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Original Research Article

Numerical simulation of formability tests of pre-deformed steel blanks

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ABSTRACT

This paper presents the results of numerical simulations of the formability tests carried out for a pre-stretched 1 mm thick DC04 steel sheet. Simulation consisted of the subsequent stages as follows: uniaxial stretching of the sheet, unloading and stress relaxation, cutting specimens out of the pre-stretched sheet and bulging the blank with a hemispherical punch. Numerical modeling has been verified by comparison of the simulation results with the experimental ones. Good concordance of the results indicates correct performance of the numerical model and possibility to use it in further theoretical studies.

1. Introduction

In engineering practice, metal sheet formability is most commonly estimated using the forming limit diagrams (FLD), in which the failure criterion is defined by the forming limit curve (FLC) given in terms of major and minor principal strains. The known drawback of the strain based FLCs is their dependence on strain paths [1]. Standard experimental tests used to determine the FLC induce linear or nearly linear strain paths, while real multi-step sheet forming processes are associated with complex deformation paths. Therefore determination of sheet metal formability for changing deformation paths is an issue of great practical importance [2,3].

Forming limit stress diagrams (FLSD) have been proposed as an alternative to the FLD for formability assessment [4,5]. Stress-based forming limit curves are less dependent on the strain path effect [6,7], however, the use of FLSD poses some inconveniences. Stresses in the deforming sheet cannot be measured directly. They can be determined from the known deformation, however, this requires the use of appropriate constitutive model. Similarly, forming limit stress curves cannot be obtained directly from experiment. Stress based FLC must be calculated from the experimental strain-based FLC or directly from a numerical model [5].

In view of the above mentioned difficulties associated with stress-based forming limit diagrams, it is understandable that strain based forming limit diagrams are still used in practice despite their drawbacks. However, when using strain-based FLCs, one must remember about the strain path effect.

Effect of strain path changes on the forming limit curve (FLC) is still the subject of intensive experimental and theoretical work [8,6,9,10]. In some experimental studies, the sheet is stretched before the formability tests [11,12].

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Pre-stretching of the material before formability tests leads to abrupt changes in deformation paths influencing the FLC [11,12]. Possibilities to produce different strain paths experimentally are limited. Numerical simulation offers much more possibilities to investigate different forming cases.

The aim of this study is to develop a numerical model allowing us to simulate complex deformation paths of the material subjected to a preliminary stretching, and then bulging tests performed to determine the FLC. The idea is to simulate the whole process of material deformation from pre-stretching to formability tests. The experimental results will be used to validate correctness of the numerical model in prediction of the failure. The numerical model employed to simulate formability tests for specimens of different widths can be used to construct numerical strain-based FLCs for different strain paths. The use of the model to calculate directly the stress-based FLCs is planned for future research work.

The outline of the paper is as follows. First, experimental results are presented in Section 2. The experimental forming limit curves for the as-received and pre-strained blanks are constructed. The strain paths and critical strains corresponding to fractures in the formability tests are presented in the forming limit diagrams of the pre-strained blank. Main assumptions and basic idea of the numerical model are presented in Section 3. Simulation process and numerical results for two selected cases of formability tests are presented in Section 4. The strains corresponding to failure predicted by the numerical simulations are compared with the experimental FLC.

2. Experimental results

Numerical modeling has been verified using experimental results of formability tests carried out for the steel grade DC04 1 mm thick. The tests were performed for the as-received sheet supplied by the manufacturer and for the blanks pre-stretched in uniaxial tension conditions. Different directions and amounts of pre-strain have been studied in experiments [13]. In this work, the results obtained for the blank pre-stretched by 13% in the rolling direction will be presented, only.

Fig. 1 shows the geometry of the tools and specimens used in the tests. Use of specimens of different widths allowed us to obtain failure for different strain paths. The uniaxial tension tests completed the experimental procedure. The tension specimens and undercut specimens for formability tests were oriented in two perpendicular directions. Half of the specimens cut from the as-received blank were aligned along the rolling direction (RD) and the other half were aligned in the transverse direction (TD). Similarly, the specimens cut from the pre-deformed blank were oriented both parallel and perpendicularly to the rolling and pre-stretching directions.

Fig. 2 presents two fractured specimens which will be later analyzed numerically. The FLD for the as-received blank is shown in Fig. 3. Note that the FLD is built taking the rolling direction as the y-axis and the transverse direction as the x-axis. This representation of the FLD is more suitable for

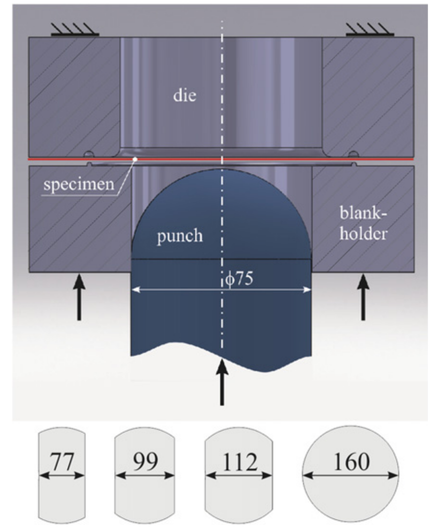

Fig. 1 – Schematic representation of tools and specimens for formability tests.

different alignment of the specimens and different strain paths than the conventional presentation in terms of major and minor principal strains.

The complete strain path and local strains in the failure zone for the circular specimen are presented in the FLD in Fig. 4. The points corresponding to the local strains are confronted with the as-received FLC and the FLC obtained by shifting the as-received FLC along the line $\varepsilon_{TD}+\varepsilon_{RD}=\text{const}$ accordingly to the pre-strain as suggested by Hosford [14]. This shift is based on the assumption that the pre-strained sheet breaks at the same thickness strain as the as-received sheet for the similar strain paths. Fig. 4 shows that fracture appears a little below the shifted FLC, however, the difference is relatively small. This may confirm that the shift of the FLC proposed by Hosford [14] gives a relatively good approximation here. However, we must remember that this is not always the case, cf. [12]. The results for the 77 mm wide specimen oriented perpendicularly to the rolling and pre-stretching directions are presented in Fig. 5. The deformation in the failure zone occurs in the plane strain condition parallel to the transverse direction. The orientation of the major principal strain coincides with the transverse direction in this case. In this case as well, the shifted FLC gives a relatively good approximation of the strain state at failure.

The complete set of results for the specimens aligned parallel and perpendicular to the rolling and pre-strain direction presented in Fig. 6 allowed us to construct the FLC for the pre-deformed blank. The effect of pre-stretching is visible in the form and shift of the forming limit curve for the pre-stretched blanks in comparison to the as received FLC. The complete set of results shown in Fig. 6 reveal the similarities and differences between the FLC for the pre-stretched sheet obtained experimentally and the shifted as-received FLC. The shifted FLC gives quite a good failure prediction for the specimens oriented along the pre-stretching direction. Significant difference appears for the specimens oriented perpendicularly to the pre-stretching direction.