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Marcin SZPUNAR[1]
Maciej BALCERZAK[2]
Krzysztof ŻABA[3]

SHAPE ACCURACY IN SINGLE POINT INCREMENTAL FORMING OF CONICAL FRUSTUMS FROM TITANIUM CP2 SHEETS

Abstract: This paper presents frustum cone drawpiece analysis made of titanium CP2 sheet by a single incremental sheet forming. Central composite design has been adopted to carry out an experiment containing 20 runs, then multi-criteria parameter optimization has been done. Optimal parameters have been validated and responses deviations do not exceed 4% compared to created models. For the drawpiece formed with optimal parameters, AGRUS optical measurement and X-ray tomography has been applied to check the obtained of the part wall thickness and general deviations compared to the CAD model. The wall angle discrepancy of the cone generatrix has also been analyzed. No gaps or ruptures have been confirmed by X-ray. The blank rolling direction has a significant effect on the drawpiece deviations. The measurement results showed deviations of the drawpiece wall angle +0.27°/-0.06°, sheet thickness on the cone +0.012/-0.04 mm and +0.151/-0.096 mm from the reference CAD geometry.

Keywords: incremental sheet forming, titanium, springback, optical forming analysis, X-ray tomography

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[1] Corresponding author: Marcin Szpunar, Doctoral School of Engineering and Technical Sciences at the Rzeszow University of Technology, Rzeszow University of Technology, al. Powst. Warszawy 12, 35-959 Rzeszów, Poland, e-mail: d547@stud.prz.edu.pl., ORCID ID: 0000-0003-1580-5357

[2] Maciej Balcerzak, Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, Faculty of Non-Ferrous Metals, AGH University of Science and Technology, al. Adama Mickiewicza 30, 30-059 Cracow, Poland., e-mail: maciejbalcerzak1@gmail.com

[3] Krzysztof Żaba, Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, Faculty of Non-Ferrous Metals, AGH University of Science and Technology, al. Adama Mickiewicza 30, 30-059 Cracow, Poland., e-mail: krzyzaba@agh.edu.pl, ORCID ID: 0000-0002-6541-885X

1. Introduction

The widespread use of numerically controlled machines (milling machines, lathes, etc.) enabled the dynamic development of incremental sheet forming (ISF) methods. The effect of this development is the possibility of forming sheet metals with free shapes. In high-volume production, incremental sheet metal forming is used when the desired effect cannot be obtained using conventional methods (Behera et al., 2017). There are several different types of forming approach that use an incremental approach: Single Point Incremental Forming (SPIF) (Martins et al., 2008), Two-Point Incremental Forming (TPIF) (Mostafanezhad et al., 2018), ultrasonic assisted ISF (Cheng et al., 2019), electromagnetic incremental forming (EMIF) (Cheng et al., 2022), water jet incremental forming (Shi et al., 2019) etc. To form hard-to-deform materials, heat-assisted incremental sheet forming was developed by Liu (2018). During the single-point incremental sheet metal forming analysis in this article, the deformation of the material is carried out gradually. The workpiece material and tools are less loaded compared to conventional deep-drawing processes. SPIF has the following advantages (Li et al., 2017; Murugesan et al., 2022; Wang et al., 2022): low force resulting from the incremental character of the process, high flexibility of the process makes it possible to quickly and easily take into account design changes in shaped elements, a conventional CNC machine can be used to carry out the process, the process does not require stamping dies. SPIF has also some disadvantages: requires a longer forming time than a conventional sheet forming process, the process is limited to prototyping and small production batches, poor surface finish.

