Influence of the sheet thickness variability on the deep drawing of a cylindrical cup

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Abstract. Sheet metal forming processes are widely used in industry. The quality of formed parts can be significantly affected by various sources of uncertainty inevitably associated with the forming process. The objective of this work is to quantify the influence of thickness variability on the forming process of a cylindrical cup. Using numerical simulation, the influence of the sheet thickness variance on the evolution of the punch force versus displacement, the equivalent plastic strain distribution, the earing profile and the thickness around the cup is studied for a given cup height. Four thickness distributions with different variance values and the same average thickness value were studied. It was concluded that an increase in variance leads to an increase in thickness dispersion (at the base and curvature of the cup) and an increase in equivalent strain dispersion along the cup. The earing profile of the cup is also affected by the thickness variability, but to a lesser extent. On the other hand, the development of the punch force is not affected by the thickness variability.

Introduction

Sheet metal forming is a widely used metalworking process in the automotive, aerospace, and metalworking industries [1]. These processes are generally designated and optimized through numerical simulation [2]. The Finite Element Method (FEM) is typically used, although it is based on a deterministic approach [3] that ignores the various sources of uncertainty that are unavoidable in a real industrial environment, such as variations in material properties, sheet thickness or process conditions [4]. These sources of uncertainty can significantly affect the quality of the final product [5-6], which can lead to inefficient manufacturing and costly redesign of the forming process.

Blank thickness is one of the most important factors in the stamping process, as it is dictated by the geometric requirements of the part, but also by its cost. The blanks are usually produced by the cold rolling process, so there is always some variability in the blank thickness along the material coil [7], for example due to mill chatter [8]. Several authors have studied the influence of thickness variability on wrinkling behaviour [9] and buckling [10-11], and conclude that the thickness uncertainty generates uneven stress and strain distributions, which in some cases can affect the forming results. In this sense, the blank thickness uncertainty can be one of the main uncertainty factors affecting the component quality.

This work presents a numerical study to quantify the influence of blank thickness uncertainty on the forming results of a cylindrical cup. The cylindrical cup was chosen because it is a commonly used benchmark test to represent sheet metal forming processes [12]. However, to the best of our knowledge, the influence of thickness uncertainty on the forming results of the cylindrical cup is still unexplored. Therefore, the aim of this work is to understand how the thickness variability can affect the forming results, in particular to evaluate the areas of the final part where the initial variations in material thickness have the greatest influence on the forming results. To this end, numerical simulations of the cylindrical cups are used to evaluate the influence of different levels of initial blank thickness variability in order to analyse their impact on the forming process results.

Numerical Model

In this work, the cylindrical cup drawing benchmark proposed in ESAFORM 2021 [12] is studied. This forming process setup consists of four tools, the punch, the blank holder, the die and the stopper. Fig. 1 illustrates the geometry and dimensions of these tools. The circular blank has an initial average thickness, t_0, of 1 mm and a diameter of 107.5 mm. The numerical simulation of the forming process consists of three stages: (i) at the start of the process, the blank holder moves downwards, pressing the blank against the die until a blank holder force of 40 kN is reached; (ii) the punch then moves downwards by 54 mm, drawing the blank completely into the die, while keeping the blank holder force constant at 40 kN; (iii) the last stage consists of the removal of the tools, resulting in the springback of the cup. During the second stage, a stopper of the same thickness as the blank is used to prevent the cup ears from being pinched.

