Experimental and numerical investigation of ironing in deep drawn parts

A. Güner¹*, M. Gösling², I. Burchitz³ and B. Carleer⁴

¹ AutoForm Engineering, Joseph-von-Fraunhofer-Straße 13a, 44227 Dortmund, Germany
² BILSTEIN GmbH & Co. KG, Im Weinhof 36, 58119 Hagen, Germany
³ AutoForm Engineering B.V., Industrieweg 2, NL-2921 LB Krimpen a/d IJssel, Netherlands

*Alper.Guener@autoform.de

Abstract. Majority of the industrially relevant deep drawn sheet metal parts undergoes an additional process after the drawing operations. Operations like flanging or hole extrusion are widely used especially in the automotive industry. In such industrial applications it is seen that process planers design the tools by using a clearance less than the sheet thickness. Due to this smaller gap between the forming steels and the post, sheet material is compressed in the thickness direction. This additional compression is definitely needed for collar forming and it is beneficial in flanging operations in terms of springback. Addition of compressive deformation state on flange regions reduces the bending effects on those parts. Ironing in sheet thickness direction is a challenging deformation state for numerical simulations. This effect can be modelled by 3D continuum elements. However, due to high computation times this solution is not feasible for industrial applications. On the other hand, shell elements are widely used in sheet metal forming problems due to their efficiency but the conventional shell elements cannot predict ironing effects since the formulation does not consider through-thickness deformation. In order to analyze the effect of ironing, cup drawing experiments were performed. Ironing level is controlled by changing the die diameter while keeping the punch diameter constant. DC04-SUPERMOD with 1.75 mm thickness was used in the experiments. The thickness distribution along the cup wall and height of the cups were measured after each operation. Same experimental procedure was modeled using new thick shell elements which accounts for the through-thickness deformation. Comparison with the experimental measurements show that the enhanced formulation of the shell elements can be used to simulate the ironing effects in deep drawn parts.

1. Introduction

Ironing occurs in stamping operations especially in flanging operations [1]. In flanging, the clearance between the forming steels and the post is set to a value which is smaller than the current sheet thickness. By this way, additional to bending, the sheet is ironed between two rigid tools. The aim hereby is to superimpose compressive stresses, in order to reduce the effect of bending moments which cause springback. Another application of ironing in stamping operations is the hole flanging or hole extrusion operations [2,3].
Process planners use conventionally shell elements to design and model the sheet metal forming processes. However, the conventional shell element formulation does not take the through-thickness deformation into account. For that reason, it is not possible to simulate ironing and its effect on springback with this methodology. There are analytical works to provide a simple solution for the deformation which is applicable to axisymmetric cups [4,5]. There are also attempts to simulate the ironing process with 3D continuum elements [6]. However, due to the disadvantages regarding the computation times, it is not feasible to utilize this solution in process planning. Hence, there is a need for an enhancement of the shell elements to account for the deformation in thickness direction. Additionally, friction state should also be characterized by using proper experiments [7,8].

In order to analyze the effect of ironing, cup drawing experiments were performed. After deep drawing, the cups were ironed using different dies having different clearances. By this way, four different cases were analyzed. Thickness distribution along the cup walls and the cup height profiles were measured. The same problem was modeled with new thick shell elements and the results were compared. It was seen that the enhanced formulation predicts the deformation of the cups with high accuracy without losing the advantages of the shell elements regarding computation times.

2. Experiments

2.1. Material characterization

The sheet material used in the experiments was a DC04-SUPERMOD with 1.75 mm thickness. The main advantage of this alloy as compared to a standard DC04 is its low coercive field strength as shown in Figure 1. Thus, the material closes the gap between mild steel and electrical steel. Applications for this material are e.g. solenoid valves in car gears.

In order to characterize the material, uniaxial tension tests in 0°, 45° and 90° to rolling directions, hydraulic bulge tests and disc compression tests were performed. Obtained flow curve of the material can be seen in Figure 1. Disc compression test was only used to obtain the $r_b$ value. By this way the yield stresses in different orientations and also the corresponding $r$-values were obtained.

![Figure 1. Flow curves and coercivity values of DC04-SUPERMOD](image)
2.2. Cup drawing and ironing
Forming experiments were performed with the sheet metal testing machine Erichsen-145-60 with a punch diameter of 33 mm. Blank diameter was selected to be 64 mm. Four different cases were defined regarding the used ironing levels. Table 1 lists the utilized tool clearance in those cases which is given as the gap between punch and die. In Case 1, only deep drawing was performed. In Case 2 and Case 3 there is an ironing operation in addition to deep drawing. Finally, in Case 4 there are two subsequent ironing operations with decreasing tool clearances.

| Case  | Deep drawing | 1. Ironing | 2. Ironing |
|-------|--------------|------------|------------|
| Case 1| 2.13         | -          | -          |
| Case 2| 2.13         | 1.77       | -          |
| Case 3| 2.13         | 1.48       | -          |
| Case 4| 2.13         | 1.48       | 1.18       |

The resulting cups and the measured cup height profiles can be seen in Figure 2. Five repetitions were performed for each case. Cup height profiles show that with increasing ironing level, the average cup height increases. Because of the anisotropy of the sheet material the cup height is not constant over the circumference. Earing intensity is also affected by the ironing level which can also be seen in Figure 2. The difference between the ear peaks and valleys decreases from case 1 to case 2 and then increases again with the other cases.

