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Detection of strain localization in numerical simulation of sheet metal forming

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This paper presents investigations on detection of strain localization in numerical simulation of sheet metal forming. Numerical simulation of the Nakazima test have been performed. The onset of localized necking has been determined using two methods. First criterion is based on the analysis of the through the 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. 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 allowed us to construct numerical FLCs. The numerical FLCs have been compared with the experimental one. It has been shown that the numerical FLCs predict formability limits close to the experimental results so these methods can be used as a potential alternative tool to determine formability in standard finite element simulations of sheet forming processes.

Keywords: *sheet forming, formability, forming limit curve, numerical simulation.*

1. Introduction

Sheet stamping is one of the most important manufacturing techniques widely used in many industries, the automotive and aerospace sectors being the most important users of this technology. Development of new theoretical models and more accurate methods for prediction of forming process manufacturability is still of great practical importance, especially due to introduction of new materials and a need of process optimization. Therefore, metal forming is a subject of intense experimental and theoretical research [1]. Formability, the ability of the sheet to undergo deformation without defects, belongs to the main fields of investigation in metal forming.

Despite many new concepts of formability prediction, strain based forming limit diagrams (FLD) are used most often in engineering practice to assess the sheet formability. Location of the points representing principal strains with respect to the forming limit curve (FLC) allows us to determine probability of defects in the form of strain localization or material fracture.

FLCs can be determined by different methods, including experimental [2, 3], theoretical [4], as well as hybrid methods combining experimental data with analytical or numerical approaches [5]. Different methods of FLC determination are reviewed in [6].

Theoretical methods are based on criteria of the loss of stability (strain localization) or damage (fracture) of the material. Although a significant progress in theoretical methods has been achieved, the most reliable methods for evaluation of formability are based on the experimental methods. The most commonly used experimental methods are the Erichsen [2], Marciniak and Nakazima [3] tests. The Nakazima testing method consists in bulging of sheet samples with a hemispherical punch. Use of samples of different width allows us to obtain different strain paths from the uniaxial to biaxial tension.

Experimental formability tests are performed with automatic strain measurements using systems such as AutoGrid, ASAME or ARAMIS. The limit strains are evaluated using different methods for the analysis of the strains measured in the critical zone. The most commonly used ones are the methods proposed by Veerman [6], Bragard [6], Kobayashi [6] and Hecker [6]. The Veerman method analyses the circular deformed grid on the fractured blank. The strains in the fractured circles are calculated as the average of the strains of the two circles on the sides of the considered fractured one. The Hecker method consists in measuring strains in three types circles (grids) in the fractured zone: fractured, necked and acceptable (with no failure). The limit curve is traced between the points corresponding to the circles with failure and the acceptable ones. The Bragard method identifies the limit strains from the strain distribution along the cross section perpendicular to the fracture. A curve fitting algorithm is used to obtain the maximum in the major strain as the limit strain. The modified Bragard method is used in the standard ISO 12004 [3]. With the development of strain measuring systems, new methods based on the analysis of time evolution of strains and their time derivatives have been developed. Volk and Hora [7] have 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 strain rate vs. time curve. The first and second time derivatives of the principal strains (strain velocities and accelerations) have been postprocessed in [8, 5]. The onset of necking is determined by the peak of the major strain acceleration vs. time curve.

The FLDs are very useful for evaluating the formability in the finite element analyses at the design stage and during the optimization process. Numerical evaluation of the forming operations formability is usually performed by confronting strains estimated in numerical simulation with the FLC obtained using one of the methods described above. In most FE programs, however, no fracture or strain localization criteria are implemented, so simulation can be continued even after a failure conditions are achieved. In consequence, the strains obtained in numerical simulation corresponding to critical zones are often unrealistically high. Forming limit diagrams allow us to determine that the strains are above the FLC assumed for the formed material but we are not able to determine a failure point in the simulation itself.

