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Determination of forming limit curve by finite element method simulations

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Abstract

This paper presents an investigation on the determination of forming limit curves (FLCs) by finite element simulations. The numerical FLCs are determined applying the criteria of strain localization in simulations of the Nakazima formability tests. Two methods to determine the onset of localized necking have been compared. The first criterion is based on the analysis of the through-thickness thinning (through-thickness strain) and its first time derivative in the most strained zone. The onset of necking is assumed to occur at the point corresponding to a sudden change of the slope of the strain rate vs. time curve. The limit strain in the second method is determined by the maximum of the strain acceleration, which corresponds to the inflection point of the strain velocity vs. time curve. The limit strains have been determined for different specimens undergoing deformation at different strain paths covering the whole range of the strain paths typical for sheet forming processes. This has made it possible to construct numerical forming limit curves (FLCs). The numerical FLCs have been compared with the experimental one, showing quite a good agreement, especially in the case of the first criterion. This shows that finite element simulations can be used as a potential alternative tool to determine formability limits for sheet forming processes.

Keywords: Sheet metal forming; Formability; Forming limit curve; Finite element simulation

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1. Introduction

Strain-based forming limit diagrams (FLD) are most often used in engineering practice to assess the sheet formability. Location of the points representing principal strains with respect to the forming limit curve (FLC) makes it possible to determine the probability of defects in the form of strain localization or material fracture. Different experimental and theoretical methods can be used to determine FLCs [1,2,3,4].

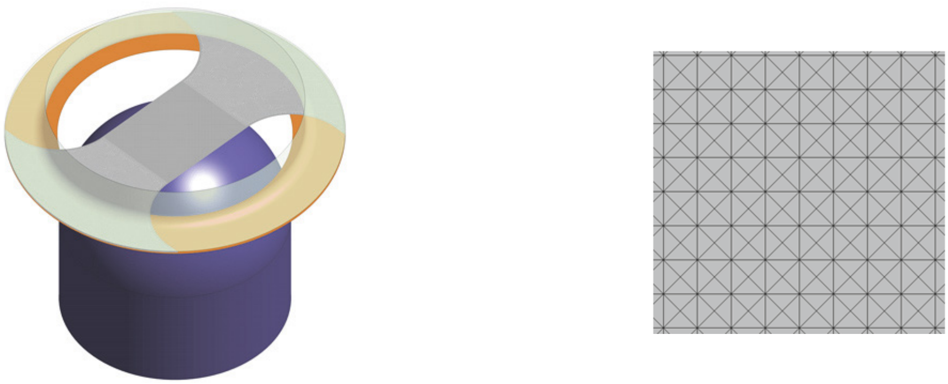
This work investigates the possibility of determining the formability limits of sheet metal forming by finite element simulations. The proposed methodology employs simulations of the Nakazima formability tests. The formability limits are evaluated using the procedures based on analysis of the time evolution of strains and their time derivatives. These procedures were originally proposed for experimental formability tests [5,6,7]. Volk and Hora [5] presented a method based on the analysis of the first derivative of the strains in the necked zone. The onset of necking is assumed to occur at the point corresponding to a sudden change of the slope of the thinning rate curve. The first and second time derivatives of the principal strains (strain velocities and accelerations) were post-processed by Situ et al. [6,7] to detect strain localization. The peak of the major strain acceleration vs. time curve was taken as the indicator of the strain localization.

These methods were adapted to the finite element simulations and were thoroughly investigated in [8]. Here, the determination of a complete FLC by finite element simulations will be presented. The numerical FLC will be compared with the experimental one.

2. Numerical model

The Nakazima testing method consists in bulging of sheet samples with a hemispherical punch. The use of samples of different widths enables different strain paths from the uniaxial to biaxial tension to be obtained.

