

Capabilities of incremental forming of thin-walled products using a universal numerically controlled machine based on numerical simulations

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ABSTRACT

Due to the lack of universal machines on the market, this paper presents a new technology and a dedicated machine for manufacturing sheet metal products with various geometries using a single set of tools. The study reports the results of numerical simulations of incremental forming of thin-walled products. The numerical analysis was performed on S355 steel sheets with thicknesses ranging from 1 to 5 mm. The bending line followed an arc-shaped trajectory. In the analyzed process, the sheet was deformed using two rollers: a shaping roller and a support roller. Simulations were carried out using Simufact Forming software. Process force parameters, as well as strain and stress distributions, were determined. The maximum forming forces obtained from the numerical simulations ranged from 2 kN for a sheet thickness of 1 mm to 24.5 kN for the maximum analyzed thickness of 5 mm. Preliminary numerical simulations indicate that wrinkling may occur in sheets with thicknesses of 1 mm and 2 mm, whereas for thicker sheets this instability was not observed in the simulations. The maximum effective plastic strain recorded for the 5 mm sheet was 1.15, while the maximum von Mises stress reached 724 MPa. Based on the simulation results, it can be stated that the proposed technology shows potential for industrial applications, particularly for single-unit production and prototyping. However, experimental validation is required.

Keywords: sheet metal forming, incremental forming, thin-walled components, numerically controlled machine, FEM.

INTRODUCTION

Thin-walled components formed from sheet metal find applications in numerous industrial sectors. In recent years, many studies have focused on improving existing methods for forming thin-walled components, as well as on developing new manufacturing approaches. Sheet metal forming is primarily carried out using bending and stamping methods. This paper discusses existing technologies for manufacturing thin-walled components. An innovative method for producing thin-walled components, developed at Lublin University of Technology, is also described.

Currently, stamping is the primary technology for manufacturing thin-walled components.

This process is most commonly carried out using rigid tools (a punch and a die), which determine the quality of the formed components. Research indicates that such a process can be disturbed by a number of undesirable phenomena, including fracture of the wall along the perimeter of the drawn part and the formation of wrinkles on the flange [1]. However, methods for preventing these adverse phenomena are well known. The stamping process should be carried out with appropriately selected drawing ratios and with the use of a blank holder [2]. Abe et al. [3] propose coating the working surfaces of the tools, which has a beneficial effect on the quality of the formed products. Using flexible tools [4] allows avoiding the unfavorable limitations of the stamping

process. This approach also reduces both the cost and the tooling preparation time, while enabling the production of drawn parts with complex geometries. However, tool deformations can make it difficult to achieve a product with specific dimensional tolerances. Sheet metal forming can also be performed using high-energy methods, including electromagnetic forming, electrohydraulic forming, and explosive forming. According to Gronostajski et al. [5], during electromagnetic forming, the forming of large components is limited by the capacitor capacity and the coil dimensions. Electromagnetic forming can only be applied to materials with good electrical conductivity. Another method of sheet metal forming is electrohydraulic forming. Maris et al. [6] reported that this method allows for higher sheet deformation and the forming of hard-to-deform materials. Tong et al. [7] indicate that explosive forming can be used to produce thin-walled products of large dimensions, up to several meters in size.

Thin-walled components can also be produced using rotary forming processes, which include conventional spinning and flow forming. Research conducted under the supervision of Gądek [8] focused on selecting the technological parameters for conventional spinning. Key parameters affecting the quality of thin-walled products formed by this method include: (1) the spindle rotational speed, (2) the feed rate of the forming tool, (3) the distance between the forming tool and the mandrel, and (4) the trajectory of the forming tool movement. Wiśniewski et al. [9] demonstrated that spinning can be combined with flow forming. Xia et al. [10] emphasize that spinning technology can also be applied to form non-axisymmetric products. For single-unit or small-batch production, incremental sheet forming is advantageous. Both single-point incremental forming (SPIF) and two-point incremental forming (TPIF) methods can be employed, using either a CNC machine or a robotic arm. In his review of incremental sheet forming, Trzepieciński [11] highlights several advantages of this process, including: the ability to form products of various geometries using a single tool, rapid modification of product geometries, low forming forces, and achieving higher limit strains. However, this technology also has drawbacks, including longer forming times, lower product quality and accuracy, and limited suitability for mass production.

Another technology enabling the forming of thin-walled components is bending. The

phenomenon of sheet springback must be considered during bending. Factors influencing springback include tool geometry, sheet and tool material properties, friction conditions, anisotropy, and bending parameters [12]. Typically, press brakes allow for V-bending, U-bending, and combinations of these methods [13]. The resulting products exhibit a bend line along a straight path, which constitutes a limitation of the process. Schiller [14] states that rotary bending can replace some stamping methods due to lower tool production costs, the ability to bend along curved paths, and the relatively fast change of product assortment. During bending, less expensive tools made of plastics or plastic inserts mounted in die bodies can also be used [15]. Sheet bending operations with large bend radii are typically performed on roll bending machines using three- or four-roll configurations [16, 17]. Sheets can also be formed longitudinally using roll forming [18]. An interesting method for forming thin-walled components is multi-point forming. Davoodi and Zareh-Desari [19] conducted research on the parameters of this method. Similar products with various curvatures can be shaped using flexible rollers (typically two or three), as demonstrated by Cai, Li, and Lan [20]. Similarly, Chang et al. studied sheet rolling using rigid tools – convex and concave rollers [21]. Fu et al. [22] investigated incremental bending of products with an elliptical shape. However, this method is not suitable for forming elements with more complex geometries. Jin and Murata [23] proposed a method for incremental sheet bending in a plane using a CNC machine. Another approach, described by Singh and Agrawal [24], involves shaping the product with a mandrel while the sheet is partially clamped. This method is thus similar to single-point incremental forming (SPIF), with the main difference being the clamping technique.

