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Fabrication and Analysis of Denture Plate Using Single Point Incremental Sheet Forming

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Abstract

Incremental sheet forming (ISF) is a metal forming technology in which small incremental deformations determine the final shape. The sheet is deformed by a hemispherical tool that follows the required shape contour to deform the sheet into the desired geometry. In this study, single point incremental sheet forming (SPIF) has been implemented in dentistry to manufacture a denture plate using two types of stainless steel, 304 and 316L, with an initial thickness of 0.5mm and 0.8mm, respectively. Stainless steel was selected due to its biocompatibility and reasonable cost. A three-dimensional (3D) analysis procedure was conducted to evaluate the manufactured part's geometrical accuracy and thickness distribution. The obtained results confirm the capability of SPIF to produce thin-walled biomedical components with satisfactory dimensional accuracy, as geometrical deviations between the developed and the actual models are predominantly in the range of ±0.25mm.

Keywords: *Denture base plate, Single point incremental sheet metal forming (SPIF), Thickness distribution, 3D analysis.*

1. Introduction

Incremental sheet forming is a flexible and innovative process that can be used in rapid prototyping and batch production; it requires no dies and no special tools and can be performed to produce customized and tailored products [1]. The process uses a hemispherical tool that deforms the sheet into the desired geometry. The final shape (3D model) is accomplished by dividing it into 2D levels so that the tool proceeds to the upcoming contour after finishing the present contour [2]. The main limitation of this process can be summarized as the lengthy manufacturing time, and the poor geometrical accuracy compared to other manufacturing processes. The poor geometrical accuracy can be attributed to the sheet bending and spring back. Furthermore, the pillow effect (a protrusion originating at the center of the SPIF made part) also accounts for the poor accuracy [3]. A schematic diagram that summarizes the single point incremental sheet forming is shown in figure 1, in which the sheet is fixed on a clamping frame and supported by a backing plate to reduce geometrical inaccuracies caused by the sheet bending. The sheet is formed by the repeated application of a minor, controlled force at a single point. The forming tool is moved incrementally along the sheet, applying force at each point and gradually forming the sheet metal into the desired shape [4].

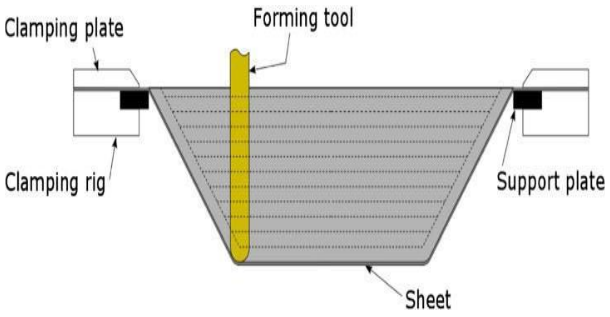


Fig. 1. Principle of the single point incremental forming process [4]

The most significant area in which Single point incremental sheet forming has been employed is in the automobile and aerospace industry [5]. SPIF is considered a relatively new technology in the manufacturing of biomedical implants. The first application of SPIF in the medical field was the fabrication of ankle support which was successfully manufactured without any die and with a sufficient geometrical deviation [6]. The most common application of SPIF in the biomedical field is the production of cranial implants. The cranial prosthesis was fabricated using biocompatible materials such as polymeric sheets [7] and titanium [8]. Other applications of SPIF regarding biomedical implants are the manufacturing of knee prostheses [9], facial implants [10], and clavicle implants [11].

A denture plate is a major dental prosthetic of a complete denture that replaces missing teeth and is positioned in the roof of the mouth in the oral cavity [12]. The most common material used in the fabrication of dentures is Polymethyl methacrylate (PMMA). However, due to several disadvantages, such as brittleness which leads to fracture [13], it is crucial to strengthen the denture with materials that impede the rupture and one of the most effective ways to ensure a steady performance is to incorporate it with a metal plate or wire [14]. The most common technique used to fabricate the denture plate is the lost wax technique (conventional method). In addition, in the last twenty years, several technologies have been developed to produce dental components, such as rapid laser forming [15], additive manufacturing [16], and selective laser melting [17]. However, the main problem in the field of dentistry is that there is a particular demand for new technologies to replace conventional techniques that are based on casting technology, as they require a high degree of skill, high equipment costs and high processing times, and SPIF is a promising technology that can be applied in these types of applications.

