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A Study on the Effect of Multistage Toolpath in Fabricating a Customized Cranial Implant in Incremental Sheet Metal Forming

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Abstract

Incremental sheet forming (ISF) process offers a high degree of flexibility in the manufacturing of different sheet parts, which makes it an ideal candidate for prototype parts as well as efficient at fabricating various customized products at low production costs compared to traditionally used processes. However, parts produced in this process exhibit notable geometrical inaccuracy and considerable thickness reduction. In this paper, the single point incremental sheet forming variant of the process has been implemented to manufacture a highly customized cranial implant starting from the computed tomography (CT) scan data of the patient's anatomy. A methodology, from the modeling to the realization of the implant, is presented and discussed. The primary aim of the research was to analyze and study the effect of the multistage toolpath strategy compared to the traditional single-stage toolpath in terms of geometrical accuracy and thickness distribution. The final results show that the part formed in the multistage toolpath strategy exhibited a more uniform thickness distribution compared to the single-stage approach. Regarding the geometrical accuracy, the deviation analysis between the nominal and actual data has revealed that the multistage forming has significantly enhanced the final geometrical accuracy of the formed part.

Keywords: *Incremental sheet forming, Multistage, Medical implant, Thickness, Geometrical accuracy.*

1. Introduction

Incremental sheet forming is an innovative forming process that was originally developed to overcome the limitations of conventional forming processes in terms of flexibility [1,2]. In this process, a hemispherical tool, typically mounted to CNC, moves progressively according to a predefined path using CAD-CAM technology. The forming tool engages with the clamped sheet at small contact areas, imposing localized plastic deformation that enhances the process's formability compared to traditional stampings. Characterized by its high flexibility, the process can accommodate different design specifications, including symmetrical and asymmetrical geometries, without changing the process setup. In addition, the process does not require dedicated dies, complex tooling, or fixtures. As a result, it dramatically reduces production costs. These features made the process efficient for prototyping and small-batch production in the automotive and aerospace industry. However, the process suffers from notable drawbacks: reduced geometrical accuracy, non-uniform thickness distribution, and formability constraints in some materials when producing certain features.

The idea of optimizing the ISF process has been studied by many researchers since it first emerged by investigating different process parameters, and as a result, there is well-established literature that provides a guideline to improve the process outcome to some extent [3]. In the last two decades, the biomedical field has exploited the flexibility and advancement of the process, in which it has been extensively implemented and researched to produce highly customized implants and devices at reduced time and cost compared to traditional methods. This includes the manufacturing of a cranial implant [4,5,6], an ankle support [7], a knee-bearing device [8], a denture base [9], a clavicle bone implant [10], and a craniofacial implant [11].

The multistage tool path strategy was developed to enhance the formability of the process by redistributing the material across the geometry from shallow to sloped areas. This allows for the production of steep features that exceed the formability limit of the material as well as the formation of vertical walls that could not be obtained otherwise using the single-step strategy. For instance, Duflou et al. [12] have experimentally implemented the multistage approach to form a cylindrical cup utilizing five forming stages. Furthermore, the author also implemented the strategy to fabricate distinctive designs, including a high wall angle cranial implant. Similarly, the gradual forming toward the final geometry using preforms has also been effective in Duflou et al. [13] work, in which the authors have tested the approach to form complex craniofacial implants using different materials (stainless steel 304 and titanium grade 2). The implant geometry features a high wall angle that exceeds the forming limit of the titanium and makes it critical in the case of stainless steel. The strategy has doubled the forming depth in the titanium sheet, but the implant cracked due to the large gap between the maximum achievable wall of the titanium and the walls of the geometry. On the other hand, the multi-step strategy successfully formed the steel sheet into the final desired shape. Liu et al. [14] describe the validity of the multi-pass tool path strategy compared to the single-pass forming. The work considered symmetrical and asymmetrical geometry. Both of these shapes are produced experimentally using the two point incremental sheet metal forming process variant. The work provided a general understanding of the multistage toolpath and its effect on the thickness distribution and formability. In the case of the ellipsoidal cup shape, the part was successfully formed using the multistage strategy, whereas it experienced fracture in the single-pass forming. Additionally, the multistage toolpath has optimized the final result in the case of the free-form shape in terms of thickness strain distribution and formability.

Mainly, most of the previous studies have implemented the multistage strategy to improve formability, and there is a general lack of research on the influence of the multistage on the final results in terms of geometrical accuracy and thickness distribution. Gonzalez et al. [15] have reported on the influence of the multistage toolpath in incremental sheet forming on the final results by comparing it with the traditional single-stage forming. The study considers two main strategies to develop the multistage toolpath. The results have demonstrated that the multistage toolpath strategy has improved the final geometrical accuracy. However, the part produced by the multistage technique showed less uniform thickness distribution than the single-stage forming. Likewise, Gajjar et al. [16] have conducted experimental work investigating the effect of using a different number of forming stages in fabricating truncated cones. The obtained results show that increasing the number of intermediate steps has reduced the spring-back phenomena and, as a result, improved the geometrical accuracy of the produced part. In this paper, a case study is adopted that concerns the manufacturing of a highly customized cranial implant from the design stage to the realization of the prosthesis through the single-point incremental sheet forming process. The primary objective of the study is to examine and analyze the impact of the multistage toolpath strategy compared to the traditional single-stage forming in terms of the final geometrical accuracy and thickness variation of the formed part.

2. Methodology

The methodology utilized to obtain the customized cranial implant consists of several phases, starting from the CT scan image processing to the fabrication and inspection of the produced parts. The process depends on reverse engineering (RE) and CAD-CAM technologies in data acquisition, modeling, and manufacturing. Each phase encompasses different challenges and is discussed in detail, see Fig. 1.

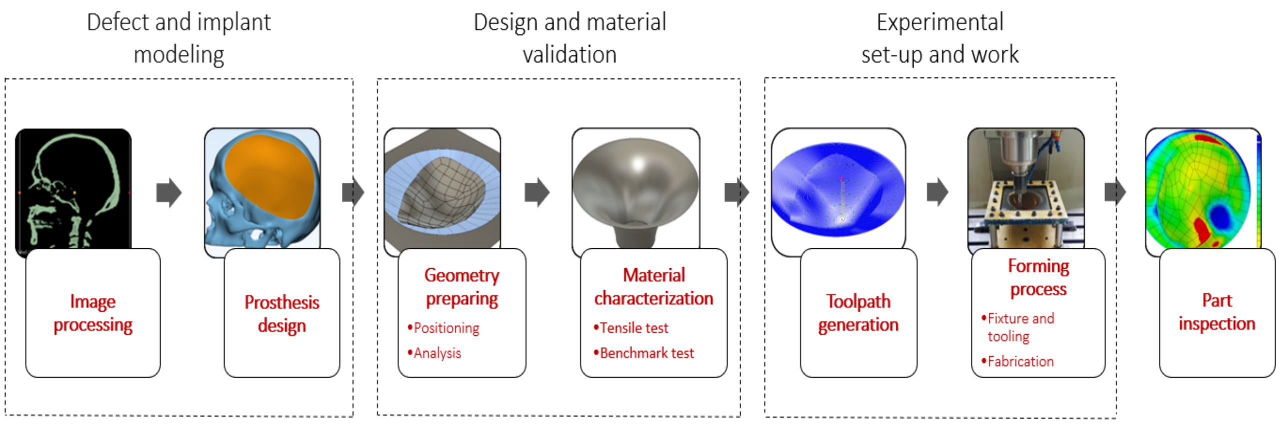


Fig. 1. The methodology used for obtaining the cranial implant.

