OPTIMIZATION OF THE FORMING PROCESS OF GUTTER END CAP USING THE FINITE ELEMENT METHOD

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The contribution deals with the optimization of the forming process with the use of FE analysis. The impact of the planar anisotropy and friction coefficient on the drawing process was evaluated in the numerical simulation. Optimization of metal blank size and shape with the use of metal forming simulation was also performed. Studied material was galvanized drawing quality steel which is used for the production of the rain gutter end cap. Effects of planar anisotropy and friction coefficient on the quality of steel stamping were evaluated with the use of FE simulation. The effect of anisotropy was also experimentally tested. The aim of this work was to determine the correct steel blank size and shape and to evaluate the effects of planar anisotropy on the thickness variation and wall wrinkling.

KEYWORDS

forming, FE analysis, numerical simulation, anisotropy

1 INTRODUCTION

New and improved finite element software systems have enabled the rapid development of simulations of forming processes. Because of this, it is possible to practically apply finite element simulations even for complex processes in a short time [Pepelnjak 2001, Hrivnak 2004, Majernik 2020].

The use of computer simulation of the forming process shortens the pre-production stage, makes better use of the material properties of the sheet, reduces the cost of preparing the production process for complex parts, detects and prevents process errors, and improves dimensional and geometric accuracy of parts [Neto 2014, Spisak 2000, Dyadyura 2021]. To optimize the surface forming parameters, the simulation program must be efficient, accurate, and easy to use. Numerical simulation of forming can help in solving technological problems, such as stamping failure, wrinkling creation and springback [Spisak 2000, Mulidran 2018].

The accuracy, reliability of the prediction of the deformation behavior of the material by numerical simulation depends on the nonlinearity of the material properties, on the defined critical values of deformations, friction ratios on the contact surfaces between sheet and tool, and on the anisotropy in the sheet thickness and sheet plane [Slota 2012, Krenicky 2012, Tomas 2019, Brusilova 2020].

In this work, the influence of surface anisotropy and friction conditions on the drawing process of the gutter end cap (Fig. 1) made of galvanized steel sheet DX53D-Z with a thickness of 0.5 mm was investigated. The influence of the anisotropy of the properties of the steel sheet during the drawing process was verified utilizing numerical simulation as well as experiments.

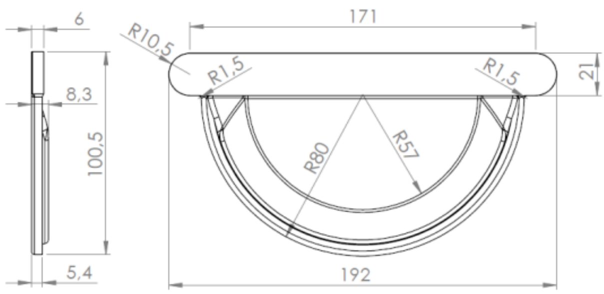

Figure 1. General dimensions of gutter end cap

2 MATERIALS AND METHODS

In the presented work, hot-dip galvanized steel DX53D-Z (EN10346:2015) with a thickness of 0.50 mm was used as the blank. This type of hot-dip galvanized steel is suitable for stamping and deep drawing. They are used in the production of car parts, in the construction and mechanical engineering industry for the production of profiles, corrugated sheets, roof coverings, etc. Mechanical properties were measured by uniaxial tensile test on TiraTest2300 testing machine. To obtain the required data for the FEM model, the specimens for the uniaxial tensile test were cut in three different orientations (0°, 45°, and 90° to the rolling direction). Specimens for the uniaxial tensile test were produced according to the ISO 6892-1: 2019 standard. Several specimens were tested for each orientation and the average values of the basic mechanical properties (Table 1).

Dir.	$R_{p0,2}$ [MPa]	R_m [MPa]	A_g [%]	r [-]	r_m [-]	n [-]	n_m [-]
0°	183	306	24.8	1.65		0.201	
45°	196	316	22.3	1.61	1.80	0.206	0.202
90°	192	313	24.2	2.15		0.199	

Table 1. Mechanical and elastic properties of DX53D-Z steel

where $R_{p0.2}$–Yield stress, R_m–Ultimate tensile strength, A_g–Uniform elongation, r–plastic strain ratio, n–strain hardening exponent, n_m–average value of strain hardening exponent, r_m–average value of plastic strain ratio.

