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MATERIAL MODELLING OF CAST ALUMINIUM BY APPLICATION OF THE WILKINS DAMAGE MODEL

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Abstract. *Since cast light metal components gain more relevance in automotive application, the development of adequate material models including consideration of damage is necessary. A key issue in material modelling of metals is the consideration of material damage in addition to the elasto-plastic behaviour. The damage behaviour is a specific property of a material which characterises the crashworthiness of a structural material, especially for cast alloys.*

These have a significant low ductility compared to wrought alloys. Numerical simulations of cast alloy panels under crash loadings show noticeable overestimated results if material damage is not considered.

A damage model for ductile fracture introduced by Wilkins is discussed, as well as the appropriate strategy to characterise the material parameters for this model. In these studies an elasto-plastic material model is set up for a squeeze cast Aluminium alloy which includes the Wilkins approach for consideration of damage. The material model is characterised and validated on flat tensile tests. The final material model is then used in models of crushed hat profiles and validated by experiments.

The comparison of the experiment and the numerical simulation demonstrate a good accordance of the force displacement data and a difference in energy absorption of 3 %.

1 INTRODUCTION

Cast aluminium alloy achieve an increasing relevance in automotive application, due to their light weight design properties. Especially, the relative low density and the well-established manufacturing processes of these components constitute this field of application. For design purpose, numerical simulations build a state of the art method. In there, appropriate material models are mandatory to capture the structural behaviour in a correct manner not only in the elasto-plastic regime, but also during damage until fracture. A common way to perform failure modelling of a material is the micromechanical consideration which observes the phenomena of void nucleation, growth and coalescence. A material model including a micromechanical approach is introduced by Gurson [1]. Further models, as the approach of Needleman and Tvergaard [2] are resulted of modifications of the Gurson Damage Model. One of the limitations of a formulation according to Gurson is the neglected influence of damage caused by shear load cases. The modification by the approach of Nahshon and Hutchinson [3] overcomes this problem.

The phenomenological approach of Johnson-Cook [4] takes temperature and strain rate for damage evolution into account. Mathematical damage models are available in finite element (FE) simulation tools. These use a damage description by the definition of curves, which constitutes the coherence of load dependent parameters, e.g. plastic strain and triaxiality, concerning their damage influence. This paper focuses on the material modelling of an Aluminium cast alloy under crushing load. Principles of failure modelling and especially the Wilkins Damage Model are introduced. It will then go to the investigation and validation of the same. A material model including Wilkins Damage approach will be defined for an AlSi cast alloy on flat tensile specimen. This material model will be validated on hat profile crushing tests.

2 FAILURE MODELLING

Material definitions are an essential input for numerical simulations. Besides the definitions of elasticity, flow rule and hardening type the additional definition of material damage are essential. Especially, where crash loadings induce high deformations it is important to correctly capture material failure and to have a convenient method for parameter characterisation. Every stress condition induced by mechanical loads or temperature causes material damage. Once damage reaches a critical, material dependent level failure is observed. In numerical simulation an incremental damage value is determined in each time step and cumulated for the description of failure.

To link the actual stress state to the damage effect, several parameters are introduced. These parameters reduce the stress tensor to equivalent values for modelling of failure. The most common parameter in this context is the stress triaxiality η, which is defined according to (1) as function of the hydrostatic stress σ_H and the equivalent stress of Mises σ_{Mises}.

$$\eta = \frac{\sigma_H}{\sigma_{Mises}} \tag{1}$$

The stress triaxiality is used in numerous damage and failure models [[4], [2], [1]], e.g. in the approach of Gurson. The purpose is the characterisation of the stress state according to the influence of material damage. Stress triaxiality is considered as a crucial factor for ductile fracture [5]. An additional way to consider damage in a material model is the formulation of the Lode Stress Parameter μ_σ.

