NUMERICAL SIMULATIONS OF NAKAZIMA FORMABILITY TESTS WITH PREDICTION OF FAILURE

DMYTRO LUMELSKYJ[1], JERZY ROJEK[1], MAREK TKOCZ[2]

Abstract. This paper presents results of numerical simulations of the Nakazima test with determination of formability without using the forming limit curve. 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 determined by the maximum of strain acceleration which corresponds to the inflection point of the strain velocity versus time. The limit strains have been determined for different specimens undergoing deformation at different strain paths covering a whole range of the strain paths typical for sheet forming processes. This has allowed us to construct the numerical FLC. The numerical FLC has been compared with the experimental one. It has been shown that the numerical FLC predicts higher formability limits but the differences are not large so the method can be used as a potential alternative tool to determine formability in standard finite element simulations of sheet forming processes.

Key words: 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, 2, 3]. 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

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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 [4, 5, 6], theoretical [7, 8, 9], as well as hybrid methods combining experimental data with analytical or numerical approaches [3, 10]. Different methods of FLC determination are reviewed in [11].

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 [4], Marciniak and Nakazima [5] 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. A new method for the experimental determination of the FLC is proposed in [6]. The procedure is based on the hydraulic bulging of two specimens. The upper blank has a pair of holes pierced in symmetric positions with respect to the center, while the lower blank acts both as a carrier and a deformable punch. By modifying the dimensions and reciprocal position of the holes, it is possible to investigate the entire deformation range of the FLC. The proposed methodology allows us to reduce the parasitic effects induced by the friction and leads to strain localization and fracture in in the polar region of the specimens.

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 [12], Bragard [13, 14], Kobayashi [15] and Hecker [16]. 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 ISO12004 [5]. 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 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 versus time curve. The first and second time derivatives of the principal strains (strain velocities and accelerations) have been postprocessed in [17, 10]. The onset of necking is determined by the peak of the major strain acceleration versus 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 a criterion of strain localization in the finite element program for sheet forming analysis and verify its performance by simulation of the Nakazima formability tests. The criterion is based on the analysis of the principal strain versus time curves and their first and second time derivatives proposed in [17, 10] and applied in numerical simulation of sheet forming problems in [18, 19]. This work is aimed to validate this criterion by applying it to simulation of the Nakazima tests. Numerical predictions of strain localization in the Nakazima test can be easily compared with the FLC determined experimentally in the same laboratory procedure.

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

2. EXPERIMENTAL RESULTS

Nakazima formability tests have been carried out for the steel sheet grade DC04 1 mm thick. Figure 1 presents the geometry of the tools. Fractured specimens of different width after the tests are shown in Fig. 2.

The strains on the specimens surface have been measured using the ASAME system to analyse the deformation of the circular grids. The FLC is build using the Hecker method [16]. The strains corresponding to failed and safe circles (the set of the failed circles include both the fractured and necked ones) have been plotted in the FLD given in Fig. 3. The limit curve is traced between the failed and safe points.

This curve is compared with the FLC provided by the steel manufacturer. A good agreement between the two curves can be observed, which confirms correctness of our experimental procedure and measurements. Friction, affecting strain paths in a tested specimen, is an undesired phenomenon in formability tests, therefore the tests have been performed using a Teflon foil between the sheet and punch in order to ensure low friction.