Among the mentioned sheet metal forming methods, incremental forming techniques deserve particular attention. Incremental forming has attracted significant research attention due to its numerous advantages. The main advantage of incremental forming over conventional manufacturing technologies is the versatility of the tooling. A single set of tools can produce multiple components differing in shape and size, thereby reducing the costs associated with tool production. Changes can be implemented by modifying the CNC program without replacing the tools. Because the tool in incremental forming exerts only a localized force on the sheet, the forming

forces are relatively low, making the process less energy-intensive. Typically, the incremental forming process takes longer than conventional bending or stamping operations. Incremental forming is carried out using CNC machines, requiring adequately trained personnel. The dimensions of the formed products are limited only by the working area of the machine. Tool contact marks may be present on the formed product. As with conventional methods, springback must be considered and compensated for. Due to the advantages of incremental forming and the lack of dedicated machines for streamlining thin-walled component production, an innovative incremental forming technology was developed. According to the authors' assumptions, the proposed method enables the forming of steel sheet products with thicknesses of up to 5 mm. It should be noted that in the case of thinner sheets, wrinkling may occur. These products can feature not only straight bending lines but also bending lines following an arc-shaped trajectory. This technology was implemented on a special CNC machine constructed at Lublin University of Technology. It enables the forming of thin-walled products of various sizes using a single set of tools, consisting of two rollers: a support roller and a shaping roller. The proposed solution demonstrates considerable potential, particularly for single-unit and small-batch production, where frequent changes in the geometry of formed products are required.

technology enables the shaping of sheet metal products with various geometries and dimensions. Figure 1a presents the initial positioning of the tools and the sheet metal blank, while Figure 1b shows the final stage of the process. For shaping, the sheet metal blank is mounted on a base fixed to the machine worktable. The shaping roller is positioned below the blank, and the support roller above it. The worktable can move along two horizontal axes and rotate. Both rollers can rotate and move along the vertical axis, either independently or as a result of friction with the sheet metal. Additionally, the shaping roller can move horizontally, allowing adjustment of the distance between the rollers. It can also be tilted. After the tool trajectory is programmed into the controller, the forming process begins. The worktable follows the defined path while the rollers shape the sheet metal. Initially, only the shaping roller moves along the vertical axis, gradually forming the sheet edge, while the support roller remains stationary. After a set number of passes, the support roller also moves along the vertical axis. From this stage onward, both rollers move simultaneously with the same feed until the end of the process. This represents the first proposed tool kinematics strategy. In future research, alternative strategies, kinematic parameters, and tool geometries will be investigated.

In the present study, the shaping of thin-walled products with a bending line along an arc was analyzed. Preliminary simulations indicate that this technology can also be applied to produce sheet metal products with more complex geometries. Consequently, elements with straight bending lines, bending lines along arcs, as well as vessel-shaped products can be formed. Examples of such products are shown in Figure 2.

METHODOLOGY

Due to the lack of dedicated machines on the market, an incremental forming technology for thin-walled components was developed. This

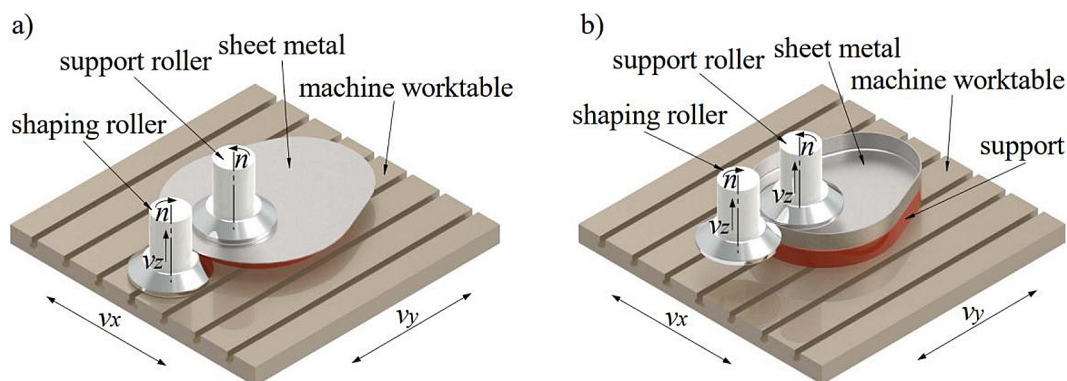


Figure 1. Proposed incremental forming technology: (a) initial stage of the process, (b) final stage of the process with the shaped product visible

RESULTS OF ANALYSIS

Numerical analysis using the finite element method (FEM) was conducted in the sheet metal forming module of Simufact Forming software 2025. The incremental forming was simulated on S355 sheet metal with dimensions presented in Figure 3a. Figure 3b presents the sheet metal product. Sheet metal of various thicknesses, ranging from 1 mm to 5 mm, was analyzed. Five variants of thin-walled products with a bending line along an arc were studied, differing in sheet thickness. The parameters used in the numerical simulations are presented in Table 1. For the numerical simulations, geometric models of the tools were created, including two rollers (shaping and support) and the sheet metal blank. The shaping and support rollers were modeled with identical dimensions, as shown in Figure 4.

The material of the sheet metal was described using the model in Equation 1, obtained from the Simufact Forming software material library.

$$\sigma_F = 853.1 \times e^{-0.0012T} \times \varepsilon^{0.11291} \times e^{\frac{-0.0106}{\varepsilon}} \times \dot{\varepsilon}^{0.0186} \quad (1)$$

where: T – temperature (C°), ε – strain effective, $\dot{\varepsilon}$ – strain rate.

