Self-pierce riveting of materials with limited ductility investigated with the Bai-Wierzbicki damage model in GISSMO

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1 Introduction

The application of mechanical joining techniques is nowadays a common practice in automotive industry. But when self-pierce riveting (SPR) lightweight materials, such as aluminum die castings, due to the limited ductility cracks in the closing head of the joint can occur. For the numerical optimization of these difficult joining tasks it is necessary to find suitable damage models, which can predict the cracking in the lightweight materials with limited ductility.

2 Model and Calibration

Advanced damage models like the one of Bai and Wierzbicki [1] have been already used for sheet metal forming, e.g. [2, 3]. They take into account that the strain at damage depends on the stress state itself. The model of Bai and Wierzbicki [1] is based on a Coulomb-Mohr hypothesis in stress space and therefore considers two of the three invariants of the stress tensor. It states that for monotonic loading failure occurs if

$$(\tau + c_1\sigma_n)\,|_f = c_2 \qquad (1)$$

Here τ is a shear stress in a certain plane in certain direction, σ_n is the normal stress orthogonal to this plane and c_1, c_2 are material constants. With Eq. (1) in every point of the material a maximization problem has to be solved. In Bai and Wierzbicki [1] a not very common form of the stress state description is used the place on the von Mises cylinder is described by triaxility η and lode angle θ as shown in Fig. 1. They are calculated from the principal stresses σ_1, σ_2, σ_3 as following:

$$\begin{aligned} \bar{\sigma} &= \sqrt{(1/2)((\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2)}, \quad & \sigma_m &= (\sigma_1+\sigma_2+\sigma_3) \\ r &= \left[(27/2)*(\sigma_1-\sigma_m)(\sigma_2-\sigma_m)(\sigma_3-\sigma_m)\right]^{1/3}, & \xi &= (r/\bar{\sigma})^3 \\ \eta &= \sigma_m/\bar{\sigma}, & \theta &= 1-ar\cos(\xi) \end{aligned} \quad , \qquad (2)$$

The maximization problem of Eq. (1) has been solved analytically in [1] and its result can be displayed in the following form:

$$\bar{\sigma} = c_2\left[\sqrt{(1+c_1^2)/3}\cos(\pi\theta/6) + c_1(\eta+(1/3)\sin(\pi\theta/6))\right]^{-1}, \qquad (3)$$

where the von Mises stress $\bar{\sigma}$ depends on triaxiality η and lode angle θ. Together with the hardening law, it is possible to describe the effective plastic strain at failure depending on triaxiality η and lode angle θ, which is the input for the **GISSMO** option of ***MAT_ADD_EROSION**.

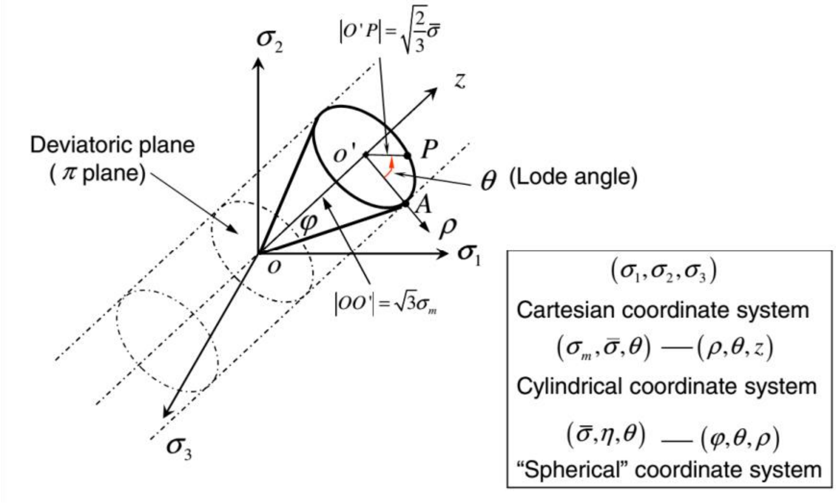

Fig.1: Transformation of the eigenvalues of the stress tensor and the used stress invariants triaxiality η and lode angle θ.