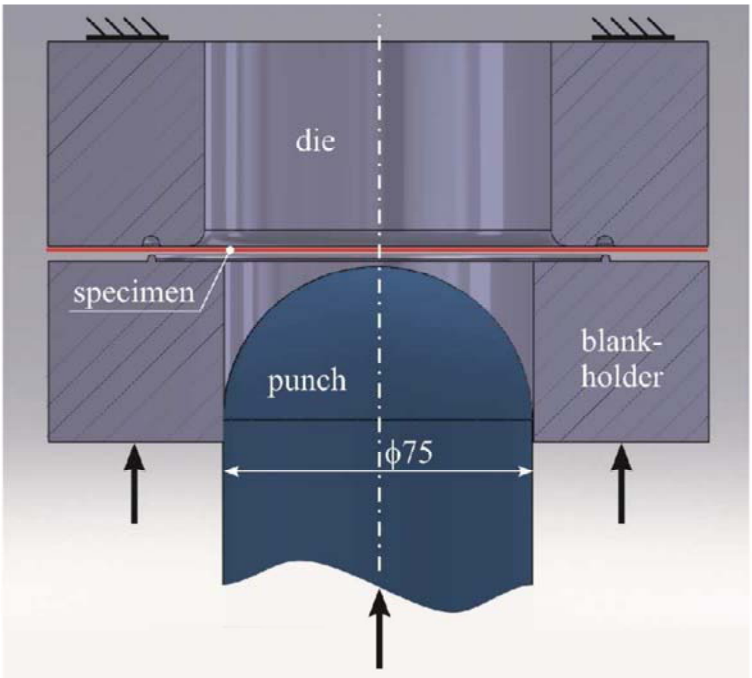


Fig. 1 – Schematic representation of tools for Nakazima tests.

The limit strains for the uniaxial tension have been determined from the tensile tests. These tests have also been used to determine the mechanical properties necessary for numerical modelling. Table 1 presents parameters determined in these tests.

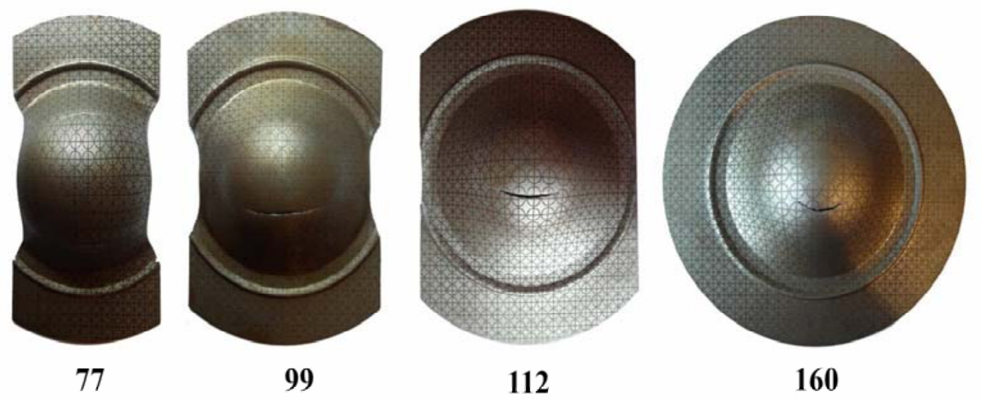


Fig. 2 – Fractured specimens of different width after the tests.

Table 1

Properties of the tested DC04 steel sheet

Direction of the sample	C [MPa]	n for $\varepsilon_i = 0.02 \div 0.2$	r
0º	498	0.26	1.7
45º	506	0.22	1.3
90º	532	0.26	1.8

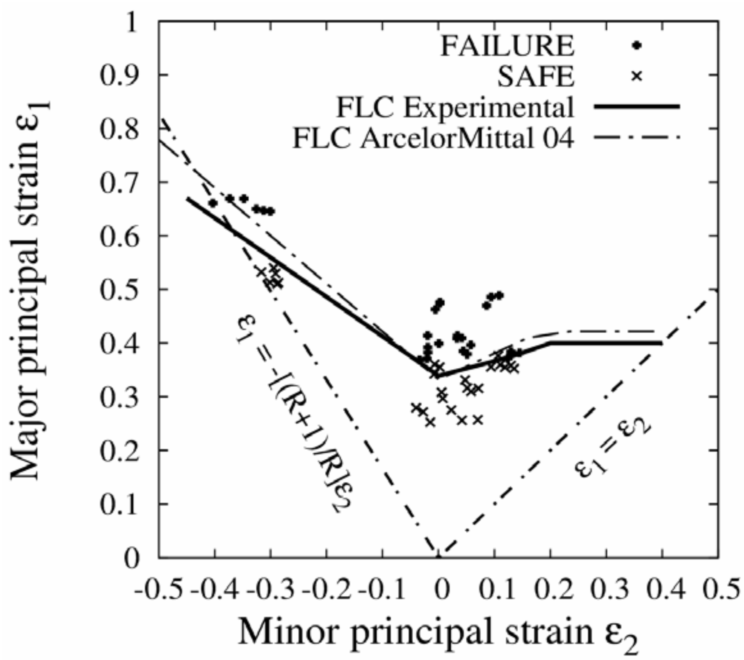


Fig. 3 – Forming limit diagram with experimental results of the Nakazima tests.