2.1 Image Processing

The process of constructing a customized cranial implant is usually initiated by acquiring the computed tomography (CT) scan data of the patient's anatomy. These data consist of sliced images that were reconstructed from the coronal plane and stored in a DICOM (Digital Imaging and Communications in Medicine) file format. This phase aims to convert the CT data into a 3D model of the defective skull. In order to select the region of interest (ROI) from these images, a process of image segmentation is carried out. In this crucial process, the cranium structure can be partitioned from the other entities using different techniques. The most commonly used, however, is global thresholding, which has been employed in this particular case using 3D slicer software (2021). The process maps out the desired ROI based on a given range of Hounsfield unit (HU) values. The values used for this specific segmentation range between 210-3070HU, which were the optimum values to highlight the bone voxels (Fig. 2). Subsequently, the 3D model of the skull was visualized and exported in STL file format. The 3D model of the skull obtained in this procedure required further post-processing, which includes triangulation and noise reduction. Fig. 3 shows the final constructed skull.

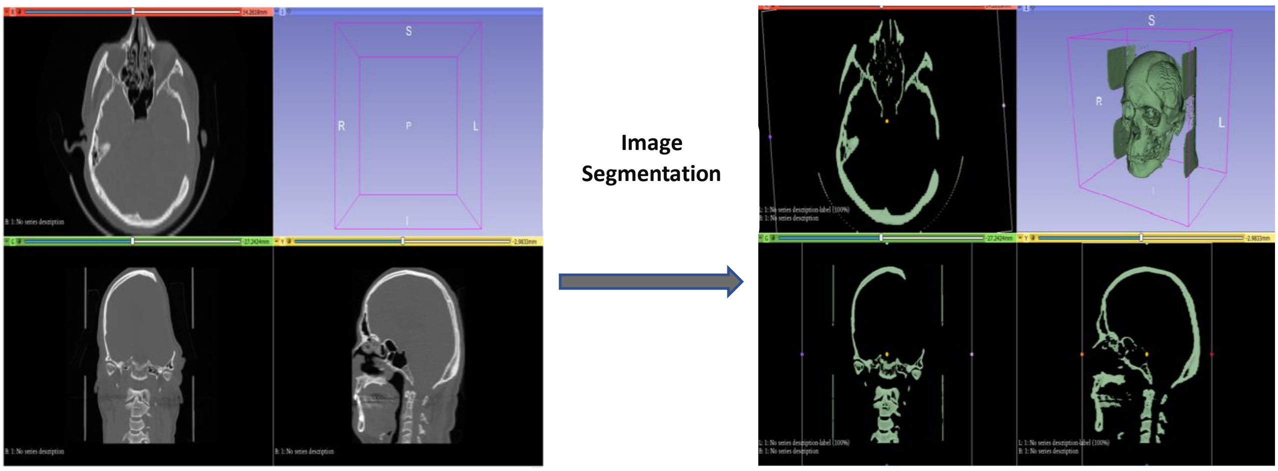


Fig. 2. Image processing of the CT scan data in 3D slicer software.

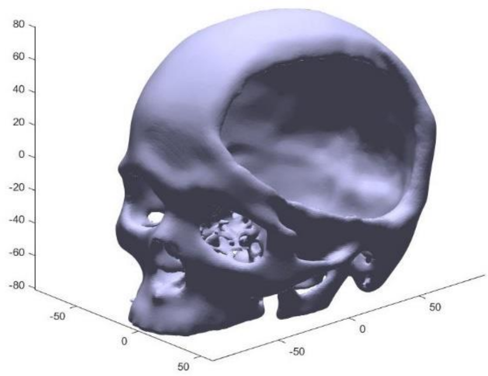


Fig. 3. The constructed 3D model of the skull.

2.2 Prosthesis Design

Different approaches can be used to construct the cranial implant. Each has its benefits and drawbacks [17]. In this study, since the defect lies beyond the centerline of the axial plane, the mirror-based method has been implemented. In this technique, the symmetry of the skull has been exploited, as reference data, to design the prosthesis. The prosthesis was established using Materialise 3 Matic software. The steps involved in the design are illustrated in Fig. 4 and are described below:

1. The first step in designing a patient-specific implant is to outline the defective area using a closed curve. The curve has been attached with an offset from the gap boundaries.
2. Constructing a mid-plane that cuts through the skull centerline, separating the two halves.
3. Mirroring the healthy side of the skull onto the defective side using the constructed plane as the mirroring tool.
4. The plane that intersects perpendicularly through the transverse plane has been established. Later, this plane is utilized to create a reference sketch.
5. A spline has been sketched along the profile of the mirrored side and between the intersection points.
6. Finally, the implant surface is constructed using the closed curve as the surrounding entity and the spline as the guideline for the final prosthesis profile.

It should be noted that the constructed cranial prosthesis has not been given a uniform thickness, nor a variable thickness was defined since the final thickness of the part produced by the ISF process cannot be predicted. Therefore, the process requires only the modeling of the inner surface of the desired CAD geometry [18].