The main objective of the present work is to implement two criteria of strain localization in the finite element program for sheet forming analysis and verify their performance by simulation of the Nakazima test one of the most commonly used experimental formability tests. The first criterion is based on the study of the first derivative of the through the thickness strain in the necked zone [7]. The second criterion is based on the analysis of the principal strain vs. time curves and their first and second time derivatives. This criterion was proposed in [8, 5] and applied in numerical simulation of sheet forming problems in [9, 10]. Numerical predictions of strain localization in the Nakazima test have been compared with the FLC determined experimentally in the laboratory procedure.

The outline of this paper is as follows. The numerical model of the Nakazima test is briefly described in Section 2. Section 3 contains presentation and discussion of numerical results in comparison to the experimental FLC. Finally, conclusions drawn from the present work are given.

2. Numerical model of Nakazima formability test

The numerical model has been created for the Nakazima tests carried out for the steel sheet grade DC04 1 mm thick. Experimental results of these tests have been described in detail in [11]. The experimental FLC has been built using the Hecker method [6].

Simulations have been performed using the authors own computer explicit dynamic finite element program [10]. Numerical modelling methodology for the whole process associated with Nakazima formability test has been developed in [10]. The sheet has been discretized with the so-called BST (Basic Shell Triangle) elements [12]. The material has been considered assuming the Hill'48 constitutive model with planar anisotropy. The stress–strain curve has been taken in the following form:

$$\sigma_y(\bar{\varepsilon}_p) = C(\varepsilon_0 + \bar{\varepsilon}_p)^n = 512(0.011412 + \bar{\varepsilon}_p)^{0.24}\,\text{MPa}\,. \tag{1}$$

The rate independent plasticity is usually assumed for sheet metal forming since strain rates effects in metalforming at room temperature and strain rates typical for these processes are small and can be neglected [13].

Simulations using the complete geometry of the Nakazima test performed in the previous authors' studies [10] have shown that the drawbead nearly completely blocks the flow of the sheet. Therefore, the simulations in this work have been carried out using a simplified model, taking into account a part of the sheet within the drawbead line, only, and assuming the restrictions of the sheet motion on the drawbead. This has allowed us to reduce considerably the number of elements and to avoid very small elements limiting the time step length.

A constant punch velocity of 1 m/s have been assumed in the numerical simulations. The contact between the sheet and punch has been modelled assuming the Coulomb friction coefficient $\mu = 0.04$. This value was identified in for the Nakazima tests performed with a Teflon foil [14].

4. Simulation results

Simulations have been performed for six different specimens: with widths of 30, 50, 60, 77 and 99 mm, and one full circular specimen with diameter of 110 mm. Figure 1 shows deformed shapes of three of these specimens with the principal (major and minor) strain distribution at the end of simulation. The forming limit diagram with strains corresponding to selected specimens (30, 77, 99 and 110 wide) is given in Fig. 2. It can be seen that the strains exceed by far the limit strains predicted by the FLC, so we can conclude that the failure (necking or fracture) has probably been achieved or even passed, but we cannot say if the level of the failure in the FE simulation agrees with that defined by the FLC.

The level of stamping at which the failure in the form of necking is achieved in numerical simulation has been assesses using two different criteria. One of these criteria is based on the analysis of the through the thickness strain evolution [7] and the other one proposed in [8, 5] employs the maximum strain acceleration. The two criteria have been applied to the most strained locations in the specimens identified from the strain distributions in Fig. 1. The strain paths at these locations for all the specimens are plotted in Fig. 3.

Determination of the onset of localized necking using both criteria has been shown for the specimen 30 mm wide in Fig. 4. Evolution of the principal strains and thinning in the failure zone of this specimen is plotted in Fig. 4a, and the curves of the first time derivative of the thinning (Fig. 4c), and the first and second time derivatives of the major principal strain are given in Figs. 4b and 4d, respectively.