The application of this model to self-pierce riveting of material with limited ductility however involves some challenging tasks. Experimental data for the strain at failure from sheet specimen is only available in a small range of triaxiality from shear to biaxial tension. During the joining process a much higher range of triaxiality occurs. For materials with limited ductility it is difficult to measure the strain at failure due to very small localization bands.
The parameters of the damage model were retrieved from notched tensile and notched shear specimen using digital image correlation. Direct evaluation of the failure strain was not possible, since the notched tensile specimens violated the plain stress assumptions. By a numerical 3D FEM simulation it has been found out that the critical points are located in the bulk material and the triaxiality reaches values up to one, see the calculated strain path of the specimens in Fig.1 left. Therefore a correction had to be done, resulting in the damage surface of Fig.1 right, where the triaxiality dependence is reduced compared to the original data.

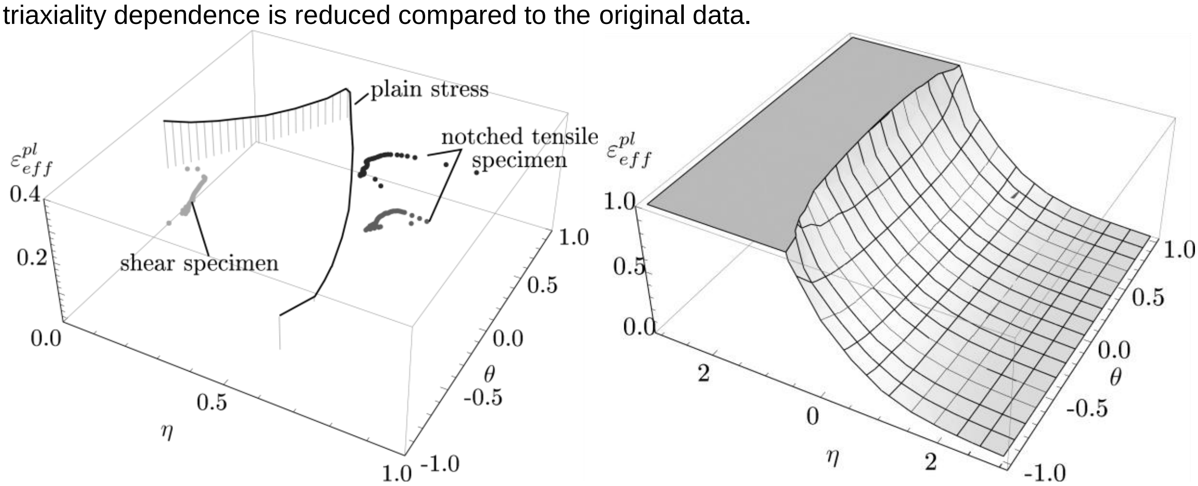

Fig.2: Left: Strain paths of the used shear and notched tension specimens compared to plane stress conditions. Right: resulting damage surface (clipped at $\varepsilon_{eff}^{pl} = 1$).

Furthermore it is useful to use a nonlinear damage evolution law, since it is commonly observed at tensile specimen that damage in the sense of pore growth mainly occurs between the end of the uniform elongation and the break of the specimen. Additionally it is in practice useful to avoid the softening influence of the damage to the plastic material behavior before the start of necking in tensile specimens. A possible damage evolution law is included in ***MAT_ADD_EROSION** in the following form:

$$\Delta D = \frac{nD^{(1-1/n)}}{\varepsilon_f(\eta,\theta)} \Delta\varepsilon_{eff}^{pl} \tag{4}$$

If η and θ are constant, meaning proportional loading, it is possible, to sum up this equation yielding in

$$D = (\varepsilon_{eff}^{pl} / \varepsilon_f)^n \tag{5}$$

If we assume that for the smooth tensile specimen the damage at end of uniform elongation is less the 1 % and take the value from the strain at failure from the fitted damage surface an exponent of. $n = 3.9$ is a good guess for the considered AlSi9Mn but this value is not very exact determinable.

