



Modelling of friction anisotropy of deep-drawing sheet in ABAQUS/EXPLICIT

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Abstract

This paper presents the experimental and numerical results of rectangular cup drawing of steel sheets. The aim of the experimental study was to analyze material behavior under deformation. The received results were further used to verify the results from numerical simulation by taking friction and material anisotropy into consideration. A 3D parametric finite element (FE) model was built using the commercial FE-package ABAQUS/Standard. ABAQUS allows analyzing physical models of real processes putting special emphasis on geometrical non-linearities caused by large deformations, material non-linearities and complex friction conditions. Frictional properties of the deep drawing quality steel sheet were determined by using the pin-on-disc tribometer. It shows that the friction coefficient value depends on the measured angle from the rolling direction and corresponds to the surface topography. A quadratic Hill anisotropic yield criterion was compared with Huber-Mises yield criterion having isotropic hardening. Plastic anisotropy is the result of the distortion of the yield surface shape due to the material microstructural state. The sensitivity of constitutive laws to the initial data characterizing material behavior is also presented. It is found that plastic anisotropy of the matrix in ductile sheet metal has influence on deformation behavior of the material. If the material and friction anisotropy are taken into account in the finite element analysis, this approach undoubtedly gives the most approximate numerical results to real processes. This paper is the first part of the study of numerical investigation using ABAQUS and mainly deals with the most influencing parameters in a forming process to simulate the sheet metal forming of rectangular cup.

Keywords: sheet metal forming, friction, coefficient of friction, friction anisotropy, finite element method

1. Introduction

Sheet metal forming of thin metal sheets is an important manufacturing technology in many forming processes and allows production of thin walled parts with complicated shapes. In particular, knowledge of the deformation mechanisms is important in the design of the drawing operations because deep drawing processes are characterized by nonlinearity both in geometry, material behavior and nature of contact. In the wall of the forming part may be distinguished regions involved stretching, drawing and various combinations of these basic modes of deformation [1, 2]. The deformation mechanism of rectangular cup drawing is very complicated for a theoretical

analysis [3]. On the other hand, conventional design processes for sheet metal forming are usually based on an empirical approach. As studies by Daxin, *et al.* [4] shows, several attempts have been tried to perform theoretical and numerical analysis of cup drawing. In those studies, the straight and the corner sides were taken as a whole and its deformation was analyzed theoretically. Further studies by Wen and Daxin [5] that focused on comparison of experimental and simulation results using Finite Element Methods (FEM) concluded that the discrepancy between the two was large. Plastic anisotropy is the result of the distortion of the yield surface shape due to the material microstructural state [6]. The anisotropy is of two types: normal and planar anisotropy. In normal anisotropy the properties differ in the thickness direction; in planar anisotropy however the properties vary with the

orientation in the plane of the sheet. Whereas drawability of sheets increases with normal anisotropy, planar anisotropy leads to the formation of ears in cup drawing [7]. Defining the anisotropic yield criteria is one central issue in analysis of cup drawing. Various approaches have emerged for developing anisotropic yield criteria. The anisotropic yield criteria proposed by Hill [8, 9] and Hosford [10] do not completely represent the general state of anisotropy, even in plane stress conditions. In 1993, Hill [11] proposed a new and user-friendly yield criterion in which the material properties were treated as independent parameters. Hill's criterion is simple to implement, but possesses a certain anomaly. The modified version of his criterion [9] is reported to be free of this defect but does not contain the shear stress term. Generally there are several quadratic and non-quadratic yield criteria which may be associated with isotropic hardening for industrial applications. Several studies [12-14] show that they can also be combined with kinematic or more advanced anisotropic hardening. Many such functions can be found in the literature elsewhere [6].

A friction model is completely defined by the friction condition which specify a set of admissible contact forces and the sliding rule which stipulates what directions of sliding are allowed [15]. The limit surface is usually assumed to be isotropic predicting a frictional behavior independent of the sliding direction. Currently, there are not so many publications focusing on frictional anisotropy and its implementation in numerical simulations of sheet metal forming processes. Attention should be paid to the work of Hjjijaj *et al.* [15] where isotropic Coulomb's frictional contact law to anisotropic friction conditions with non-associated sliding rule were generalized. Based on a model of rigid anisotropic asperities, a theoretical investigation on friction limit surfaces and sliding rules has been carried out by Michałowski and Mróz [16].