3. NUMERICAL MODEL

Simulation of the Nakazima test have been performed using the authors own computer explicit dynamic finite element program [20, 21]. Numerical model for the whole process associated with Nakazima formability test has been developed in [19]. Sheet has been discretized with the so-called BST (Basic Shell Triangle) elements [22]. The material has been considered assuming the Hill'48 constitutive model with planar anisotropy [23]. The stress-strain curve has been taken in the following form:

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

Simulations with a model representing the complete geometry of the Nakazima test performed in the previous authors studies [19] 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 [24] for the tribological conditions in the Nakazima tests with a Teflon foil.

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 4 shows deformed shapes 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. 5. It can be seen that the strains exceed much 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.

In order to determine the level of stamping at which the failure in the form of necking is achieved the criterion of the maximum strain acceleration proposed in [17, 10] has been applied to the most strained locations in the specimens. Determination of the onset of localized necking has been shown for the specimen 30 mm wide in Fig. 6. Evolution of the principal strains in the failure zone of this specimen is plotted in Fig. 6a, and the curves of the first and second time derivatives of the major principal strain are given in Figs. 6b and 6c, respectively. According to the criterion used, the strain localization is determined by the inflection point in the major strain rate curve shown in Fig. 6b. The inflection point corresponds to the maximum of the major strain acceleration. The maximum of the curve shown in Fig. 6 is achieved at the time $t = 3.4 \cdot 10^{-3}$ s. Thus, the limit principal strains for the considered specimen, are given by the values of the minor and major principal strain at time $t = 3.4 \cdot 10^{-3}$ s, $\varepsilon_1 = 1.003$ and $\varepsilon_2 = -0.51$. The critical strains have been obtained in this way for all the specimens shown in Fig. 5.