As opposed to the medical field, research is scarce concerning SPIF technology in the dental field. M.Sbaytietal. [18] applied single point incremental sheet forming to fabricate a titanium denture plate with a satisfied geometry by providing an optimization strategy based on numerical simulation and finite element analysis. In addition, M. Milutinovic et al. [19] used low-carbon steel (EN DC04) and manufactured a denture base with acceptable geometry. In our study, we used two types of stainless steel. The type 316L is one of the most widely used materials in biomedical applications, however, there has never been a study about this material in incremental sheet forming applications. Taking the previously mentioned into consideration, the main purpose of this study is to investigate the ability of SPIF to be applied in the field of dental restorations by evaluating the geometrical accuracy and thickness distribution of the fabricated parts to determine if SPIF is capable of producing a geometrically correct dental plate using stainless steel sheets.

2. Material and Mechanical Properties

Stainless steel is one of the most used metals in biomedical implants for cardiovascular, dentistry, craniofacial, and orthopedic applications [20]. This is due to its good mechanical properties, acceptable biocompatibility, and reasonable cost compared to titanium, cobalt, and vanadium alloys [21]. The most common stainless steel used in dentistry is the austenitic series 300, which has been utilized widely in the manufacturing of crowns, dental bridges, and orthodontic wires [22], especially the 316L stainless steel type. However, stainless steel made implants can only be used for a short term due to their poor corrosion resistance, which increases the infection risk [23]. The chemical compositions of 304 and 316L stainless steel are listed in Table 1.

The mechanical properties of the materials were obtained using the tensile test. The tensile test provides information about the material's ductility and flow stress, as these properties are key factors that affect the ISF process. The ductility is used as a formability indicator for the materials during the forming process to ensure the successful implementation of ISF. At the same time, flow stress (the initial yielding and tensile stress) determines the forming load and the contact pressure between the tool-sheet interfaces. Using a united universal hydraulic testing machine, the tests were executed for 316L and 304 stainless steel sheets of 0.8 and 0.5mm. Three tensile test specimens having different orientations with respect to the sheet rolling direction were cut from each sheet: 0° to the rolling direction, 45° diagonal to the rolling direction, and 90° transverse to the rolling direction.The tensile test specimens were fabricated according to the standard for the traction testing of metallic materials, SR EN 10002- 1: 2002. The mechanical properties are listed in table 2. Concerning material ductility, both materials exhibited good elongation characteristics, and with the consideration of the increased formability that ISF offers compared to the tensile test, it can be reasonable to assume that both materials have good potential to be used in ISF processes.