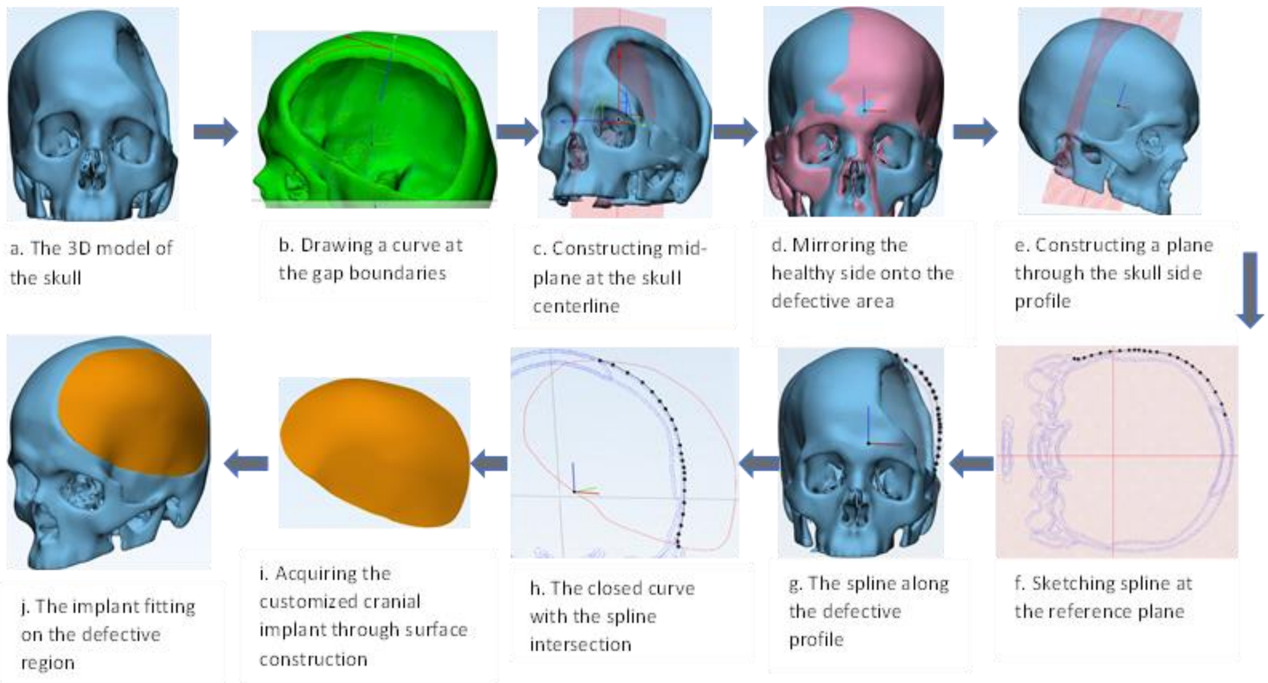


Fig. 4. Steps involved in designing the cranial prosthesis.

2.3 Geometry Preparing

2.3.1 Geometry Positioning

Complex, organically shaped geometries, such as medical implants and devices, contain curved features distributed asymmetrically along the part and at the edge. Consequently, these geometries cannot be feasibly formed from a flat sheet in the SPIF process. Thus, in order to prepare the model for CAM processing, the desired implant must conform to the process constraints. This can be done by attaching the geometry to an auxiliary surface that properly connects the prosthesis geometry to the planar sheet. The virtual flat sheet is considered the reference XY plane at which the tool engages to form the defined geometry outward along the Z-axis. The construction of an extended surface can also be advantageous in effectively reducing the maximum wall angle of the geometry by allowing flexible orientation of the part as well as supporting the implant during the forming process [19]. The prosthesis has been embedded within the surrounding surface using lofting within Fusion 360 (Fig. 5).

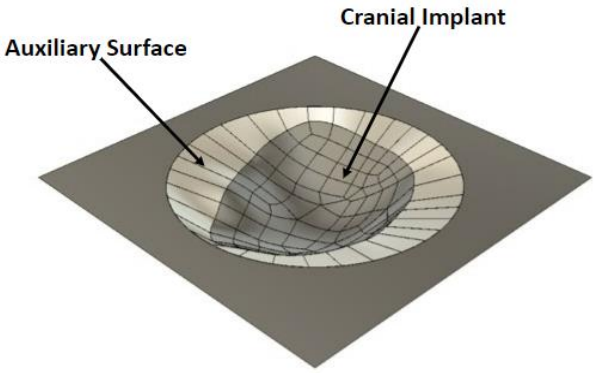


Fig. 5. The attachment of the cranial implant to the flat sheet with an auxiliary surface.

2.3.2 Geometry Analysis

The analysis includes identifying the maximum wall angle of the geometry, which is an essential value that can be used to evaluate the feasibility of the process of forming this particular shape by comparing it to the maximum wall angle achievable by the material in the next section. The analysis involves taking a cross-section of the surface model. One is in the X-Z section where Y equals zero, and the other is in the Y-Z section where X equals zero, see Fig. 6.

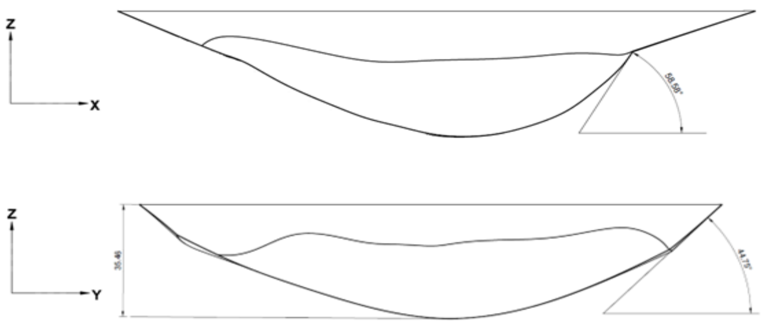


Fig. 6. Section analysis of the final geometry.

2.4 Material Characterization

The material used in the experimental work is a stainless steel AISI 304 sheet of 0.5mm in thickness. Table 1 shows the material's chemical composition. In this phase, the formability of the material has been analyzed and evaluated in terms of tensile and benchmark tests. These tests aim to establish and define the material limit and behavior prior to the forming process. Thus, predictions can be made about whether or not the design can fail during manufacturing. In this context, the analysis functions as an input to address the challenges before carrying out the process.

Table 1,
Chemical composition of stainless steel AISI 304

Elements	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	Cu	Ti	V	F
Composition (%wt.)	0.0483	1.03	0.606	0.0005	0.001	18	8.49	0.0474	0.0122	0.403	0.0002	0.095	Balanced

2.4.1 Tensile Test

The tensile test was carried out in a universal tensile machine. To examine the material anisotropy, three samples were cut out from the steel sheet at different orientations (0, 45, and 90) with respect to rolling direction, see Fig. 7. Material ductility was the main characteristic to investigate. In the ISF process, the material is plastically deformed. Therefore, the material elongation during a tensile test gives a viable indicator of sheet formability. The stainless-steel elongation averages 55.83% in all directions, which is considered relatively high in formability. This is expected to be further enhanced during the ISF due to localized deformation. The material's mechanical properties are listed in table 2

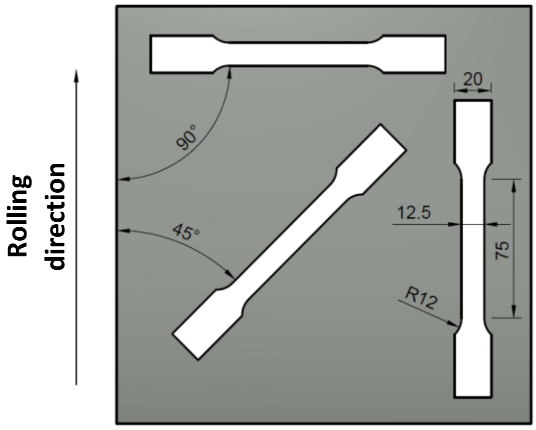


Fig. 7. Tensile test specimens at different orientations with respect to rolling direction.

Table 2,
Mechanical properties of stainless steel 304 at different orientations.