One of the main problems in ISF are geometric deviations of the workpiece material after unloading which means that the resulting shape is not necessarily the desired shape. Honarpisheh et al. (2019) investigated the incremental forming process of explosively welded Cu/St/Cu multilayer sheets in order to determine the springback phenomenon on different layers. Spindle speed, tool feed, and incremental step depth were found to affect springback in SPIF. Khan et al. (2015) developed a classifier-based intelligent process model and its application to analyse the shape errors of square-based modified pyramids made from DC04 steel sheet. Cédric et al. (2020) proposed a technique to compensate, after the fact, for shape defects related to forming and springback in the micro-single-point incremental forming technique (μ-SPIF). The advantage of this method is to avoid geometric discontinuities by using B-spline curves. Micari et al. (2007) discussed several methods to improve the ability of the SPIF and concluded that tool path optimization approaches are the most promising in reduction of the springback defects. Karim et al. (2021) used a numerical response surface methodology with a Design of Experiments (DOE) to improve thickness reduction and the effects of the springback. Furthermore, the Gurson-Tvergaard-Needleman damage model was used to analyse the damage evolution during deformation of a truncated pyramid. It was found that the wall angle is the most influential parameter on the springback amount. Jain et al. (2021) investigated the effect of various parameters on springback and thinning while performing SPIF on polypropylene sheets. The springback was found to increase with increasing tool diameter. Rusu et al. (2021) studied the behaviour of different EN AW-2007, EN AW-5754 and EN AW-6060 aluminium alloy sheets deformed through SPIF regarding springback effect. Frustum pyramids made of EN AW-2007 alloy presented the highest springback. Liao et al. (2022) investigated the effects of ultrasonic vibration and temperature on springback of polyether-ether-ketone drawpieces during the incremental forming process. As the temperature rises, the springback of most areas of the drawpiece decreases. They also found that ultrasonic vibration is beneficial to improving the geometric accuracy of SPIFed parts. Mezher et al. (2021) predicted the springback during the SPIF process of DC04 and EN AW1050 aluminium alloy sheet. They concluded that the degree of springback is increased as a result of increasing the wall angle. Wang et al. (2018) tried to reduce the springback for double-sided incremental forming and found that reverse bending and squeezing can decrease the springback of EN AW-7075 aluminium alloy drawpieces. Jung et al. (2020) proposed a procedure to construct the tool path for counter SPIF to decrease shape error. The two-stage SPIF was very effective in increasing the geometric accuracy of the EN AW-5052 aluminium alloy conical drawpieces. Oleksik et al. (2014) predicted springback of DC04 steel parts using the ARAMIS computational system. The lowest amount of springback is found in the opposite corner of the frustum of pyramid, compared to the corner where the maximum value of springback appears. A four camera system designed for measuring the shape variations of a sheet metal part during a SPIF process has been presented by Orteu et al. (2011).

In this paper, optical analysis ARGUS and computer tomography methods have been applied to determine the drawpiece thickness distribution as well as shape deviations caused mainly by a springback effect after the SPIF process of titanium CP 2 sheet. The drawpiece formed with optimized parameters as a result of multi-criteria optimization form central composite design of experiment has been taken into account.

2. Experimental setup

Titanium CP 2 has been selected as the material for a geometry formation of truncated cones. The initial sheet thickness was 0.4 mm and cut for round blanks with a diameter Ø100 mm. The mechanical properties of the material selected are presented in Table 1.

Table 1. Properties of the material selected for the drawpieces – titanium CP2

Density	**Hardness**	**Ultimate Tensile Strength**	**Tensile Yield Strength**	**Elastic modulus**
4.51 g/cm^3	235 HV	430 MPa	340 MPa	102 GPa

The Makino PS95 3-axis milling machine has been selected for a test stand. To firmly clamp the sheet blanks, a dedicated fixture for the incremental forming process has been produced. The fixture has been located inside the milling machine zone and attached to the CNC working table. A solid carbide hemispherical end tool with diameter Ø8 mm has been selected as a punch tool. The tool was ground from an ISO K30-K40 tungsten carbide rod and mounted in a collet chuck ER32. To reduce the friction coefficient and improve the lubrication between the tool and the formed sheet, 75W85 synthetic oil has been deposited. NX Siemens PLM software has been selected to create a drawpiece CAD shape and to generate CNC paths (Fig. 1a). An experimental stand prepared for the incremental forming process is presented in Fig. 1b. The drawpiece geometry has been assumed as 45° truncated cone ended with radius equal to the tool tip R = 4 mm (Fig. 2).