The chemical composition of the DX53D-Z steel is shown in Table 2.

C	Si	Mn	P	S	Al	N
max 0.04	max 0.02	max 0.18	max 0.015	max 0.012	max. 0.05	max 0.006

Table 2. Chemical composition of DX53D-Z steel [%]

Numerical simulations were conducted in the AutoForm software. This software uses a special implicit method and adaptive meshing algorithms. The tool geometry is an important factor in sheet metal forming. Therefore, it is also important to correctly model forming tools that are then used in the numerical simulations. After importing CAD models of tool parts into the software environment, the tool surfaces needed for the simulation were meshed with triangular shell elements. The blank shape and dimensions were the same as in physical experiments.

The accuracy of the numerical simulation was set to fine. With this setting, the software automatically generates mesh parameters for tool surfaces. Blank and tool surfaces consisted of triangular elements. The size of the blank shell element was user-defined and set to 0.8 mm. Radius penetration was set to

0.16 and the number of integration points in the sheet metal thickness was set to 11, both of these parameters were set by the software. The maximum time step was set to 1.6 s and the friction coefficient value was set to 0.20 by the user. One of the most important criteria in the sheet metal forming simulation is yield surface, also known as yield locus. The yield surface describes the material transition from the elastic state to the plastic state. The relationship between stress components at the moment of yielding due to the multiaxial stress state during sheet metal forming is also expressed by the yield surface. In this work, Hill48 yield criterion was used. To describe material hardening during deformation Swift's hardening law was used.

The experiments were conducted in the Laboratory of mechanical testing of the Institute of technology and materials engineering, Faculty of Mechanical engineering, Technical University of Košice. Stampings were produced on the ZD-40 hydraulic press.

3 OPTIMIZATION OF THE BLANK SHAPE AND SIZE

The determination of the initial dimensions of the steel blank was based on the law of conservation of volume. This means that the volume of the semi-finished product, in this case, the blank, should be equal to the volume of the final product - stamping. The volume of the stamping in this case is V = 8989.86 mm^3. From the volume it is also possible to determine the area S according to the relation [Spisak 2000]:

$$\boldsymbol{S} = \frac{V}{a_0} = \frac{8\,969.86}{0.5} = \mathbf{17\,979.72} \qquad (1)$$

where: S is blank area [mm^2], V is blank volume [mm^3] and a_0 is sheet thickness [mm].

Based on the calculated area, the first variant of the blank was designed (Fig. 2). The CAD model of the first blank was designed in the program SolidWorks and further exported to the simulation software, on this first blank the forming simulation was performed (Fig. 3).

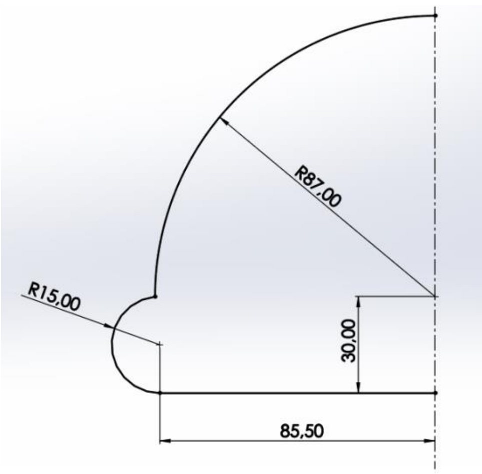

Figure 2. Dimensions of the first blank used in the forming simulation

The shape of the stamping achieved in the numerical simulation can be seen in Fig. 3. The height of the wall around the perimeter of this stamping is uneven and does not correspond to the required dimensions (the perimeter wall of the stamping ensures the position and water tightness of the gutter end cap), therefore it is necessary to optimize the dimensions of the blank.

Figure 3. First stamping from the FE simulation made of blank with incorrect shape and dimensions

To achieve the desired shape and the stamping wall size, approximately five variations of the blanks were created in SolidWorks software. These models of blanks were sequentially exported and simulated in AutoForm software. A relatively high number of blank variants arose due to obtaining the required wall height on the perimeter of the component. The height of the wall in the so-called semicircle area is not identical to the height in the so-called slot area, which also did not facilitate the design of the blank. The resulting shape and basic dimensions of the blank are shown in Fig. 4.