Orientation	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
Rolling (0°)	285	620.78	58.75
Diagonal (45°)	275	651	55
Transverse (90°)	300	677.38	53.75

2.4.2 Benchmark Test

The failure mechanism in the incremental sheet forming process, when using standard-sized tools (between 6 to12 mm), is initiated by the onset of fracture. During the forming process and due to localized plastic deformation at small contact zones, the sheet experiences uniform thinning with the absence of necking till fracture takes place [20]. In this context, the maximum wall angle, i.e., the rupture angle, is considered the formability limit of the material. An efficient way to evaluate and define this limit is through a benchmark test using a truncated cone with a variable wall angle [21]. The design of the cone used in this test is illustrated in Fig. 9. In this test, the steel sheet was formed until a fracture occurred (Fig.8), and the CNC machine was immediately stopped. Subsequently, the depth of the fracture was measured using a depth gauge, and as a result, the corresponding wall angle was obtained. From this test, it has been deduced that the maximum wall angle amissible by the steel sheet is 65.7, which is larger than the maximum wall angle of the desired geometry. Thus, failure is unlikely when forming in a single pass since the design lies within the forming zone of the material.

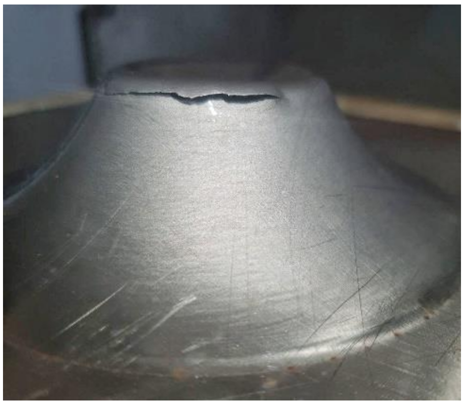


Fig. 8. The fractured truncated cone sample

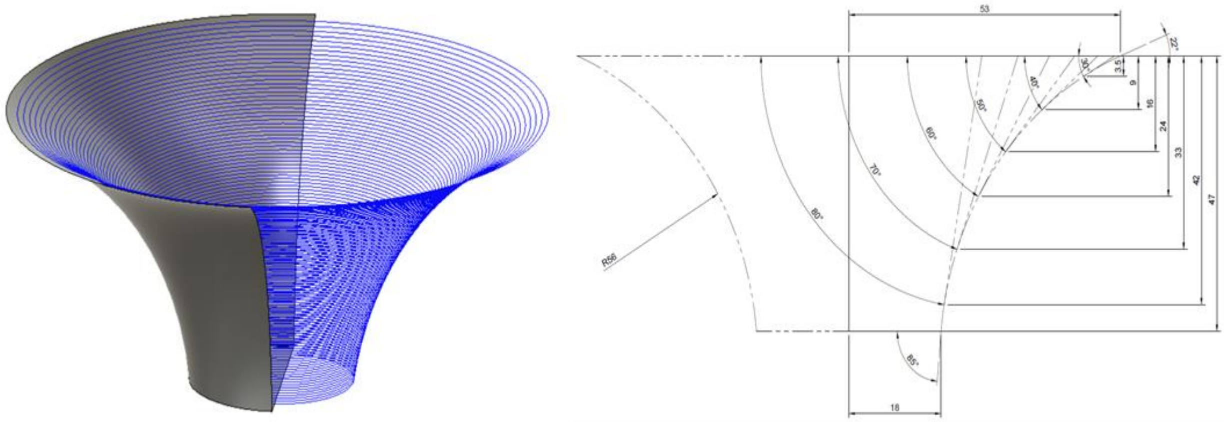


Fig. 9. Truncated cone used for formability test.

2.5 Toolpath generation

The movement of the forming tool across the sheet metal in order to fabricate the desired geometry is considered the most crucial aspect of the ISF process, considering that it directly and significantly affects the final geometrical accuracy, thickness distribution, and surface roughness of the produced part. Milling CAM software packages are usually utilized to define and generate the toolpath in the ISF process since there is no dedicated CAM software for that purpose. In this work, a contour toolpath, a strategy that is mainly used for finishing, was generated using Fusion 360. In this strategy, the tool starts from a reference XY plane and moves to the next successive plane contour by following a downward motion along the Z-axis. By reducing the step-down value, i.e., the distance between two consecutive profiles, the surface roughness of the final formed part is dramatically reduced [6]. In single-stage forming, the toolpath is defined directly on the final desired geometry, whereas in multistage strategy, intermediate shapes, also known as pre-forms, are used. For each form or shape, a toolpath is generated (Fig. 11). In other words, each stage essentially functions as a single-stage strategy.

Thus, rather than forming the part directly, the sheet will be formed gradually at each stage before reaching the desired geometry. As a result of this flow, the strategy enhances the process's formability. Unlike the techniques used to develop pre-forms for symmetrical parts in which various well-established multistage strategies can be utilized and implemented, there is no standardized approach for developing intermediate shapes for complex free-form geometries since each geometry entails separate procedures due to its distinctive shape. In this study, the multistage toolpath has been constructed using three stages, including two pre-forms and the final desired geometry (table 3). Each form was derived from the original cranial implant using scaling and lofting techniques. The pre-forms were developed to satisfy three critical considerations. These are:

- Each pre-form is characterized by a lower wall angle and depth than the successive form, see Fig. 10.
- The overall interaction between stages was aimed to drive the material along all three axes to allow a

more consistent and balanced flow during the forming process.

• The shifting between passes was maintained at a relatively small gap, and toolpath overlapping was avoided.

Table 3,
The intermediate shapes and the desired geometry characteristics.

Geometry	Maximum wall angle	Final depth
Preform 1	40	20mm
Preform 2	49	26mm
Desired shape	58.58	35.5mm

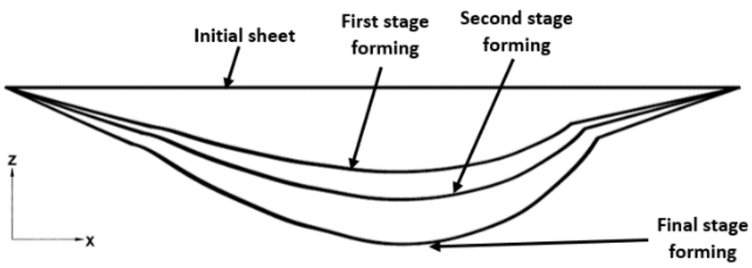


Fig. 10. Cross section of the preforms and the final shape.

The toolpath parameters are presented in table 4. The speed and feed values were selected to minimize the friction induced at the tool-sheet interface in order to prevent the tool from wearing out since it has not been heat-treated nor coated. The step-down values were increased in the initial stages in order to decrease the overall processing time.