For the numerical simulations, the semi-finished product was modeled as an elastic-plastic body, while the tools were assumed to be rigid and undeformable. The forming process was carried out under cold conditions, with an initial semi-finished product temperature of 20 °C. Temperature variations during the process were not considered. Coulomb friction was assumed between the rollers and the semi-finished product, with a friction coefficient of $\mu = 0.15$ for

both the shaping and support rollers. The semi-finished product was discretized into cuboidal elements with a size of 1.75 mm, resulting in a total of 48,000 elements. It was fixed to the support using the “glued” option, except for the portion undergoing shaping, which remained free. The tool kinematics implemented in the simulations corresponds to the strategy planned for the experimental study. Figure 5a shows the initial positioning of the tools and the semi-finished product, while Figure 5b shows the final stage of the simulation. The shaping roller was positioned below the semi-finished product, and the support roller above it. The support and the semi-finished product moved along a predefined trajectory an arc – rotating about an axis located 275 mm from the edge of the support. The rotational speed was set to 3.3 rpm for 3 seconds, after which the movement continued in the opposite direction (Figure 6). After each pass along the arc, the shaping roller was fed vertically by 3.75 mm at a speed of 7.5 mm/s. The displacement of the support roller is shown in Figure 7, and that of the shaping roller in Figure 8.

In the initial stage of the simulation, the support roller remained stationary in the vertical axis, serving to hold the semi-finished product against the support and partially participating in shaping. In the final stage, both rollers moved along the vertical axis with the same feed rate. In all simulation variants, the support roller was positioned 9 mm below the shaping roller at the final stage, as shown in Figure 9. The shaping roller rotated due to contact with the semi-finished product, while the support roller rotated at a constant speed of 11 rpm, reversing its direction in accordance with the movement of the support and semi-finished product. The overall course of the numerical simulation is illustrated in Figure 10a–h.

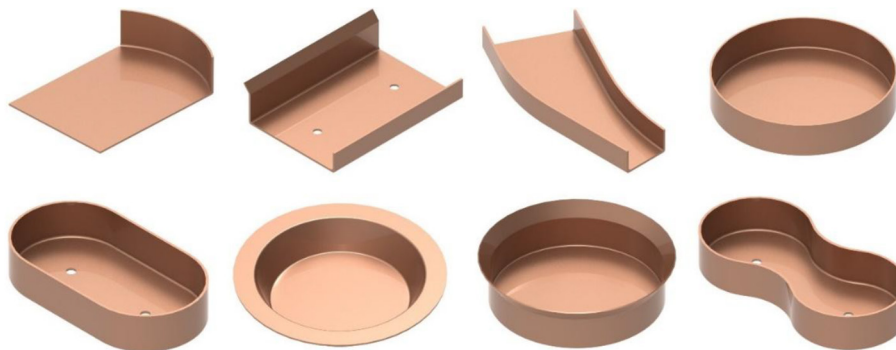


Figure 2. Examples of thin-walled products that can be obtained using the proposed incremental forming technology

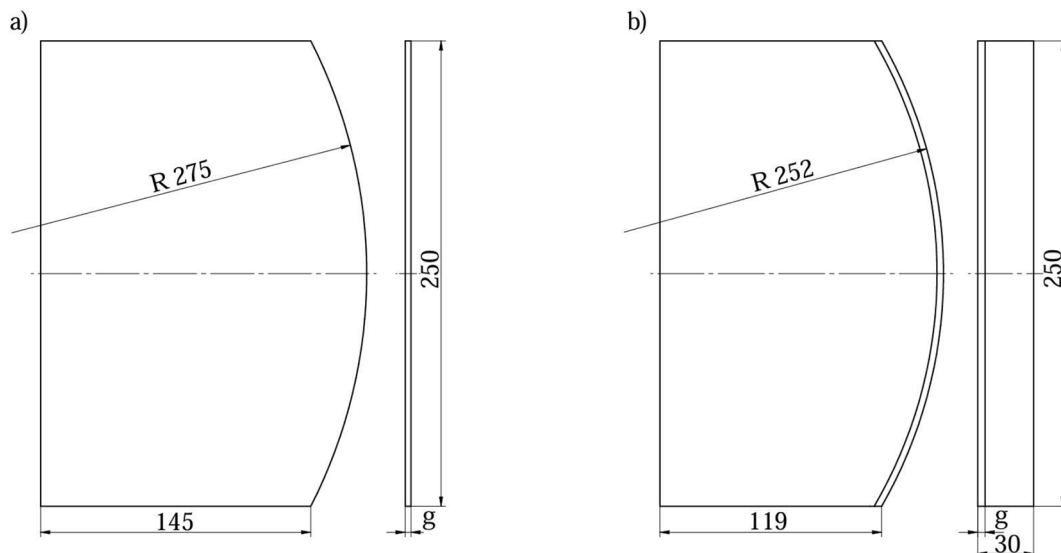


Figure 3. Dimensions: (a) semi-finished product, (b) final product

Figure 11 shows the effective plastic strain distributions obtained during the incremental forming of thin-walled products. Analysis of the strain distributions indicates that effective plastic strains appear at the beginning of the process in the zone where the sheet bend is formed and at the contact point between the semi-finished product and the shaping roller, i.e., at the edge of the sheet. This

effect is particularly pronounced for thicker semi-finished products, which require higher forming forces. In the subsequent stage, the greatest deformations occur in the forming zone, when the semi-finished product is simultaneously shaped by both rollers. It should be noted that at a certain point, the shaping and support rollers are at the same height along the vertical axis. Towards the end of the process, the shaping roller is positioned higher, resulting in intermediate material deformations. For products with thicknesses of 1 mm and 2 mm, the strain distribution is uneven due to sheet wrinkling. Moreover, the deformations are not uniform across the cross-section. The highest values are concentrated near the surface, which can be explained by the kinematics of the process, where tangential strains are generated at the tool – material contact surface. Cross-sectional analyses allow the identification of minor shape defects, such as a slight S-shaped bend at the sheet edge. However, this analysis serves primarily to preliminarily assess the potential of incremental forming for thin-walled products. In future work, the authors plan to investigate tool movement strategies and modify tool geometries to achieve higher dimensional and shape accuracy.