2. Experiments

In this experiment, deep drawings of cylindrical flat and square punches were performed by a device consisting of a die, a punch and a blank holder (Fig. 1). The die is a flat surface with a rectangular hole 61.4 mm by 40.4 mm, rounded at the edges with a radius of 3 mm. The rectangular punch with a size 60 mm by 40 mm is chamfered by an angle of 30° and rounded at the edges with the same 12 mm radius. The die set is constructed of cold-worked NC6 tool steel, hardened to a minimum of 58 HRC. The drawing of cups was run in dry friction conditions. The complete drawing apparatus was conducted within the Schenck UTS 100 hydraulic test machine with forming speed of 0.3 mm/s at a room temperature. The drawing processes presented in this work were achieved with a form of deep drawing quality (DDQ) cold-rolled steel sheet with a sheet thickness of 1 mm. The mechanical properties of the sheet metal have been determined through tensile tests along three directions with respect to the rolling direction (0°, 45°, 90°). The anisotropy of plastic behavior of sheet metals is characterized by the Lankford's coefficient r [6], which is determined by uniaxial tensile tests.

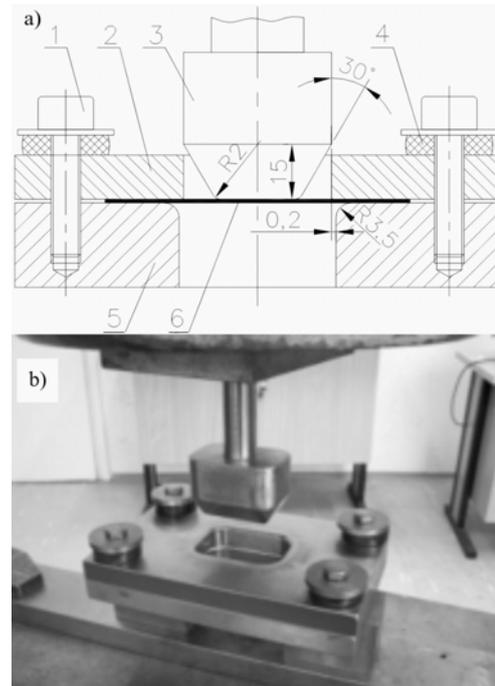


Fig. 1. Dimensions of the stamping tool (a) and view of setup in testing machine (b): 1 – set bolt, 2 blank holder, 3 - punch, 4 – elastomeric washer, 5 - die, 6 – blank

The r value is defined as the ratio of the true strain ϵ_2 in width and the true strain ϵ_3 in the thickness direction of a specimen put to uniaxial tension.

$$r = \epsilon_2 / \epsilon_3 \quad (1)$$

Due to the fact that measuring the longitudinal elongation is easier to perform, the condition of volume constancy $\epsilon_1 + \epsilon_2 + \epsilon_3 = 0$ was assumed. Taking into consideration that $\epsilon_1 = \ln(l/l_0)$ and $\epsilon_2 = \ln(b/b_0)$, equation (1) can be rewritten as:

$$r = \ln\left(\frac{l}{l_0}\right) / \ln\left(\frac{l_0 b_0}{lb}\right) \quad (2)$$

where b and l are the measured values of the initial (b_0, l_0) and final (b, l) width and length of the specimen, respectively.

A measured r -value that differs from unity shows that there is a difference between mechanical properties measured in plane and through-thickness, which is usually characterized by the normal plastic anisotropy ratio, defined as:

$$r_{mean} = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (3)$$

where r_0 , r_{45} and r_{90} are the strain ratio in the longitudinal direction, measured 45° to the rolling direction and in the transverse direction, respectively.