The Lode Stress Parameter is determined by the deviatoric part of the stress tensor with the deviatoric principal stresses $s_1 > s_2 > s_3$ in the form

$$\mu_\sigma = \frac{2\,s_2 - s_1 - s_3}{s_1 - s_3} \ . \tag{2}$$

The Lode Stress Parameter is defined in the range of $[-1, 1]$, whereas the value of $\mu_\sigma < 0$ denotes tensile stress state, $\mu_\sigma = 0$ denotes pure shear stress state and $\mu_\sigma > 0$ indicates a compression stress condition. A characterisation of the stress state using the Lode stress Parameter in addition to the stress triaxiatity is a convenient way for modelling ductile fracture behaviour. The Lode Stress Parameter distinguishes the stress state in axisymmetric and shear dominated stress conditions [6].

3 WILKINS DAMAGE MODEL

The damage model introduced by M. L. Wilkins [7] uses a phenomenological approach for the formulation of damage and failure. It takes into account that material damage which is introduced by the weighting of two factors in a mechanical loading case. First the hydrostatic part and second the deviatoric part of a stress tensor. During loading, both of them imply incremental damage until failure occurs. The damage effect of hydrostatic pressure is observed as spalling mechanism in the material. The deviatoric stress part leads to linkage of voids in a material [7]. Strain rate effects are not included in the approach of Wilkins. The cumulative damage formulation by Wilkins is implemented in the numerical simulation code LS-Dyna [8] as

$$D = \int \omega_1 \, \omega_2 \, d\varepsilon_{pl,equ} \ , \tag{3}$$

where

$$\omega_1 = \left(\frac{1}{1-\gamma \, \sigma_H}\right)^{\alpha} \tag{4}$$

and

$$\omega_2 = (2 - A_D)^{\beta}. \tag{5}$$

In equation (3) the cumulative damage *D* is a function of the two weighting terms ω_1, ω_2 and, furthermore, of the equivalent plastic strain increment $d\varepsilon_{pl,equ}$. The parameters α, β and γ in equations (4) and (5) are material dependent values according to the particular damage behaviour. These values have to be identified for the specific AlSi cast alloy of this investigation.

The approach of Wilkins calculates damage history by hydrostatic stress σ_H and the deviatoric part of the stress tensor. The deviatoric part of the stress tensor is determined by the deviatoric principal stresses s_1, s_2 and s_3 in parameter A_D as follows [8]:

$$A_D = \max\left(\left|\frac{s_2}{s_3}\right|, \left|\frac{s_2}{s_1}\right|\right) \tag{6}$$

Equations 3-6 describes material damage *D* caused by mechanical stresses. An additional criterion is needed for the definition of material failure.

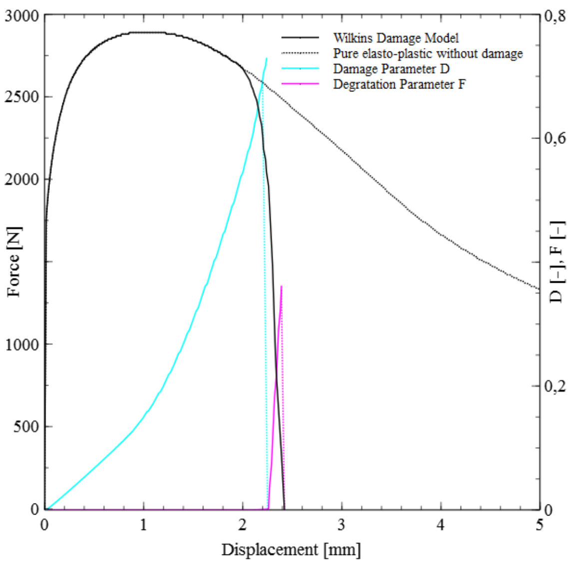
The following approach is implemented in LS-Dyna [8] by coupling of damage evolution and material degradation in the form