![Figure 2. Deep drawn and ironed cups with the corresponding height profiles and mean ironing heights.](image-url)
3. Numerical analysis

A new thick shell element formulation was used in this study in order to analyse the four cases. The enhancement of the shell element aims at a more efficient modelling of forming processes such as flanging. A homogeneous finite element mesh with triangular elements was used. Side length was set to 1.0 mm without any adaptive refinement. The material was modelled by using the BBC model (BBC2005) with the information coming from tensile tests in three orientations, hydraulic bulge test and disc compression test [9]. This model allows consideration of the yield stresses and r-values under uniaxial tension in three orientations and under biaxial tension. A constant coulomb friction coefficient of 0.23 was used in the models. The full blank was modelled without any symmetry and the tools were assumed to be rigid.

Figure 3 presents the measured and numerically obtained thicknesses along cup walls for the four cases. The cups were cut along the rolling direction and transverse direction to analyse the thickness of the cups in two main directions. Therefore, for each case there are two diagrams showing the results in longitudinal and transverse directions. Cup height \( h \) is defined as the vertical height of the measurement points with respect to the bottom of the cup. Final measurements with the maximum heights were performed directly on the outer edge of the cups. In those diagrams, it can be seen from left to right (Case 1 to Case 4) that thickness reduces gradually as a function of the ironing level.

In Case 1, thickening occurs at the ends of the cups which is correctly predicted by the shell elements. Hereby, the thickness along the transverse direction at the ends of the cup corresponds to the set tool clearance, which means that there is a slight ironing which occurs at the end of drawing operation. In Case 2, the thickened parts of the cup wall are ironed which are captured by the last three measurements from the end of the cup. Case 3 is the first case where the whole cup was ironed and this effect shows itself as a constant wall thickness along the whole cup height. The results of the Case 4 show the thickness distribution after the second ironing operation which represents the most severe ironing case. The results of all the cases show that the new thick shell element formulation can predict the thickness distribution with an error less than 5%.

![Figure 3. Measured and numerically predicted thicknesses along the cup wall](image-url)
The cup height profiles are presented in Figure 4 for the studied cases. In Case 1, which is solely a deep drawing operation, cup heights distribution reflects the anisotropy of the sheet material. There are four ears in the cup. The effect was also captured correctly by the finite element simulations. In Case 2, there is a slight increase of the cup height with an average of 0.5 mm. The height profile was predicted with a high accuracy having a difference of less than 2%. In Case 3, there is an average height increase of 3 mm. In this case, there is a maximum difference of 4% between the simulation and experiment. In Case 4 an average height increase of 8.5 mm was achieved. New thick shell elements predicted the cup height in this very severe ironing case with an error less than 3%.

Figure 4. Cup height profiles of the four cases
Hereby, it should be noted that in Case 4 the cup thickness is reduced from 2.1 mm to 1.2 mm which generates high plastic strains on the cup wall. In flanging operations, utilized ironing levels do not exceed 15 % of the initial sheet thickness which corresponds to the Case 2. This slight plastification is enough to reduce the bending effects. For that reason, it can be said the enhanced element formulation was verified by using very severe deformation levels which are higher than the expected deformations in technologically relevant flanging operations.

4. Conclusion
Currently, the ironing process in flanging operations is not simulated by the process engineers since the conventional shell element formulation does not consider the through-thickness stresses. Therefore the level or ironing in flanging operations is determined during the tryout phase which is a very time consuming issue. In order to be able to predict the effect of ironing on the springback in process design phase, a new thick shell element formulation was developed and used in this study. The experimental cup drawing and ironing results were compared with the numerical results. It was shown that the enhancements in the element formulation can capture the material flow with a high accuracy. Maximum error in numerical predictions of thicknesses or cup heights is less than 5 %. Even in the most severe ironing case with 45 % ironing level, numerical predictions are in agreement with the experiments. From the technological point of view, as a result of this study, capability of the process engineers in design phase was improved by including the accurate simulation of ironing effects in flanging processes.

References
[1] Adamovic D, Mandic V, Zivkovic M, Gulisija Z, Stefanovic M and Topalovic M 2013 Numerical modeling of ironing process J. Technol. Plast. 38
[2] Kacem A, Krichen A and Manach P 2011 Occurrence and effect of ironing in the hole-flanging J. Mater. Process. Technol. 10 1606–13
[3] Rachik M, Bompierre M and Maillard A 2014 Experimental And Numerical Investigation Of The Hole-Flanging Process IDDPRG 2014 Conference pp 381–5
[4] Yoon J W, Dick R E and Barlat F 2010 Evolution of Earing during Drawing and Ironing Processes Proceedings of the 12th International Conference on Aluminium Alloys pp 1195–200
[5] Yoon J W, Dick R E and Barlat F 2008 Analytical prediction of earing for drawn and ironed cups Numisheet2008 97–100
[6] Barros P D, Alves J L, Oliveira M C and Menezes L F 2012 Earing Evolution During Drawing and Ironing Processes 10th World Congr. Comput. Mech. 1 3954–73
[7] Üstünyagiz E, Nielsen C V., Christiansen P, Martins P A F and Bay N 2017 Continuous Strip Reduction Test Simulating Tribological Conditions in Ironing Procedia Eng. 207 2286–91
[8] Djordjević M, Aleksandrović S, Lazić V, Arsić D, Nikolić R R and Hadžima B 2016 Investigation of the lubrication influence on single-phase and multi-phase ironing processes Procedia Eng. 149 40–7
[9] Banabic D 2010 Sheet Metal Forming Processes (Springer-Verlag)