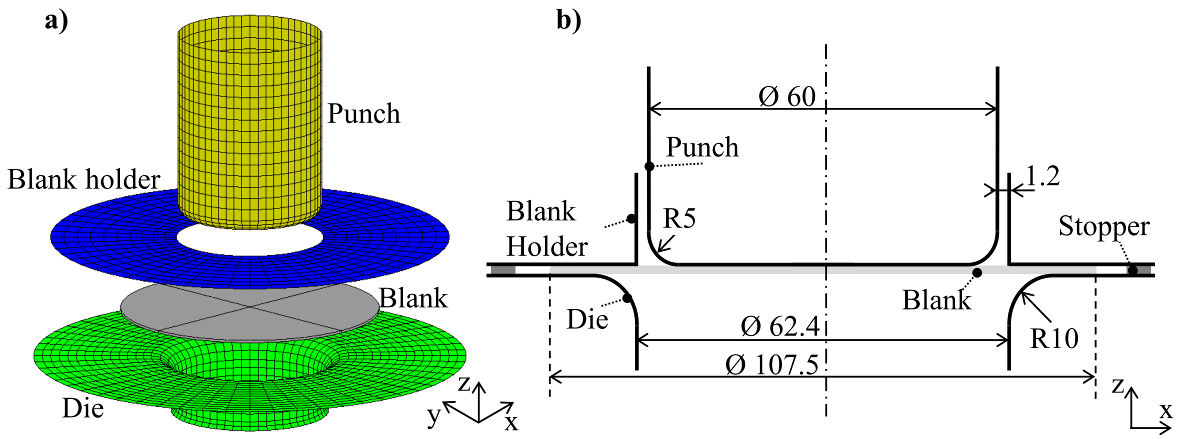

Fig. 1 - Cylindrical cup forming process: (a) numerical model; (b) dimensions of the tools and blank in mm (adapted from [12]).

The numerical simulations were carried out using the software DD3IMP (Deep Drawing 3D Implicit Code) [13]. In order to reduce the computational cost of the numerical simulation, only a quarter of the model was simulated due to the symmetry conditions of the material, geometry and boundary conditions. The friction between the tools and the sheet was assumed to be described by Coulomb's law with a constant friction coefficient of 0.07. The blank is discretised with 67968 (8-node hexahedral solid) elements, with 2 elements in thickness, combined with a selective reduced integration technique [13]. The final mesh is shown in Fig. 2 (a). It can be seen in this figure that the mesh is coarser in the centre because the blank is not significantly deformed in this area (bottom of the cup). In the most discretised area, i.e. the area between the flange and the punch corner, at least one element per 0.3 mm is used to represent the spatial distribution of the thickness variability. Each numerical simulation took an average of 36 hours on a computer equipped with an Intel® Core™ i7-8700K Hexa-Core processor (4.7 GHz).

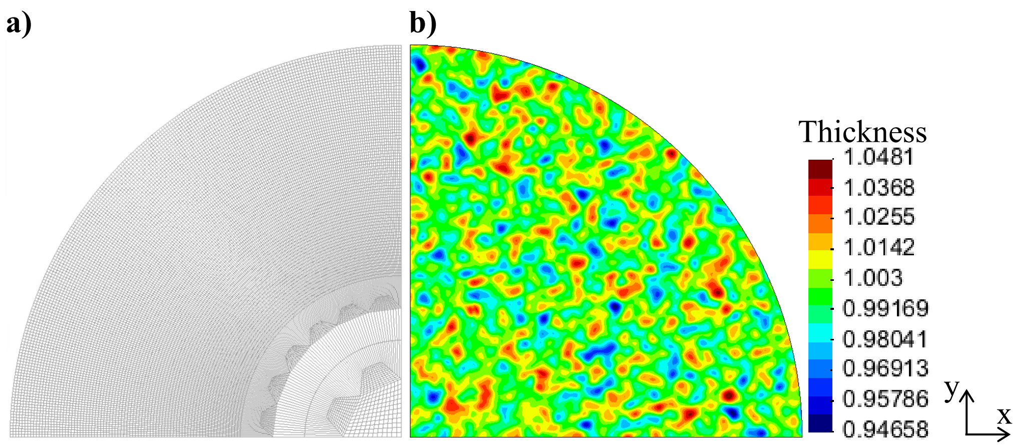

Fig. 2 – Blank model: (a) mesh discretization; (b) thickness distribution (Case 4).