Table 4,
Toolpath parameters

stage	Step-down (mm)	Travel direction	Feed-rate (mm/min)	Spindle-speed (RPM)
Stage 1	0.4	CW	1000	100
Stage 2	0.3	CW	1000	100
Final stage	0.2	CW	1000	100

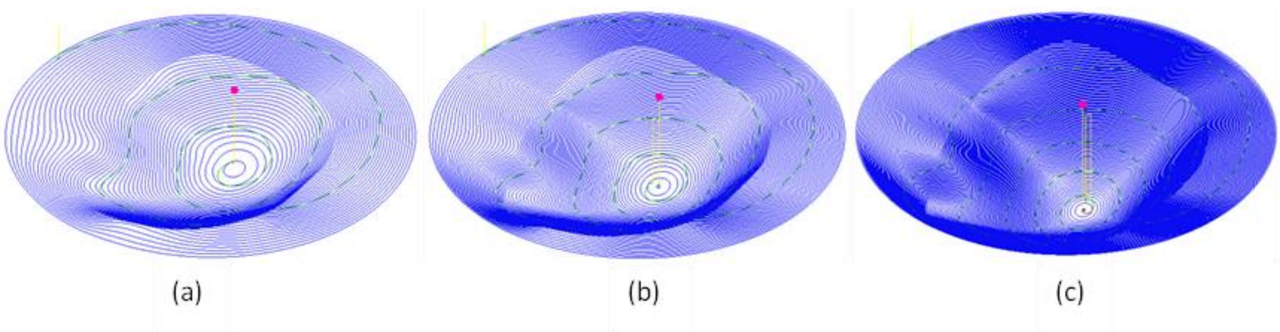


Fig. 11 Multistage toolpath strategy: a) stage 1 b) stage 2 C) The final stage.

2.6 Forming Process
2.6.1 Fixture and Tooling

The stainless-steel sheet has been mounted and fastened firmly between the upper and lower blank holders. The sheet is supported by a backing plate that has an orifice offset of 2mm from the original geometry in order to prevent excessive bending during the forming process. The forming tool used in the process is high-speed steel (HSS) of 10 mm in diameter (Fig. 13). Fig. 12 depicts the assembled fixture accommodating the desired geometry.

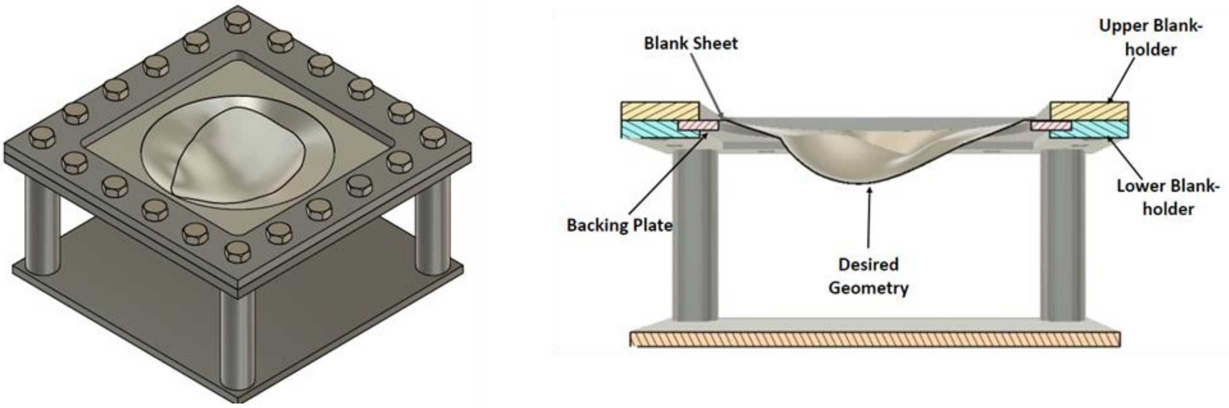


Fig. 12 Process fixture set-up.

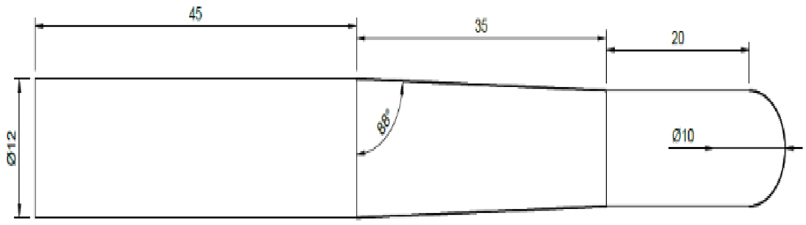


Fig. 13 forming tool dimensions

2.6.2 Fabrication

A 3-axis CNC machine type C-Tek (Fig. 14) has been employed to carry out the forming process. The clamping fixture set-up was assembled on the X-Y table and fixed firmly using clamping tools. The sheet was lubricated using oil to reduce friction at the interface between the sheet and the forming tool. Fig. 15 shows the forming process and the final formed part.

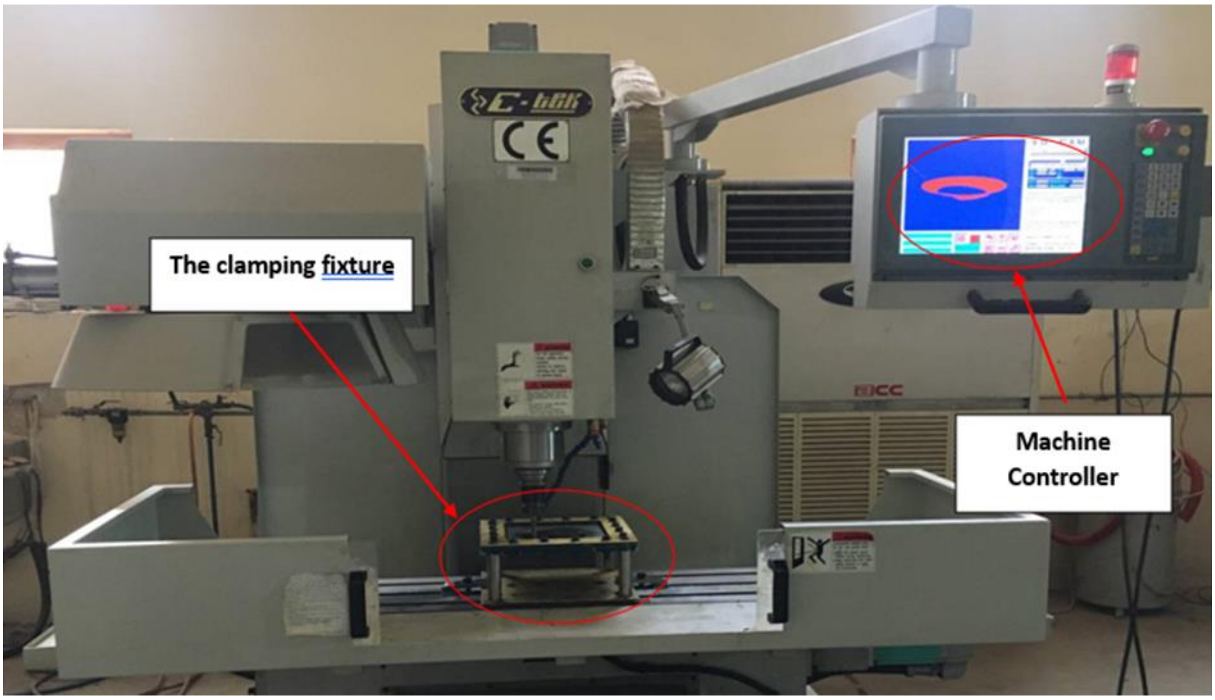


Fig. 14. 3-Axes CNC machine type C-tek machine used for the forming process.

Fig. 15. The forming process and the final produced part.