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. 4c is determined by intersection of the extensions of approximately straight segments of the thinning curve before and after necking. The intersection corresponds to the time $t = 3.034 \cdot 10^{-3}$ s. Thus, the limit principal strains for the considered specimen, are given by the values of the minor and major principal strain at time $t = 3.034 \cdot 10^{-3}$ s, $\varepsilon_1 = 0.568$ and $\varepsilon_2 = -0.323$.

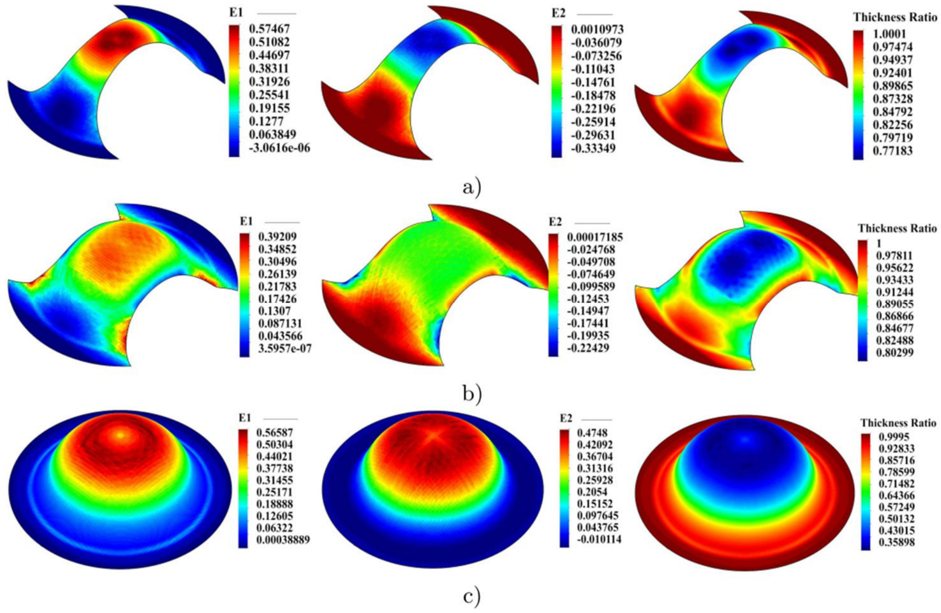

Figure 1. Principal (ε_1 - major and ε_2 - minor) strain distribution at the end of simulation on deformed shapes of the specimens: a) 30 mm wide, b) 60 mm wide, c) circular with diameter of 110 mm

According to the second criterion used, the strain localization is determined by the inflection point in the major strain rate curve shown in Fig. 4b. The inflection point corresponds to the maximum of the major strain acceleration curve plotted in Fig. 4d. The maximum is achieved at the time $t = 3.4 \cdot 10^{-3}$ 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, $\varepsilon_1 = 1.003$ and $\varepsilon_2 = -0.51$.

In the described way, the critical strains have been obtained for all the specimens. The points corresponding to the critical state have been plotted in the FLD shown in Fig. 3. Green points on each strain path defines the limit strain value calculated from the thickness strain rate criterion. The end points of each strain path (red points) correspond to the limit strains determined using the criterion based on the second derivative of the principal strains. In order to obtain additional strain paths two selected specimens have been analysed with modified friction, the specimen 99 mm wide with the friction coefficient μ = 0.25 and the full circular specimen with μ = 0.1. Analogously, the strain paths of the most strained locations and the critical strains determined according to both criteria have been plotted in Fig. 3. The critical strains for all the strain paths in Fig. 3 have been approximated by the curves which can be considered as the numerical FLCs. The FLCs are constructed for both limit strain criteria. It can be observed that while the criterion of the maximum strain acceleration predicts higher critical strains than the experimental FLC, the numerical obtained from the thickness strain rate criterion is very close to the experimental FLC.