For isotropic materials r_{mean} is equal to 1. $r_{\text{mean}} > 1$ when the strength in the thickness direction is greater than the average strength in the directions lying in the plane of the sheet. The higher the r_{mean} value, the deeper the draw can be achieved [6]. The mechanical parameters of DDQ steel sheet are presented in Table 1 below. The sheet metal exhibits in-plane anisotropy in the yield stress and the r value, while the hardening exponent value is not significantly affected by the sample orientation. The r value in the rolling direction is smaller than measured value in the transverse direction because it is inversely proportional to the thickness strain. As the study by Yi *et al.* [17] asserts, the variation of the r value in different loading directions has a strong relationship with the texture.

Table 1. Mechanical properties of the deep-drawing sheet

Orientation	Yield stress [MPa]	Ultimate tensile stress [MPa]	Lankford's coefficient	Strain hardening parameters	
				n	C [MPa]
0°	162	310	1,55	0.211	554
45°	163	322	1,27	0.205	541
90°	168	312	1,67	0.208	530

The friction properties of the deep drawing quality steel sheets used in the experiments were determined by using the pin-on-disc tribometer T01-M in dry friction conditions. To confirm that steel sheets are characterized by the anisotropy of tribological properties, friction anisotropy on a given surface has to be clearly distinguished from friction anisotropy for different perpendicular orientations between the pin and the surface. Changes of friction coefficient value exhibit two maxima for a rotation through 360° ($\mu = 0.142$ and $\mu = 0.157$). They correspond to the measurement of friction coefficient value transverse to the rolling direction.

3. Numerical simulations

The blank, die and punch were modeled corresponding to the experimental set-up. Symmetry of the process was utilized in order to reduce the CPU time, i.e., only one quarter of blank and tool with appropriate boundary conditions were modeled. The blank was modeled with 4-node reduced integration, doubly curved shell elements, called S4R in ABAQUS terminology [18]. Five integration points through the thickness direction were employed. This shell element type is intentionally applied for analysis of sheet metal forming processes [19-20], and this element accounts for the change of thickness in its output variables, unlike solid and plane strain elements. As the tools were considered to be rigid, no deformation was assumed in these parts during forming the process. The blank model is composed of 3103 4-node elements. The tools were consisted of 9586 linear quadrilateral elements. To prevent wrinkling, uniform blank holder force of 7,85 [kN] corresponding to the experiment was applied on the top surface of a blank holder plate. The boundary

conditions applied to the blank holder allow displacement in the normal direction to the blank surface so that the wrinkling formation was prevented and the frictional resistance in flange region was minimized.

Numerical simulations were performed with material behavior described by Huber-Mises yield criterion with isotropic hardening and with anisotropic yield condition described by Hill [8]. For ideal case of isotropic materials, Huber-Mises [21, 22] yield condition is expressed as

$$2\bar{\sigma}^{-2} = (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \quad (4)$$

As mentioned previously, Hill's [8] formulation is the most frequently used yield function for steel sheet metals. It can be regarded as an extension of the isotropic Huber-Mises function, which can be expressed in terms of rectangular Cartesian stress components as follows:

$$\bar{\sigma}^{-2} = F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 2L\tau_{zx}^2 + 2M\tau_{yz}^2 + 2N\tau_{xy}^2 \quad (5)$$

where $\bar{\sigma}$ - equivalent stress, σ_x , σ_y , σ_z , τ_{xy} , τ_{yz} , τ_{zx} - stress components determined in main orthotropic axis. Coefficients F, G, H, L, M, N are determined on the basis of mechanical parameters of the sheet measured in x, y and z direction [18].

The anisotropic friction model was implemented by specifying different friction coefficients in two orthogonal directions on the contact surface. These orthogonal directions coincide with the defined slip directions. To use an anisotropic friction model two friction coefficients ($\mu = 0.142$ and $\mu = 0.157$) were specified, where the first is the coefficient of friction in the first slip direction along the rolling direction and second is the coefficient of friction in the perpendicular slip direction. For simulation models with isotropic friction an average friction coefficient value of 0.1495 was received. The critical shear stress surface is defined by a piece of ellipse defined by Eq. 6.

$$\tau_1 = \tau_1^{\max} \cos \alpha \quad \text{where } \alpha \in (0, \pi/2) \quad (6)$$

$$\tau_2 = \tau_2^{\max} \sin \alpha$$

This elliptic surface has two extreme points given by $\tau_1^{\text{crit}} = \mu_1 P$ and $\tau_2^{\text{crit}} = \mu_2 P$ (Fig. 2). The size of ellipse will change with the change in contact pressure between surfaces.