2.7 Part Inspection

The final produced parts have been 3D scanned using the EinScan-Pro scanner (Fig. 16), which has an accuracy of up to 0.05 mm, in order to acquire the virtual 3D model of the actual implant (mesh file) to examine and analyze the final geometrical accuracy as well as the thickness distributions across the formed part. The geometrical accuracy and thickness variation analyses have been conducted using the GOM inspect software.

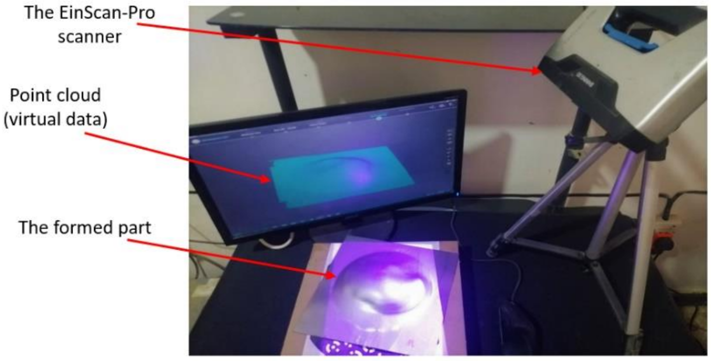


Fig. 16 The scanning process set-up.

3. Results and Discussion

3.1 Geometrical Accuracy

The scanned part (STL) and the nominal CAD design have been aligned in order to establish the geometrical deviation colormaps for both strategies, see Fig. 17. The positive values indicate that the sheet has been over-formed, whereas areas with negative values suggest that these regions have been under-formed with respect to the nominal surface.

For a thorough examination and analysis of the final geometrical results, the formed part is divided into two regions: the actual implant geometry and the surrounding surface. As can be seen, the edge of the exterior surface for the sample produced by the single-stage approach shows significant geometrical error due to over-forming. Conversely, when the multistage toolpath was implemented, the formed edge aligned more correctly with the CAD surface due to the gradual forming of the walls at smooth increments of depth and slope, showing improved bending characteristics. Additionally, the second distinct deviation error in the single pass strategy is at the high-sloped sidewall of the auxiliary surface near the edge, which has experienced an under-forming. This error, however, has been reduced effectively when the sheet is formed at multiple forming stages.

A maximum geometrical inaccuracy can be noticed in both strategies in the mutual area between the addendum surface and attached cranial implant where a smooth concave-convex transition feature is located. A cross-section analysis was utilized to examine the impact of the two approaches on this specific feature. Figure 18 shows the section analysis of the two strategies along the curved area. Both techniques have produced errors with respect to the CAD model in this region. This can be attributed to the process set-up, in which the variant SPIF can barely maintain concave-convex transition within the formed surface. In this particular setup, the forming tool moves downward along the Z-axis, imposing force in one direction without any support or opposite tool that acts as a counterforce. Thus, when forming a convex feature within a container-like surface, the tool would push against this area, causing an over-forming. However, the deviations are lower in the case of the multistage toolpath. The formed cranial implant region yields negative values in the shallow areas, suggesting an under-forming of the actual geometry compared to the nominal surface when the sheet was formed using a single-pass approach. However, these distinct regions improved dramatically in the multistage strategy, showing low deviation values. This is attributed to the reduced local spring-back phenomena when the part was fabricated at multiple levels by the multistage toolpath.

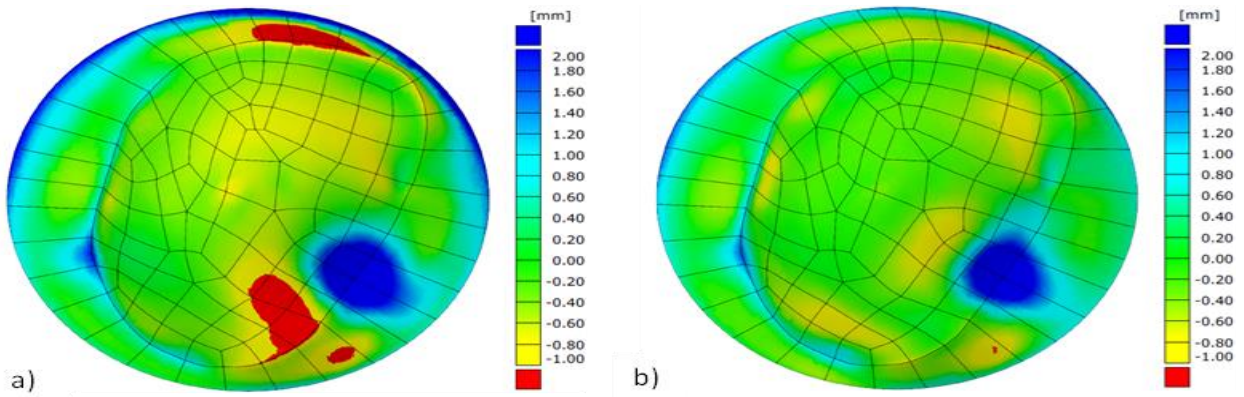


Fig. 17 The geometrical deviations between the actual and nominal data: a) single-stage strategy b) multistage strategy

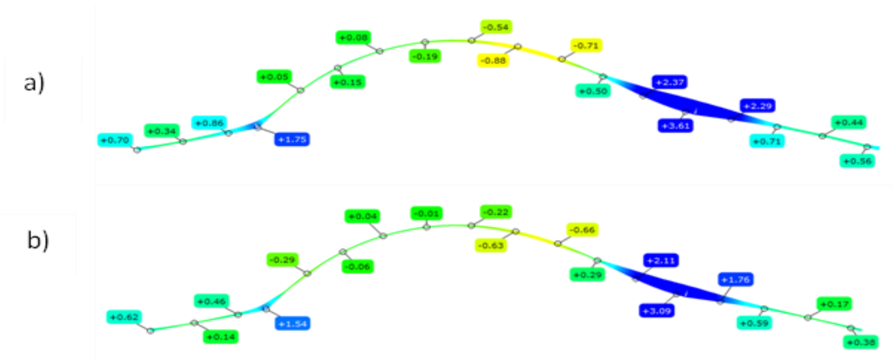


Fig. 18. Section analysis of the geometrical accuracy: a) single-stage strategy b) multistage strategy

3.2 Thickness Distribution

The thickness distributions of the formed parts were obtained by scanning the internal and external surfaces. Subsequently, both point cloud surface data have been aligned, merged, and exported as an STL file. The thickness variation colormaps for both parts are illustrated in Fig. 19. As can be noticed, as the wall angle of the geometry increases, the thickness reduction increases accordingly. This is due to the fact that steep areas drive a considerable amount of deformation compared to shallow regions. Consequently, the maximum thickness reduction originated at the maximum wall angle of the geometry for both approaches. However, there is a slight difference in the thinning locations for both strategies, in which the thinning of the part produced by the multistage toolpath has shifted clockwise, i.e., with the toolpath movements for the implemented stages. Moreover, the thickness at the maximum wall was distributed more efficiently in the multistage forming technique, which resulted in a less dark region compared to the traditional single-stage forming.

