Design of a reverse deep drawing experiment enhancing strain path changes

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Abstract. To evaluate a priori the amount of strain path changes in forming processes in order to adjust the complexity of constitutive equations, it is necessary to develop forming tests at the laboratory scale sensitive to strain paths changes. In this work, a micro-forming experiment is designed in order to perform reverse deep drawing tests on ultra-thin metallic sheets, typically 0.1mm-thick copper alloys. This experiment is supposed to be set on a Zwick-Roell BUP 200 device. The work presents the design of the device and the evolution of strain path changes occurring during both stages of the process. The experimental results obtained after both stages (force-displacement, thickness) are presented. Finally, a sensitivity analysis of a strain path change indicator is proposed through the numerical simulation of the reverse deep drawing test by varying the geometry of the tools.

1. Introduction

The deep-drawing process is increasingly used for miniature parts made of ultra-thin sheets mainly for its suitability for large productions. In such process, the forming parts are usually obtained through multi-stage operations due to geometrical complexity or formability problems, leading to strain path changes. Reverse deep drawing process, as defined in [1] falls into this category: in such process, the movement of the punch during the subsequent operation occurs in the opposite direction for the first operation. One reason is that in the reverse process, the surface finishing is better since the outside of the part is in contact only once with the die radius [1]. Because of the complex kinematics of the tools, this type of process is at the origin of severe strain path changes that make it possible to highlight the sensitivity of constitutive laws to this indicator [2].

In order to evaluate a priori the amount of strain path changes in forming processes in order to adjust the complexity of constitutive equations to represent peculiar behaviors arising from strain path changes, there is an interest to develop forming tests at the laboratory scale which are sensitive to strain path changes. For example, in the case of cylindrical cups, similar cups may be obtained with different strain paths; for example, a two-stage process consisting of a first cup drawing followed by either reverse or direct redrawing. These two processes may exhibit different strain paths and certainly different strain path changes.

Several studies have focused on strain path changes generated during the reverse deep drawing process [2], but none of them emphasized the influence of the geometry of the tools on the amplitude of theses strain path changes. In this work, a micro-forming device is designed in order to perform reverse deep
drawing tests on ultra-thin metallic sheets, typically 0.1 mm-thick copper alloys. These ultra-thin sheets are selected with more than 20 grains through the thickness, so that any constitutive approaches are valid on a theoretical ground, i.e. phenomenological or crystal plasticity. The device will be set on a Zwick-Roell BUP 200 device. The work presents the design of the device and the evolution of strain path changes occurring during both stages of the process. The numerical simulation results obtained after both stages (force-displacement, thickness) are presented. Finally, a sensitivity analysis of a strain path change indicator is proposed through the numerical simulation of the reverse deep drawing test by varying the geometry of the tools.

2. Design of a specific device
As shown schematically in Fig.1, the first drawing operation involves a hollow punch, a die and a blank-holder. Then, in the second operation, a punch moves in the opposite direction [1], to fit the shape of a hollow die. The process reverses the direction of the material flow. Returning the inside of the cup to the outside, a second cup with new dimensions is then obtained. The numerical simulation of the reverse deep drawing process allows to optimize the parameters involved in the design of this process and to determine the configuration that maximize strain path changes.

![Figure 1. Scheme of the forming tools used in the reverse deep drawing test of a cylindrical cup](image)

Firstly, a device is designed to be machined and set on a hydraulic press Zwick-Roell BUP 200. The drawing ratio of this cylindrical cup forming process of the first stage is $\beta = 1.39$ and the second stage is $\beta = 1.43$. The tools of the first stage are composed of a punch with an external diameter of 43 mm, the drawing radius being 2.7 mm, and a die that gives the centering of the circular blank. The die has an internal diameter of 43.32 mm with a drawing radius of 3 mm. The gap between the punch and the die is set at 0.16 mm in the first stage and 0.2 mm in the second stage. An identical procedure is adopted in the second stage, where the blank-holder and the die have become conjugate, shape allows the centering of the first cup to form the final cup.

3. Numerical simulation of the reverse drawing test
The numerical simulation of the reverse deep drawing process was performed using Abaqus Explicit FE code in a 2D axisymmetric approach. The dimensions of the tools are summarized in Table 1. The modelling of the forming tools is carried out with analytic rigid shell, while the blank is meshed with axisymmetric CAX4R elements, linear with reduced integration. The blank-holder force is supposed constant at 2 kN and the friction coefficient between the sheet and tools is estimated equal to 0.12 [3]. The material is a pure copper of 0.1 mm thick, which behavior is modelled using an isotropic hardening of Hollomon type [4], while the anisotropy is not considered here.
Table 1. Tool geometry and dimensions (in mm) of the reverse deep drawing test

|                  | Stage 1     | Stage 2     |
|------------------|-------------|-------------|
| Blank: diameter, thickness | 60, 0.1     | -           |
| Die opening diameter   | 43.32       | 30.4        |
| Die radius            | 3           | 2.7         |
| Punch diameter        | 43          | 30          |
| Punch radius          | 2.7         | 2.5         |
| Blank-holder opening diameter | 43.32       | 30.4        |
| Gap punch/die         | 0.16        | 0.2         |

The evolution of the punch-force versus the punch-displacement is plotted in Fig.2. As it can be seen, the force increases to reach a maximum value of about 2782 N in the first step for a displacement of 8 mm. However, in the second step, the force reaches 1664 N for a displacement of 15 mm and then tends to vanish towards the end of the punch stroke. It does not reach the zero-value due to friction forces.