Simulation of the Nakazima test was performed using the authors' own explicit dynamic finite element program [9,10]. The finite element model at the initial configuration for one of the specimens analyzed is shown in Fig. 1. The sheet was discretized with the so-called BST (Basic Shell Triangle) elements [11]. Equally spaced structured mesh (Fig. 1a) refined at the central part of the specimens was used. This model takes into account only a part of the sheet within the drawbead line, assuming that the flow of the sheet through the drawbead can be neglected. Analyses of the Nakazima test performed in [12] showed that such a model gives formability limits similar to those obtained with the complete geometry of the Nakazima test, while being much more computationally efficient. It allows a considerable reduction in the number of elements and the avoidance of very small elements limiting the time step length. Therefore, such a simplified model was used in the present work.



(a) (b)

Fig. 1. FEM model of the Nakazima test (a) and the mesh pattern at the central part of the specimen (b).

The numerical studies were carried out for 1 mm thick DC04 steel sheet. The material was considered assuming the Hill ’48 constitutive model with planar anisotropy [13]. Material properties were determined through the tensile tests performed with specimens cut at different orientations with respect to the rolling direction. The Hollomon constants C and n, and Lankford coefficients r for the three orientations are given in Table 1.

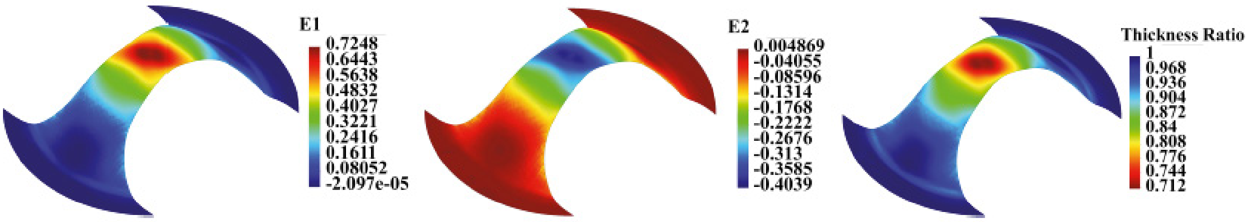
Table 1. Properties of the DC04 steel sheet.

Orientation of the sample	*C* (MPA)	*n*	*r*
0°	498	0.26	1.7
45°	506	0.22	1.3
90°	532	0.26	1.8

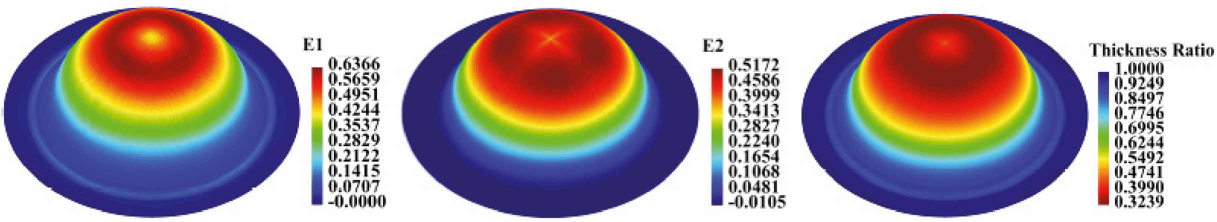
3. Simulation results

Simulations were performed for six different specimens with widths of 30, 50, 60, 77 and 99 mm, and one full circular specimen with the diameter of 110 mm. All the specimens were discretized using the finite element mesh with the characteristic element size h = 0.5 mm in the central part of the specimens where the failure was expected. A constant punch velocity of 1 m/s was assumed in the numerical simulations. The contact between the sheet and punch was modelled assuming the Coulomb friction coefficient μ = 0.04. This value was identified in [14] for the tribological conditions in the Nakazima tests with a Teflon foil. Additional strain paths were assessed by applying different friction conditions defined by μ = 0.1 and μ = 0.25. Figure 2 shows the deformed shapes of two selected samples, the 30 mm wide and the full circular one, with the principal (major and minor) strain and thickness ratio distribution at the end of the simulations for the punch strokes of 31 and 38 mm, respectively.

