Numerical determination of the onset of local necking using time dependent evaluation method and dynamic material parameters

D Jocham and W Volk
Institute of metal forming and casting, Technische Universität München, Walther-Meißner-Straße 4, 85748 Garching, Germany
David.Jocham@utg.de

Abstract. The forming limit curve (FLC) is a valid instrument for the evaluation of failure in sheet metal processes. However, its experimental evaluation is challenging, in particular for modern lightweight sheet metals, in which the failure occurs without an evident necking transition. Therefore, the numerical analysis can represent a valid alternative for the investigation of the onset of necking phenomena. Prerequisite for realistic failure prediction are an accurate material characterization for high strain levels and a stable and coherent numerical model. Within this paper, an approach for the determination of forming limits by using the time dependent evaluation method is investigated and an analysis of the material sensitivity on the simulation results is performed. The results are discussed for mild steel DX56 and first suggestions for the improvement of the simulation input data are derived.

1. Introduction
To predict the formability in sheet metal forming process simulation the forming limit curve is state of the art. Herein local instability due to local necking in thickness direction is the predominant failure mechanism. In ISO 12004-2 [1] the experimental procedure to create the forming limit curve in form of the Nakajima test [2] and an evaluation method, the so called cross section method, are standardized. The principle of the cross section method is the fitting of a parabola curve through the strain values along a cross section, which is perpendicular to the occurring crack. The limit strains are determined as the values of the curve at the location of the crack. Merklein et al. [3] showed that this method leads to reliable results for mild steels but shows weaknesses for bainitic steel, due to the immediate fracture without necking. The evaluation method is also not suitable for aluminum and steel grades, which show more than one necking zone, because the parabola fit gets inaccurate. To overcome this disadvantages different authors proposed time dependent evaluation methods, which are more physically motivated [3-6]. The principle is to use the thinning rate as a physical quantity. The remaining plastic deformation concentrates in small shear bands. This leads to high thinning rates, while the thinning rates outside of the shear bands nearly vanish. By using the time dependent evaluation method the onset of local necking can be determined directly in the necking zone. Furthermore, with this method the limit strains can be examined easily in finite element simulations [7,8]. For the numerical determination of forming limits the material, e.g. hardening, strain rate sensitivity, temperature sensitivity and anisotropic behavior, has to be described as precise as possible to avoid high deviations between simulation and experimental data. The material properties also interact strongly with each other, whereby simulation results in
relation to experimental data can be misinterpreted. In this paper the influence on the resulting forming limits for different stress states by using dynamic material parameters is investigated.

2. Experimental and numerical setup

2.1. Material characterisation

The material properties of the mild steel DX56 with thickness 0.8 mm were recorded in hydraulic bulge tests and in tensile tests with tactile and optical measurement systems. The usage of optical measurement enables the determination of the material behavior directly in the necking zone [9]. Tactile measurement is only suitable until yield strength. The results of the tensile tests are the Lankford coefficient in different directions, the elastic modulus and the yield curve at specific strain rates for different strain levels depending on the measurement system. By performing a hydraulic bulge test, data for extrapolation of the yield curve for equivalent plastic strain up to 0.7 is possible. Jocham et al. [10] detected the strain rate sensitivity under biaxial stress in the hydraulic bulge test. The described procedure was applied on the mild steel DX56. Figure 1 displays the dynamic behavior of the strain rate sensitivity in dependence on the true strain and the load case. The correlation can be described with the equation, proposed by Jocham et al. [10], to display the dynamic hardening. Further the Lankford coefficients in 0°, 45° and 90° to the rolling direction were determined in tensile tests until 0.8 true strain, whereby a significant decrease was observed, see figure 2. Nowadays in most simulation cases this dynamic behavior of the strain rate sensitivity and anisotropy is not taken into account, though the strain dependence of the Lankford coefficients is commonly known.

![Figure 1. Dynamic strain rate sensitivity of mild steel DX56 determined in hydraulic bulge and tensile tests.](image1)

![Figure 2. Dynamic Lankford parameters of mild steel DX56 for directions 0°, 45° and 90° to the rolling direction and different true strains.](image2)