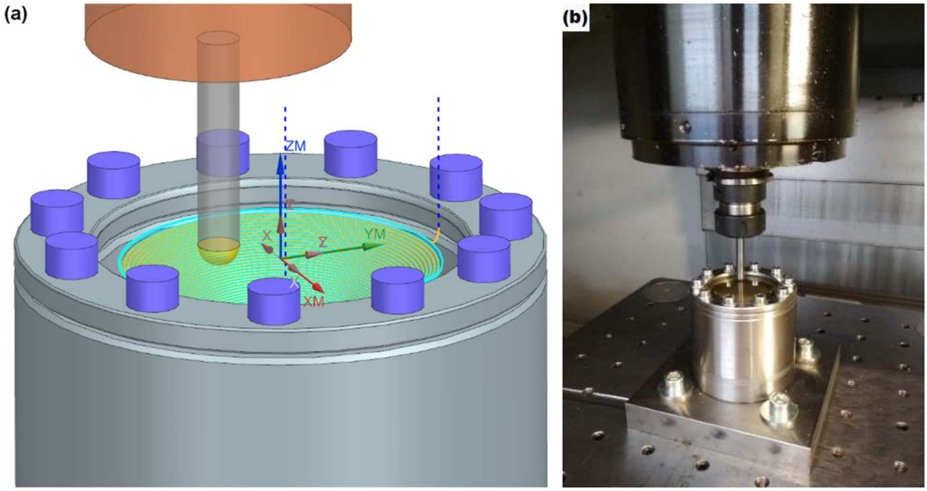


Fig. 1. (a) Programmed CNC tool path in NX Siemens CAM, (b) Test stand – Makino PS95 with SPIF dedicated device

Process input parameters have been determined as following: spindle speed, tool feed and incremental step depth, while incremental step depth means the vertical pitch between the spiral tool path during one loop. The central composite design of the experiment has been developed (Fig. 3) to determine the influence of input parameters on forming outputs such as axial forming force, in-plane forming force, surface roughness Rz parameter and forming success. On the basis of the created models, optimal forming parameters have been determined with optimization criteria taken into account. Detailed information on the experiment can be found in the previous manuscript (Szpunar et al., 2021).

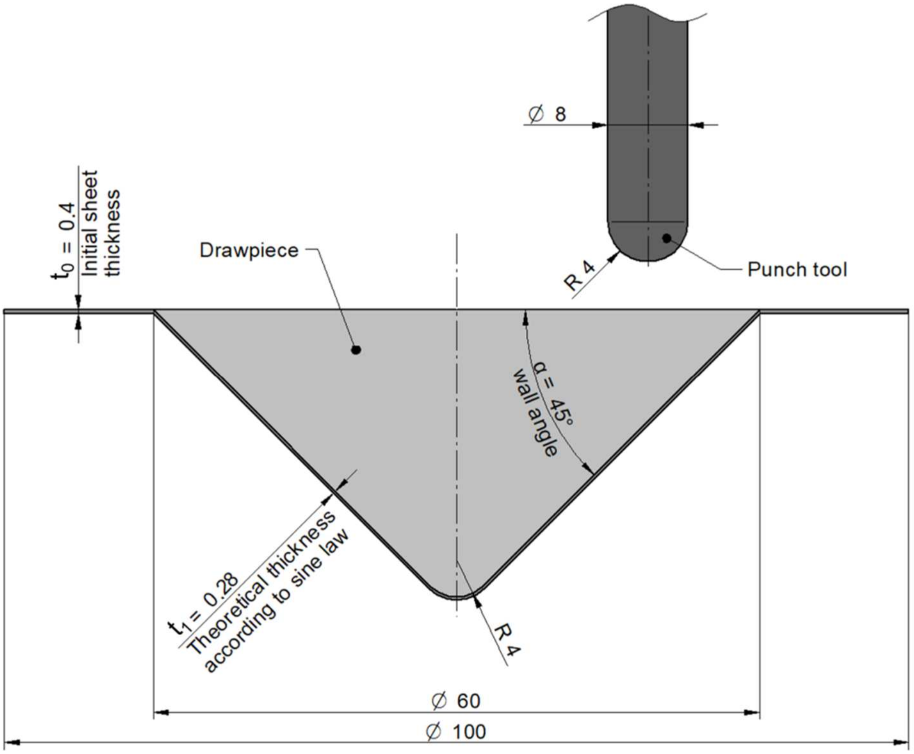


Fig. 2. Cross section of the desired drawpiece intended for deviation analysis

$$t_1 = t_0 \sin(90° - \alpha) \tag{1}$$

where t_1 – sheet thickness in forming stage,
t_0 – initial sheet thickness,
α – drawpiece wall angle.