3 Results

At the considered material combination the aluminum sheet EN AW-6016 T4 (t = 2.0 mm) is positioned punch-sided and the non heat-treated aluminum die casting AlSi9Mn F (t = 2.0 mm) is positioned on the die side. In the investigation ball-shaped dies with different die depths h_{m1} = 1.0 mm and h_{m2} = 1.5 mm are considered. Only when using the deeper die geometry cracking in the aluminum die casting was observed. Since the focus was on the occurrence of cracks in the die casting, a geometrical cutting criteria for the upper sheet has been used.
For the flat ball shaped die the damage level in the lower sheet stays at all times during the process below 0.3 so no cracks occur as has been observed in the joining process, see Fig. 3.
For the deep ball shaped die, a crack appears in the closing head shortly before it touches the die, and the crack starts from the die side. This crack is observed in the joining process as shown in Fig. 4. In the further course of the simulation the bottom side of the aluminum die casting comes into contact with the die contour. Because the damage is already at intermediate level of 0.4 to 0.7 this elements are soon reaching the final damage value of 1 and are deleted. This is not in agreement with the experiments. But at least it is possible to predict that cracking occurs and to determine where the crack starts.
Additionally a chamfered die contour is considered. As aluminum die casting comes into contact with the die contour, the damage level increases very fast and element deletion occurs too early compared to experiment, see Fig. 5.

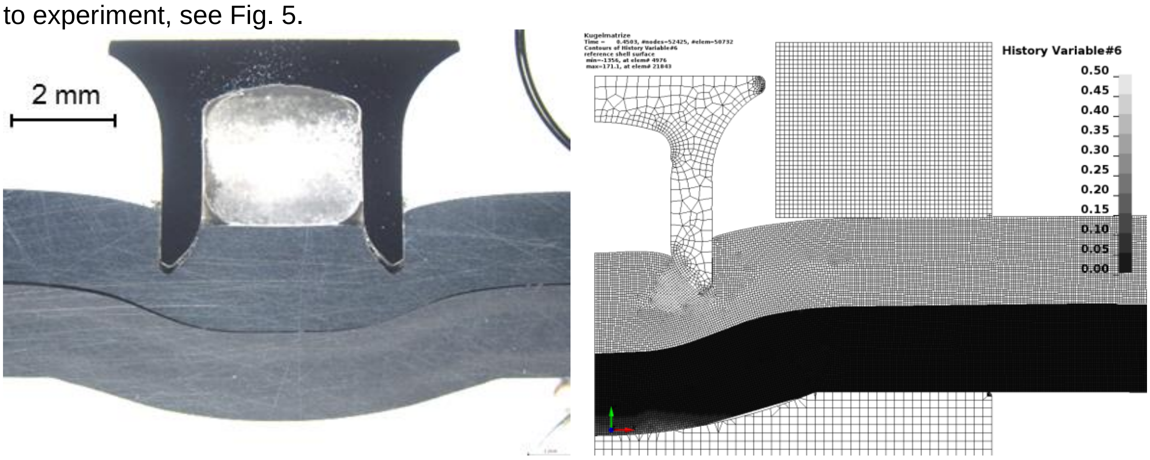

Fig.3: SPR joint with flat ball-shaped die. Left: Cross section showing no cracks, right: Damage values of the model in the aluminum die casting with comparable rivet position without crack.