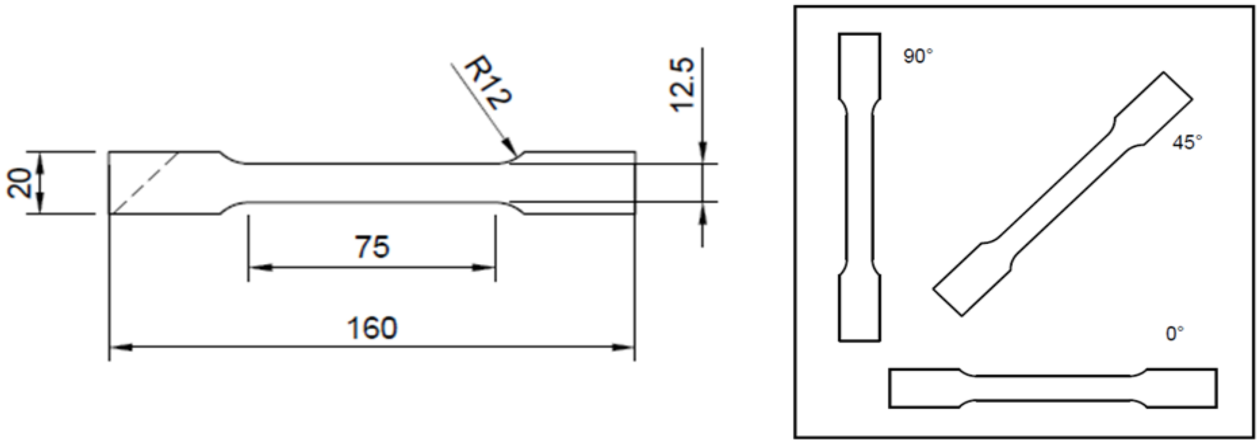


Fig. 2. Tensile test specimen dimensions (mm) taken at different rolling directions.

Table 1,
Chemical composition of Stainless steel 304 and 316L (content%)

Material	C	Mn	Fe	SI	Cr	Al	Ni	Pb	Mo
304	0.0479	1.04	70.7	0.630	18.2	0.0189	8.46	0.0020	-
316L	0.0328	1.96	66.8	0.335	17.8	0.413	9.26	0.0250	1.77

Table 2,
Mechanical properties of stainless steel with respect to the rolling direction.

Material	Rolling angle	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
	0	638.03	370	46.25
316L	45	649.80	358.66	43.75
	90	667.02	410	45
	0	620.78	258	58.75
304	45	651.02	275	55
	90	677.38	300	53.75

3. Process Design

This section consists of three parts. The first part focuses on the computer-aided design (CAD) modeling aspect of the denture plate, whereas the second and third sections focus on the computer-aided manufacturing (CAM) modeling and experimental work. The methodology used for manufacturing the denture plate is presented in Figure 3.

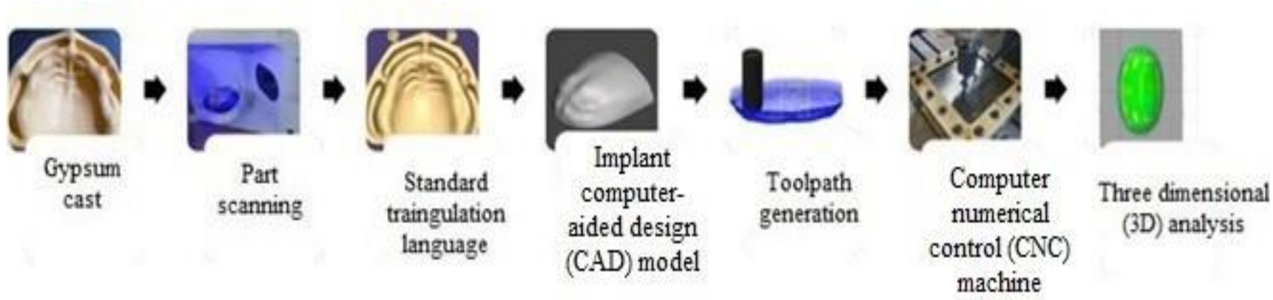


Fig. 3. Workflow methodology applied in the manufacturing of the denture plate.

3.1. CAD modeling of denture base

The manufacturing process of a denture base starts with the creation of a denture base CAD model. By applying the reverse engineering concept, the CAD model of a denture base can be acquired either by using medical imaging techniques such as magnetic resonance imaging (MRI) or computer tomography scan (CT) of the patient's jaw or by digitizing a master cast (a cast that replicates the entire oral structure) of the patient's mouth. In this research, a gypsum working cast was scanned using a desktop scanner (Medit T710). Multiple overlapping scans were taken to produce the cast in the standard triangulation language file format (STL) to achieve maximum scanning accuracy. The acquired geometrical data was then imported into CAD software (EXOCAD) to create the denture plate model. The CAD software was chosen due to its high capability of designing dental prostheses and implants. The CAD modeling process of the denture plate is presented in Figure 4.