Optimal forming parameters have been determined and validated with a deviation of outputs less than 4%. Figure 4 presents optimal forming parameters with predictions of the results according to the models obtained. The drawpiece formed using optimal parameters has been selected for further shape analysis (Fig. 5).

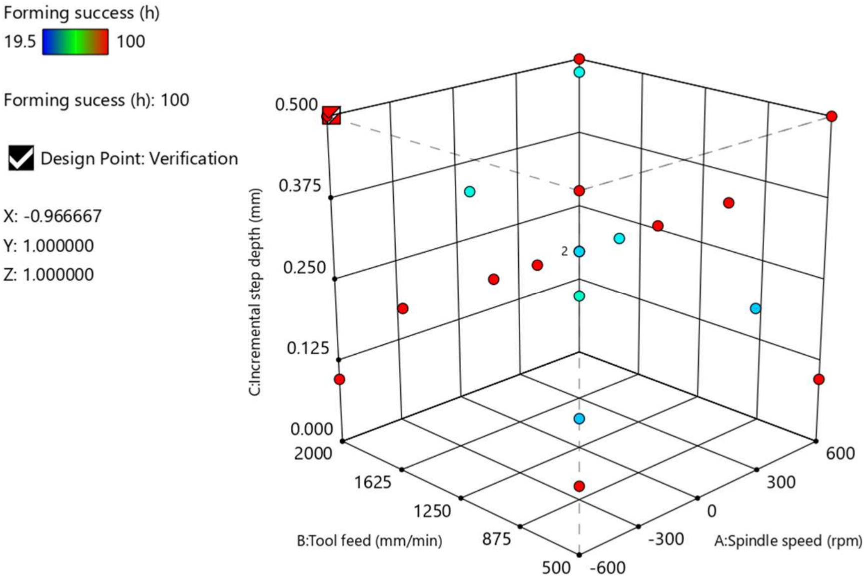


Fig. 3. 3D graph presenting the central composite design with a verification run

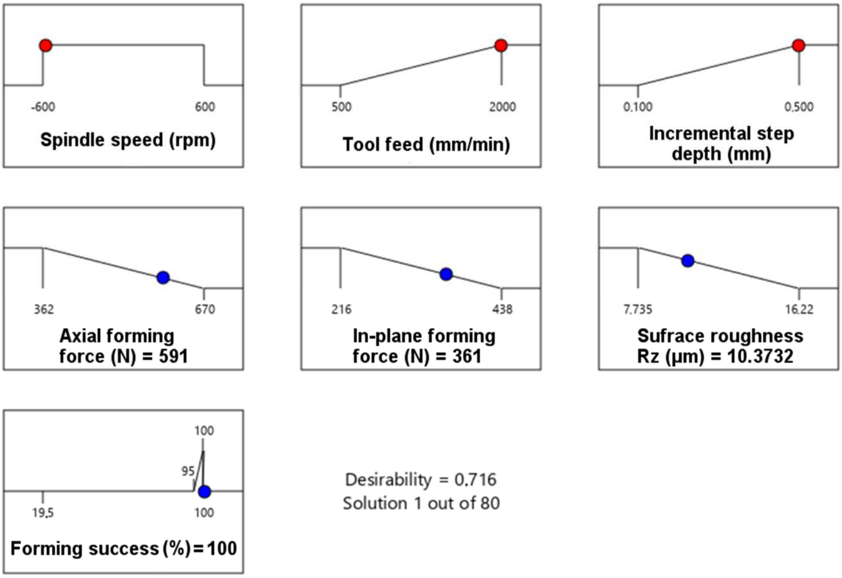


Fig. 4. Optimal ISF parameters with predicted process output received as multi-criteria optimization

Fig. 5. Successfully achieved the drawpiece using optimized parameters

The specimen was analyzed by the ARGUS system, which allows one to create 3D models from the scans. By these possibilities, drawpiece deviations and sheet thickness distribution measurement could be obtained. To be sure that there are no internal cracks, computer tomography using GE V | TOME | X M300 has been performed and several X-ray intersections have been captured. The major advantages of visual scanning methods are rapid analysis of drawpieces and non-destructive form of exploration. The theoretical thickness of the sheet can be described by Equation 1 using the principle of constant volume of material. Figure 2 presents the ideal shape of the drawpiece with the calculation of the sheet thickness (Eq. 1) taken into account. This method of necking estimation has been applied by many researchers (Chen et al., 2017; Harhash & Palkowski, 2021; Su et al., 2021). The CAD model of the drawpiece has been selected as a reference for the analysis of the sheet thickness differences as the well as shape deviations.