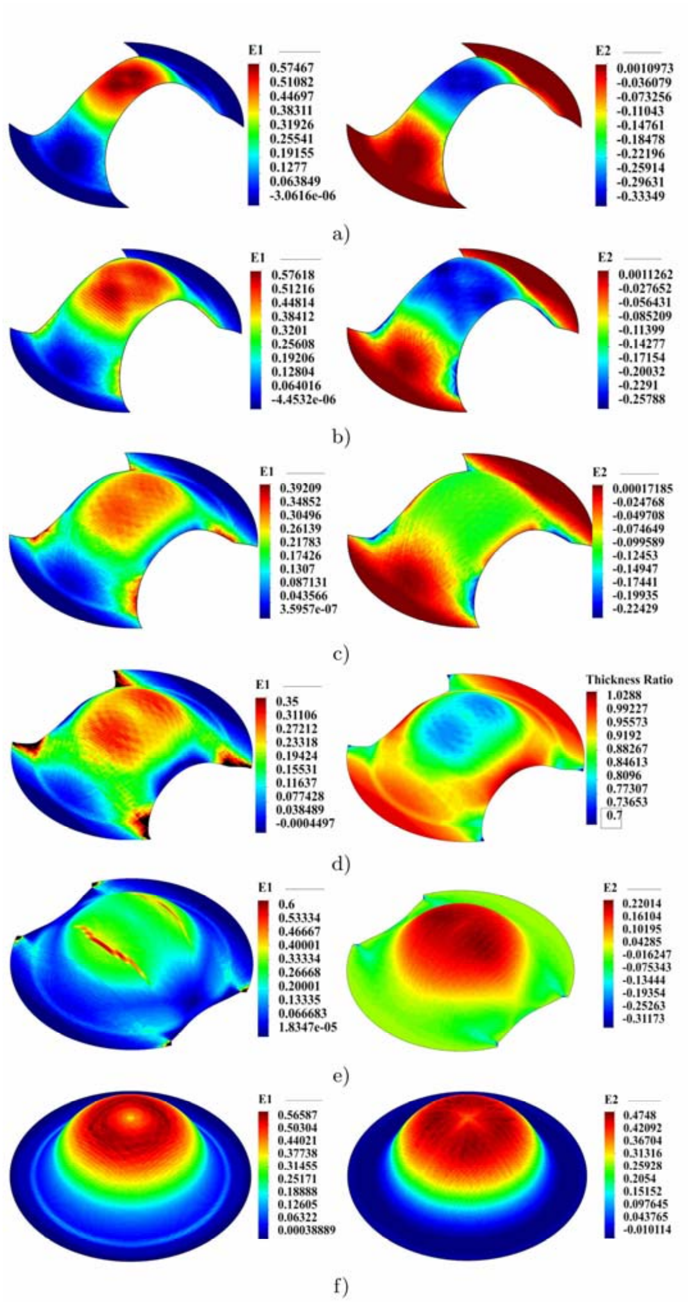


Fig. 4 – Principal (ε_1 –major and ε_2 –minor) strain distribution at the end of simulation on deformed shapes of the specimens: a) 30 mm wide; b) 50 mm wide; c) 60 mm wide; d) 77 mm wide; e) 99 mm wide; f) circular with diameter of 110 mm.

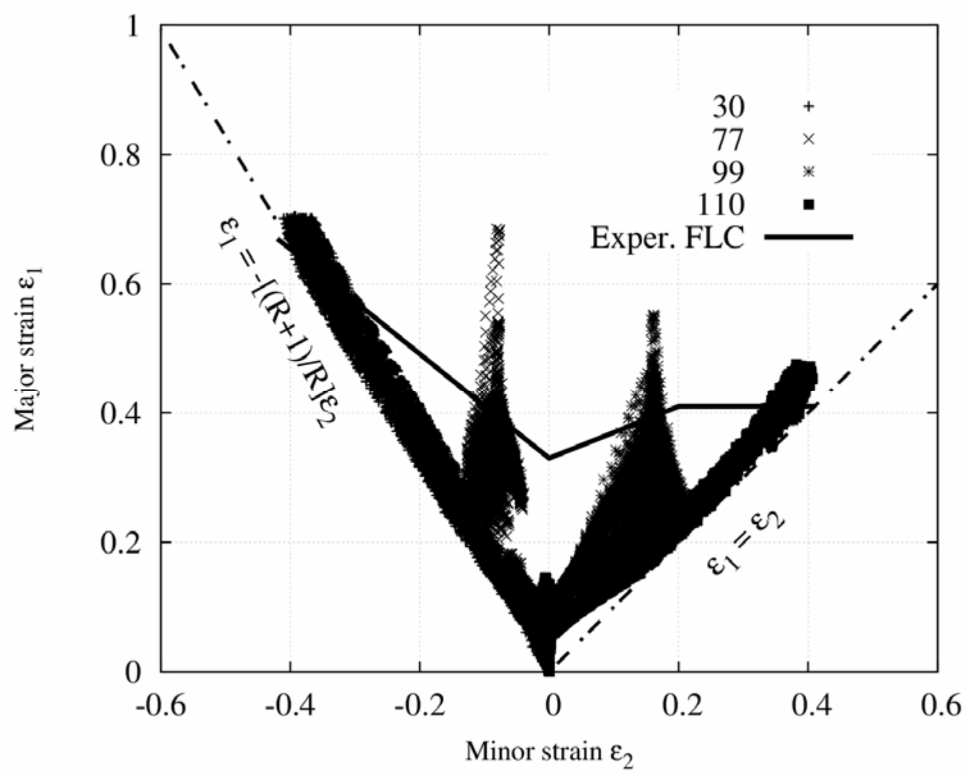
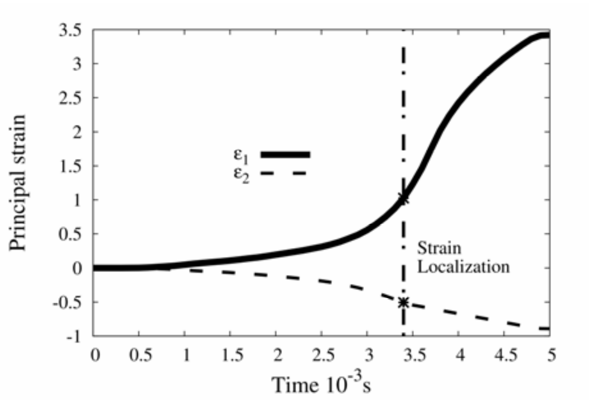
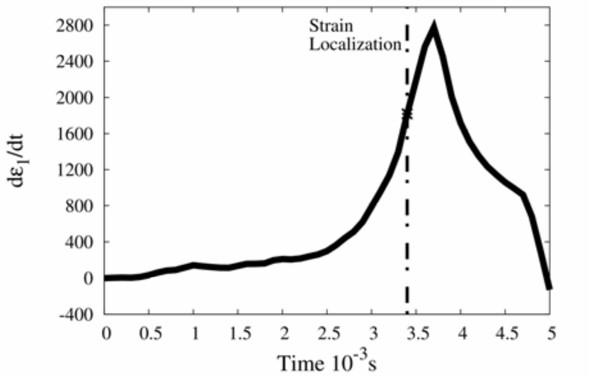