Table 1. Parameters used in the numerical simulations

Process parameter	Value
Range of sheet thicknesses	1–5 mm
Number of FEM mesh elements	48000
Friction coefficient (shaping roller – sheet)	0.15
Friction coefficient (support roller – sheet)	0.15
Rotational speed of the working table	3.3 rpm
Rotation time of the working table	3 s
Feed of the shaping roller	3.75 mm
Feed rate of the shaping roller	7.5 mm/s
Number of passes of the shaping roller	15
Inclination angle of the shaping roller	0°
Rotational speed of the support roller	11 rpm
Activation time of the support roller (start of the first feed)	38.5 s
Initial feed of the support roller	2.75 mm
Initial feed rate of the support roller	5.5 mm/s
Feed of the support roller during the process	3.75 mm
Feed rate of the support roller during the process	7.5 mm/s
Distance between the rollers in the plane perpendicular to the roller symmetry axis at the final stage of forming	9 mm

Figure 12 shows the distribution of von Mises equivalent stress. The highest equivalent stresses occur in the deformation zone of the semi-finished product along the trajectory followed by the tools. This distribution is more uneven for thinner semi-finished products, due to folding at the edges, which prevents the forming tools from

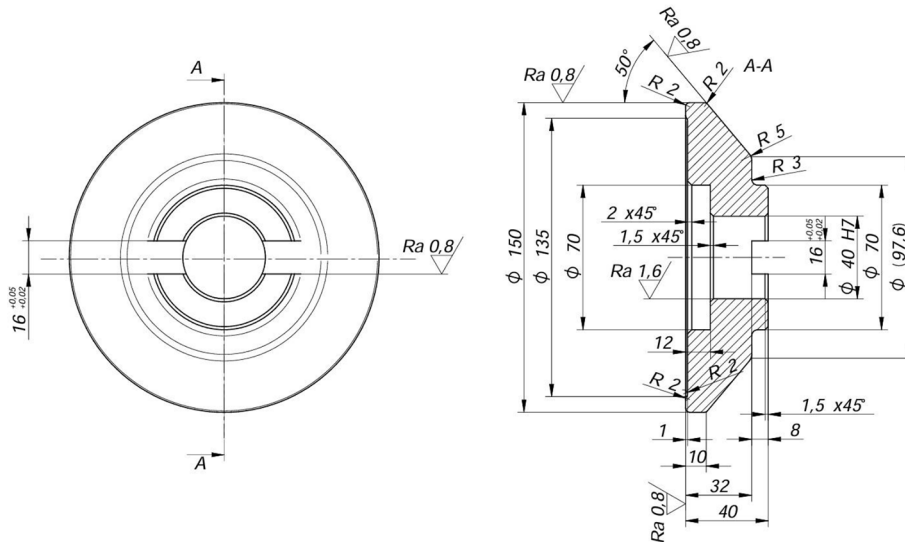


Figure 4. Roller tool dimensions

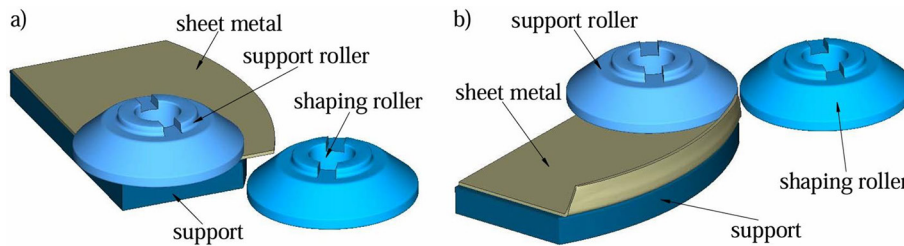


Figure 5. Geometric model of the incremental forming process: (a) initial positioning of the tools and semi-finished product, (b) final stage of the process

maintaining full contact along the prescribed tool path. The equivalent stress reaching a value of 724 MPa occurs directly in the forming zone and represents a resultant of stresses induced by tool interaction, associated with bending and

compression of the material, as well as residual stresses that remain after unloading. Outside the forming zone, only residual stresses remain in the material, and their values are significantly lower than those observed in the direct tool–material interaction zone.

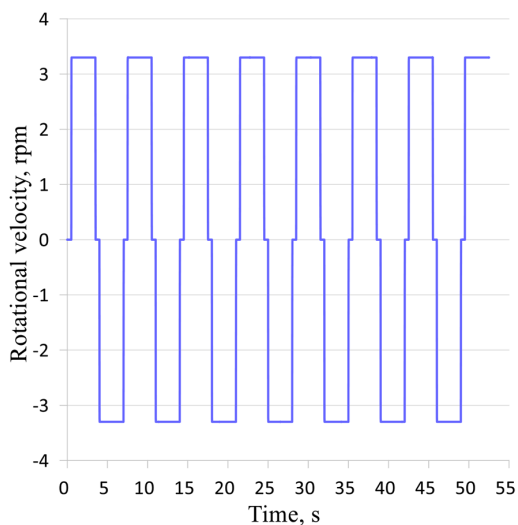


Figure 6. Changes in the rotational speed of the worktable with the sheet metal over time

Figure 13a shows the distribution of the minimum principal stresses, while Figure 13b presents the distribution of the maximum principal stresses for a product formed from a 5 mm thick sheet. Based on these distributions, it can be concluded that on the outer surface of the formed component the stresses take negative values, whereas on the inner surface they take positive values. Therefore, the process is characterized by the occurrence of both compressive and tensile stresses. These stresses result from the final geometry of the product. A different stress distribution would occur in the case of bending along a straight line or along an arc, where the center of the arc (i.e., the point about which the working table rotates) would be located on the opposite side relative to the rollers. The principal stress distributions are presented for

