Numerical determination of the forming limit diagram for thin sheet metal foil from a ductile damage model identified via Micro-Single Point Incremental Forming tests

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Abstract. In this paper, the micro-formability of thin sheets is investigated by a numerical approach. A coupled elastic-plastic-damage model is used to predict forming limit diagram according to the micro-Marciniak tests. The identification of the ductile damage model is first performed from micro-single point incremental forming tests using inverse finite element method. Finally, both the micro-forming limit curve and the micro-forming limit stress curve are plotted.

1 Introduction

Microforming is a promising technique for producing miniature parts and the success of the latter is often associated with the so-called size effect, which is affected by the thickness and the grain size [1]. The material formability is limited by problems arising from size effects, especially the grain size [2]. The reliable determination of forming limit which assures the prediction of the microforming process lies in the determination way of the forming limit curve (FLC). The FLC is plotted in a major-minor strain diagram referred to as the forming limit diagram (FLD), which initially developed by Keeler and Backofen [3] and Goodwin [4]. The most common methods for FLDs determination are the Nakajima test, which uses a hemispherical punch and the Marciniak test which uses a flat punch. The Nakajima test is complicated by strain gradients due to friction, normal loading, and bending, while the Marciniak test provides in-plane stretching, which makes easier the strain measurements.

Several researchers recognize that FLD is insufficient for evaluating the part safety, especially when the strain path changes. Nevertheless, the results showed that the forming limit stress diagram (FLSD) is a more precise tool for characterizing sheet formability. In recent years, the FLSD has been intensively studied and has been considered being path-independent [5-7].

The initiation of localized necking that precedes fracture indicates commonly the formability limit of sheet metal.

Several studies used the ductile fracture criteria to predict the localized necking by finite element method, such as [8-10]. However, the success of the numerical determination of the FLDs depends on the accuracy of the input data, such as the boundary conditions, the constitutive law, and the material parameters.

This paper introduces a method for numerical determining the forming limit diagram of a thin copper sheet (210 µm) by simulations of the micro-Marciniak tests. The micro-single point incremental forming process (micro-SPIF) is initially used as a characterization test for thin sheets under complex loading conditions to identify the parameters of the ductile damage model by inverse method. Finally, the micro-FLD and micro-FLSD are plotted.

2 Numerical procedures

2.1 Micro-Marciniak test simulations

The micro-Marciniak test is a stamping test that allows for deforming a clamped blank until fracture. The tooling is composed of a fixed die, a blank holder and a punch with a circular section. In order to obtain different modes of mechanical solicitations (uniaxial tensile, plane strain tensile and biaxial tensile) the geometries of the specimens range from full disk to a band. In this study, the modes of mechanical solicitations change from biaxial tensile to a uniaxial tensile when the specimen width decreases from L=24 mm to 6 mm. Different from conventional specimen shape, a dedicated specimen with a non-uniform thickness is used in this work (Fig 1.a). A sub-thickness of 0.1 mm is set in the central part of the specimen to ensure strain localization in this zone,

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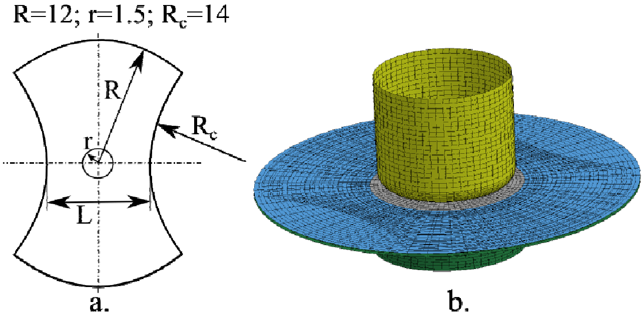
making unnecessary the use of the driving plate. This approach has already been used by Sene et al. [11] in the case of micro-FLD determination.

A fully parametric toolbox, programmed in Matlab language, has been developed to prepare the input files necessary for the simulation of the micro-Marciniak test (mesh, boundary, load and initial conditions, material parameters). The associated finite element mesh is presented in Fig. 1.b.



a. b.

Figure 1. Micro-Marciniak test : a. Blank geometry, b. Mesh model.

The blank is meshed with 8-node, fully integrated solid elements having four elements in the central sub-thickness and eight in the thickness. The tools are meshed with 4-node, rigid shell elements. During the simulation test, the blank is clamped along its edges, i.e., each node of the contour is fixed. The blank holder is set to have a concentrated force of 200 N along the punch motion axis. The LS-DYNA software with the explicit integration method is used to simulate this test.

A coupled damage-plasticity model, which is able to represent the main mechanisms of inelastic behaviour, including plastic deformation, the change of elastic response and the localized failure, is used. The continuum damage mechanics concepts developed by Lemaitre and Desmorat [12] are considered. The material parameters of the behaviour law are identified by inverse analysis using the micro-SPIF process. The friction law chosen to simulate the tribological behavior at the interfaces between tools and the blank is Coulomb's friction law, with a friction coefficient equal to 0.2.

2.2 Identification of the ductile damage parameters

The ductile damage model and its identification are completely detailed in the study proposed by Ben Hmida et al. [13]. The identification method consists of simulating a micro-SPIF test, whose results (in terms of axial forming force) are sensitive to the material parameters to be adjusted. The test is initially simulated with the initial set of parameters extracted from a tensile test. Then, the numerical results are compared with the experimental measurements and the material parameters are adjusted iteratively using an optimization algorithm (Levenberg-Marquardt). The identification procedure is performed by using the Matlab toolbox MIC2M, developed by Richard [14]. The comparison between the numerical axial forming force F_Z and the experimental one is presented in Fig. 2.