4. Results

In order to investigate the variations in the wall thicknesses of rectangular cups, several experiments were carried out through gradual increment of the punch displacement. While forming at each grade, thickness distribution was separately investigated.

Verification of numerical results in characteristic sections was then carried out on the basis of the measurements of wall thickness of the drawpieces. Parts formed to examine the thickness changes after the stamping experiments were cut along the rolling and transverse directions starting from the centre of the part. Furthermore, the cups were cut in the corner at an angle of 45° with respect to the rolling direction (Fig. 3), which results are not presented in this article.

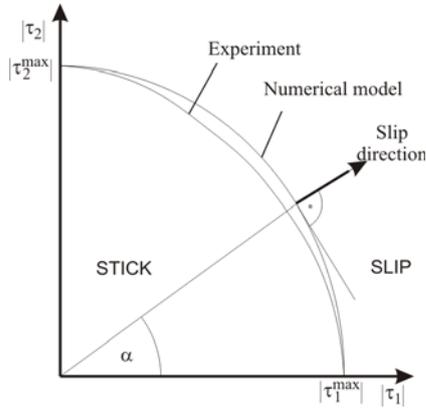


Fig. 2. Anisotropic friction model

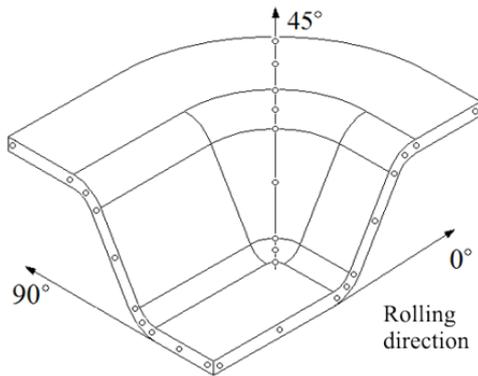


Fig. 3. Scheme of measurement points of wall thickness

The thickness strain distributions along 0° , 45° and 90° directions referred to the rolling direction are shown in Fig. 5. Three deformed profiles determined for true distance along each path were compared with experimental measurements. As expected, the thickness strain distributions are different along these directions for all punch displacements. The decisive impact on this character exerts the non-axisymmetrical shape of parts. The thickness distribution of the sheet under the punch is found to be more or less uniform to the initial sheet thickness. However, the thickness of the sheet, which was above the flat portion of the die, is observed to be slightly larger than the initial thickness. The thickness measured in the rolling direction (the long side) is smaller than that from the transverse direction (the short side) near the punch shoulder. The main reason for this effect is the unsymmetrical shape of the process, where a higher fraction of

radial tension stress exists along the short wall of the rectangular drawpiece along the long side wall. Other studies [23] also show that the short side wall of the rectangular drawpiece near the punch edge is the most expose to the fracture.

