Efficient simulation of ironing process for deep drawn parts

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Abstract. In deep drawing of automotive components, the thickness distribution of the workpiece is a major concern regarding the feasibility of the process. A major geometrical parameter regarding the thickness distribution is the clearance between the punch and the die. The general industrial convention regarding this clearance is to use the initial blank thickness combined with a tolerance. This approach assures that the sheet is not compressed in the thickness direction which leads to undesired or undefined deformations and also high forces. Nevertheless, deformation in the thickness direction during stamping operations can be desired or advantageous in some cases. For instance, in flanging operations, ironing is used to reduce springback. There are already applications using solid elements for modelling such operations but these simulations are industrially not relevant due to high computation times. Currently, there is a need for an efficient simulation solution using shell elements. In order to address this problem, the shell element formulation was enhanced by taking the through-thickness deformation into account. In order to verify the new formulation, cup drawing experiments were performed using three different degrees of ironing. The material was a DC04-SUPERMOD with 1.75 mm thickness that was characterized by tensile tests in three directions, a bulge test and a layer compression test. Numerical and experimental results were compared in terms of the thickness distribution along the cross-section and the cup heights. Results show that the ironing process, which occurs in automotive stamping parts, can be simulated with enhanced shell elements without significant additional computational cost.

1. Introduction

Ironing is a widely used method of producing sheet metal parts. It differs from deep drawing in that the clearance between the punch and the die is smaller than the sheet thickness. There are a multitude of applications in the automotive industry. They are used for rotationally symmetrical hollow bodies with high demands on the roundness and the sheet thickness distribution. Examples can be found in the transmission and brake system. A further example is the flanging process where the distance between the flanging steels and supporting post is less than the sheet thickness. In such cases, it is attempted to superimpose compressive stresses and reduce springback [1]. Other examples are hole extrusion or collar forming which can be found commonly in structural members [2,3].

Especially in flanging operations, ironing provides a flexible tool to control springback. In this case, additional deformation in flanged regions superimposes compressive stresses along the flange, which reduces springback. This deformation state creates a challenge for analytical and numerical

analyses [4,5]. Conventionally utilized shell elements are not suitable to simulate ironing due to their plane stress formulation. For that reason, there are attempts to use solid continuum elements which increase the computation times considerably. However, they are less suitable for the industrial applications. Another challenge hereby is the characterization and modelling of friction conditions during ironing [6].

Hence, there is a need for further understanding of the ironing process which occurs in stamping operations with the aim to supply an effective tool especially for process engineers. In that respect, this study focuses on improving the prediction capability of shell elements and verification of the results with ironing tests performed on axisymmetrical cups. For that purpose, a mild steel alloy was selected and characterized. Afterwards, ironing experiments were performed with different ironing levels. Cup heights and thickness distribution along the cup wall were recorded as experimental results. The same problem was modeled with thick shell elements and the results were compared.

2. Experiments

2.1. Material
As material for these experiments, a DC04-SUPERMOD in 1.75 mm sheet thickness was selected. The development towards electro mobility will increase the importance of sheet metal materials with special electromagnetic properties. High-alloy electrical steel strip offers a range of metallurgical features as standard (and included in the cost), that in some cases may not be required completely. Unalloyed steel grades such as the DC04-SUPERMOD can also fulfill such requirements. Compared to a standard DC04, this material shows a low coercivity H_{cJ} (coercive field strength, see Fig. 1). This means that this material is easy to magnetize and demagnetize and can be used as a magnet housing. Thus, the material closes the gap between mild steel and electrical steel. Applications for this material include solenoid valves in car gears.
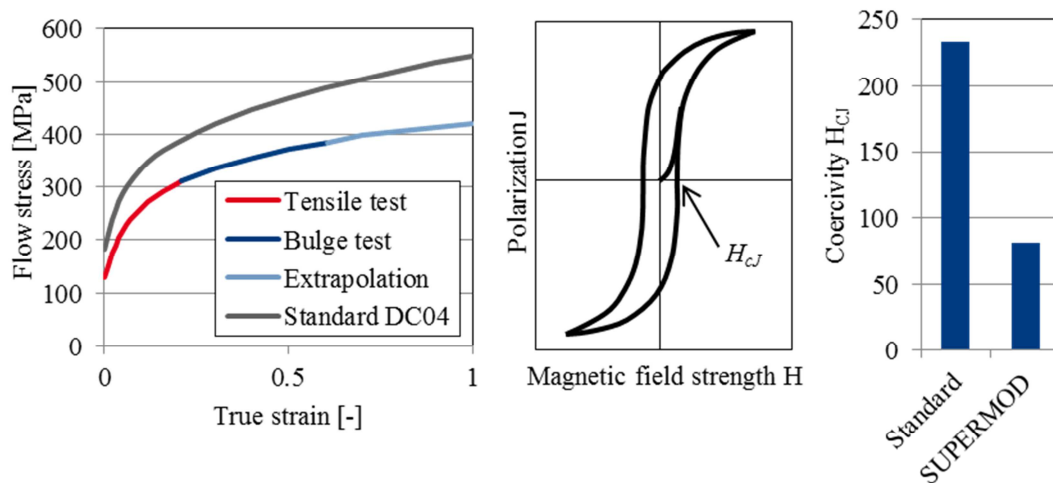