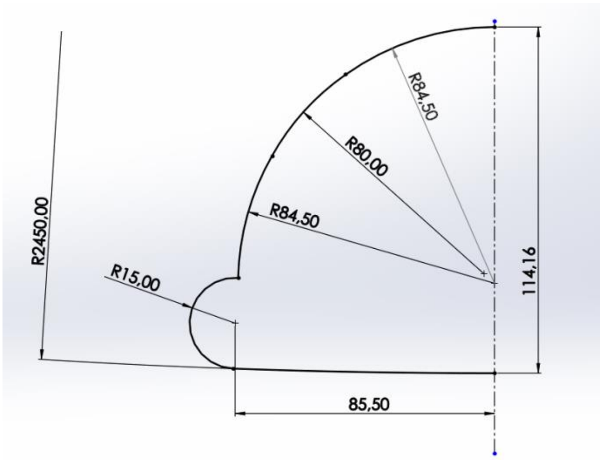

Figure 4. Final blank shape and dimensions

In addition to the shape and size of the blank, the location of the blank on the die surface also has an effect on achieving the correct shape of the stamping and the required height of the walls.

In Fig. 5 are shown two stampings, where the upper stamping had properly placed sheet blank on a die (the walls of the stamping had the required dimensions), the lower stamping was made of an incorrectly placed blank. On both stampings, wrinkling can be observed in the wall area. This wrinkling does not have a negative effect on the functionality of the finished stamping, because when mounting the gutter end cap on the gutter, the peripheral wall of the gutter end cap stamping is sealed with a sealant, or is soldered directly to the gutter. The sidewall wrinkling could have been eliminated or reduced by the blank holder, but the production tool had to be as simple as possible to limit the production costs.

Improper placement of the blank would result in a reduction in the functionality of this stamping, because the wall of the stamping in the so-called semi-circular part ensures the required tightness and correct position of at the end of the gutter. Insufficient wall height in this part could cause a leak or the gutter end cap to fall out of the gutter. The final steel stamping with the correct shape and wall height is shown in Fig. 6.

Figure 5. Influence of the blank location on the stamping shape

Figure 6. Final shape of the gutter end cap stamping

4 IMPACT OF PLANAR ANISOTROPY AND FRICTION IN FE SIMULATION

The anisotropy of the mechanical properties of the sheet is related to drawing. Sheets show two types of anisotropy - planar and normal. Planar anisotropy expresses the unevenness of mechanical properties in different directions of the sheet plane. To determine the planar anisotropy, the values obtained from tensile tests taken from the sheet at different angles to the rolling direction are required. Planar anisotropy has an adverse effect on the drawing of circular stampings not only for the formation of tips that need to be removed but can also cause thinning of the wall thickness of the stampings and cause deviations in the roundness of the cylindrical stamped parts [Mulidran 2019].

To determine the influence of the planar anisotropy of mechanical properties and the coefficient of friction on the quality of the stamping, several numerical simulations of the drawing process were performed [Spisak 1995, Spisak 2016, Spisak 2015]. Figure 7 shows the forming limit diagrams (FLD) taking into account the anisotropy of the tested steel sheet, i. j. blanks with an orientation of 0 °, 45 ° and 90 ° to the sheet rolling direction were used.