The material under investigation has an isotropic elastic behaviour described by the generalised Hooke's law and an orthotropic plastic behaviour described by the Voce hardening law and the Hill'48 yield criterion. The yield criterion is defined by:

$$F(\sigma_{yy}-\sigma_{zz})^2+G(\sigma_{zz}-\sigma_{xx})^2+H(\sigma_{xx}-\sigma_{yy})^2+2L\tau_{yz}^2+2M\tau_{xz}^2+2N\tau_{xy}^2=Y^2, \quad (1)$$

where σ_{xx}, σ_{yy}, σ_{zz}, τ_{xy}, τ_{yz} and τ_{xz} are the components of the Cauchy stress tensor; Y is the yield stress; F, G, H, L, M and N are anisotropy parameters. The parameters follow the conditions $G+H=1$ and $L=M=1.5$ (von Mises). The Voce hardening law is defined by:

$$Y=Y_0+(Y_{sat}-Y_0)(1-\exp(-c_Y\bar{\varepsilon}^p)), \quad (2)$$

where $\bar{\varepsilon}^p$ is the equivalent plastic strain; Y_0 is the initial yield stress, Y_{sat} is the saturation stress and c_Y is the hardening rate. The material parameters used in the study are given in Table 1. These parameters were identified for an AA 6016-T4 aluminium alloy.

Table 1 – Material Parameters.

E [MPa]	ν	Y_0[MPa]	Y_{sat} [MPa]	C_Y	F	G	H	$L=M$	N
65113	0.33	157.95	368.07	9.311	0.5980	0.5981	0.4019	1.5	1.2716

Thickness Distribution

To assess the influence of thickness variability, four sheet thickness distributions were analysed. These distributions are characterised by different levels of thickness variance but identical average thickness values. For each distribution, the influence of the thickness variability on the numerical results of the cylindrical cup was evaluated, in particular the evolution of the punch force, the earing profile, the cup thickness and the equivalent plastic strain distribution.

The spatial distribution of the blank thickness is generated with a spatial random field following a Gaussian covariance model. This approach ensures a smooth spatial distribution of the random thickness values, which better represents the experimental thickness distribution [14]. In contrast, using a pure random thickness distribution could lead to a spatial distribution where the minimum and maximum thickness values could be in neighbouring points, which is unlikely due to material continuity. The fields are generated numerically using the randomisation method described in [15] and the Gaussian variogram given by:

$$\gamma[d] = \xi^2 \left(1 - exp\left(-\left({}^{d}/_{l}\right)^2\right)\right), \tag{3}$$

where ξ^2 is the random field variance, d is the distance between two points in the field and l is the length scale, which defines the distance at which the correlation between points becomes negligible. It is assumed that $l = 2/\sqrt{\pi}$, meaning that 95% of the random field variance is reached at a distance of 2 mm.

To investigate the influence of the random field variance, four blank thickness distributions were generated. These distributions are characterised by different levels of thickness variance (indicated in Table 2) but identical average thickness values, $t_0 = 1$ mm. For a clear physical meaning, the minimum and maximum thickness values for each case are also given in Table 2. Case 1 represents the ideal situation where the thickness is constant along the blank, while Case 4 represents an extreme situation where the difference between the maximum and minimum thickness values is approximately 0.1 mm. The distribution of Case 4 is shown in Fig. 2 (b).

Table 2 – Characteristics of the blank thickness distributions.

Case	Variance, ξ^2 [mm^2]	Minimum thickness [mm]	Maximum thickness [mm]
1	0	1	1
2	0.00003	0.987	1.012
3	0.00013	0.973	1.025
4	0.0004	0.947	1.048

Forming Results

In this section, the influence of the four thickness distributions on the results of the cylindrical cup are analysed, namely the evolution of the punch force versus displacement, the equivalent plastic strain distribution, the earing profile, η, and the thickness, t, around the cup for a given cup height, h. Fig. 3 illustrates the measurement locations of the earing profile and thickness.