3. Results and Discussion

The 3D scan has been analysed in case of wall angle difference. 2D sections in a rolling and perpendicular to rolling direction were extracted and compared by measuring wall angle. Figure 6 presents the drawpiece wall angle determination through the intersection generatrix and the not deformed face. The resulting wall angle was 45.27° and 45.16° in the rolling direction, while 44.94° and 45.03° perpendicular to the rolling direction.

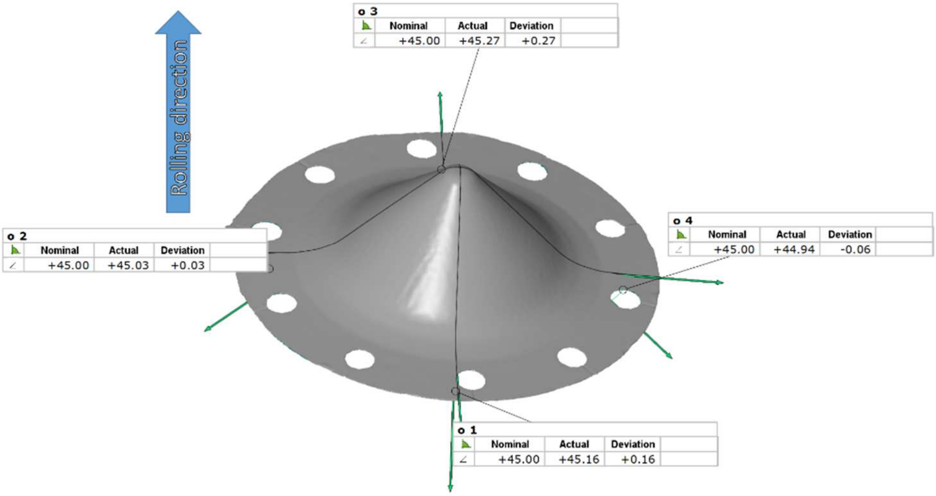
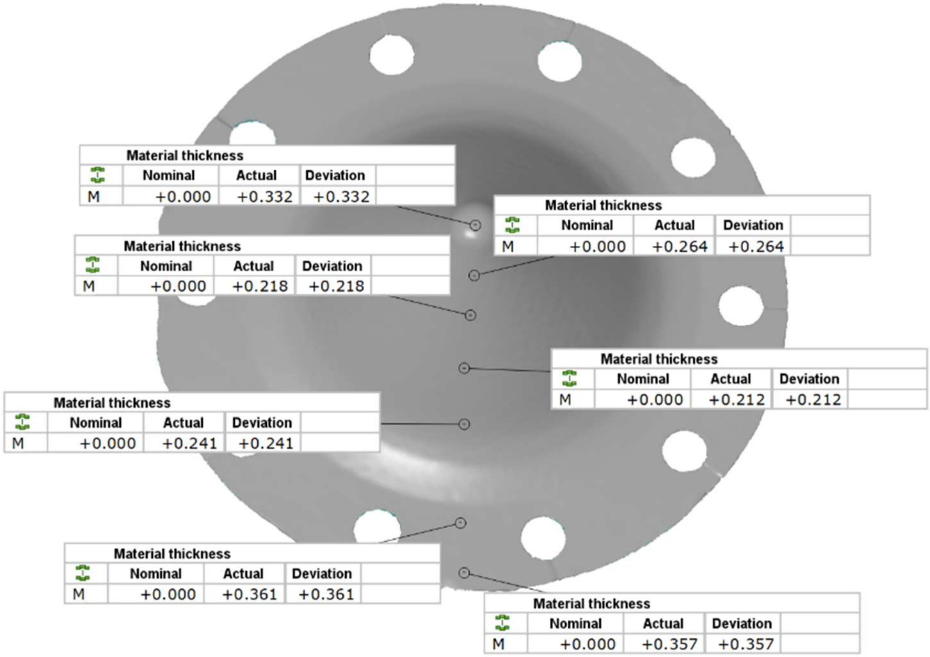


