AA1100-O cylindrical cup-drawing using 3D servo-press

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Abstract. In this paper, the flexibility of a 3D servo-press is used as the inspiration to numerically demonstrate the ability to improve the final product, in this case reduced equivalent plastic strain, increased forming depth, and reduced punch force, during cylindrical cup-drawing. The material investigated is AA1100-O which exhibits significant anisotropy, i.e., r-values of 0.45 to 1.2 in 45 degree and transverse direction to rolling, respectively. This leads to earing during cup-drawing, which is used to validate numerical simulation efforts. A unique 3D servo-press at the Institute for Production Engineering and Forming Machines at the Technische Universität Darmstadt allows for tilting and orbital motion of the blank holder and with this a variation of the blank-holding force during the punch progression. Numerical simulations are used to demonstrate improvements with respect to equivalent plastic strain and forming depth.

1. Introduction
Non-linear and orbital stroke trajectories have been the focus of research in bulk forming and incremental forming for several years. In bulk forming, a superposition of oscillations resulted in reduced forming forces [1]. In sheet metal forming, an enhancement of the quality of the formed part, an extension of the process limits, and a reduction of the forming force were achieved by the superposition of oscillations, as well [2]. In conventional deep drawing of cylindrical cups, pulsating BH forces increase the formability [3]. Altering tribological conditions due to the pulsating forces are the main reason for this effect [4, 5]. Furthermore, some materials show an improved forming behavior under pulsating loads [5-9].

Besides oscillating punch and BH movements, non-linear punch movements in various dimensions are a promising approach to improve forming processes. In comparison to linear punch movements, orbital trajectories result in smaller contact areas between workpiece and tooling (Figure 1) and, therefore, lower forming loads [10]. The achievable degree of deformation is usually higher than in ordinary, linear forming, at the expense of increased cycle times due to the incremental nature of the forming process [10].
In bulk forming, the use of orbital trajectories produces an improvement of part quality [11]. In sheet metal forming processes, the use of orbital trajectories is presently limited to incremental forming applications [12]. In comparison to ordinary sheet metal forming processes, incremental forming is slower and, therefore, less competitive [13]. Doege and Elend [14] showed an improvement of formability in deep drawing when a pliable, passive BH instead of a rigid one was employed. The authors ascribe this to an optimized contact pressure distribution. This finding suggests that active control of the BH movements to adapt locally the BH pressure is a promising approach to improve formability in deep drawing.

To date, the design of presses enabling orbital movements usually only provides the option for periodical orbital movements. In the past 10 years, servo-presses have come to the forefront, allowing for non-monotonic movements of the ram, which improves formability [15, 16]. A unique, state-of-the-art 3D servo-press at the Institute for Production Engineering and Forming Machines at the Technische Universität Darmstadt [17] provides a flexible ram motion with various degree of freedoms, and as a result of that, a locally distributed blank holding force is possible. The tilting motion of the ram is achieved by rotation along the x- or y-axis, which is transferred by translational motions and springs in the x-y plane. Based on the combination of the rotations, a variable blank-holding force can be applied to the blank during a cup-drawing. The main advantage of this new press design is the possibility to provide non-linear and orbital movements, controlled independently by servo motors. Therefore, arbitrary, non-periodical orbital or tilting movements are possible, without additional actuators.

In this paper, the inspiration of the 3D servo-press is used to numerically investigate possible improvements during cylindrical cup-drawing of AA1100-O, which exhibits significant anisotropy. Earing that is produced validates the numerical simulation efforts. Results show improvements in the equivalent plastic strain and forming depth, but extensive parametric studies are still required for further improvements.

2. Plasticity characterization and model calibration
Plastic anisotropy of AA1100-O (0.5 mm thick.) is characterized by uniaxial tension (UT), disk-compression (DC), and plane-strain tension (PST) experiments (Figure 2 (a)): 7 uniaxial tensions in every 15° from the RD (Figure 2 (b)), disk-compression (Figure 2 (c)), and 3 plane-strain tensions in the RD, 45°, and TD (Figure 2 (d)). The plastic anisotropy in the flow stress is normalized by the uniaxial tension in the RD, and the results are summarized in Table 1. Note that the directional anisotropy of the flow stress is not as strong compared to that of the r-values (Figure 3 (a)).

The experiments are used to calibrate parameters of the Yld2000-2d non-quadratic anisotropic yield function [18]. 8 parameters $\alpha_1$ are optimized by 18 experiments using a least square method, in which 18 experiments are equally weighted (see the results in the Table 2). Exponent of Yld2000-2d is given as $m=8$ for the fcc crystal structure. The calibrated yield locus of Yld2000-2d is shown in Figure 3 (b) with the experiments and von Mises (vM) results also provided. In addition to the yield function, strain hardening of the uniaxial tension in the RD is fitted by Voce law. The constitutive material models are implemented into user subroutine code and the models with calibrated parameters are used for the finite element (FE) simulations.
Figure 2. Experiments for the plasticity characterization: (a) specimen geometries for uniaxial tension, disk-compression, and plane-strain tension, (b) stress-strain curves of uniaxial tension, (c) strain ratio of equibiaxial tension in disk-compression, and (d) stress-strain curves of plane-strain tension.