The procedure to determine the strain localization was applied to the most strained locations in the specimens (Fig. 2) identified from the strain distributions. The limit strains were assessed using two criteria: (i) the criterion proposed by Volk and Hora [5], which is based on the analysis of the thinning (negative through-thickness strain) rate evolution, and (ii) the criterion proposed by Situ et al. [6,7], employing the maximum strain acceleration as the failure indicator.



(a)



(b)

Fig. 2. Principal in-plane E1 – major and E2 – minor strains and thickness ratio (deformed to initial thickness) distribution at the end of simulation on deformed shapes of the specimens: (a) 30 mm wide, (b) circular with the diameter of 110 mm.

The determination of the onset of localized necking using both criteria is shown for the 30 mm wide specimen in Fig. 3. The evolution of the principal in-plane strains and thinning in the failure zone of this specimen is plotted in Fig. 3a, and the curves of the first time derivative of the thinning (Fig. 3b), and the first and second time derivatives of the major principal strain are given in Figs. 3c and 3d, respectively.

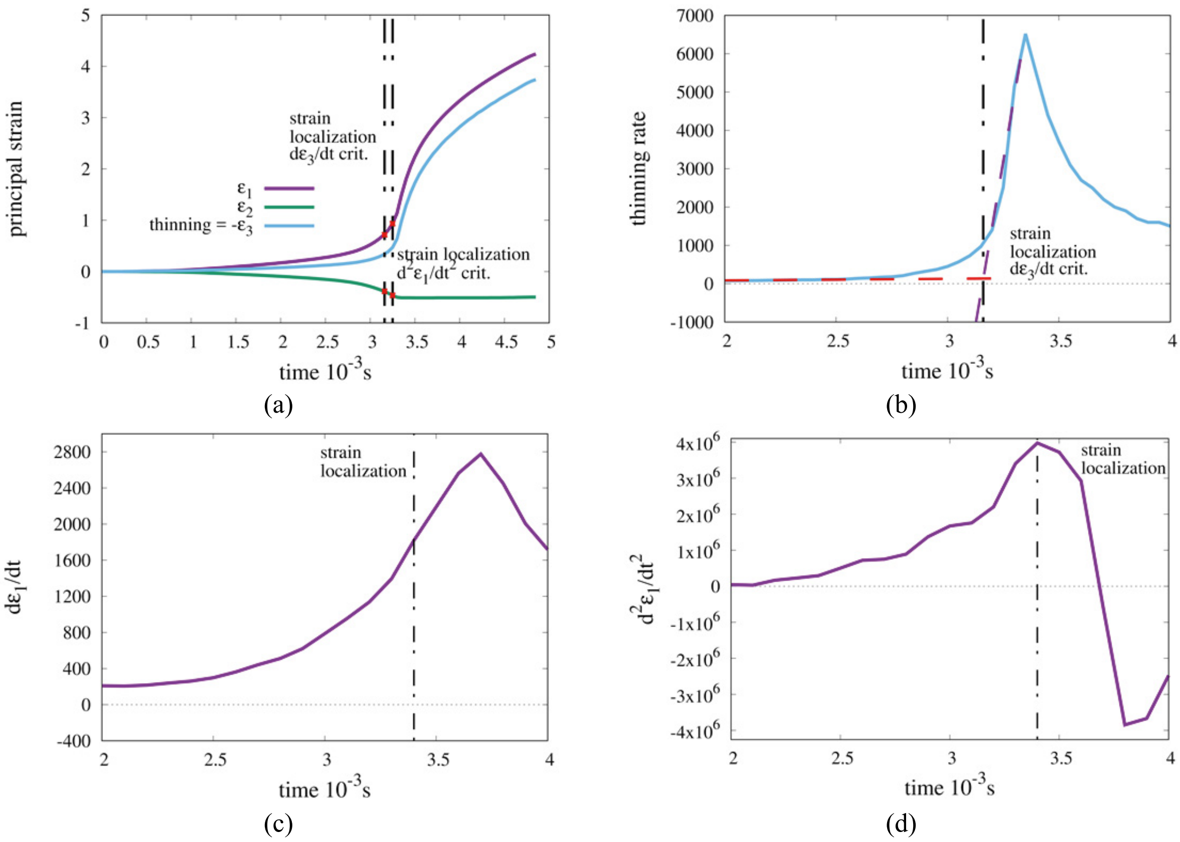


Fig. 3. Determination of the onset of localized necking in numerical simulation for the 30 mm wide specimen: (a) evolution of principal strains, (b) thinning rate history, (c) major principal strain rate history, (d) major principal strain acceleration history in the failure zone.

