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Detection of strain localization in Nakazima formability test - experimental research and numerical simulation

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Abstract

This paper presents the investigation on detection of strain localization in experimental research and numerical simulation of sheet metal forming. Experimental tests and numerical simulations of the Nakazima test have been performed for the DC04 grade steel sheet. The onset of localized necking has been determined using the criterion based on analysis of the major principal strain and its first and second time derivatives in the most strained zone. The strain localization has been evaluated by the maximum of strain acceleration which corresponds to the inflection point of the strain velocity vs. time. The limit strains have been calculated numerically and experimentally for specimens undergoing deformation at different strain paths. It has been shown that the numerical model predicts formability limits close to the experimental results. Analyzed criterion can be used as a potential alternative tool to determine formability in standard finite element simulations of sheet forming processes.

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Keywords: sheet forming; formability; forming limit curve; numerical simulation.

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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

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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 compare the criterion of strain localization applied in the numerical and experimental analysis to experimental FLC. Criterion has been implemented in the finite element program for sheet forming analysis and verified its performance by simulation of the Nakazima formability test. Nakazima test was selected because of its popularity as a formability test. The 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 strain paths, limit strains, and FLC determined experimentally in the laboratory procedure. Two specimens with different strain paths for these comparisons have been chosen.

The outline of this paper is as follows. The experimental results and numerical model of the Nakazima test are briefly described in Section 2 and 3 accordingly. Section 4 contains presentation and discussion of numerical results in comparison to the experimental FLC. Finally, conclusions drawn from the present work are given.

Nomenclature

σ	uniaxial yield stress
r	anisotropy (Lankford) coefficient
n	strain hardening exponent
K	strength coefficient in the Hollomon and Swift strain-hardening laws
σ_y	yield stress
ε_p	effective plastic strain
ε_0	pre-deformation in the Swift strain-hardening law

2. Experimental results

Nakazima formability tests have been carried out for the steel sheet grade DC04 0.85 mm thick. In tests PTFE foil with 0.05 mm thickness has been used to decrease friction conditions between tools and specimen. The diameter of the punch is 100 mm. Six samples with width range from 30 to 180 mm have been used to build the FLC. Specimens used in comparison to numerical results have been presented on figure 1. The strains on the specimens surface have been measured using the GOM ARAMIS system to analyze the deformation. The experimental FLC has been built using the GOM ARAMIS software according to ISO 12004 [3].

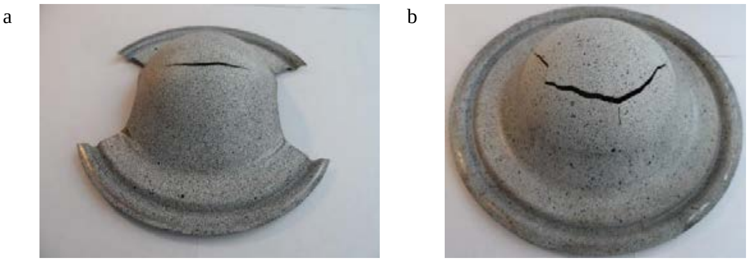

Fig. 1. Fractured specimens of different width after the tests: (a) 110 mm width; (b) circular (180 mm diameter).

3. Numerical model of Nakazima formability test

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 [11]. The material has been considered assuming the Hill'48 constitutive model with planar anisotropy.

Table 1. Properties of the tested DC04 steel sheet.

	σ [MPa]	r	n	K [MPa]
0°	196	1.96	0.21	527
45°	211	1.3	0.203	544
90°	206	2.19	0.201	513

The stress–strain curve has been taken in the following form:

$$\sigma_y\left(\varepsilon_p\right)=K\left(\varepsilon_0+\varepsilon_p\right)^n=528\left(0.0097+\varepsilon_p\right)^{0.205}\text{MPa} \quad (1)$$

The use of Hill'48 criterion is slightly simple but sufficient for the present research. 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 higher friction between the blank holder, die and sheet instead of modelling drawbead. This has allowed us to reduce the number of elements considerably and to avoid very small elements limiting the time step length.

4. Simulation results

Simulations have been performed for two specimens: with widths of 110 and one full circular specimen with diameter of 180 mm. Figure 2 shows deformed shapes of the two specimens with the principal (major and minor) strain distribution and relative thickness at the end of simulation.

The level of stamping at which the failure in the form of necking is achieved in numerical simulation has been assesses using criterion proposed in [8, 5] employs the maximum strain acceleration. The criterion have been applied to the most strained locations in the specimens identified from the strain distributions in Fig. 2.