Figure 2. Numerical punch-force versus punch-displacement curves for stage 1 (a) and stage 2 (b) of reverse deep drawing

When moving the punch to push the blank to take the form of the die, the sheet thickness is subjected to variations depending on the area considered on the cup. Consequently, phenomena of thinning and thickening take place in the cup wall. These phenomena consist of a change in the thickness values comparatively with the original or initial value in the blank [5]. The distributions of the thickness are measured from the center to the outer diameter. As it can be observed in Figs.3a and 3b, the thickness of the bottom of the cup remains almost intact after both steps of the process. The lower zone of the cup, which is subjected to tensile stress, undergoes a thinning of 0.094 mm. Towards the end of the wall, which is the forming zone where almost all the deformation of the blank takes place, an increase in thickness is observed that exceeds slightly 0.1 mm.
4. Strain path change magnitude

Schmitt et al. [6] proposed a parameter Θ to quantify the intensity of strain path changes. This parameter is defined as the cosine of the angle between strain rate tensors during the pre-strain D₁ and the subsequent strain path D₂. The parameter Θ is given as follows:

\[ \Theta = \frac{D_1^p \cdot D_2^p}{||D_1^p|| ||D_2^p||} \]  

Θ is equal to 1 in the case of a monotonic loading, -1 for the Bauschinger type loading and 0 for the orthogonal strain path change [8]. The purpose of this work is to identify the geometrical parameters that influence the parameter Θ. In order to highlight such strain path changes during this process, the calculation of the parameter Θ is performed with Matlab software from the values of the incremental plastic strain tensors D_p^δt in Abaqus given at each increment δt of the finite element resolution and is calculated in-between two states corresponding to two distinct positions of the punch in the simulation, by using Eq. (1). Different maximum time increments were tried, to investigate their sensitivity on the calculation but it was rather weak. An increment of δt = 0.1 s was retained for the first stage since the variation of Θ was difficult to capture in this step, although an increment of δt = 0.2 s was set for the second stage.

Strain path changes occur both during the first stage (Fig.4a) and the second one (Fig.4b) but with a rather different magnitude. The plotted values are calculated for a point located in the cup wall, at a
radial distance of 3.5 mm from the cup bottom, on the side in contact with the first punch. From the given tool dimensions in Table 1, values of 0.6–0.8 are encountered in stage 1, down to values close to 0.35 in stage 2. It should be noted that the values plotted in Fig.4 are the lowest strain path change ($\Theta$=0.6) observed in the first stage, while in the second stage, a lower value of $\Theta$=0.35 is recorded, but both results were reported in a given area that may be different for the first and second stages.

4.1. Strain path indicator in the first stage

Fig.5 presents the evolution of $\Theta$ for a given die radius, ranging from 2.6 mm to 3 mm, while varying the punch radius in the first stage. It is observed that this parameter has a weak influence on the recorded strain path changes, since the lowest value of $\Theta$=0.599 is similar to the value obtained previously. The lowest value is obtained for the same punch stroke (8mm), for a die radius of 3 mm and a hollow punch radius equal to 2.3 mm.

![Figure 5](image1.png)

**Figure 5.** Evolution of the parameter $\Theta$ as a function of the punch radius during the first stage

4.2. Strain path indicator in the second stage

In the second stage, severe strain path changes are expected due to bending-unbending on the die radius. Fig.6 presents the evolution of $\Theta$ for a given die radius ranging from 1.8 mm to 2.5 mm, while varying the punch radius from 1.6 mm to 2.3 mm. It is interesting to note that the punch radius is the key parameter that governs strain path changes in the second stage. The scattering of $\Theta$ is quite large for the different configurations, the lowest value of $\Theta$=-0.1 being for a die radius equal to 2.3 mm and the hollow punch radius equal to 1.7 mm.

![Figure 6](image2.png)

**Figure 6.** Evolution of the parameter $\theta$ as a function of the punch radius during the second stage
4.3. Influence of the punch-die gap

Fig. 7 presents the evolution of Θ when the gap between the punch and the die varies with respect to the initial thickness of the cup in each stage. Even if the thickening of the sheet is weak in the first stage and lower than the gap, the evolution is slightly sensitive to this parameter and the value of Θ is minimum for a gap equal to 0.17mm. For the second stage, the gap between the punch and the die has a large influence on the evolution of the parameter Θ since its value drops down to values lower than 0 due to wrinkling when the gap reaches 0.2mm. Then, the minimum of Θ without wrinkles, corresponding to a gap equal to 0.16mm, seems to be a good compromise.

![Figure 7. Evolution of the parameter Θ as a function of the gap between the punch and the die during both stage](image)

5. Conclusion

This study deals with the design and the numerical simulation of a reverse deep drawing test of ultra-thin metallic sheets, typically 0.1mm-thick industrial copper. 2D simulations are performed to optimize the process design parameters and to quantify the evolution of strain path changes occurring in both stages of the process. It was found that large strain path changes occur in the second stage. The retained configuration exhibiting higher strain path changes in order to obtain a final 30 mm diameter cup has a die radius of 3 mm and a hollow punch radius equal to 2.3 mm for the first stage, and a second punch radius equal to 1.7 mm with a die radius of 2.3 mm. For both stages, a gap between the punch and the die of 0.16 mm may be used.

References

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