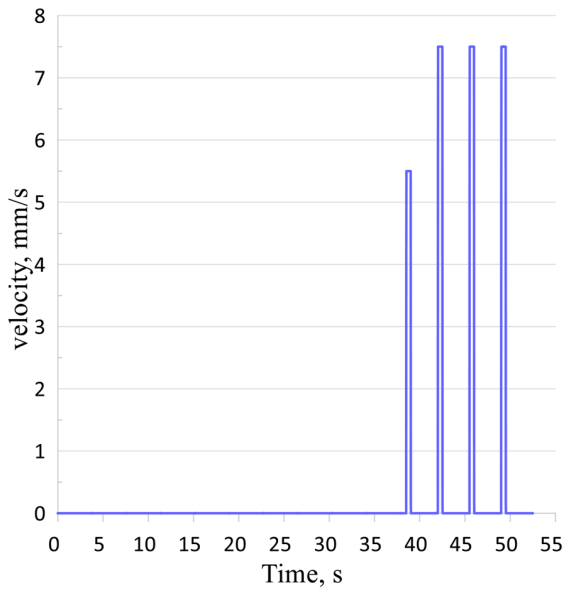


Figure 7. Vertical displacement speed of the support roller during the incremental forming process

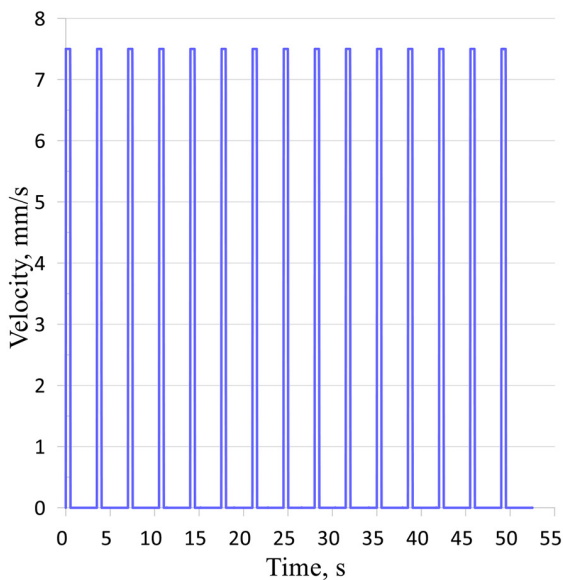


Figure 8. Vertical displacement speed of the shaping roller during incremental forming

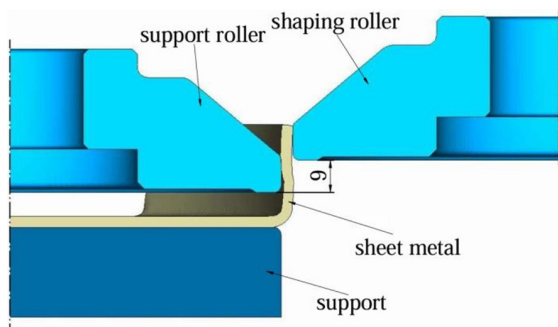


Figure 9. The method of setting the tools when the support roller starts moving in the vertical axis

only one variant in order to highlight the occurrence of stresses with different signs.

Table 2 presents a summary of the maximum values of forces, strains, and stresses for the individual sheet thicknesses. These results were obtained from numerical simulations. Based on the obtained results, it can be seen that the maximum forming force of 24.5 kN and the maximum stress of 724 MPa were reached during the forming of the 5 mm thick sheet. In the case of sheets with thicknesses of 1 mm and 2 mm, wrinkling affects the resulting stress and strain values. The maximum value of effective plastic strain is 1.42 and occurs during the forming of the 2 mm thick sheet. However, the final results indicate that the 2 mm sheet exhibits better surface quality (no pronounced wrinkles at the edge) compared to the product with a thickness of 1 mm. Therefore, it can be assumed that this high strain value results from the final stage of the forming process, where the rollers form the product in the presence of previously generated wrinkles. Such high strain values are not observed in the 1 mm sheet due to its lower stiffness. Due to the occurrence of wrinkling, higher maximum von Mises stress values are observed for products formed from sheets with thicknesses of 1 mm and 2 mm compared to the 3 mm sheet. Therefore, this phenomenon should be considered when comparing numerical simulation results for different sheet thicknesses. The obtained results indicate that forming components from semi-finished products with thicknesses close to the wrinkling threshold leads to an increase in both strain and stress in the material. This can be explained by additional bending induced by the tools, acting on small distortions that represent the initial stage of wall wrinkling. In the case of forming thicker semi-finished products, such distortions do not occur, which contributes to lower strain levels in the material.

One of the design assumptions of the developed machine was the ability to shape sheet metal products using a maximum force of 50 kN. Analysis of the force curves obtained from numerical simulations indicates that this limit is not exceeded (Figure 14). Each temporary increase in force occurs during the vertical movement of the shaping roller. The highest force values are observed just before the midpoint of the process. Initially, only the edge of the semi-finished product is in contact with the shaping roller, explaining the low forces at the beginning