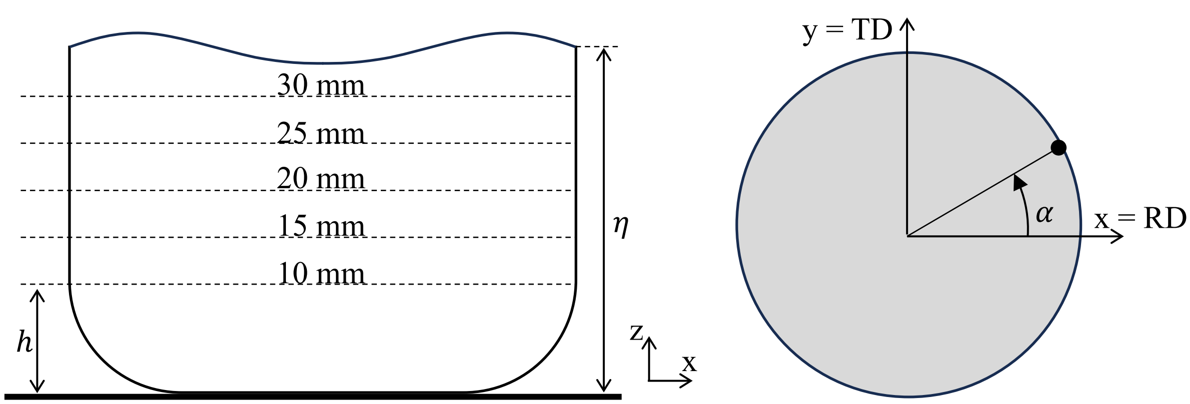

Fig. 3 – Representation of measurement locations of the earing profile and thickness.

Punch Force Evolution. This subsection analyses the influence of blank thickness variability on the evolution of punch force versus displacement. Fig. 4 shows these results for the 4 cases studied. It can be seen that the force reaches its maximum value of 42.5 kN at a displacement of 19 mm. After this maximum, the punch force decreases in a non-linear behaviour up to a displacement of 27 mm, i.e. the moment when the blank holder loses contact with the blank. After this point, the force continues to decrease, but in a linear trend. When the thicker parts of the blank (caused by

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the radial deformation of the blank) are embedded in the die, the punching force first increases (between 36 mm and 42 mm) and then decreases (between 42 mm and 44 mm) as the ears are embedded. When the blank is fully embedded (44 mm), the punching force is practically constant to counteract the frictional force. This behaviour is identical in all cases, so it can be concluded that the punching force is not influenced by the thickness variation. This conclusion is to be expected since the force is a global result, i.e. it is influenced by the deformation that occurs along the blank, so it is less sensitive to local thickness variations and more sensitive to the average thickness value.

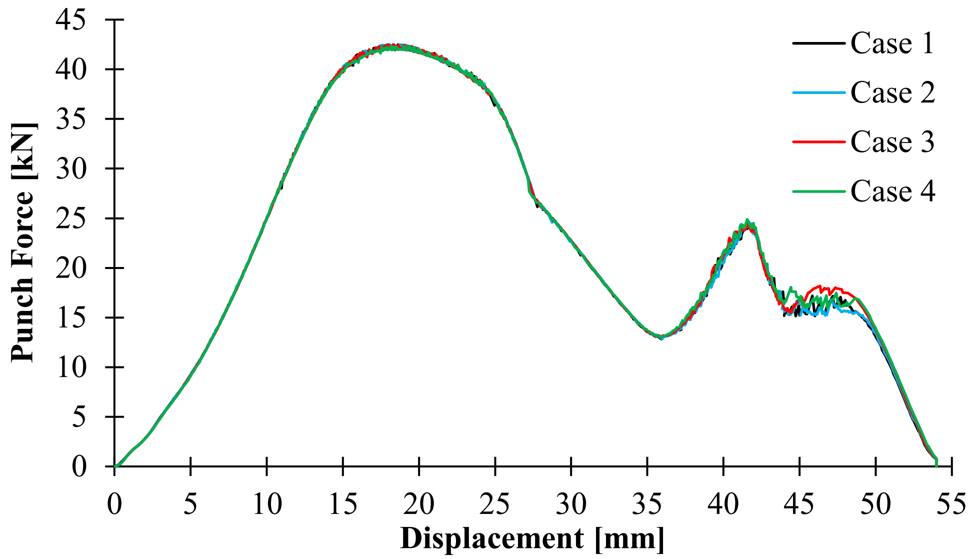

Fig. 4 – Evolution of the punch force for the 4 thickness distributions.