The limit strain in the first criterion is defined by the point corresponding to a sudden change of the slope of the thinning rate vs. time curve. Actually, the change is not so abrupt, and the critical point in Fig. 3b is determined by the intersection of the extensions of approximately straight segments of the thinning rate curve before and after necking. The intersection corresponds to the time t = 3.15·10-3 s. Thus, the limit principal strains for the considered specimen are given by the values of the minor and major principal strain at time t = 3.15·10-3 s, ε1 = 0.716 and ε2 = -0.384.

According to the second criterion, the strain localization is determined by the inflection point in the major strain rate curve shown in Fig. 3c. The inflection point corresponds to the maximum of the major strain acceleration curve plotted in Fig. 3d. The maximum is achieved at the time t = 3.25·10-3 s, and the point of strain localization for the considered specimen is given by the values of the minor and major principal strains at this time, ε1 = 1.059 and ε2 = -0.519.

The results for all the simulated cases are shown in Fig. 4 in comparison with the experimental FLC. The critical strains determined by the two investigated methods are marked with the points on the respective strain paths. The critical strains determined by the two methods were approximated by the two curves which can be considered as the numerical FLCs. It can be observed that the numerical FLC determined by the method proposed by Volk and Hora [5] is very close to the experimental FLC. The numerical FLC determined by the method proposed by Situ et al. [6,7] predicts slightly higher critical strains than the experimental FLC.

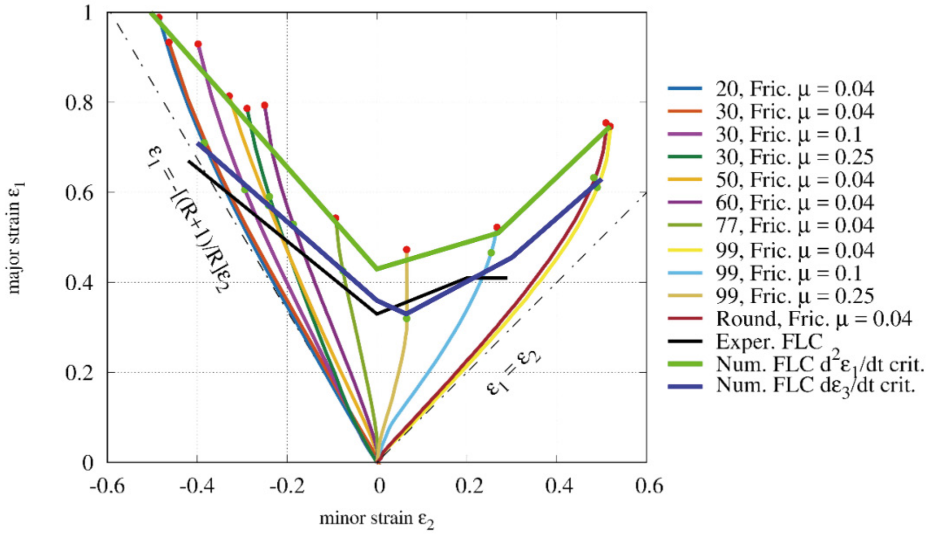


Fig. 4. Simulated strain paths and the numerical FLC compared with the experimental FLC [8].

Conclusions

Comparison of the numerical results with the experimental FLC confirms the possibility of determining the FLC by finite element simulations. The criteria of strain localization analyzed in this work can also be used in standard finite element simulations of sheet stamping as a tool to determine formability limits without the need to use the FLC. Further investigation will be performed in order to validate this methodology.

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