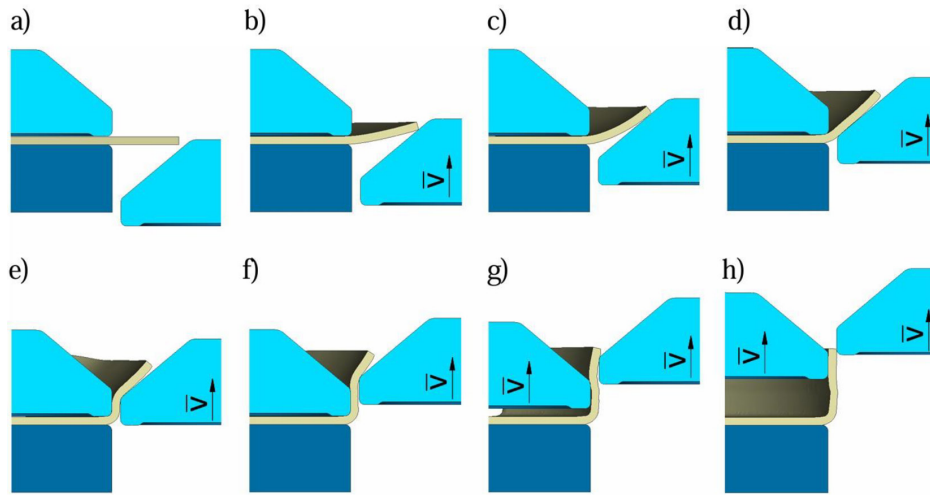


Figure 10. Incremental forming simulation process

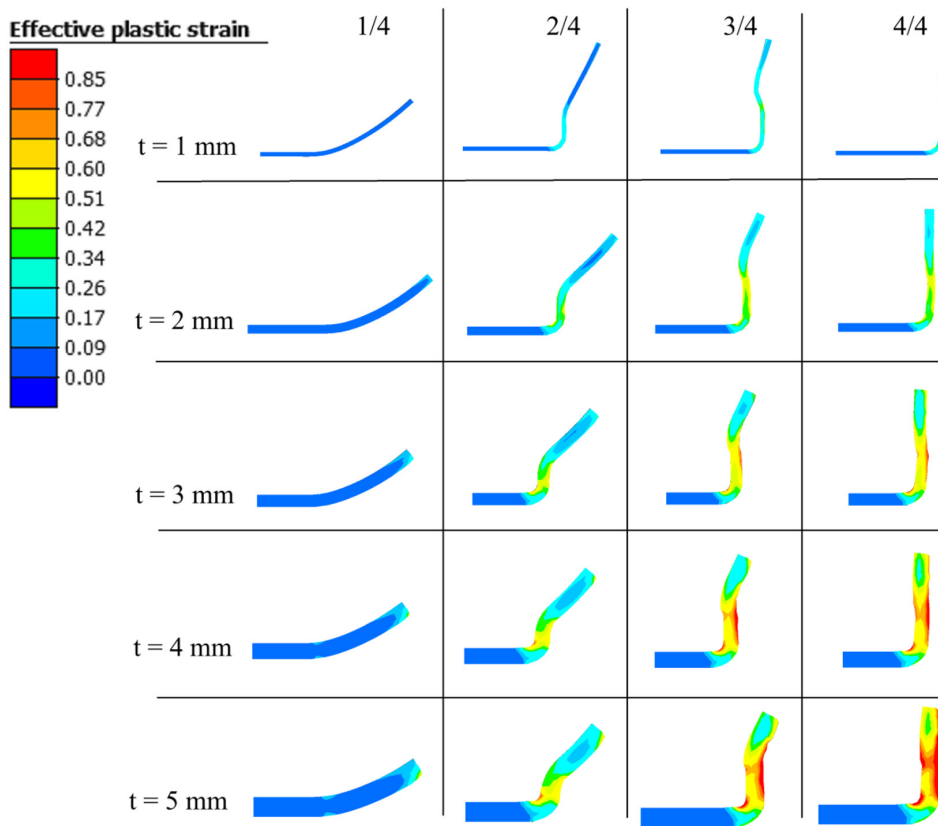


Figure 11. Distribution of effective plastic strain in thin-walled products with different thicknesses

of the simulation. Simultaneous contact of the forming roller with the sheet metal through its conical and cylindrical surfaces results in a significant increase in force up to the maximum value. Subsequently, the force decreases with each successive tool pass. At the end of the simulation, forces may assume negative values due to undesired bending of the semi-finished product, forming an S-shaped cross-section. At this

stage of the process, the support roller is located below the shaping roller in the vertical axis. During the vertical movement of the support roller, it interacts with both the sheet and the shaping roller. As a result, negative values of the vertical force acting on the shaping roller occur. Therefore, if the shaping roller were not moved during the final stage of the simulation, the negative force values would not appear. As expected,

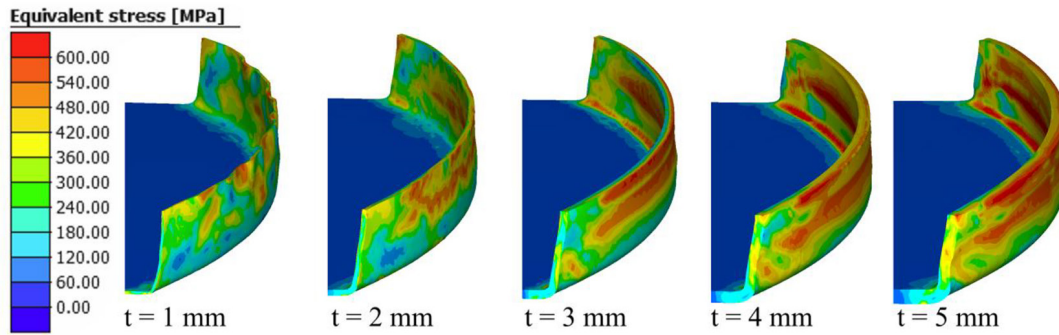


Figure 12. Von Mises equivalent stress distribution

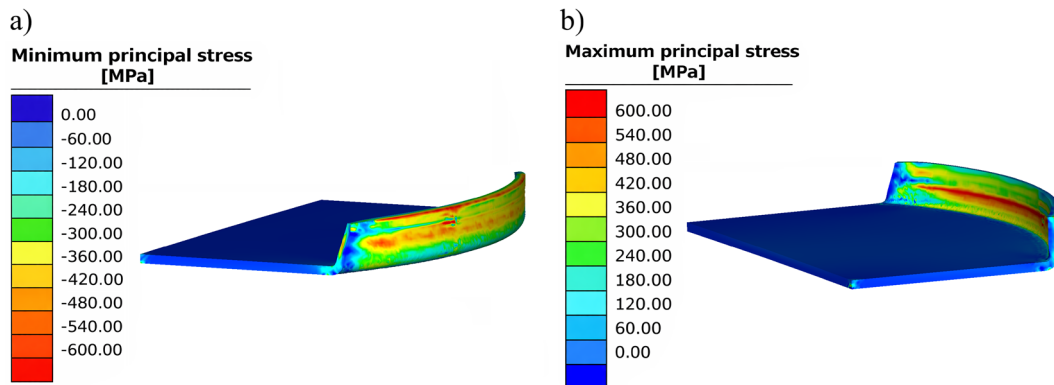


Figure 13. Distribution of: (a) minimum principal stresses, (b) maximum principal stresses

Table 2. Results obtained from the numerical simulations

Thickness t , mm	Strain ϵ , -	Stress σ , MPa	Force F , kN
1	0.85	654	2.5
2	1.42	697	7.3
3	0.99	615	13.2
4	1.09	710	19.1
5	1.15	724	24.5

higher forces are required when forming thicker components. Thicker sheets are characterized by higher stiffness. Additionally, cold plastic deformation leads to material strain hardening.