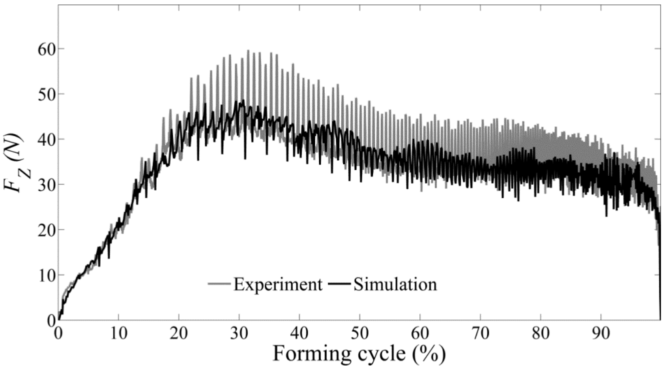
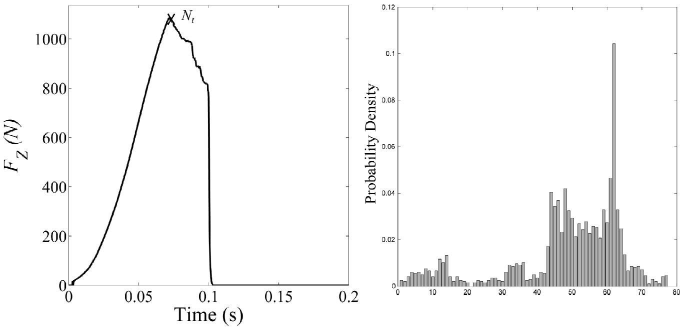


Figure 2. Evolutions of experimental and numerical axial forming forces identified from micro-SPIF test.

3 Numerical forming limit diagram

The numerical determination of forming limit curve is performed with a criterion to predict the onset of necking, namely the Maximum Force Criterion (MFC) (Fig. 3.a). This criterion is based on the instability of the punch force (dF=0), i.e., the necking localization N_t occurs when the force reaches its maximum during the micro-Marciniak test. In this study, the MFC criterion is applied to the eight blank geometries (L=6, L=8, L=10, L=12, L=14, L=16, L=18, L=24).



a. b.

Figure 3. a. Evolution of the punch force during the micro-Marciniak test, b. Probability distribution of the major strain calculations.

At the point of time when the necking localization is assumed to occur, the major and minor strains of the central zone are extracted from statistical analysis. Indeed, the values of the major strain in the central zone follow the normal distribution (Fig.3.b). Finally, the retained value of the major strain is the mean value obtained by the profile of the normal distribution of the major strain (denoted μ with a standard deviation σ). The same method is applied to extract the minor strain.

The couple major and minor strains extracted according to the method described above constitutes a point in the forming limit curve. Finally, this procedure is applied for the each specimen geometry and the micro-FLD is therefore plotted (Fig. 4). The major and minor stresses are calculated by the same method described above and the micro-FLSD is obtained by considering von Mises yield function and Voce hardening law.

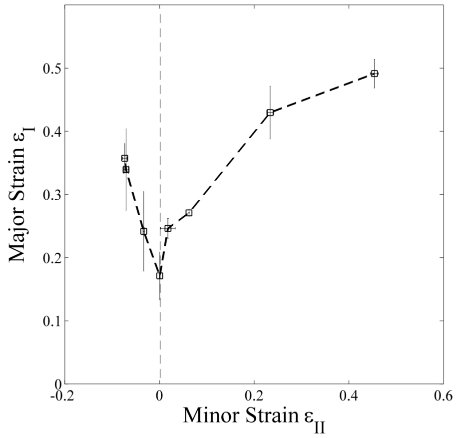


Figure 4. Micro-FLD of a thin copper alloy (t=210 µm).

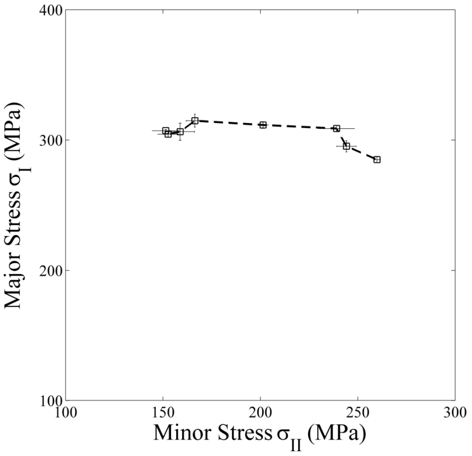


Figure 5. Micro-FLSD of a thin copper alloy (t=210 µm).

4 Conclusions

In the present work, the numerical micro-FLD and micro-FLSD for a 210 µm thick copper alloy sheet are determined using micro-Marciniak test with different sample geometries. This test allowed for the determination of the complete micro-FLD and micro-FLSD by varying only the samples width. A ductile damage model is used to simulate the stamping operations and the identification of its parameters is performed by a micro-SPIF test using the finite element updating method.

Future studies will focus on the comparison with the experimental data and the analysis of grain size influence on the formability in order to accurately predict the micro-forming processes.

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