Figure 1. Material properties of DC04-SUPERMOD.

Material properties, such as anisotropy, affect the experimental measurements and numerical predictions of earing profile and thickness distribution. Because of this, the material was characterized by using uniaxial tensile tests at 0°, 45° and 90° to rolling direction, a hydraulic bulge test and a disc compression test. The determined flow curve, which is a combination from tensile test and hydraulic bulge test, is shown in Figure 1. The planar anisotropy of the material is $\Delta r = 0.23$, which means that a small degree of an earing profile is to be expected during cup-drawing.

2.2. *Deep Drawing and Ironing*

The deep drawing and ironing tests were carried out on the Erichsen-145-60 sheet metal testing machine. A punch and blank diameter of 33 mm and 64 mm was used respectively. Due to the cup size, bending effects are expected around punch and die radii. The selected setup ensures a radius-thickness ratio of 2.0 around the die profile radius. Hence, it was assumed that bending is not the dominant deformation state, especially after ironing operations. The deep drawing setup can be seen in Figure 2. A constant binder force of 6 kN and a punch stroke of 40 mm were used in the experiments. A semi-solid lubricant was used for lubrication. In the subsequent ironing operations, the tool clearance shown in the figure was varied.
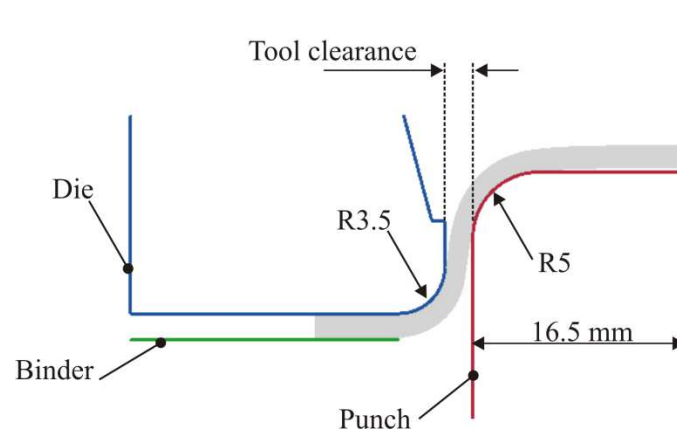

Figure 2. Deep drawing setup and definition of tool clearance.

The drawing and ironing clearance of the dies can be found in Table 1. Four cases were studied in total. Case 1 is solely a deep drawing operation. However, due to thickening of the flanges during drawing, some ironing occurs towards the end of the operation. Cases 2 and 3 have an additional ironing operation with different clearances. Case 4 is the most severe ironing condition having two subsequent ironing operations after drawing with decreasing clearance.

Table 1. Tool clearances in drawing and ironing operations.

	Tool clearances in mm			
	Case 1	Case 2	Case 3	Case 4
OP1 (Deep drawing)	2.13	2.13	2.13	2.13
OP2 (Ironing)		1.77	1.48	1.48
OP3 (Ironing)				1.18