Sheet metal forming machine

Preliminary numerical analyses confirmed the feasibility of applying incremental forming technology to thin-walled products. To implement this technology, a dedicated machine was designed. Figure 15 shows the machine developed for incremental forming of thin-walled products. The machine worktable is mounted on the frame

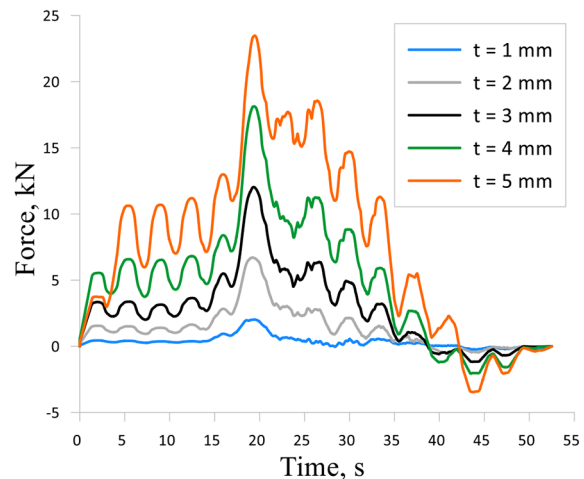


Figure 14. Forming forces during incremental forming of thin-walled products with different thicknesses

and is driven by stepper motors, enabling precise positioning. Vertical movement of the spindles, to which the rollers are attached, is achieved via electric screw actuators. The distance between the spindles can be adjusted using a drive unit for transverse feed, also powered by a stepper motor.

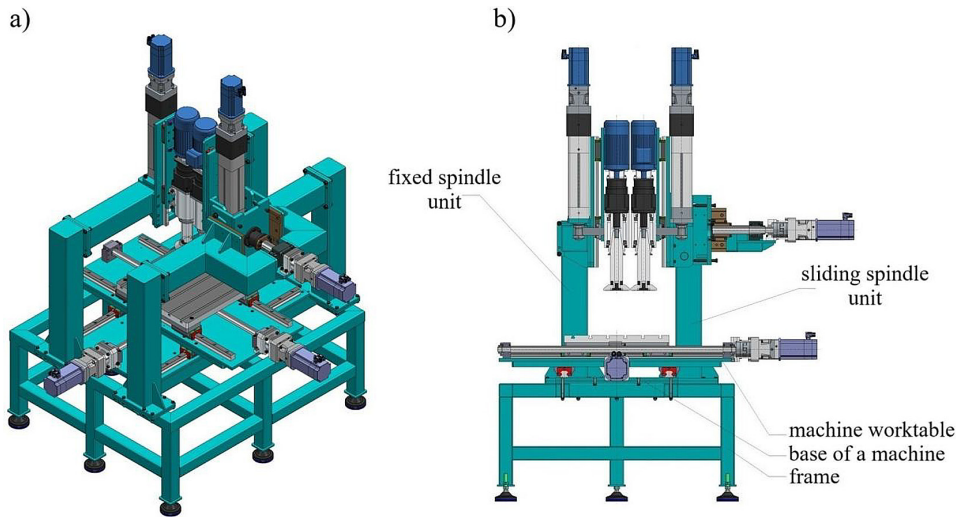


Figure 15. Numerically controlled machine designed at Lublin University of Technology for incremental forming of thin-walled products: (a) isometric view, (b) side view

Table 3. Parameters of the numerically controlled machine

Parameter	Value
Machine worktable dimensions	600 × 600 mm
X-axis travel	700 mm
Y-axis travel	700 mm
Z-axis travel	150 mm
Maximum product dimensions	600 × 600 × 100 mm
Maximum spindle speed	50 mm/s
Maximum worktable speed	50 mm/s
Stepper motor power	4.5 kW
Induction motor power	4.0 kW
Overall machine dimensions	2100 × 2100 × 2600 mm
Machine weight	2500 kg

The rollers are independently rotated by induction motors. The spindle included in the sliding spindle unit can be mechanically tilted by 0–10° relative to the vertical axis. The movement of the worktable and spindle units is controlled by an industrial controller. Therefore, in order to carry out the forming process, the tool movement trajectory must be entered into the controller. The basic machine parameters are listed in Table 3.

CONCLUSIONS

Based on the conducted studies, the following conclusions can be drawn:

- During the forming of steel sheets with thicknesses of 1 mm and 2 mm, there is a risk of unfavorable wrinkling.

- The force values obtained from numerical simulations confirm the applicability of the designed machine for forming steel thin-walled products with thicknesses up to 5 mm.
- In prototype production, the production time may be reduced due to the lack of need to change tools when changing the sheet metal product type.
- In prototype production, the production time may be reduced due to the lack of need to change tools when changing the sheet metal product type.
- Due to the incremental nature of material deformation, forming forces are expected to be lower than in conventional stamping and bending processes.
- The cost of changing the manufactured product range is low, making the process a universal and economical forming method.
- The forming tools (rollers) feature a relatively simple design.

Based on the preliminary numerical analyses, the incremental forming of thin-walled components may serve as a potential alternative to conventional bending and stamping processes, offering the possibility of reduced manufacturing costs and increased production flexibility. Further research is required to experimentally validate the numerical simulations and to assess the feasibility of industrial implementation using a numerically controlled machine. The technology was developed in response to the needs of the domestic industry, where universal machines for sheet metal forming are currently lacking.