Equivalent Plastic Strain. Fig. 5 (a) shows the distribution of equivalent plastic strain along the cup for the 4 cases. It can be seen in this figure that as the variance increases, the distribution of equivalent plastic strain becomes less uniform (i.e. relative to Case 1). The maximum value of the equivalent plastic strain also increases with the variance, reaching values of 0.777, 0.807, 0.848 and 0.886 for cases 1, 2, 3 and 4, respectively. For the most extreme variance (Case 4) there is an increase of 14% in the maximum equivalent plastic strain compared to the case with no variability in thickness (Case 1). Comparing Fig. 5 (a) with Fig. 5 (b), it can also be concluded that the regions where the blank thickness is initially smaller (black circles in Fig. 5 (b)) correspond to regions where the equivalent plastic strain reaches higher values (black circles in Fig. 5 (a)). Although this is to be expected in regions subjected to stretching, this observation is also valid in regions that are subjected to ironing (e.g. the upper part of the cup wall).

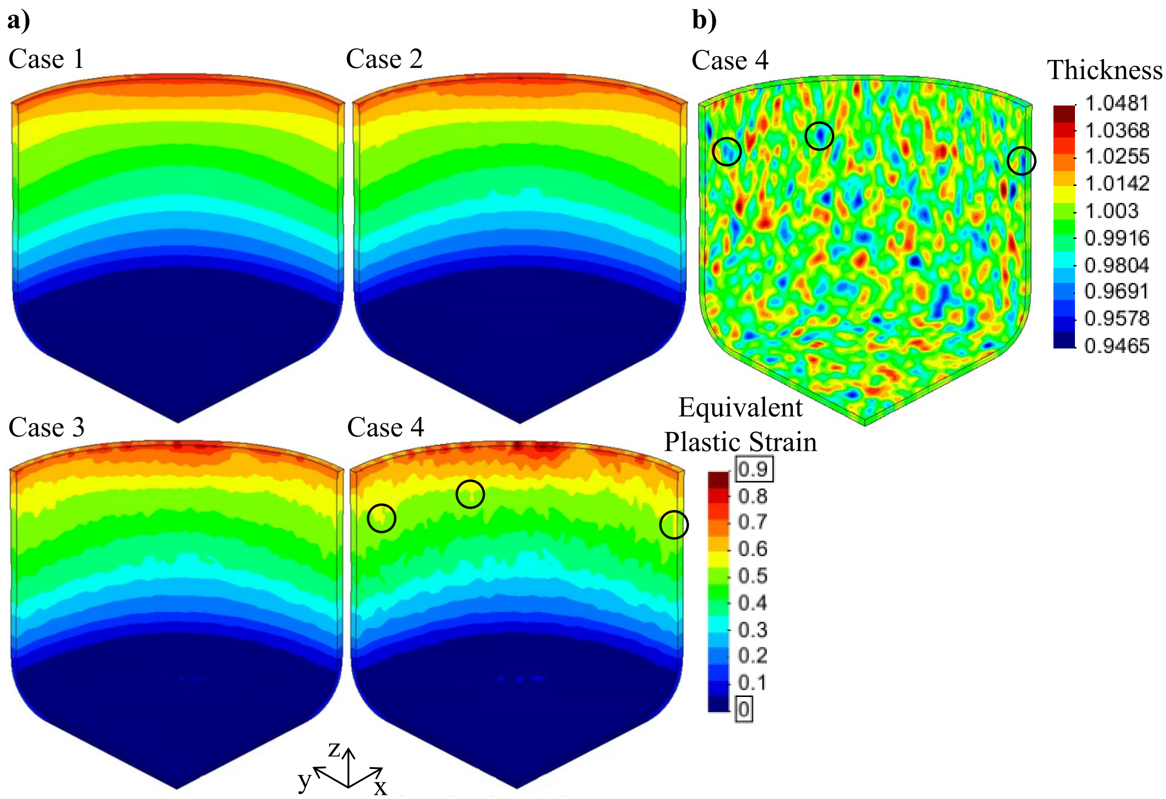

Fig. 5 – Distribution of the: (a) equivalent plastic strain for the 4 cases; (b) thickness distribution for the Case 4.

