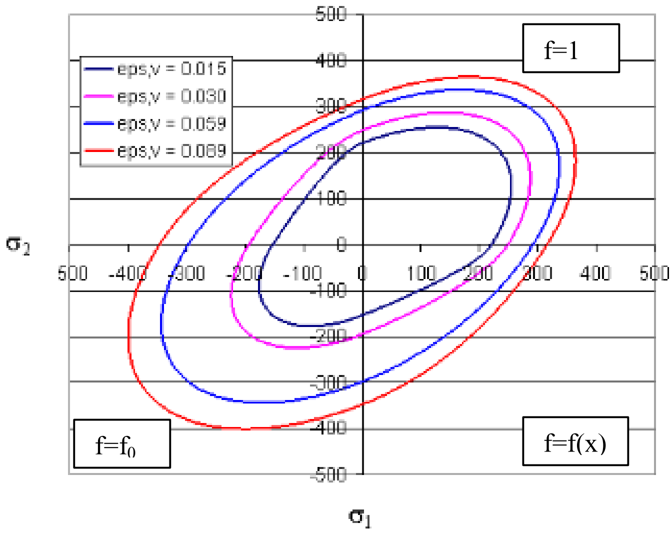


Figure 5 Yield locus of extruded magnesium for different strain states: Material AZ61 [1]

Hardening [1]

For extruded magnesium profiles, like AZ61, experimental results show that hardening is asymmetric in tension and compression (Experimental results on Magnesium extrusion AZ61 from EADS Cooperate Research Center München in the framework of the InMak-project). Therefore a asymmetric function $f_0\,(\varepsilon_{eq})$ has been used, which describes the difference between yield in tension and yield in compression as a function of equivalent plastic strain for the uniaxial case. For the hardening model it is assumed:

- uniaxial tension as equivalent stress state,
- the volume normalized work of the plastic deformation as hardening parameter.

The logarithmic strain in uniaxial tension is used as a equivalent plastic strain for which the normalized work is equivalent to the work of the considered deformation process. This results in an equivalence of the flow curve with the flow curve of the tension test ($\sigma_{eq} = \sigma_z$, $\varepsilon_{eq} = \varphi$). The material behavior is ruled by two functions of the equivalent plastic strain: $\sigma_{eq}(\varepsilon_{eq})$ and $f_0(\varepsilon_{eq})$. $f_0(\varepsilon_{eq})$ is the asymmetry function, which is derived as follows: According to the flow curve in uniaxial tension the correlation between equivalent plastic strain and normalized plastic work is given by:

$$w(\varepsilon_{eq}) = \int_0^{\varepsilon_{eq}} \sigma_{eq} d\varepsilon_{eq} \quad (5)$$

In the same way the function $w(\varepsilon_{eq,c})$ is determined using the uniaxial compression flow curve, where $\varepsilon_{eq,c}$ is the plastic strain in compression. These two functions allow the transition from the $\varepsilon_{eq,c}$ to equivalent plastic strain. The flow curve in pure compression is now plotted as a function of ε_{eq}. With this curve and the flow curve from the tension test the function $f_0(\varepsilon_{eq})$ can be determined. An expanded formulation describes the dependence of the asymmetric factor from equivalent strain and strain-rate ($f_0(\varepsilon_{eq}, \dot{\varepsilon}_{eq})$).

For the approximation and extrapolation of the flow stress vs. strain curves an adiabatic hardening model has been used. This model is described in detail in [2]

Fracture

An instantaneous fracture model for ductile fracture and shear fracture (equation [1]) has been added to the user defined material law. The adaptation of the corresponding fracture parameters is done for Mg-profile and Mg-casting. For validation purpose the stress-strain behaviour resulting from the simulation of 1-element tests under different loading conditions (uniaxial tension, uniaxial compression and eqiubiaxial tension) has been simulated. During simulation the element is deleted when the calculated safety factor reaches a critical value of 1.