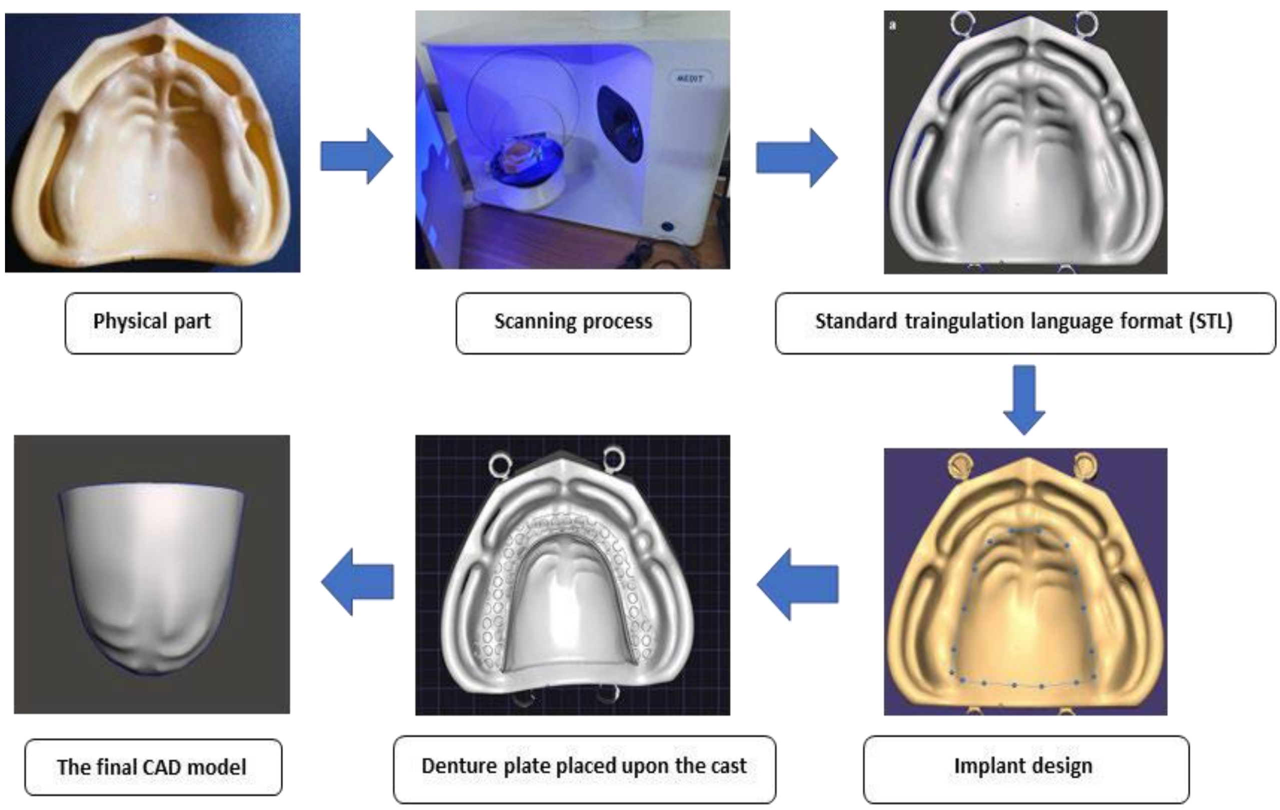


Fig. 4. CAD modeling process.