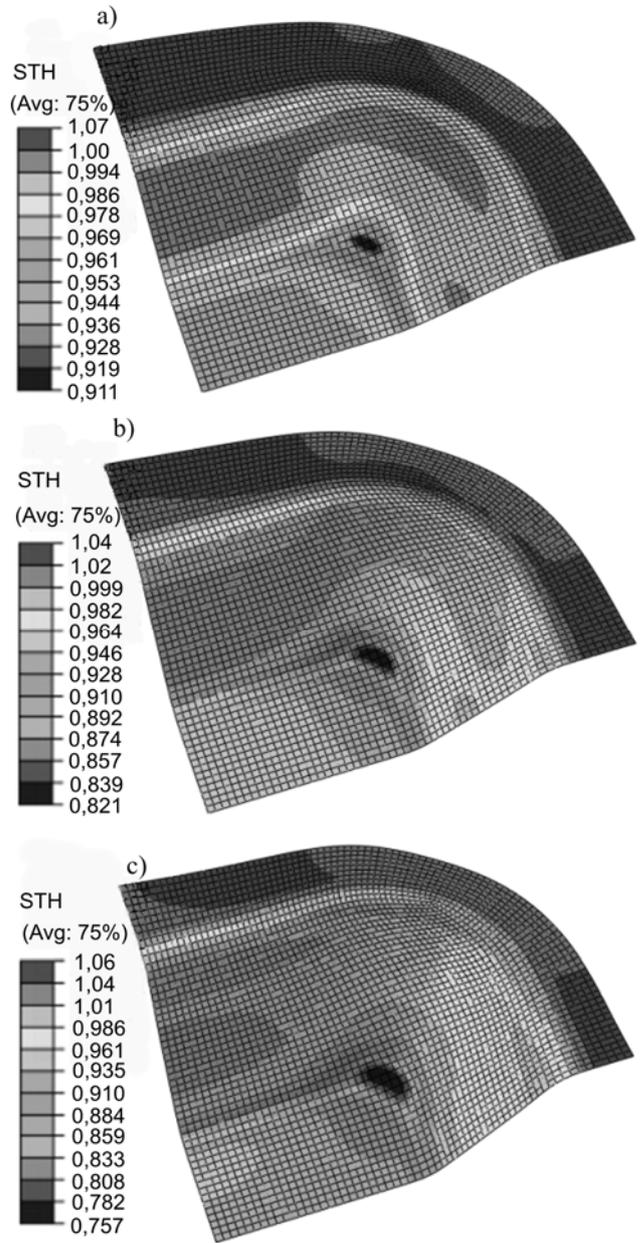


Fig. 4. Contour of the sheet thickness (Hill material model + anisotropic friction) under punch displacement of a) 7 mm, b) 11 mm and c) 16 mm

The trends of the variation of thickness for all configurations are coincident (Fig. 5). Further the variation of the position where the minimum thickness occurred is also very small for different

punch penetrations. There is close similarity between experiment and theory, and the variation of thickness in every part is also very similar. There appears minimum thickness at the punch corner (on the arc of drawpiece) due to stress concentration and the tensile stress. Obvious peak strains can be observed in the figures, especially at the corner.

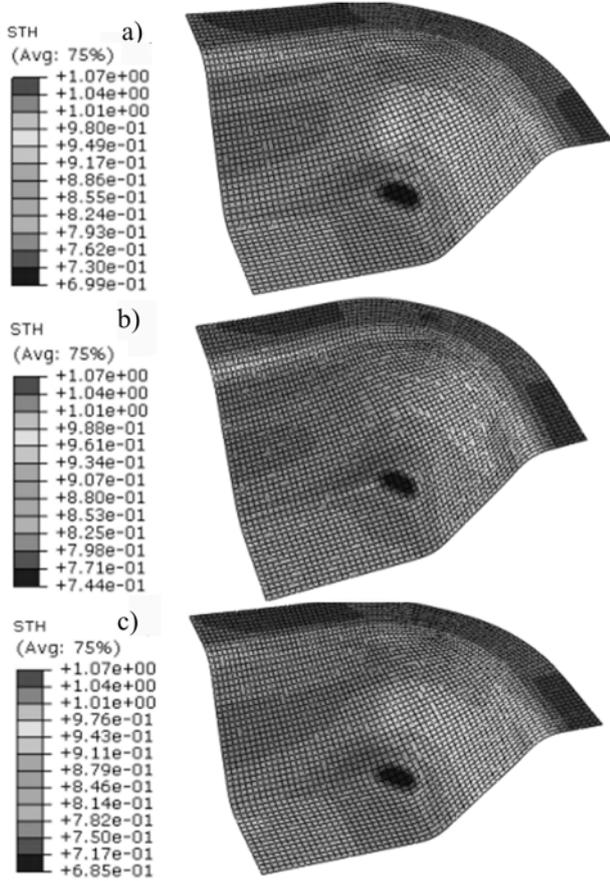


Fig. 5. Contour of sheet thickness for following configurations: Huber-Mises material + AF (a), Hill material + IF (b) and Huber-Mises material + IF (c)

The distributions of wall thickness measured and calculated at the end of drawing on the symmetrical lines of long and short sides and the diagonal line passing through the corner, are shown in Fig. 6-8. The differences of the results obtained from analyzed anisotropy strategies can be seen clearly from the thickness contours of some models. The good predictive capability of the proposed Hill anisotropy model plus anisotropic friction (AF) has been demonstrated. The maximum wall thickness in all directions is observed near the edge of blank. Replacement of anisotropy friction model by isotropic friction (IF) model in both models of material causes slight decrease in thickness. It is also clearly visible that the character of the thickness variation is similar at the bottom of drawpiece. In other parts of drawpiece this phenomenon is more complicated.