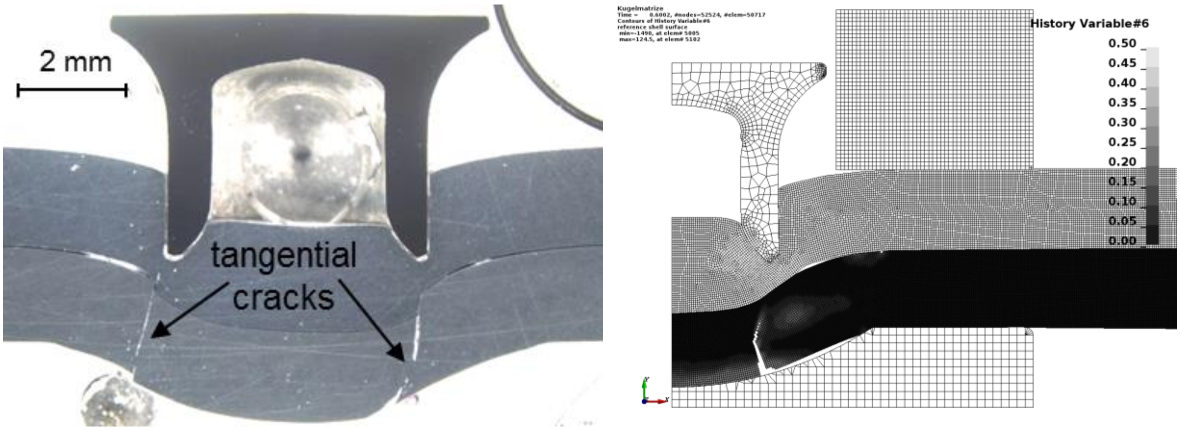

Fig.4: SPR joint with deep ball-shaped die. Left: Cross section showing tangential cracks, right: Damage values of the model in the aluminum die casting with crack at correct position.

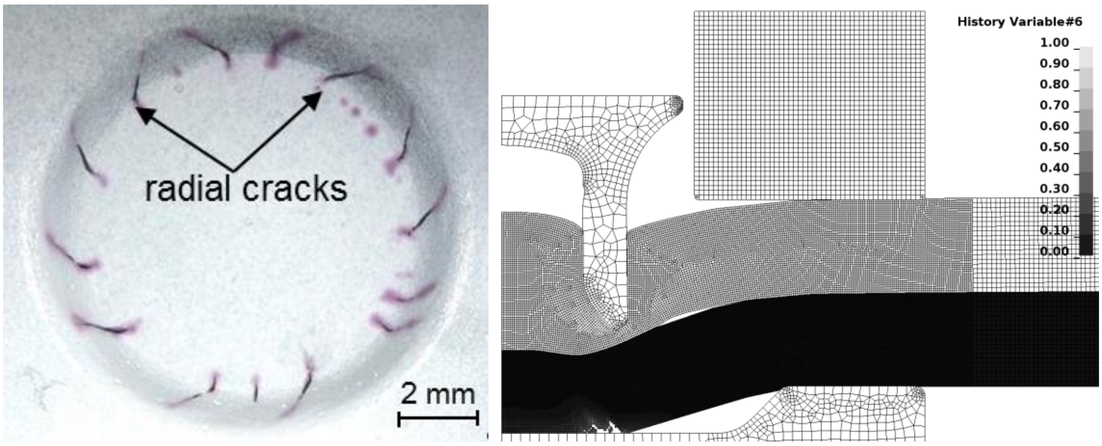

Fig.5: SPR joint with chamfered die. Left: Color penetration test of closing head showing radial cracks, right: Damage values of the model in the aluminum die casting at error termination with too early crack start.

4 Summary

The advanced damage model of Bai and Wierzbicki [1] has been applied to model self-pierce riveting of aluminum die casting with different die geometries. Currently only start and location of cracking can be predicted and only if this occurs without contact in this region being present. Regions with contact of pre-damaged areas are problematic, since there element deletion occurs too early. This might especially in the case of involved contact due to artificially introduced plastic strain resulting from pushback of penetrations. The element deletion due to damage leads to convergence problems with a significant increase of the calculation time. Also there occur terminations sometime during remeshing, caused by the complicated geometries of the areas with deleted elements. Therefore further investigations have to be done. Possibly it might be more suitable using other methods than finite elements like smooth particle hydrodynamics (SPH), because there no remeshing will be needed and the blurry boundaries of the particles will reduce convergence problems during contact.

5 Literature

[1] Bai, Y.; Wierzbicki, T.: A new model of metal plasticity and fracture with pressure and Lode dependence. *International Journal of Plasticity,* 24, 2008, 1071 – 1096

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