Thickness distribution. This subsection analyses the influence of the initial thickness variance on the thickness results around the cup for a given cup height, h. The thickness evolution in the circumferential direction was evaluated for 5 different cup heights, 10, 15, 20, 25 and 30 mm (as shown in Fig. 3). Fig. 6 shows the evolution of the cup thickness as a function of the angle with the rolling direction for the 4 cases. It can be seen that the increasing variance of the initial blank thickness leads to a greater dispersion of the thickness distribution at the bottom and in the curvature zone of the cup. However, for a cup height of 30 mm, there is almost no influence of the initial thickness variance on the thickness distribution. In fact, as the height of the cup over which the thickness distribution is analysed increases, there is less variation in the thickness results, because the ironing of the blank tends to uniformise the blank thickness in the upper part of the cup wall.

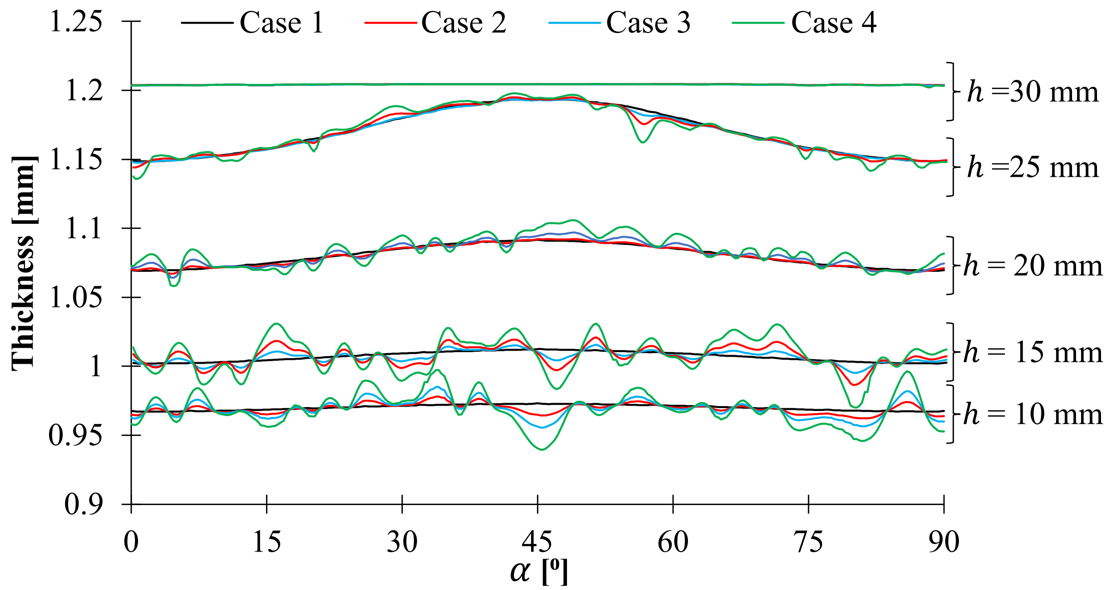

Fig. 6 – Thickness distribution evaluated for cup heights, h, of 10, 15, 20, 25 and 30 mm, for the 4 cases.

