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CRASHWORTHINESS SIMULATION OF ALUMINUM PRESSURE DIE CASTINGS INCLUDING FRACTURE PREDICTION

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1 INTRODUCTION

Due to their economical benefits, aluminum pressure die cast components have become a new trend in automotive lightweight structural design. By using this method, a component with a complex geometry usually made of several smaller connected parts now can be produced in one process, as a single component. As a consequence of fewer components, the number of production steps can be significantly reduced. This includes the elimination of joining processes and the simplification of logistics, which results in cost savings and a higher production rate.

However, in comparison, pressure die castings are generally at higher risk of failure due to a) porosity and other micro-structural defects resulting from the casting and solidification process, which in turn reduce the fracture strain of the material, and b) stress and strain concentrations as a result of a complex component geometry. Furthermore, due to the nature of the casting process, properties generally are inhomogeneous between different sections of a component. All these effects thus must be considered in crashworthiness simulations in order to obtain accurate results. For this purpose, an experimental die cast component was specially designed to investigate an appropriate procedure. Porosity levels at different sections of the component are identified and related to fracture criteria found by coupon testing at corresponding locations. Finally, representative crash tests and comparison with simulation results validate the procedure.

2 CASTING PROCESS SIMULATION

To account for the effects of the production process, the first step in the current approach is a casting process simulation in order to predict the inhomogeneous distribution of mechanical properties, in particular the porosity distribution within a given aluminum die cast part. The employed software Procast is an implicit Navier-Stokes finite element code with full thermal coupling. Free surfaces are tracked by volume of fluid (VOF) technique. As boundary conditions for the fluid flow Reichardt's law for turbulent wall traction is used. Furthermore, simulation of the die is included to account for the thermal interaction between the die and the aluminum melt. The melt is modeled as a temperature dependent Newtonian fluid. In addition, reduced permeability due to the phase changes during solidification is considered by an additional source term in the momentum equations. Material properties are calculated using the thermodynamic database for multi-component alloys provided by Thermotech Ltd.[1]. Finally, shrinkage porosity in isolated pockets of liquid is computed via temperature dependency of the density. Comparison of numerical porosity predictions with CT-scans and micrographs show good agreement, see Figure 1.

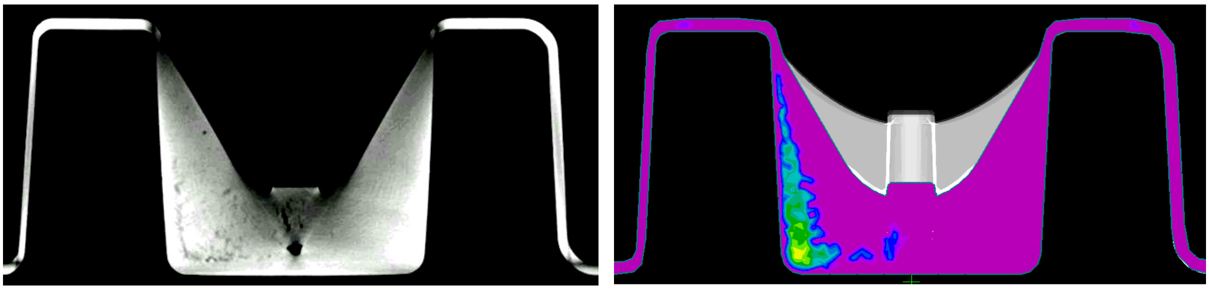

Figure 1: Shrinkage porosity - comparison between CT scan (left) and numerical prediction (right)

3 FRACTURE MODEL

Similar to other metallic materials, aluminum pressure die cast components generally fail due to one or a combination of the following mechanisms:

- ductile fracture (based on initiation, growth and coalescence of voids)
- shear fracture (based on shear band localization)