3.2. Tool Path Generation

After developing the denture base CAD model, the second step will be generating the tool path required to manufacture the denture plate. The tool path is a significant step in incremental sheet forming since it strongly influences manufacturing time, surface finish, thickness distribution, and geometrical accuracy. The tool path consists of points representing the contact between the tool and the sheet along a programmed and confined space. The SPIF process is similar to the milling process, which enables commercial CAM software to generate the tool path and NC code for the milling machine. In this research, Autodesk Fusion 360 was used to generate the tool trajectories in SPIF. The tool path strategy selected to fabricate the denture plate is contour milling, and was programmed to manufacture two denture bases simultaneously. The implant perimeter is open, a region must be constructed to join the perimeter and create a closed space for the tool to move. The process parameters were selected to achieve a high-quality surface finish. They were chosen according to the findings in [24] and [25] and for both materials (304 and 316L): a stepdown of 0.02 mm, a tool diameter of 10 mm, a spindle speed of 110 rpm, and a feed rate of 1000mm/min. After performing the simulation, the computer numerical controlled (CNC) machine codes had to be post-processed to create a G-code specific to the CNC machine where the denture plate was fabricated. The CAM modeling process is shown in Figure 5.

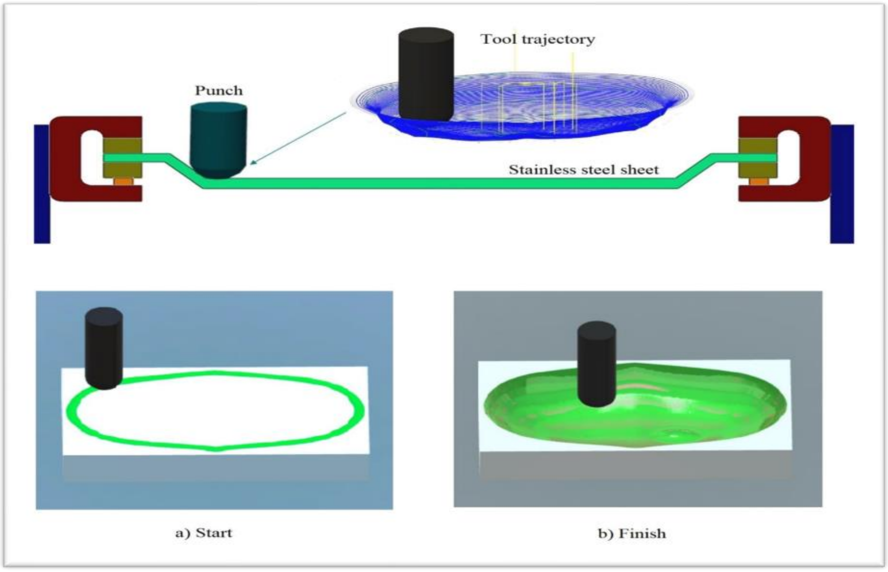
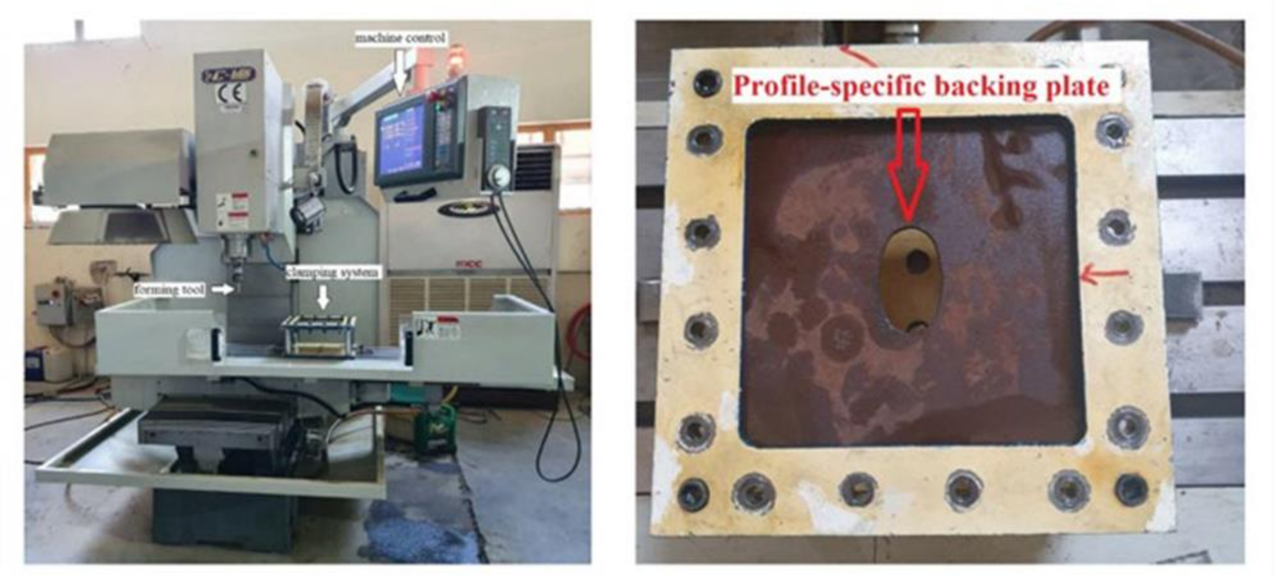