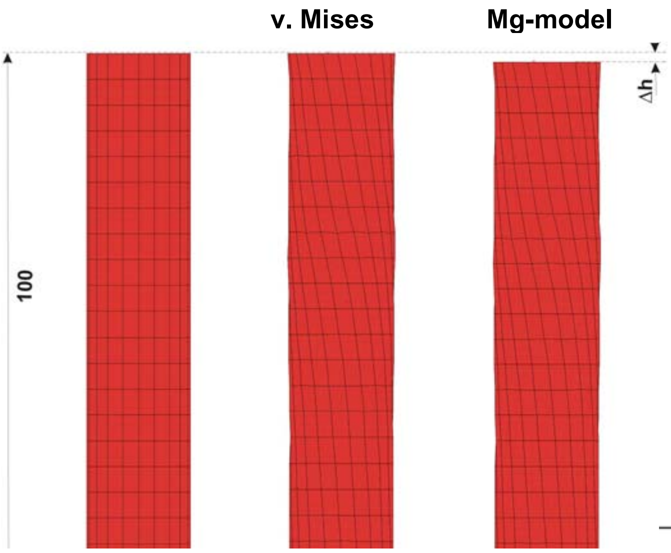
The fracture curve can be displayed either in coordinates of fracture strain versus $\alpha = \varphi_2 / \varphi_1$ like it is done in Figure 4. In the special case of plane stress condition the parameter θ can be directly correlated to the corresponding α value.

VALIDATION EXAMPLES

TORSION TEST/3-POINT BENDING TEST/ SECTION COMPRESSION TEST

Important inputs about material models behavior can be achieved from the torsion test without axial force. In this case of shear loading an asymmetric material model that obeys the associated flow rule has to show straining in axial direction. This axial straining does not appear in case of a material model with flow based on the v. Mises yield locus. This fact is explained by the yield loci in Figure 6 schematically. In case of the v. Mises yield locus pure shear stress leads to pure plastic shear deformation.

In case of an asymmetric yield locus with associated plastic behavior an additional strain component (in this case shortening) is superimposed.



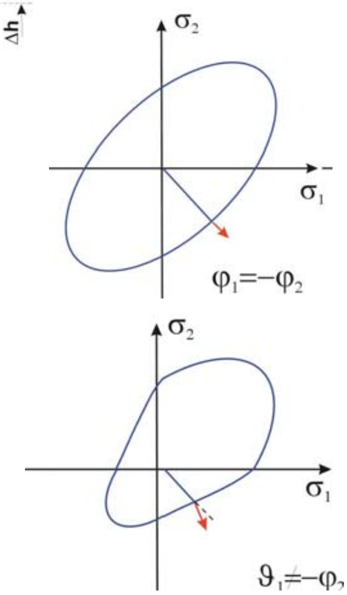


Figure 6 Tube shortening in the torsion test

Figure 7 shows the shortening of the tube under pure torsion load in experiment and simulation using the magnesium yield locus. Comparable simulations performed with the conventional v. Mises yield locus (and also asymmetric material law 124 in LS-DYNA [3]) does not show this shortening.

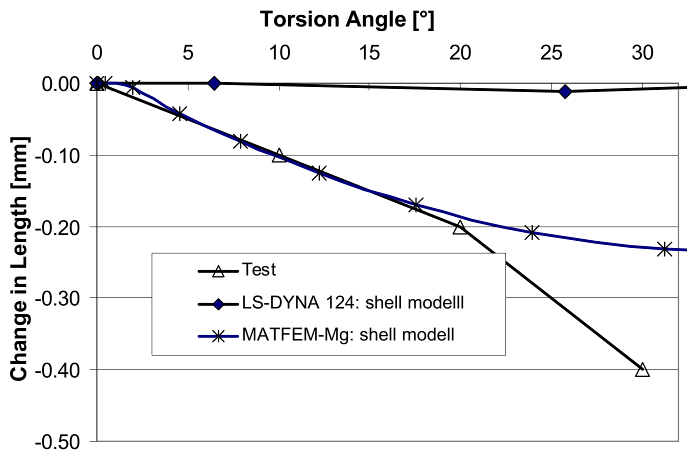


Figure 7 Tube shortening in the torsion test

In Figure 8 the torsion moment versus rotation angle is displayed for experimental tests and simulation with the new magnesium model.