Fig. 5 – FLD for selected specimens.

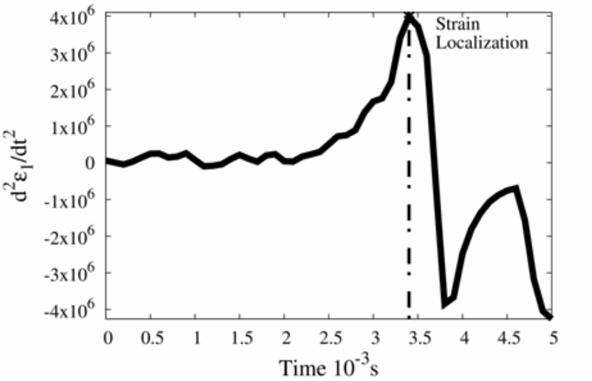
The strain paths for the most strained locations of these specimens until the critical state have been plotted in the FLD shown in Fig. 7. In order to obtain additional strain paths two selected specimens have been analysed with modified friction, the specimen 99 mm wide with the friction coefficient $\mu = 0.25$ and the full circular specimen with $\mu = 0.1$. Analogously, the critical strains have been determined and strain paths have been plotted in Fig. 7. The critical strains from all the specimens have been approximated by the curve which can be considered as the numerical FLC. The numerical FLC is quite close to the experimental FLC for the strain paths close to the plain strain. 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 [10].



a)



b)



c)

Fig. 6 – 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) major principal strain acceleration history in the failure zone.

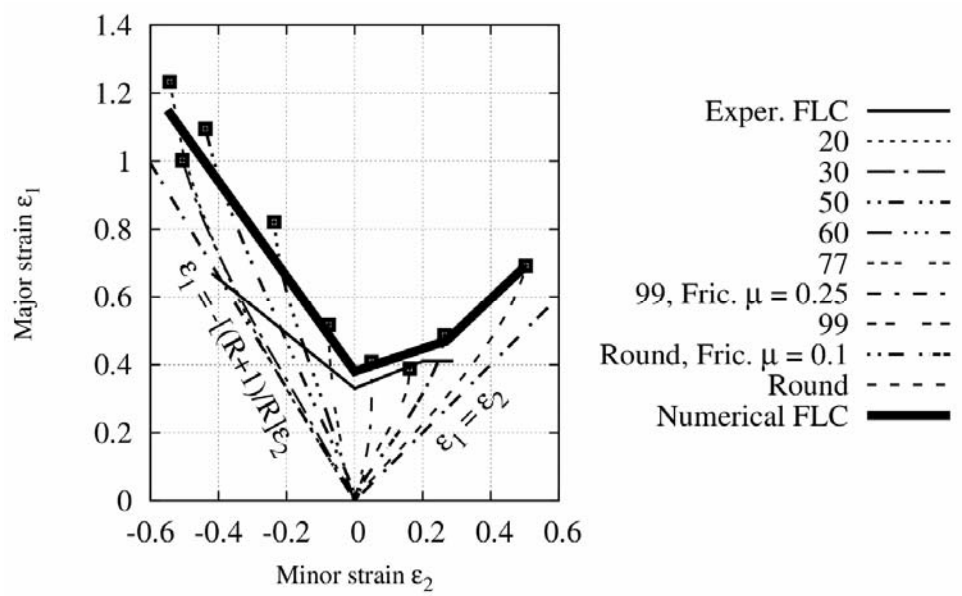


Fig. 7 – Simulated strain paths and the numerical FLC compared with the experimental FLC.

5. CONCLUSIONS

Analysis of numerical results obtained in simulations of Nakazima tests performed for the whole set of specimens confirms 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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