This may be due to material shifting from shallow areas on the side wall of the geometry to the steep regions. A cross-section analysis was employed to examine the thickness distribution across the formed region. Figs 20 and 21 show the thickness values plotted in relation to the displacement at two planes (XZ section and YZ section). The data along the XZ plane shows that the part formed by the single stage strategy has a sharp drop in thickness along the maximum wall angle in which the sheet thickness reaches a thinning of around 50% from the original sheet thickness, which results in the reduced strength of the fabricated cranial implant. On the other hand, the sample formed at multistage has shown better uniform thickness variations in that particular region with a thickness reduction of 34%. The data obtained along the YZ plane appear approximately similar. Overall, the results show that the part formed by the multistage toolpath approach gives a more uniform thickness distribution across the formed region compared to the traditional single-stage forming.

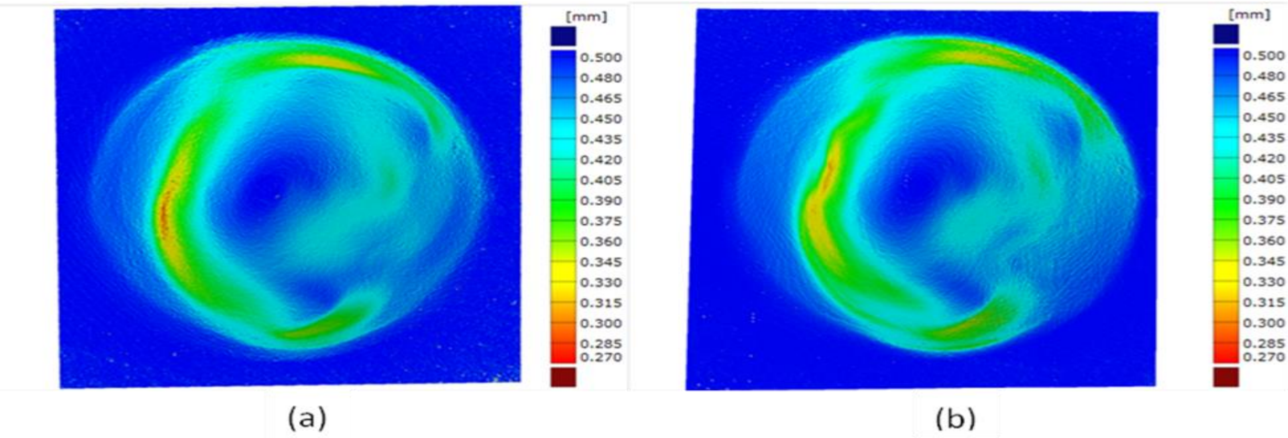
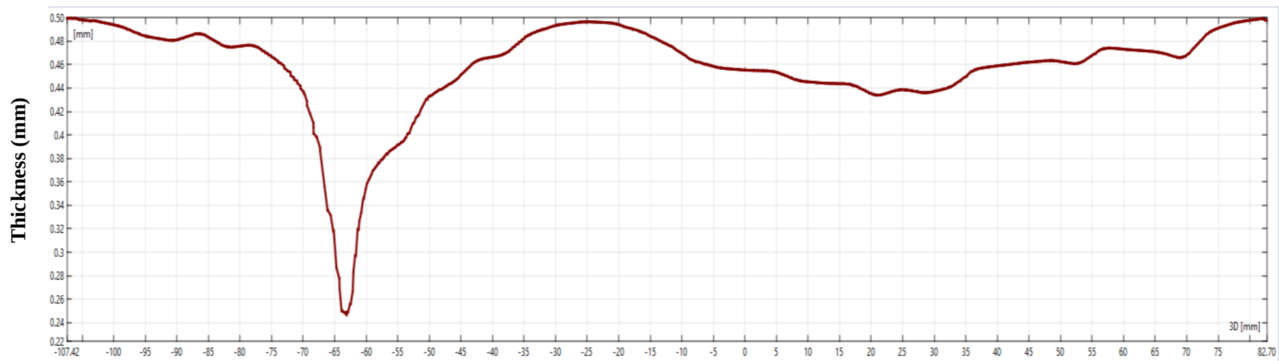
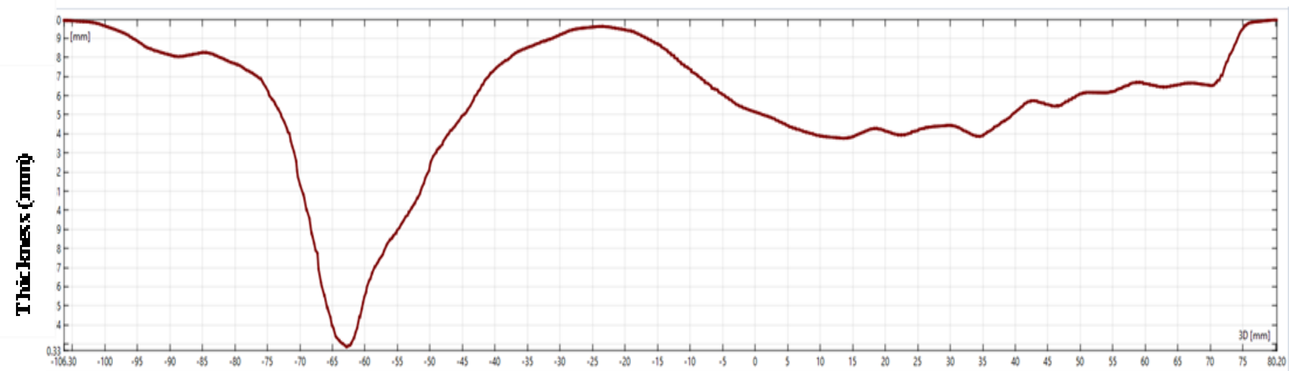


Fig. 19. Thickness distribution for: a) single-stage forming b) multistage forming.



X(mm)
(a)



X(mm)
(b)