Figure 3 shows deep-drawn (Case 1) and ironed cups (Cases 2-4). For each case, 5 repetitions were performed. In order to measure the wall thickness, cups were cut along the rolling direction and transverse direction. By this way, thickening and ironing could be measured directly on the cup. The deep-drawn cup shows an uneven distribution of the sheet thickness over the cup height and also over the angle to the rolling direction. By ironing, a more uniform distribution of the sheet thickness is produced. The greater the ironing degree, the more uniform the sheet thickness distribution becomes.
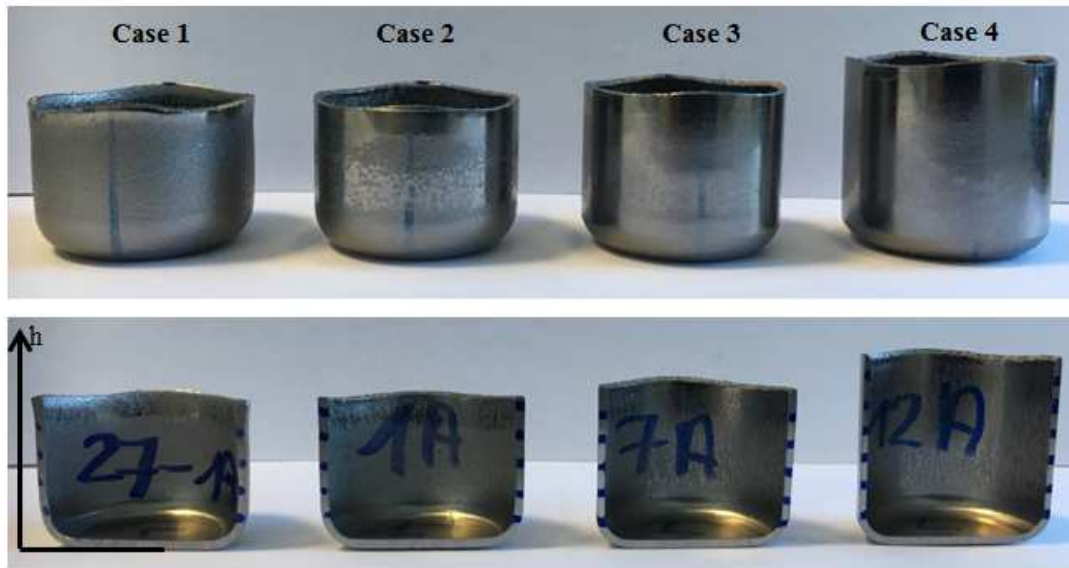
Figure 3. Cups after deep drawing and ironing.

Figure 4 shows measured cup heights. Due to the anisotropy of the material, the cup height is not constant over the circumference. The height differences of the cup walls can be described by the mean earing height h_e. The mean earing height h_e is the difference between the mean value of the ear peak h_p and ear valley h_v. After the first ironing step, the earing height decreases and then increases again in the further ironing steps. The height increase of the cup is the main result of ironing (in addition to the sheet thickness decrease). In order to be able to clearly compare the simulation result and the experimental result, the mean height increase is defined:

$$\Delta h = h_{m,OPi} - h_{m,OPi-1} \ with \ h_m = \tfrac{1}{2}(\bar{h}_p + \bar{h}_v) \tag{1}$$
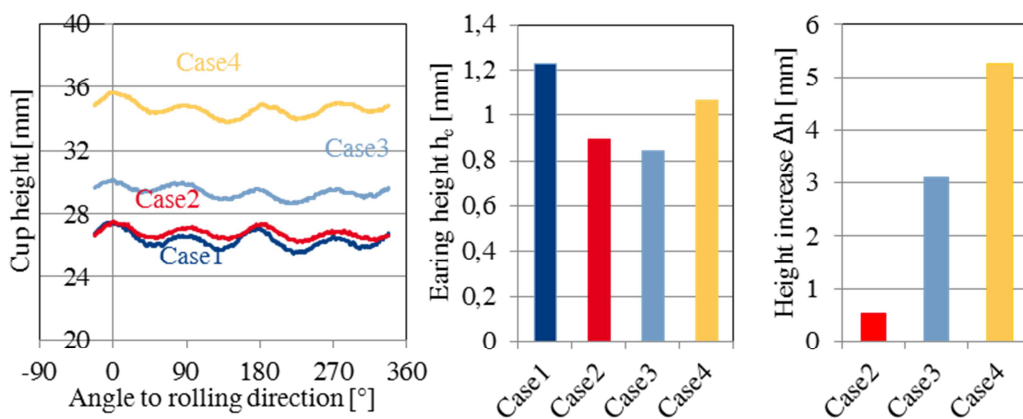

Figure 4. Cup height profiles (experimental measurements).