Fig. 6. Drawpiece wall angle scan using the ARGUS device

The ARGUS system allows thickness distribution analysis. The scan presented in Fig. 7 shows multilocation measurement of the drawpiece thickness. Taking into account the initial sheet thickness tolerance ±0.03 mm as well as measurement uncertainty of ARGUS device ±0.02 mm, a 0.357 mm (0,4 mm ± 0,05 mm) initial sheet thickness was obtained. Applying the sine law (Eq.1) theoretical thickness 0.252 mm ±0.05 mm should be achieved on a generatrix. All measurement points located at generatrix meet the criteria of the sine law equation (Fig. 7).

The inaccuracy caused mainly by a springback effect was revealed by analyzing the deviations scanned by ARGUS (Fig. 8). Large discrepancies were located at the initial stage of forming, where the bending zone appears. The bending zone is a part of the sheet where tool-workpiece contact does not exist; however, the sheet bends under the forming forces in the process. The vertex of the drawpiece is also burdened with shape error caused by the tool retraction from the workpiece and also high acceleration demanded by the CNC machine to achieve the set feed rate on a short path. Such a quick change of axis movement direction also causes vibrations of the entire system, which negatively effects accuracy. Lower deviations can be observed at the generatrix located in accordance with the rolling direction +0.09/-0.051 mm, while perpendicular to the rolling direction +0.151/-0.096 mm.



Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.332	+0.332

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.264	+0.264

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.218	+0.218

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.212	+0.212

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.241	+0.241

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.361	+0.361

Material thickness

	Nominal	Actual	Deviation
M	+0.000	+0.357	+0.357

Fig. 7. The sheet thickness distribution measured by ARGUS system

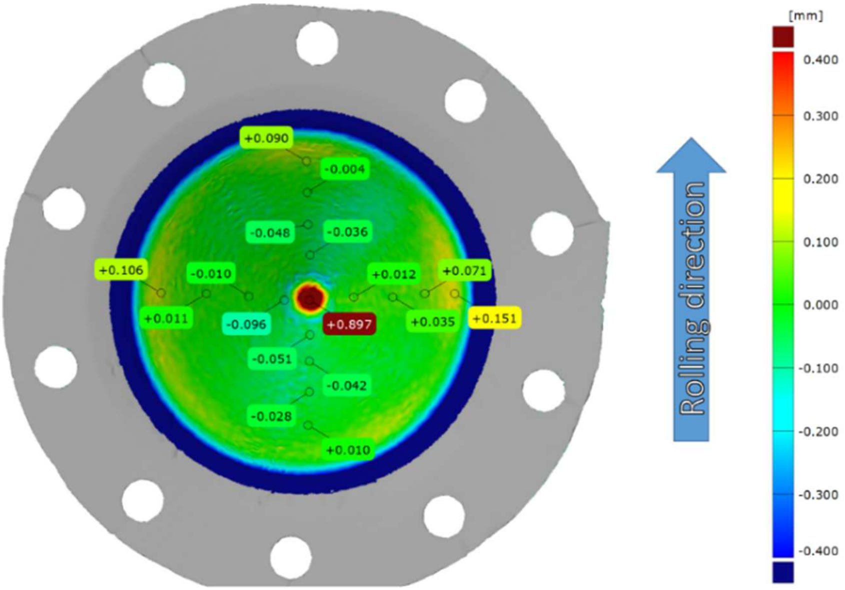


Fig. 8. Drawpiece shape deviations measured using ARGUS system

Tomography X-ray devices has possibilities to obtain multiple high resolution intersections of the measured part. This option allows one to inspect the drawpiece in case of internal cracks or breakages. It is also possible to compare the obtained drawpiece with reference to the CAD geometry. The high resolution intersection analysis of the tomography approved that there was no internal crack or break in the drawpiece. Figure 9 presents deviations of the captured cross section. The maximum shape error is located in a bending zone.