Figure 3. Result of parameter calibration for the yield function and hardening law: (a) directional anisotropy of uniaxial tension, (b) yield locus predicted by Yld2000-2d model, and (c) flow curve extrapolated by Voce law.
Table 1. Summary of mechanical properties

|                  | UT    | RD    | 15°   | 30°   | 45°   | 60°   | 75°   | TD    |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Young’s modulus  | 1.000 | 1.019 | 1.047 | 1.055 | 1.069 | 1.038 | 0.998 |       |
| Poisson’s ratio  |       |       | 0.714 | 0.495 | 0.445 | 0.560 | 0.858 | 1.183 |
| r-value          | 0.943 |       |       |       |       |       |       |       |

Table 2. Material parameters of Yld2000-2d model

|     | m     | α₁    | α₂    | α₃    | α₄    | α₅    | α₆    | α₇    | α₈    |
|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 8   | 0.9689| 1.0414| 1.0252| 0.9950| 1.0058| 1.0034| 0.8912| 0.9431|       |

3. FE simulation for the conventional cup-drawing

As a comparison of the cup-drawing with an orbital motion, i.e., blank holder is subjected to an orbital rotation so that blank holding pressure can be locally distributed in the flange area, a conventional cup-drawing simulation is conducted initially. The blank holder is placed above the blank with a constant gap δ=0.02 equivalent to 4% of the thickness and is fully constrained (Figure 4 (a)). The blank is constructed by shell elements with full integration points (S3 and S4), and only a quarter size is modeled by considering symmetries in x- and y-plane (see Figure 4 (b) for mesh). The simulation results are represented in Figures 5 (a) and (b). Yld2000-2d model successfully predicts the earing profile along the cup height, which is developed by the plastic anisotropy, while vM shows the constant cup height due to isotropic nature of the model.

Figure 4. FE modeling for the conventional cup-drawing: (a) tooling and (b) a quarter size of blank.

Figure 5. Prediction results using von Mises (vM) and Yld2000-2d models: (a) equivalent plastic strain and (b) earing profiles of the prediction and experiment.
4. FE simulation for the orbital motion cup-drawing

The simulation for the orbital motion cup-drawing is conducted using the same tooling with the conventional cup-drawing (Figure 4 (a)) except that the blank holder is not fully constrained but allowed to move in an orbital fashion. A full size blank is used with the same mesh pattern of the quarter model in Figure 4 (b). Three parameters of the orbital motion of the blank holder are considered (Figure 6 (a)). 1) Initial gap between the blank and blank holder for the orbital motion is $\delta = 0.1$, which is larger than that for the conventional cup-drawing model ($\delta = 0.02$), to increases the potential for wrinkling as the blank draws-in. 2) The maximum orbital angle is $\theta = 0.368^\circ$, which is $\sim 2.5\%$ compressive strain in the axial direction applied at the blank edge initially. 3) 3 cycles of the blank holder orbital motion are applied as the blank is drawing-in (Figure 6 (b)). For the parametric study of the orbital motion, only the von Mises model is used at the moment for simplicity.

Figure 7 (a) shows equivalent plastic strain distribution of fully drawn cups with the conventional and orbital motion. Both reach similar levels of max. equivalent plastic strain, but the orbital motion ($\varepsilon_{\text{max}} = 0.618$) is slightly lower than the conventional cup-drawing ($\varepsilon_{\text{max}} = 0.62$). Meanwhile, the orbital motion yields a higher cup height ($h_{\text{max}} = 10.652$ mm) than the conventional cup-drawing ($h_{\text{max}} = 10.392$ mm). Although the current orbital motion represents a minor improvement, this observation proves a potential for the orbital motion and further investigations will be pursued in the future through an extensive parametric study. In contrast, a visible difference of conventional and orbital motion cup-drawings is observed in the punch force-displacement curves as shown in Figure 7 (b). The force level of the orbital motion is lower than the conventional cup-drawing because of the lower friction effect in the flange area.

![Figure 6. FE modeling for the orbital motion cup-drawing: (a) tooling and (b) orbital path.](image)

![Figure 7. Comparison of conventional and orbital motion cup-drawings for (a) equivalent plastic strain and (b) force-displacement curves in](image)
5. Conclusion

Cup-drawing of AA1100-O is investigated with a conventional process and one with orbital motion of the blank holder. In conventional cup-drawing simulation, Yld2000-2d model shows a good agreement with the experiments of the earing profile, which validates the modeling efforts and implies an importance of anisotropic plasticity modeling for the cup-drawing simulations. In contrast, the orbital motion cup drawing mainly focuses on the parametric study of the blank holder motion using von Mises model. The simulation results predict that the orbital motion is expected to slightly improve the drawing depth compared to the conventional cup drawing. For future works, Yld2000-2d will be used for the orbital motion cup drawing simulation to investigate the effect of orbital motion on the earing profile and the result will be compared with the experiments further.

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