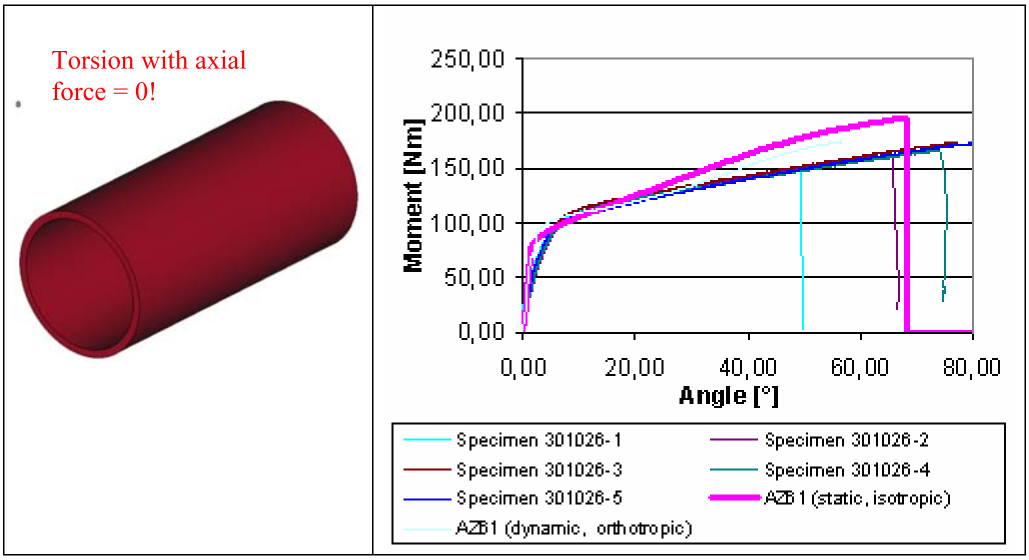


Figure 8 Geometrical model of the tube specimen; Torsion moment as a function of the torsion angle

Additional comparisons between experimental results and simulation with the Mg-model are displayed in Figure 9 for a component under 3-point bending load. The simulation with the new magnesium model shows a good correlation of the force-deflection curve including the point of materials failure to experimental results. The simulation with the symmetric v. Mises yield locus leads to a significantly to high force-deflection curve.

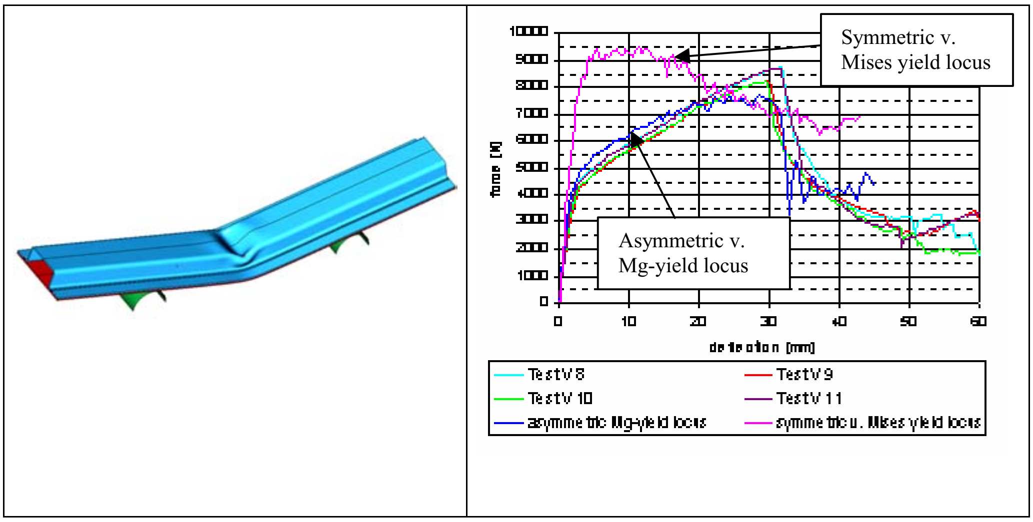


Figure 9 Force deflection diagram from component test; component made of AM50-extrusion and AM50 casting; fracture parameters have been evaluated for both materials

DISCUSSION OF THE VALIDATION SAMPLES

Previous studies showed, that for magnesium extrusions the use of the isotropic v. Mises model with material data from the tensile test consequently leads to a too high level of predicted forces compared to the experiment. The use of the new magnesium model in the validation samples from above shows a good correlation with the experiment including the point of material failure due to shear fracture. Remaining deviation might be a consequence of the fact that specimens orthotropic behavior has not been considered in this first step.

SUMMARY AND CONCLUSIONS

During the InMak-projekt (Innovative Magnesium Compound Structures for Automobile Frames) a new material model for magnesium has been developed for shell elements. This material model is able to describe the significant asymmetric yield behaviour in compliance with the associated flow rule as well as the strain rate dependent hardening through an adiabatic hardening model. In order to cover material failure due to fracture an instantaneous fracture model has been added. Experimental tests showed, that shear fracture is the only relevant failure mechanism for the investigated magnesium extrusions and casted components. For material model validation different experimental tests have been performed and simulated. A good correlation of experiment and simulation has been detected and small deviations from test results supposed to be a result of slightly different parameters of material for parameter evaluation and component material.

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