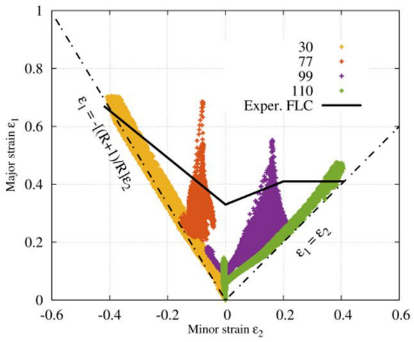

Figure 2. FLD for selected specimens

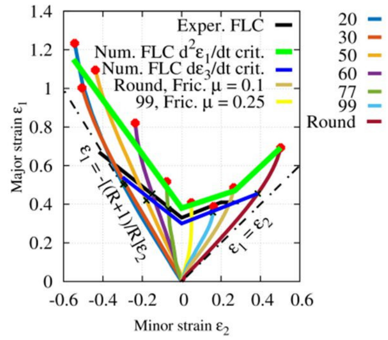

Figure 3. Simulated strain paths and the numerical FLCs compared with the experimental FLC

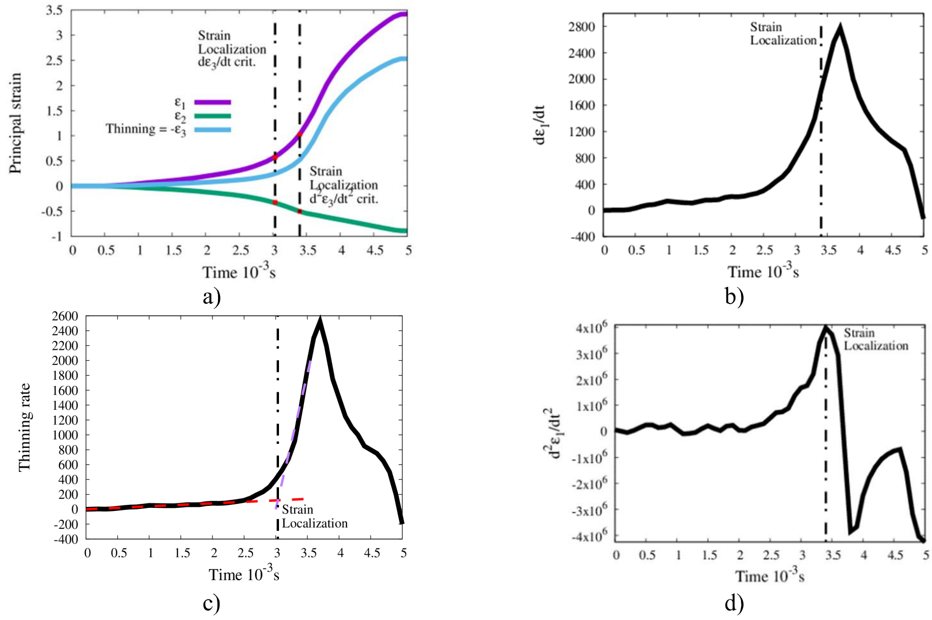

Figure 4. Determination of the onset of localized necking in numerical simulation for the specimen 30 mm wide: a) evolution of principal strains, b) major principal strain rate history, c) principal thickness strain rate history, d) major principal strain acceleration history in the failure zone

5. Conclusions

Analysis of numerical results obtained in simulations of Nakazima tests performed for the whole set of specimens confirms validity of the numerical model and possibility of determination of the onset of strain localization in numerical simulation of sheet metal forming. Accuracy of theoretical predictions has been verified using the experimental FLC. It has been found out that the criterion based on the criterion of the maximum strain acceleration overestimates limit strains and a very good coincidence with the experimental FLC is obtained for the criterion of the thickness strain rate. This shows that this criterion can be used in standard finite element simulations of sheet stamping as a tool to determine formability limits without need to use the FLC, although, further testing and experimental validation of this methodology are necessary.

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