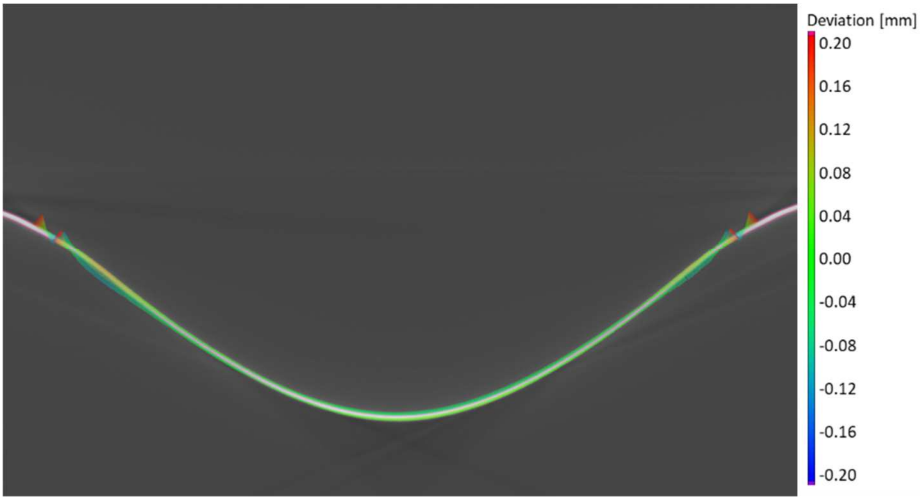


Fig. 9. One of the drawpiece sections with marked deviations captured using X-ray tomography

4. Conclusions

In this research paper, the springback effect on the accuracy of the drawpiece has been investigated. The optical measurement system has been applied to the wall angle discrepancy, drawpiece thinning analysis, as well as deviations from the reference CAD model. The following conclusions can be drawn:

- The blank rolling direction significantly affects the springback, which resulted in a difference in drawpiece deviations.
- The sine law can be applied to predict the wall thickness of the generatrix of the 45° cone drawpiece with optimal parameters.
- X-ray tomography analysis allows for a drawpiece fracture detection as well as deviation analysis. The achieved drawpiece does not contain gaps or breakages in material continuity.
- The measured deviations of the frustum cone formed with optimized parameters are as follows: wall angle +0.27°/-0.06°, generatrix thickness +0.012/-0.04 mm and deviation from the reference CAD geometry +0.151/-0.096 mm.

- To reduce deviations at the vertex of the frustum cone, tool feed reduction may be applied at the end of the forming path or vertical (axial) plunging while the tool axis overlaps the drawpiece axis.

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DOKŁADNOŚĆ KSZTAŁTU W JEDNOPUNKTOWYM KSZTAŁTOWANIU PRZYROSTOWYM STOŻKÓW ŚCIĘTYCH Z BLACH TYTANOWYCH CP2

Streszczenie

W pracy przedstawiono analizę wytłoczek w kształcie stożka ściętego wykonanego z blachy tytanowej CP2 metodą jednopunktowego przyrostowego kształtowania. Do przeprowadzenia eksperymentu obejmującego 20 przebiegów przyjęto centralny plan kompozycyjny, następnie dokonano wielokryterialnej optymalizacji parametrów. Dokonano walidacji optymalnych parametrów, a uzyskane wyniki nie przekraczają 4% w odniesieniu do stworzonych modeli. Dla wytłoczki uformowanej z optymalnymi parametrami zastosowano pomiar optyczny AGRUS oraz tomografię rentgenowską w celu sprawdzenia uzyskanej grubości ścianki wytłoczki i odchyłek w porównaniu z modelem CAD. Przeanalizowano również rozbieżność kątów ścian tworzących stożka. Za pomocą skanu rentgenowskiego potwierdzono brak szczelin i pęknięć wytłoczki. Kierunek walcowania półfabrykatu ma istotny wpływ na odchyłki. Wyniki pomiarów wykazały odchylenia kąta ścianki wytłoczki +0,27/-0,06°, grubości ścianki na stożku +0.012/-0.04 mm oraz +0.151/-0.096 mm od geometrii referencyjnej CAD.

Słowa kluczowe: kształtowanie przyrostowe blach, tytan, sprężynowanie, analizy optyczne kształtowania, komputerowa tomografia.

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