3. Finite Element Simulations

In order to analyze the problem numerically, a finite element model was constructed and simulated using AutoForm-Solver[plus]. A new thick shell element formulation that allows consideration of through-thickness deformation of the material was used. Homogeneous mesh with an element size of 1 mm was used in all simulations without any adaptive refinement. 11 integration points were used through the thickness. The sheet material was modeled with isotropic hardening using the BBC model

(BBC2005) with the information coming from uniaxial tension tests in three orientations, hydraulic bulge test and disc compression test [7]. A coulomb friction coefficient of 0.23 was used throughout the simulations, which was assumed to remain unchanged during ironing. The blank was simulated without any symmetry boundary condition. All the tools were assumed to be rigid.

Figure 5 shows the predicted and measured thickness distribution along the cup wall. Measurements were performed after cutting the cup. Cutting was performed along rolling direction (designated as LD in the figure) and along the transverse direction (designated as TD in the figure). Cup height h corresponds to the vertical position with respect to the bottom of the cup and the last measurements were performed on the cup ends. In Case 1 which is a deep draw operation, it can be seen that there is thickening especially at the ends of the cups. The final thickness in the transverse direction is equal to the tool clearance, meaning that the final part of the cup in transverse direction was ironed even in deep drawing operation (slightly). The numerical thickness distribution predicts the experimental distribution with an error less than 4%.

Case 2 is the first case with ironing at the mildest ironing level. Again, the thickness prediction matches with the experimental measurements. The final three measurements hereby correspond to the ironed regions of the cup and in those measurements the thicknesses were predicted correctly. For Cases 3 and 4, the same behaviour can be observed. In particular, Case 4 shows the effect of ironing directly where almost all the cup wall thickness is constant meaning that the whole cup was ironed in the second ironing step.
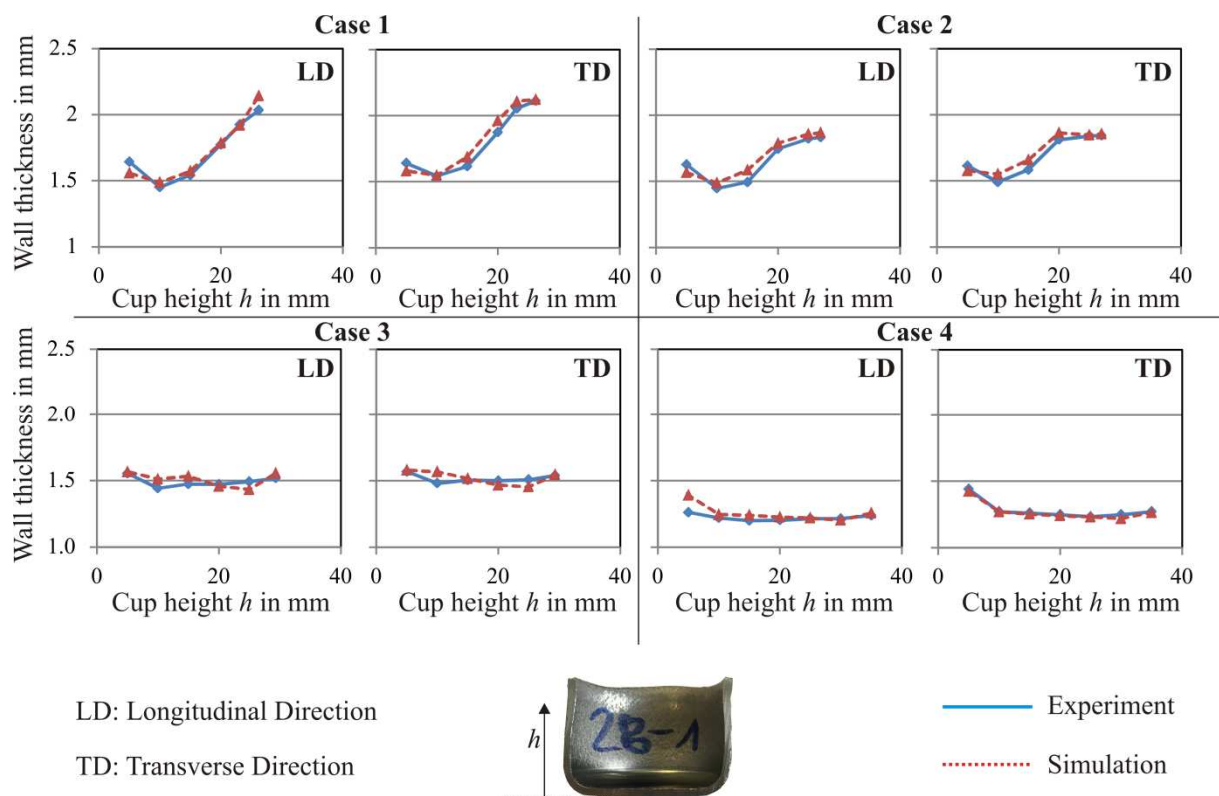

Figure 5. Experimental and numerical thickness distributions along the cup wall.