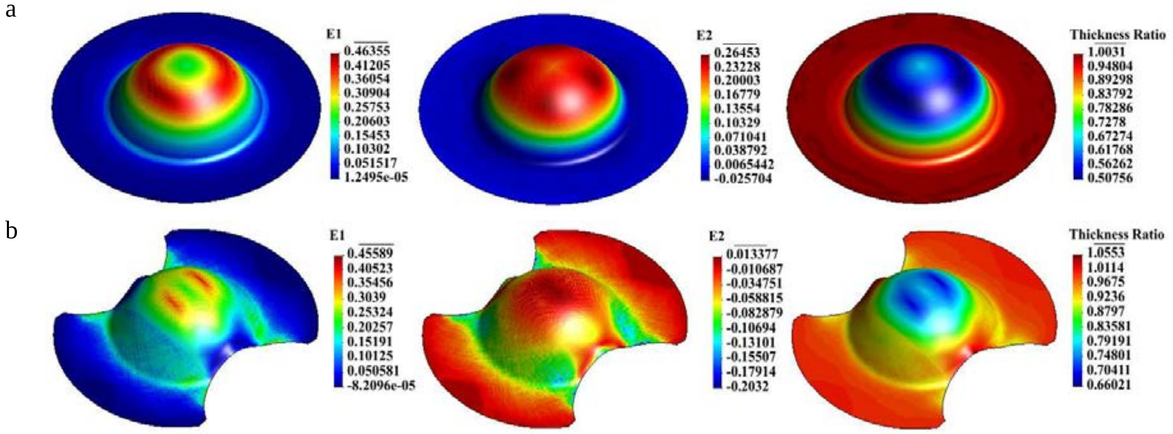

Fig. 2. Principal (ε_1 - major and ε_2 - minor) strain distribution and relative thickness on deformed shapes of the specimens: (a) circular with diameter of 180 mm, b) 110 mm wide.

Determination of the onset of localized necking has been shown for the specimen circular and 110 mm wide in Fig. 3. Evolution of the principal strains in the failure zone of this specimen is plotted in Fig. 3a, 3b, and the curves of the first and second time derivatives of the major principal strain are given in Figs. 3c, 3d and 3e, 3f, respectively. According to the criterion used, the strain localization is determined by the inflection point in the major strain rate curve shown in Fig. 3c, 3d. The inflection point corresponds to the maximum of the major strain acceleration. The maximum of the curves shown in Fig. 3 is achieved at the time $t = 4.19 \cdot 10^{-3}$ s – circular and $t = 3.77 \cdot 10^{-3}$ – 110 mm wide specimen. Thus, the limit principal strains for the considered specimens, are given by the values of the minor and major principal strain at time $t = 4.19 \cdot 10^{-3}$ s, $\varepsilon_1 = 0.49$ and $\varepsilon_2 = 0.24$ (circular specimen) and time $t = 3.77 \cdot 10^{-3}$, $\varepsilon_1 = 0.46$ and $\varepsilon_2 = -0.019$ (circular specimen). The critical strains have been obtained in this way also for the experimental case. The strain paths for the most strained locations of these specimens until the critical state have been plotted in the FLD shown in Fig. 4. In order to obtain strain paths for these specimens as close as possible to the experimental strain paths calibration procedure for the friction conditions have been performed. Friction conditions between the punch and sheet have been analyzed for several friction values and by the inverse analysis it was found that for the specimen 110 mm wide friction coefficient assessed value μ = 0.05 and the full circular specimen with μ = 0.1. Limit strains obtained numerically have been confronted with limit strains obtained experimentally and with FLC. The numerical limit strains is quite close to the experimental FLC for the strain paths close to the plain strain. Experimental strains obtained by the criterion are close to the values of strains before the fracture.