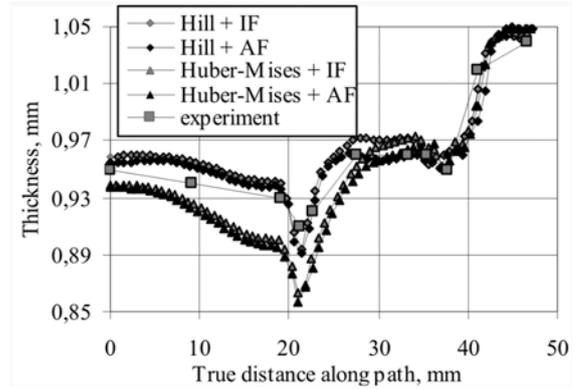


Fig. 6. Plot of thickness strain under punch displacement of 16 mm measured in the rolling direction

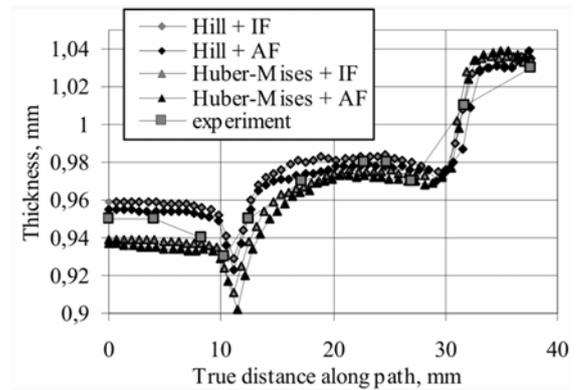


Fig. 7. Plot of thickness strain under punch displacement of 16 mm measured transverse to the rolling direction

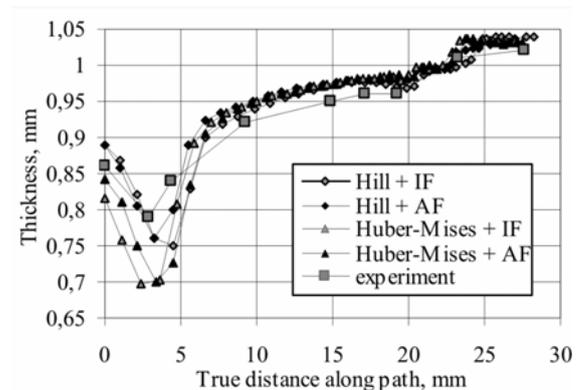


Fig. 8. Plot of thickness strain under punch displacement of 16 mm measured at an angle of 45° with respect to the rolling direction

5. Conclusions

This study has attempted to investigate the anisotropy problem in sheet metal drawing using both experimental and numerical approach. Hill's yield criterion was implemented in the

material description of the numerical model. Together with friction anisotropy condition, this model gave simulation results that can better approximate the experimental measurements. Though both static implicit and dynamic procedures are successful in analysis of sheet metal forming, the simulations show that a dynamic explicit approach is computationally more efficient. It is considered that distribution of wall thicknesses obtained by means of experiments and FEM includes material and friction anisotropy generally demonstrates a great harmony, and that minor differences are due to the fact that conditions in the finite elements method are considered ideal. Although the simulated thickness in the flange area along all directions is slightly overestimated, the agreement between predicted and experimental thickness distributions is generally excellent. Plastic anisotropy of sheet material is the main factor that determines high conformity of the numerical simulation results with the reality. Additionally, consideration of the anisotropy of resistance to friction slightly influences the numerical results on variation of the thickness and strain distribution compared with isotropic friction model. All in all, this investigation has demonstrated that application of FEM method for optimization of initial blank shape is an attractive approach which eliminates time-consuming experimental methods.

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