$$\frac{D}{D_c} > 1 \tag{7}$$

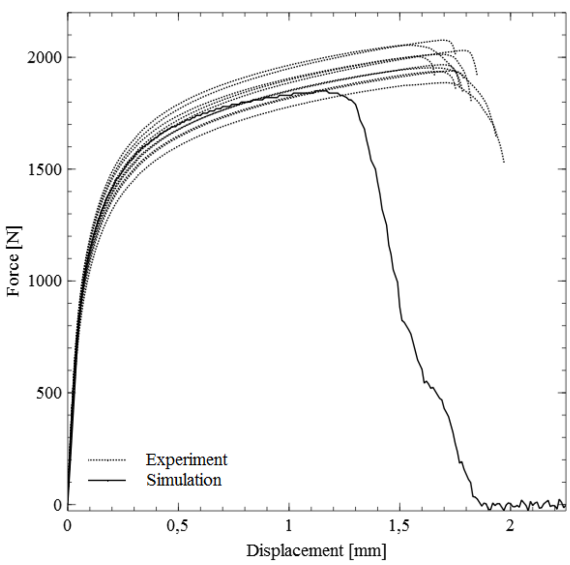
with D_c being a critical damage value for the material in use and the material degradation parameter F defined as

$$F = \frac{D - D_c}{D_s} \tag{8}$$

with the material dependent parameter D_s. To link the theory of failure modelling in the present work to the approach of Wilkins, a closer view into the damage formulation is necessary. In common material models, the influence of hydrostatic stress related to material damage is carried out by the stress triaxiality parameter η. Obviously, in the approach of Wilkins the unscaled amount of the hydrostatic stress is applied in equation (4). Furthermore, the Lode Stress Parameter is implemented to consider the effects of material damage [6]. It can be shown that the parameter A_D shows a similar characteristic as the absolute value of the Lode Stress Parameter [9]. Equations 3-8 include the material dependent parameters β, γ, D_c and D_s. The determination of these parameters asks for a material characterisation strategy. Therefore, four flat tensile specimen with different geometries are used, e.g. Merklein Geometry [10]. A pure tensile load is applied on these geometries until failure occurs. The different geometries cause failure by various stress triaxiality histories. On basis of the experimental force-displacement curves a reverse engineering process is done, which delivers the parameters for the Wilkins Damage Model [9].
To point out the principle of the implemented Wilkins Damage Model including failure criterion in LS-Dyna, a brief simulation of a flat tensile test is performed (Figure 1a, black full line) and compared to a model without consideration of damage and failure (Figure 1a, dotted line). The force-displacement curve of the simulation is extracted.



(a)



(b)

Figure 1: (a) Investigation of the implemented Wilkins Damage Model in LS-Dyna by simulation of a tensile test geometry, (b) Experimental force-displacement data of the Merklein test geometry in comparison to a simulation curve including the Wilkins Damage Model

In Figure 1a the damage history variable D and the material degradation parameter F of the element with initial failure is plotted in parallel to the force-displacement history. It is apparent from Figure 1a that the damage parameter D increases steadily. At the point of critical damage D_c the material degradation parameter F is initiated. Once F reaches a value of 0.7 the element is deleted from the simulation. The selected element of the tensile geometry is the last element that failed, before fracture of the cross section is fully established. Hence, it is a gap between initiation of material softening and initiation of material degradation due to damage.
Figure 1b shows ten experimental force-displacement curves of a Merklein Geometry in dotted representation. In comparison a numerical simulation of the Merklein Geometry is considered and depicted in Figure 1b, full line.
The reverse engineering process of the test geometries delivers a set of parameters for the investigated AlSi cast alloy. The identified parameters in this study are listed in Table 1.

Table 1: Identified Parameters of the Wilkins Damage Model for the AlSi cast alloy of this study

Wilkins Damage Model Parameter	Determined value for an AlSi cast alloy
α	900
β	0.2
γ	10^{-5}
D_s	0.3

4 EXPERIMENTAL VALIDATION

A validation of the material is carried out to ensure that the calibrated material model is applicable to FE simulations of structural aluminium alloy. For this purpose, an experimental crushing test of a squeeze cast hat profile is performed in parallel simulation by means of FEM (Figure 2, cross section geometry). The length of the depicted hat profile is 250 *mm*.