For ductile fracture, it is assumed that the equivalent strain at fracture $\varepsilon_{eq,fd}$ is a function of the equivalent strain rate $\dot{\varepsilon}_{eq}$ and the stress triaxiality, i.e. the ratio of the hydrostatic stress and the equivalent stress $\eta = \sigma_m / \sigma_{eq}$:

$$\varepsilon_{eq,fd} = f\left(\dot{\varepsilon}_{eq}, \eta\right) \tag{1}$$

For shear fracture, it is assumed that the equivalent strain at fracture $\varepsilon_{eq,fs}$ is a function of the equivalent strain rate $\dot{\varepsilon}_{eq}$ and the shear stress factor θ:

$$\varepsilon_{eq,fs} = g\left(\dot{\varepsilon}_{eq}, \theta\right) \quad \text{with} \quad \theta = \frac{1 - k_s \eta}{\phi} \quad \text{and} \quad \phi = \frac{\tau_{\max}}{\sigma_{eq}} \tag{2}$$

where k_s is a material parameter and ϕ is the ratio of the maximum shear stress and the equivalent stress. Furthermore, to account for non-linear strain paths, a scalar integral fracture criterion as presented by Kolmogorov[2] is used:

$$\psi = \max(\psi_d, \psi_s) = 1 \quad \text{with} \quad \psi_d = \int_0^{\varepsilon_{eq}} \frac{d\varepsilon_{eq}}{f(\dot{\varepsilon}_{eq}, \eta)} \quad \text{and} \quad \psi_s = \int_0^{\varepsilon_{eq}} \frac{d\varepsilon_{eq}}{g(\dot{\varepsilon}_{eq}, \theta)} \tag{3}$$

For more details on the fracture model see Hooputra et al.[3].

Finally, due to approximately isotropic deformation behavior of die cast aluminum, the stress-strain relation is modeled by v. Mises plasticity.

4 PARAMETER IDENTIFICATION AND MAPPING OF POROSITY DATA

The functional relation between fracture curves and different levels of porosity is identified via extensive coupon testing. Hereby, specimens are taken from locations with representative porosity levels identified through the casting simulation. In the current investigation, two levels of porosity are differentiated: low porosity < 1 % and high porosity ≥ 1 %. Coupon test results and resulting fracture curves for quasi-static loading at $\dot{\varepsilon}_{eq} = 0.002\,s^{-1}$ are shown in Figure 2. Note, for ductile fracture the curves differ significantly, whereas for shear fracture the curves where found to be independent of the porosity level. Furthermore, no significant strain-rate sensitivity was observed up to $\dot{\varepsilon}_{eq} = 100\,s^{-1}$.

Using this phenomenological approach, all porosity values computed in the casting simulation are translated into the parameters of the fracture criteria to be applied in the crash simulation. This data then is mapped from the casting simulation results onto the discretization for the crash simulation.

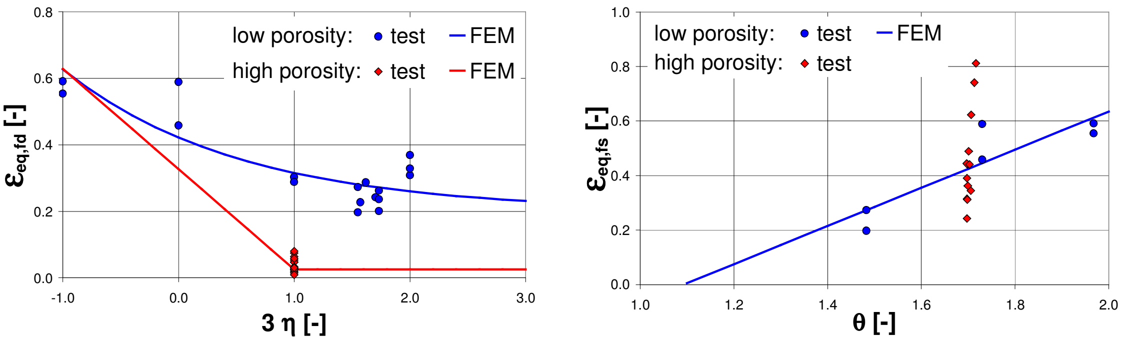

Figure 2: Ductile and shear fracture curves for low and high shrinkage porosity under quasi-static loading