2.2. Simulation and material model

For the simulation the software Abaqus™ 6.12-3 supplied by Dessault Systèmes was utilized. The simulation model of the Nakajima test consists of a rigid spherical punch with 50 mm radius, a rigid blank holder and rigid die with edge radius of 5 mm. The specimen is elasto-plastic and consists of shell elements with element size of 0.1 mm in the evaluation area, which was shown as best suited in a sensitivity analysis. 5 different specimens with widths of 40, 70, 100, 120 mm and one full sample were used. To create the same condition as in the experiment the lubrication system in form of an elastic pad was implemented. The contact between punch and pad as well as the contact between pad and specimen were frictionless. The clamping force was neglected and replaced with displacement boundaries in the area of the blank holder. The reference punch velocity was 1 mm/s. For the description of the hardening behavior of the steel grade DX56 a combination of the approaches by Swift and by Hockett-Sherby was used, see equation (1). To take into account the additional hardening through the increase of strain rate in the necking zone the Johnson-Cook model was implemented, see equation (2). The parameter $C_{J-C}$
can be calculated directly from the m-value from figure 1. The anisotropy was displayed by the Hill48 yield locus. The material parameters of a conventional determined material card are displayed in table 1.

$$
\sigma_0(\varepsilon) = (\alpha) \cdot \left( A - (A \cdot B) \cdot e^{C \cdot \varepsilon^D} \right) + (1 - \alpha) \cdot \left( E \cdot (\varepsilon + F) \right)
$$

$$
\sigma(\varepsilon, \dot{\varepsilon}) = \sigma_0(\varepsilon) \cdot \left( 1 + C \cdot \varepsilon \cdot \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right)
$$

**Table 1.** Conventional determined material model.

| $\alpha$ [-] | A [MPa] | B [MPa] | C [-] | D [-] | E [MPa] | F [-] | G [-] |
|--------------|---------|---------|-------|-------|---------|-------|-------|
| 0.35         | 415.9   | 147.4   | 4.44  | 0.78  | 518.9   | 0.00877 | 0.2685 |

C$_{\text{J-C}}$ $\varepsilon$=15% $\quad$ $\varepsilon_0$ [-] $\quad$ $r_0^\epsilon$=8-12% $\quad$ $r_{45}^\epsilon$=8-12% $\quad$ $r_{90}^\epsilon$=8-12% $\quad$ Elastic modulus [GPa] $\quad$ Density [kg/m$^3$] $\quad$ Poisson’s ratio [-] $\quad$ 0.0204 $\quad$ 0.00025 $\quad$ 2.543 $\quad$ 1.73 $\quad$ 2.525 $\quad$ 210 $\quad$ 7850 $\quad$ 0.3

3. **Experimental and numerical results**

The simulations were terminated at the strain rate level, which occurred in the experiments before crack. For the time dependent evaluation method equal output parameters as in the experiments were applied. The output frequency was 10 Hz. For the stable line fit 40-20 stages and for the instable line fit 3 stages before termination were selected. In figure 3 the results of the experiments and simulations with different material parameters are compared.

![Simulation and experimental results for different material models.](image)

_3. Simulation and experimental results_
The mild steel DX56 shows a high strain rate sensitivity and anisotropy for low strain levels, whereby a high deviation between experimental and simulation results occurs, see figure 3a. Also the strain paths do not match. By neglecting the strain rate sensitivity, see figure 3b, or by using a 100% Hockett-Sherby extrapolation approach, as you can see in figure 3c, the FLCs fit each other quite well. Nevertheless the strain paths do not fit in both cases. In contrast to this, the implementation of the 100% Swift approach leads to a higher deviation compared to the FLC resulting by a conventionally determined material model, see figure 3d. The variation of the extrapolation approach do not describe the real physical material behavior, which was characterized in tensile and hydraulic bulge tests. First by considering Lankford coefficients at higher true strain levels the strain paths fit quite well, see figure 3e. With this setup the biaxial limit strains increase in figure 3e compared to figure 3a. This depends on the nonexistent alteration of the texture under biaxial strain condition.

4. Conclusions
In this paper the influence of the dynamic strain rate sensitivity and Lankford coefficients on the results of a Nakajima simulation was investigated. By applying the time dependent evaluation method the forming limits were determined. The strain rate sensitivity of the mild steel DX56 shows a high variation between uniaxial and biaxial load case. Further the strain rate sensitivity decreases with increasing true strain. The same behavior shows the anisotropy, described by Lankford coefficients and determined in tensile tests. By neglecting the strain rate sensitivity, which corresponds to high strain levels, the resulting forming limit curve in simulation fits the experimental data quite well. Nevertheless the interpolation points and corresponding strain paths are different. The strain paths can be displayed correctly by taken decreasing Lankford coefficients into account. In future investigations the dynamic strain rate sensitivity and anisotropy will be implemented in the simulation model by using subroutines. This enables an accurate modelling of the material parameters, which were measured already in bulge and tensile tests. Furthermore the influence of different yield loci will be investigated.

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