Earing profile. This subsection analyses the influence of the variability of the initial blank thickness on the earing profile. Fig. 7 shows the evolution of the earing profile as a function of the angle with the rolling direction for the 4 cases. It can be seen in this figure that the earing profile has a similar evolution for the 4 cases, with four ears in total, due to the fact that it is an anisotropic material described by the Hill'48 criterion with a minimum anisotropy coefficient at 45º with the rolling direction. It can be seen in Fig. 7 that increasing the variance of the initial thickness leads to an increase in the dispersion of the earing profile. In particular, it can be seen that the cup height at 0º decreases as the variance increases.

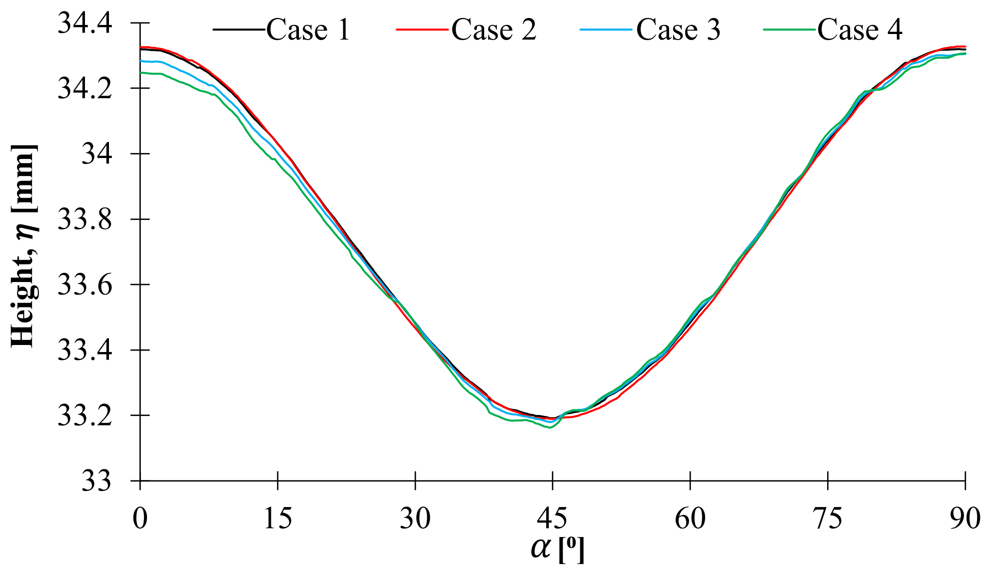

Fig. 7 – Earing profile of the cup for the 4 cases.

Conclusion

This work numerically analyses the influence of blank thickness variability on the forming results of a cylindrical cup. For this purpose, four blank thickness distributions characterised by different levels of thickness variance but identical average thickness values were studied. The influence of the thickness variability was evaluated in the evolution of the punch force versus displacement, the equivalent plastic strain distribution, the earing profile and the thickness distribution around the cup for a given cup height.

From the numerical results of the cylindrical cup, it could be concluded that the results of thickness distribution, equivalent plastic strain and earing profile are influenced by the thickness variability, while the influence in the evolution of punch force versus displacement is negligible. As the thickness variance increases, there is an increase in the scatter of the thickness distribution, equivalent plastic strain and earing profile. However, some regions of the cylindrical cup are more sensitive to this variance than others. In particular, the thickness distribution is more affected at the bottom and in the curvature zone of the cup. On the upper part of the cup wall, the influence of the variance on the variability of the thickness distribution is insignificant because it is subjected to ironing.

In future work, the influence of the thickness variability on the results of the cylindrical cup will be analysed for different thickness distributions. For example, using distributions generated for different variogram models or characterised by anisotropy, which can be caused by the rolling process. It would also be interesting to carry out a study similar to the one presented in this work, but considering the numerical simulation of the entire cup (i.e. without assuming geometrical symmetries in the numerical model), with the aim of understanding, for example, whether the thickness variability can lead to a decentralisation of the cup during stamping.

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