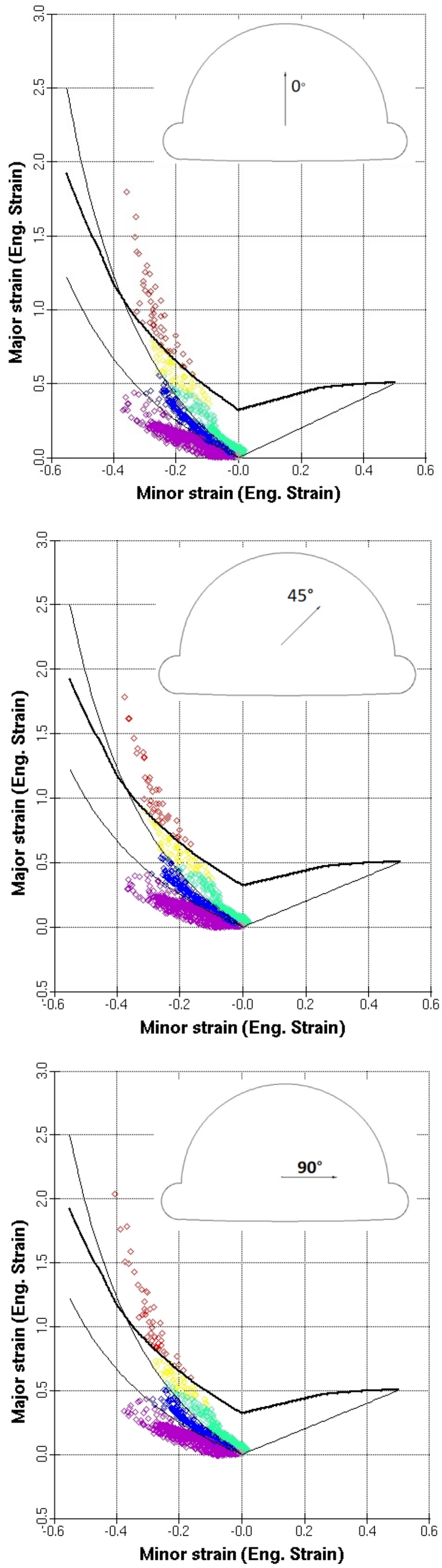

Figure 7. Forming limit diagrams (FLDs) for blanks with different orientation to the rolling direction

Based on the values from the forming limit diagrams, the majority of deformation is located in the area of tension-compression (left side of the diagram). The 90 ° direction shows the highest values of major strain, the 45 ° and 0 ° directions are similar in the magnitudes of the strain values.

The dots highlighted in purple represent the area of sheet metal thickening and wrinkling. The blue colour highlights compression deformation, which is expected to form a wrinkling on a stamping. The green colour represents a safe zone of deformations, the yellow colour indicates the limit deformations at which cracks may or may not occur. Deformations causing failure, cracks of the stamping are marked in red; these deformations are located above the forming limit curve (FLC). Thin solid lines devide deformation areas mentioned above. In this case, the stamping had cracked due to excessive thinning of the sheet in the critical area, but this crack did not have a negative effect on the functionality of the stamping. The position of the crack between semi-circular and slot-shaped area actually allows easier installation of the end cap (it is easier to shape the wall of the end cap in the semicircular area to allow proper installation on the gutter).

Using numerical simulation, in addition to FLD diagrams, outputs in the area of wrinkling and changes in wall thickness were also obtained. These phenomena on the stampings are shown in Fig. 8. Wrinkling occurred in the sidewalls of the stamping, mainly in the semi-circular area of the stamping (Fig. 8a). The cracks were present in the area between the semi-circular and slot-shaped area of the stamping (Fig. 8b). The reason for it was excessive thinning in this section, which was caused by sharp transition (edge) between the semi-circular and slot-shaped area in a die.

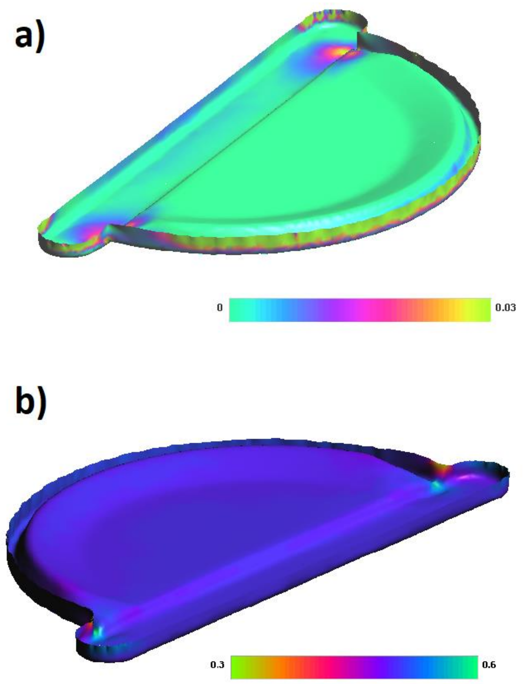

Figure 8. Wrinkling tendency (a), Thickness distribution (b)

Based on the results obtained from the simulation, several parameters were compared (Tab. 3), which affect the formability of the used steel sheet:

- Max. value of major strain in safe zone φ_1
- Max. value of minor strain φ_{2max}
- Min. value of minor strain φ_{2min}
- Max. sheet thickness a_{0max}
- Min. sheet thickness a_{0min}
- Max. forming force F_{max}

	Dir. 0° f=0,15	Dir. 0° f=0,05	Dir. 45° f=0,15	Dir. 45° f=0,05	Dir. 90° f=0,15	Dir. 90° f=0,05
φ_1 [-]	0.444	0.436	0.452	0.459	0.433	0.425
φ_{2max} [-]	0.017	0.016	0.017	0.016	0.016	0.014
φ_{2min} [-]	-0.463	-0.496	-0.474	-0.501	-0.523	-0.512
a_{0max} [mm]	0.623	0.647	0.635	0.655	0.623	0.636
a_{0min} [mm]	0.279	0.296	0.296	0.292	0.277	0.268
F_{max} [kN]	62.51	58.71	62.79	59.06	63.04	58.63

Table 3. Values of selected parameters for different friction values and sheet direction from FE simulation

Table 3 shows that by reducing the friction, a reduction in the maximum tensile force F_{max} of about 7 to 8 % can be achieved. Friction further affects the increase of the maximum sheet thickness a_{0max} by approximately 4%. There was also a decrease in the value of the maximum minor deformation φ_{2max} by approximately 9%. In general, it can be stated that based on these results, reduced friction has a positive effect on the forming process, although this effect is relatively small. The sheet direction also affects the formability. The highest values of major strain φ_1 were measured for 45° direction. The highest values of maximal sheet thickness a_{0max} were measured in this direction. The usability of the sheet metal stock in direction 45° is less compared to direction 0° and 90°, which would result in increased material costs [Cacko 2014]. The use of lubrication in the forming process would negatively impact production costs. Based on the results, the use of sheet metal blank with direction 0° without lubrication for the production was suggested.

5 EXPERIMENTAL VERIFICATION OF THE GUTTER END CAP FORMING

In experimental verification of forming process, it is possible to combine the potential of engineering thinking supported by simulation software with the experimental base of the workplace [Hudak 2011]. Experimental verification of the proposed forming technology, i.e. verification of the function of the forming tool, testing of blanks was performed on a hydraulic tearing machine ZD-40. The effect of planar anisotropy on the final shape of the stamping was also verified experimentally. The blanks were hand-cut from galvanized steel sheet in 0°, 45° and 90° to the rolling direction of the sheet, no lubrication was used.

Traces of ejector pins can be observed in the corners of the stampings, the stampings correspond to the required dimensions, and they differ mainly in the amount of wall wrinkling and in the wall thickness. The largest wrinkling of the sheet in the semi-circular area of the stamping occurred in the stamping made of blank with 90 ° direction. The smallest wrinkling was observed for the stamping made of blank with 0° direction. The wrinkling of the stamping walls in the semi-circular area is depicted in Fig. 9. The wrinkling of the walls for the slot area of the stamping is shown in Figure 10. The wrinkling of the stampings walls was observed for all stampings, but it does not affect the usability of the gutter end cap stamping.