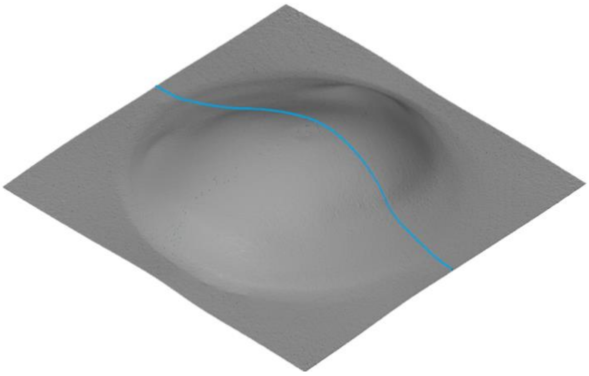
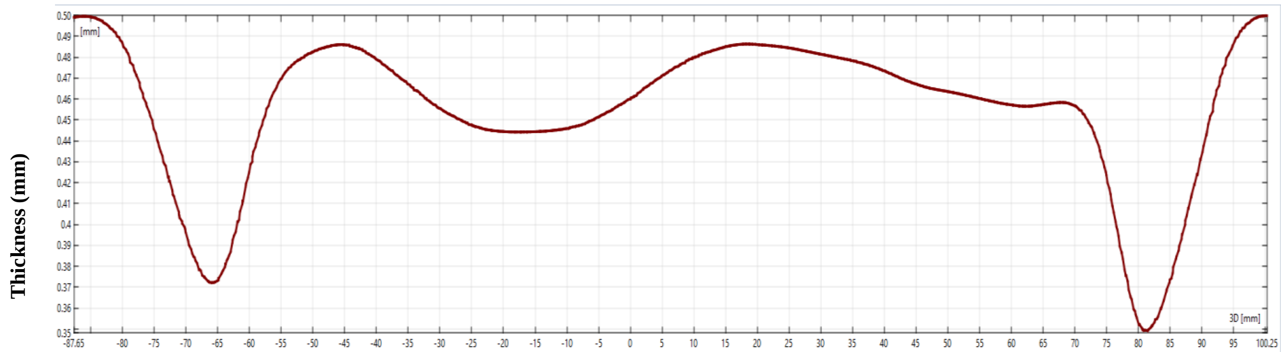
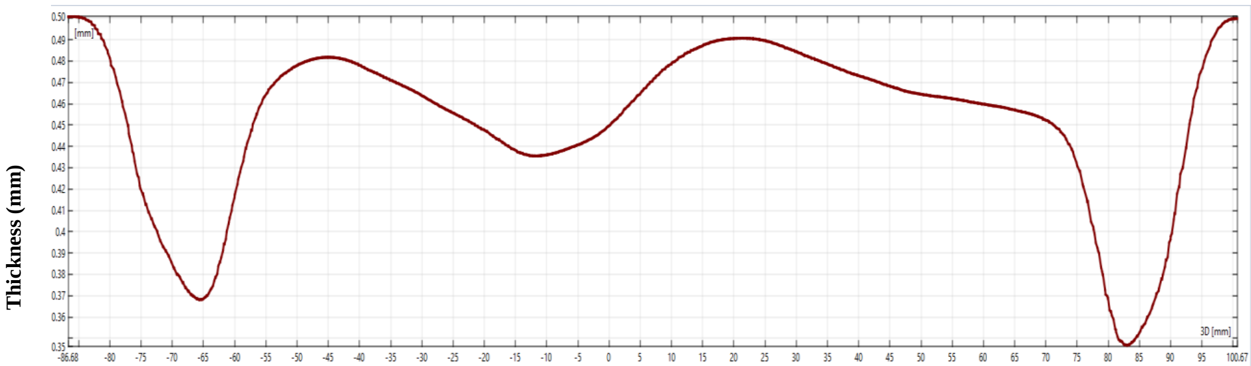


Fig. 20. Thickness distributions for both strategies at XZ cross-section: (a) single-stage (b) multistage



Y(mm)
(a)



Y(mm)
(b)

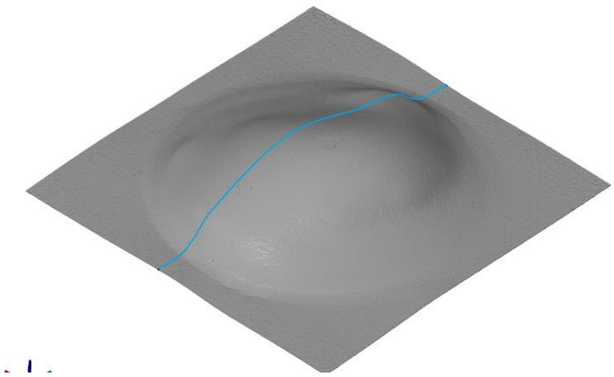


Fig. 21. Thickness distributions for both strategies at YZ cross-section: (a) single-stage (b) multistage.

4. Summary and Conclusion

The work established within the present paper generally deals with the manufacturing and analysis of a complex customized medical product through a well-established methodology using the single point incremental sheet metal forming by employing two forming strategies, namely, single-stage forming and multistage forming. The paper focused on studying the influence of the multistage toolpath strategy on the final formed part compared to the single-stage approach with regard to the geometrical accuracy and thickness distribution, aiming to provide a baseline understanding of the effect of the multistage toolpath approach and how it contributes to the final results. Consequently, the following conclusions can be drawn from the present study:

1. The multistage toolpath strategy has significantly improved the final geometrical accuracy of the formed region. Furthermore, the multistage toolpath achieved more accurate bending characteristics as well as exhibited less error in forming a convex-concave transition feature compared to the traditional single-stage method.
2. The multistage toolpath strategy achieved a more uniform thickness distribution compared to the sample produced by single-stage forming in the critical region where the maximum wall angle of the implant is located. In this area, the single-stage forming has yielded a sharp drop in thickness of 50% from the initial sheet thickness, whereas the part formed by the multistage tool path has experienced a thickness reduction of 34% in the same region.
3. Although the multistage toolpath has optimized the results in terms of geometrical accuracy and thickness distribution, the strategy takes a longer lead time compared to the single-stage forming to produce the same part. The forming time required to obtain the final desired shape in the single-stage forming is roughly 59 minutes, whereas, in the multistage forming strategy, the forming time reaches around 104 minutes:

The first stage forming: 16:52 minutes (16.2% of the total time).
The second stage forming: 28:35 minutes (27.4% of the total time).
The final stage forming: 59 minutes (56.4% of the total time).

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دراسة تأثير التشكيل متعدد المراحل على تصنيع زراعة طبية للجمجمة في التشكيل التراكمي للصفيحات المعدنية

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الخلاصة

التشكيل التراكمي للصفيحات يقدم مرونة عالية في تصنيع مختلف المنتجات مما يجعلها خيار مثالي في عمليات النمذجة السريعة بالإضافة الى تصنيع مختلف المنتجات حسب المواصفات المطلوبة بتكلفة انتاجية قليله بالمقارنة مع الطرق التقليدية. لكن الاشكال التي يتم تصنيعها بهذه الطريقة تظهر دقة قليلة ونقصان كبير في السمك النهائي. في هذه الورقة البحثية، التشكيل النقطي المتراكم تم استخدامه لتصنيع زراعة طبية مصممة خصيصا لتلائم المنطقة المفقودة من الجمجمة بالاعتماد على الصور المقطعية للجزء التشريحي للمريض. تم تقديم منهجيه لتصميم وتصنيع الزراعة الطبية بداية من مرحلة التصميم الى تشكيل المنتج النهائي. الهدف الرئيسي من هذا البحث هو تحليل ودراسة تأثير التشكيل على عدة مراحل بالمقارنة مع التشكيل التقليدي على مرحلة واحدة من ناحية دقة الابعاد والتوزيع للسمك النهائي وخشونة السطح. النتائج النهائية بينت ان العينة التي تم تشكيلها على عدة مراحل اظهرت توزيع أفضل للسمك مقارنة بالعينة التي تم تصنيعها من خلال مرحلة تشكيل واحدة. فيما يخص الدقة للجزء المصنع، تحليل الانحرافات اظهر ان التشكيل المتعدد ساهم في تحسين الدقة النهائية للشكل المصنع. بالإضافة الى ذلك التشكيل المتعدد ساهم في زيادة خشونة السطح للشكل النهائي.