Cup height profiles were measured for each case and compared with the numerical predictions. These results can be seen in Figure 6. The vertical axes of the diagrams were set to a range of 10 mm but the cases have different heights due to ironing. In Case 1, there is a difference less than 0.5 mm between the experimental measurements and numerical results. In case 2, cup height profiles match with a high accuracy. It can be seen that the height increase between Case 1 and Case 2 is less than 1

mm. With this slight ironing, the main effect can be observed in the mean earing height which reduces in Case 2. On the contrary, a considerable height increase is observed in Case 3 which is about 3 mm. In Case 4, the overall height of the cup is predicted with a difference less than 0.5 mm. Hereby, there is a height increase of almost 9 mm as compared to Case 1.
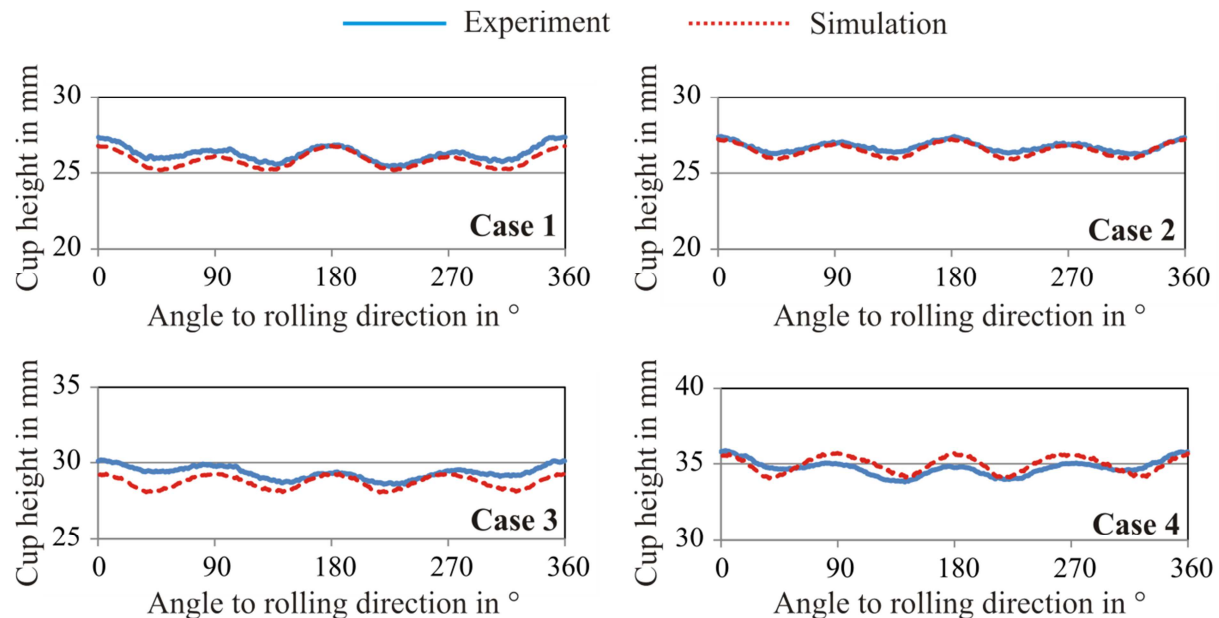

Figure 6. Experimental and numerical cup height profiles for the four analysed cases.

4. Conclusion

In stamping operations, ironing occurs either due to thickening of the flange regions during deep drawing or due to flanging operations which are designed with a tool clearance smaller than the sheet thickness. In this work, ironing was realized on cups by using dies having different clearances and different ironing levels were achieved which are presented in four cases. All of the cases were simulated by using enhanced shell elements which consider the through-thickness stresses. The results show that the enhanced formulation can predict the material flow with a high accuracy. This was verified by thickness distributions and cup height profiles. As a result of this work, process engineers can analyze the effect of ironing during method planning.

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