5 VALIDATION

To validate the model, numerical crash simulations are compared with experimental results of dynamic axial crush tests and three-point bending tests. Numerical simulations are performed with the explicit finite element code PamCrash using material type 52 (isotropic v. Mises plasticity combined with the fracture model presented in section 3.1)[4]. Approximately 240’000 and respectively 740’000 quadratic tetrahedral elements are used to discretize the test scenarios. The numerical predictions show good agreement with the actual experimental results. Particularly with regard to the usual scatter between test runs, locations and initiation times of fracture are well predicted for both tests, see Figure 3 and Figure 4. Likewise, force deformation curves match experiments, however, after significant fracture, force levels are partly over- and underestimated, due to the lack of an appropriate fracture propagation model.

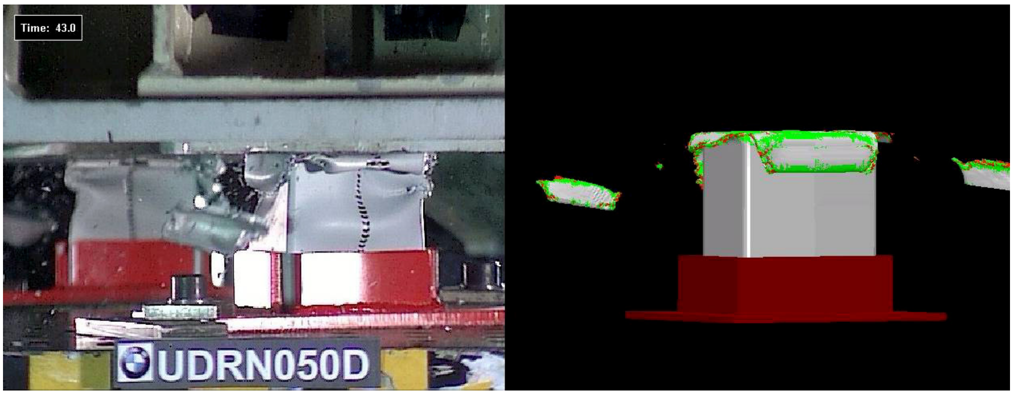

Figure 3: Dynamic axial crush test - comparison between experiment and numerical simulation

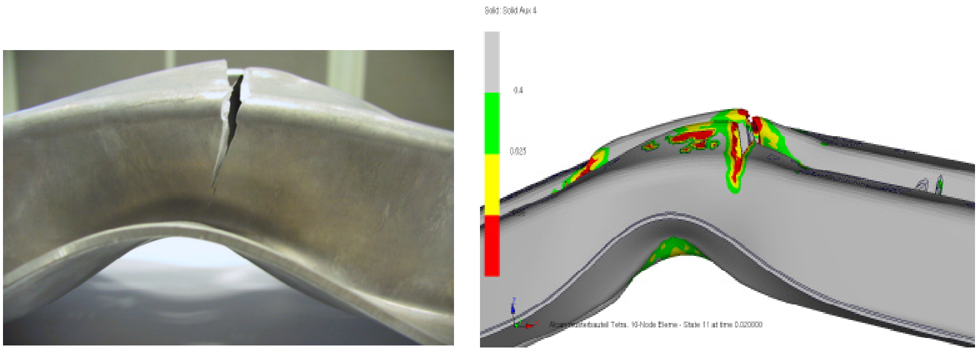

Figure 4: Static three-point bending test - comparison between experiment and numerical simulation

6 CONCLUSIONS

Comparison of numerical results with experimental data from three-point bending tests and axial compression tests shows good agreement and demonstrates the effectiveness of the presented approach for crashworthiness assessment of pressure die cast aluminum components. Fracture initiation is very well predicted, however, reliable predictions of crack propagation remain difficult. Regularization methods are needed to overcome the problem of serious mesh dependency due to strain localization and the singularities at crack tips.

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