REFERENCES

1. Singh R. Deep drawing behaviour of CRCA sheet and wrinkling congestion of round flange cup. *Journal of Manufacturing Engineering*. 2013; 8(2): 92–95. <https://smenec.org/index.php/1/article/view/328> (accessed on 10 February 2026)
2. Drenger T., Pawlicki M. Modern blank holding systems in the process of stamping. *Metal Forming*. 2011; 22: 83–109.
3. Abe Y., Ohmi T., Mori K., Masuda T. Improvement of formability in deep drawing of ultra-high strength steel sheets by coating of die. *Journal of Materials Processing Technology*. 2014; 214(9): 1838–1844. <https://doi.org/10.1016/j.jmatprotec.2014.03.023>
4. Krakowski M., Bartnicki J. Analysis of the extrusion process using a flexible tool. *Mechanik*. 2017; 11. <https://doi.org/10.17814/mechanik.2017.11.156>
5. Gronostajski Z., Pater Z., Madej L., Gontarz A., Lisiecki L., Łukaszek-Solek A., Łuksza J., Mróz S., Muskalski Z., Muzykiewicz W., Pietrzyk M., Śliwa RE., Tomczak J., Wiewiórowska S., Winiarski G., Zasadziński J., Ziółkiewicz S. Recent development trends in metal forming. *Archives of Civil and Mechanical Engineering*. 2019; 19(3): 898–941. <https://doi.org/10.1016/j.acme.2019.04.005>
6. Maris C., Hassannejadasl A., Green D.E., Cheng J., Golovashchenko S.F., Gillard A.J., Liang Y. Comparison of quasi-static and electrohydraulic free forming limits for DP600 and AA5182 sheets. *Journal of Materials Processing Technology*. 2016; 235: 206–219. <https://doi.org/10.1016/j.jmatprotec.2016.04.028>
7. Tong Z., Li Z., Cheng B., Zhang R. Precision control of explosive forming for metallic decorating sphere. *Journal of Materials Processing Technology*. 2008; 203(1–3): 449–453. <https://doi.org/10.1016/j.jmatprotec.2007.10.042>
8. Gądek T., Majewski M., Nowacki Ł., Drender T. Tests of forming symmetrical products using the spinning method supported by FEM simulations. *Metal Forming*. 2019; 30(4): 273–290.
9. Wiśniewski J., Drender T., Nowacki Ł., Ulatowski Z. Combination of the spinning technology with flow forming. *Metal Forming*. 2006; 17(1): 3–5.
10. Xia Q., Xiao G., Long H., Cheng X., Sheng X. A review of process advancement of novel metal spinning. *International Journal of Machine Tools and Manufacture*. 2014; 85: 100–121. <https://doi.org/10.1016/j.ijmactools.2014.05.005>
11. Trzepieciński T. Incremental sheet forming – possibilities of its application in the aircraft industry. *Stal, Metale & Nowe Technologie*. 2019; 5: 48–54.
12. Bakhshi-Jooybari M., Rahmani B., Daezadeh V., Gorji A. The study of spring-back of CK67 steel sheet in V-die and U-die bending processes. *Materials & Design*. 2009; 30(7): 2410–2419. <https://doi.org/10.1016/j.matdes.2008.10.018>
13. Tschaetsch H. *Metal Forming Practise: Processes – Machines – Tools*. Springer. 2005; 194–211. <https://doi.org/10.1007/3-540-33217-0>
14. Schiller M., Frohn-Sörensen P., Engel B. 3D-swivel-bending – a flexible and scalable forming technology. In: *Proceedings of the 12th International Conference on Numerical Methods in Industrial Forming Processes (NUMISHEET)*. 2022; 125–139. https://doi.org/10.1007/978-3-031-06212-4_12
15. Zaragoza V.G., Strano M., Iorio L., Monno M. Sheet metal bending with flexible tools. *Procedia Manufacturing*. 2019; 29: 232–239. <https://doi.org/10.1016/j.promfg.2019.02.131>
16. Fu Z., Tian X., Chen W., Hu B., Yao X. Analytical modeling and numerical simulation for three-roll bending forming of sheet metal. *International Journal of Advanced Manufacturing Technology*. 2013; 69(5–8): 1639–1647. <https://doi.org/10.1007/s00170-013-5135-2>
17. Wu K., Sun Y., Cao C., Zhou C., Liu Q., Chang X. Simulation analysis of plate forming and deformation compensation technology of the side roll for four-roll plate bending machine. *Procedia Engineering*. 2017; 207: 1617–1622. <https://doi.org/10.1016/j.proeng.2017.10.1088>
18. Safdarian R., Moslemi Naeini H. The effects of forming parameters on the cold roll forming of channel section. *Thin-Walled Structures*. 2015; 92: 130–136. <https://doi.org/10.1016/j.tws.2015.03.002>
19. Davoodi B., Zareh-Desari B. Assessment of forming parameters influencing spring-back in multi-point forming process: a comprehensive experimental and numerical study. *Materials & Design*. 2014; 59: 103–114. <https://doi.org/10.1016/j.matdes.2014.02.043>
20. Cai Z.Y., Li M.Z., Lan Y.W. Three-dimensional sheet metal continuous forming process based on flexible roll bending: principle and experiments. *Journal of Materials Processing Technology*. 2012; 212(1): 120–127. <https://doi.org/10.1016/j.jmatprotec.2011.08.014>
21. Chang X., Fu W., Li M., Wang X., Yang W., Deng Y. An investigation into the effect of rolling reduction on 3D curved parts rolling process. *Metals*. 2021; 11(8): 1209. <https://doi.org/10.3390/met11081209>
22. Fu Z., Chen W., Tian X., Hu B. Modeling and simulation for multiple-step incremental air-bending forming of sheet metal. *Journal of Materials Processing Technology*. 2014; 72: 561–570. <https://doi.org/10.1007/s00170-014-5708-8>