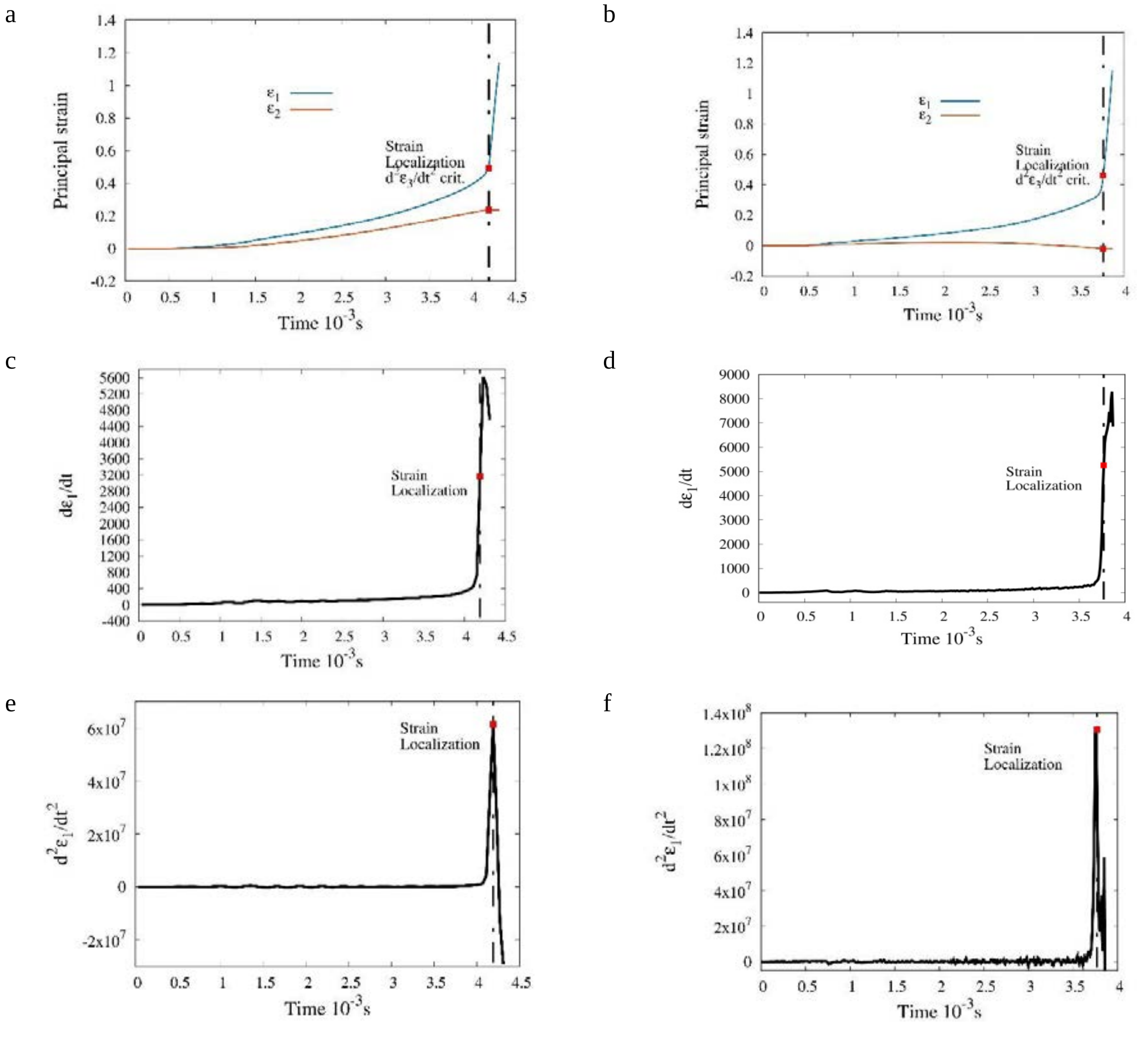

Fig. 3. Determination of the onset of localized necking in numerical simulation for the specimens circular and 110 mm wide: (a), (b) evolution of principal strains, (c), (d) major principal strain rate history, (e), (f) major principal strain acceleration history in the failure zone respectively.

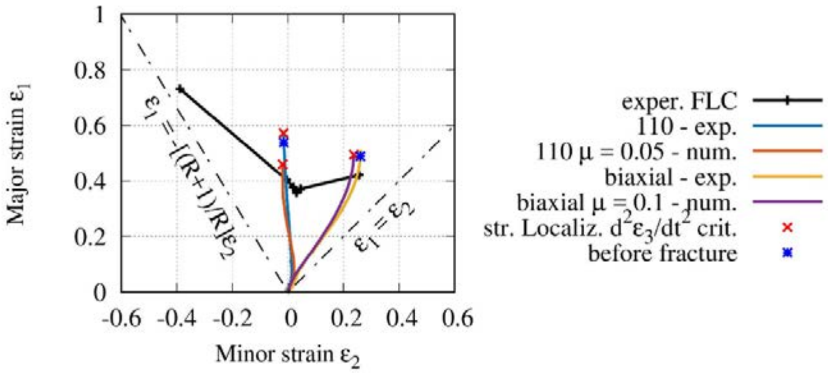

Fig. 4. Simulated strain paths and the numerical FLC compared with the experimental FLC

In general, it can be seen that the numerical FLC predicts higher critical strains than the experimental FLC. This is understandable, since different criteria lead to different FLCs, and the criterion of the maximum strain acceleration used for experimental results predicts higher critical strains than other methods as it is shown in [5].

5. Conclusions

Analysis of numerical results obtained in simulations of Nakazima tests performed for the selected specimens confirms the validity of the developed numerical model. The numerical prediction of the strain distribution and failure is close to the experimental results. The criterion of the maximum strain acceleration used in the determination of the onset strain localization produced the formability limits quite close to the experimental FLC. This shows that it 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 are necessary.

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