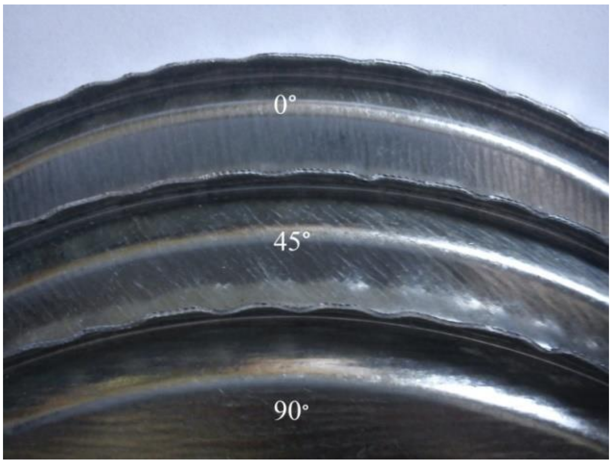

Figure 9. Comparison of the wall wrinkling in the semi-circular area

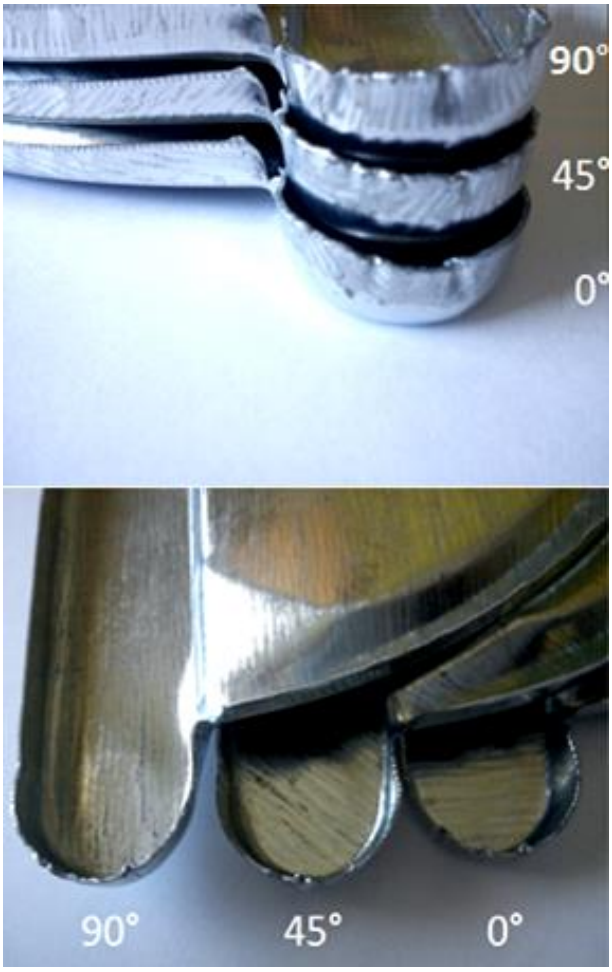

Figure 10. Comparison of the wall wrinkling in the slot area

Based on the above findings, it can be concluded that the planar anisotropy of the tested material affects the formation and size of the wall wrinkling on the stampings. Additionally, the maximum and minimum thickness was measured in the same areas as in the stampings from the simulation. The minimal thickness was measured at the point of stamping failure (crack), the maximum thickness was measured in the area of the "slot" where the wrinkling was formed. The sheet thickness was measured with a micrometer, five measurements were conducted. Tab. 4 shows the average values of the minimum sheet thickness a_{0min} and the maximum sheet thickness a_{0max}. The smallest measured value of the minimum sheet thickness a_{0min} was measured for the stamping made of blank with 90° direction, the largest value of the minimum sheet thickness was measured for the blank with 45° direction. The smallest value of the maximum sheet thickness a_{0max} was measured for stamping made of blank with 90° direction. The highest value of a_{0max} was found for the stamping made of blank with 45° direction. The comparison between experimental and simulation values of thickness a_0 is shown in Table 4.

	Dir. 0° Exp.	Dir. 0° Sim.	Dir. 45° Exp.	Dir. 45° Sim.	Dir. 90° Exp.	Dir. 90° Sim.
a_{0max} [mm]	0.62	0.62	0.64	0.63	0.60	0.62
a_{0min} [mm]	0.30	0.28	0.31	0.29	0.27	0.28

Table 4. The average values of the minimum sheet thickness a_{0min} and the maximum sheet thickness a_{0max}

6 CONCLUSION

The paper provides information on the influence of planar anisotropy of mechanical properties and friction conditions on the process of forming gutter end cap stamping. The effect of anisotropy and friction was investigated using numerical analysis; the effect of planar anisotropy was experimentally tested as well. The FE simulation was also used to optimize the blank shape and its dimensions. Based on the experimental and numerical results, the following outputs can be stated:

- FE simulation is a useful tool for designing blanks for complex-shaped stampings, in this case, gutter end cap stamping.
- The quality of the stamping (wrinkling, thinning) is influenced by the planar anisotropy of the mechanical properties of the DX53D-Z steel.
- The influence of the friction conditions did not have a significant effect on the wrinkling of the stamping in FE simulation, but by reducing the friction it is possible to achieve lower values of thinning of the stamping as well as a reduction of the forming force.
- The thickness values from the FE simulation were not identical to the experimental ones; the difference was up to ± 0.02 mm.
- Based on the data obtained, a blank with direction 0° was suggested to be used in manufacturing practice without the use of a lubricant to produce the gutter end cap stampings.

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