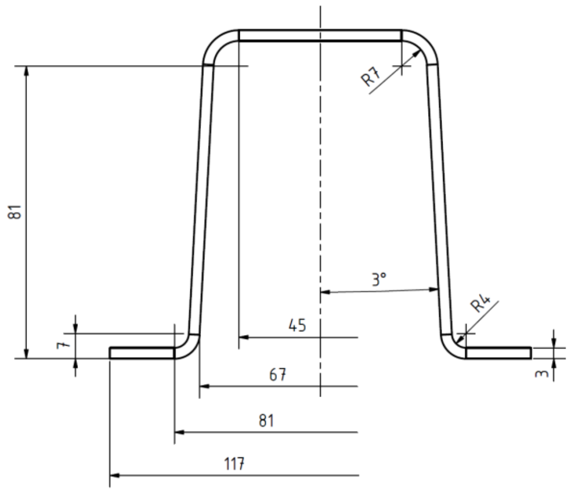
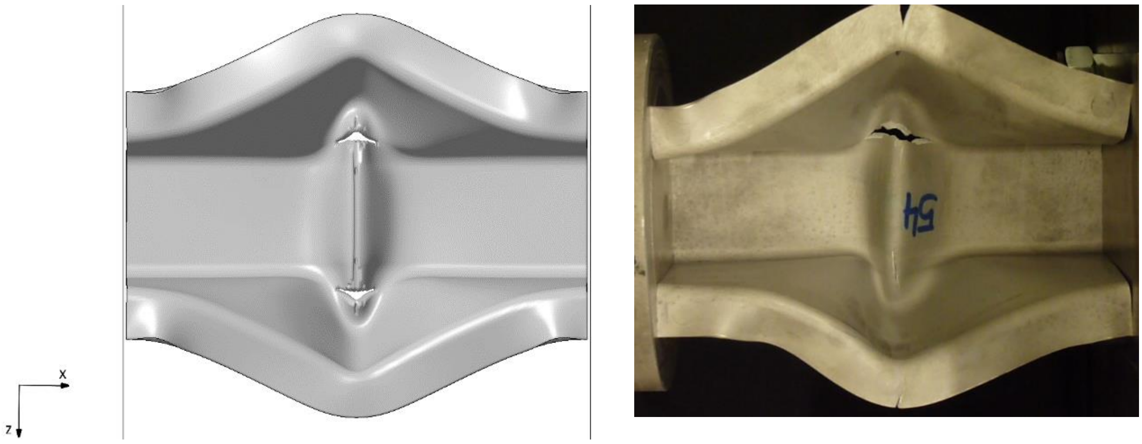


Figure 2: Cross section of the hat profile for the validation of material models

The experimental test setup is apparent from Figure 3 (a) in a 90° view rotated representation. The hat profile is crushed at a test speed of 5 $\frac{mm}{s}$ for a length of $100\ mm$ in an ITC Interlaken 1000 *kN* press.

A total number of six experiments are performed. In parallel a numerical simulation is performed (Figure 3a). The hat profile is modelled by solid hexahedrons with an edge length of 1 *mm*. The test rig is simplified in the numerical model with two rigid shell planes. Contact definitions between shells and profile are applied and an additional contact for self-penetration is defined for the profile. Figure 3 shows the test geometry after an applied crushing displacement of 25 *mm*, simulation (a) and experiment (b). Under this test load, the middle sections of the hat profile observe material failure. The visual comparison of experiment and simulation shows a similar deformation mode of the model. Furthermore, the areas of the middle material failure are predicted properly in the simulation. On both edges of the experimental test geometry cracks are observed, which are not apparent in the simulation at this timestep. This effect may be caused by the ejector stamps and resulting differences in material properties in these areas. The appearance of these surface imperfections is a result of the casting process and is not considered in the FE simulation.



(a) (b)

Figure 3: Comparison of deformation and failure in a crushing test after 25 mm displacement. A hat profile of AlSi cast with a not deformed lenth of 250 mm

In Figure 4, the force-displacement curves of the experiments and two different simulation models are plotted. The results of the experimental data is reduced to the upper and lower deviation bounds. One simulation model uses a pure elasto-plastic material mode. The second simulation model uses the same elasto-plastic material model with enhanced Wilkins Damage approach.

The initial loading phase including force peak and force drop shows a proper agreement between simulation and experiments. Only after displacements of 20 *mm* the numerical model results start to deviate significantly from each other.

The curve of the Wilkins Damage Model runs within the bounds of the experiments up to a displacement of 90 mm. In the remaining displacement area the difference to the experiments increases. The occurrence of ruptures through the entire cross section is observed in experiments. This behaviour is also predicted in the FE simulation and is apparent by the zero force level at a displacement of 90 *mm* in the curve of the Wilkins Model. Compared to the results of simulation including the Wilkins Damage Model, the pure elasto-plastic model leads to far higher force in the phase after 20 *mm* of displacement. The resulting energy absorption of the models is highly effected by this deviation.

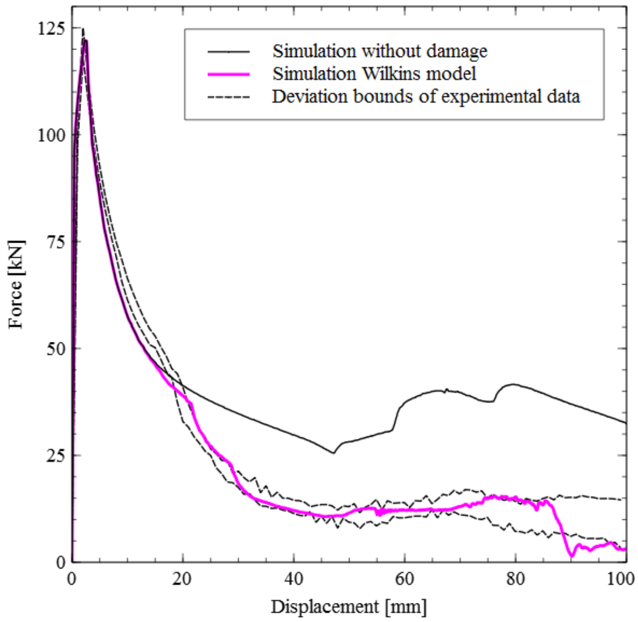


Figure 4: Force-Displacement curves of experimental data and simulations

Table 1 illustrates the relative deviation of force peaks and the absorbed energy from the simulations compared to the mean experimental value. The energy absorption is overestimated by +66.94 % if material damage is not considered with the pure elasto-plastic model. In the case of the Wilkins Damage Model, an excellent agreement of the energy absorption can be achieved with a deviation of -3.63 %.

Table 2: Relative deviation of the numerically calculated maximum force peak and the absorbed energy compared to the experimental mean curve

Model approach	Elasto-plastic + Wilkins Damage	Elasto-plastic
Force peak [%]	-0,66	-0,66
Absorbed energy [%]	-3,63	+66,94

5 CONCLUSIONS

The mayor aspects of this paper can be summarised as follows:

1. FE simulations of cast aluminium with pure elasto-plastic material models lead to distinctively overestimated results under crush loading.
2. FE simulations of cast aluminium with elasto-plastic material models and Wilkins Damage Model lead to very good results under crush loading.
3. The results of the investigation show that the Wilkins Damage Model is applicable for AlSi cast alloys.
4. The regions of rupture are well predicted by the Wilkins Damage Model. This grants applicability in numerical crash simulation.
5. The findings are limited, as the influence of the strain rate on the damage behaviour of AlSi cast alloys is not included in the approach of Wilkins.

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