Fig. 5. CAM modeling process.

3.3. Experimental setup

The manufacturing process was carried out using a C-tek three-axis (KM-80D) CNC vertical milling machine, as shown in figure 6 (a), equipped with a maximum spindle speed and feed rate of 6000 rpm and 10000mm/min. The forming tool was made from high-speed steel (molybdenum-MAX cobalt high-speed steel, M42) and designed with a hemispherical tip (10mm diameter). as shown in figure 7. The forming fixture frame was built and designed by [26] and is mounted on the CNC machine to fix the sheet during the manufacturing process. The Initial blank dimensions were 225mm×225mm, and a thickness of 0.5 and 0.8 for 304 and 316L, respectively. The frame consists of a square blank holder and a square backing plate. The backing plate was made from mild steel with dimensions of 225mm×225mm×5mm with a profile-specific hole, as shown in Figure 6 (b).

The profile-specific hole represents the CAD model's top view (x-y) plane to ensure maximum accuracy and correlation with the tool path and minimize geometrical deviation caused by sheet bending and material spring back. The hole was made with an offset of 2mm to account for sheet thickness and tool material. Lubrication was applied between the tool and the sheet to reduce friction and tool wear. The manufacturing process of the denture plate is shown in Figure 8.



a) Computer numerical controlled (CNC) machine b) Profile-specific backing plate

Fig. 6. Experimental setup.

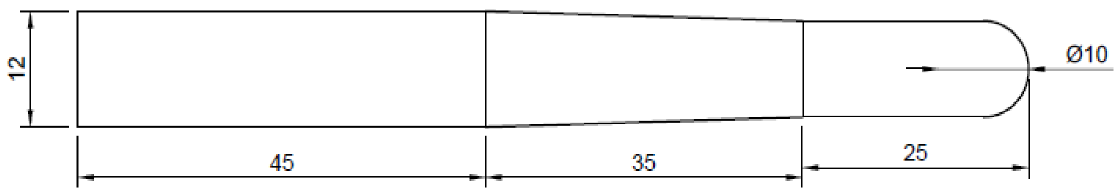


Fig .7. Tool dimensions (mm).

Fig .8. Manufacturing process of the denture plate.

3.4. Measurement procedure

A three-dimensional (3D) comparison analysis to evaluate the geometrical discrepancies between the manufactured parts and the reference CAD model was conducted by using GOM to inspect the 3D data test software. The scanned blank dimensions were 80×60mm as the sheets' excess material was removed for the blank to be scanned. The external surfaces of the 304 and 316L denture bases were scanned using the MeditT710 lab scan, as shown in figure 9. The lab scan consists of four 5.0 MP camera systems and employs blue light scanning technology, ensuring high scanning accuracy (<4 µm). The scanned data (points of clouds) were reconstructed to the STL model to be imported into the GOM inspect software. The analysis starts by defining the scanned data (STL) as the actual model and the designed CAD model as the reference model. The scanned data and the CAD model were aligned (as shown in figure 10) using the pre-alignment strategy to detect dimensional discrepancies and generate the deviation map. The outcome of this analysis is represented graphically, as shown in figures 11 and 12. Colors represent different geometrical deviations along the part in mm. Negative values show that the produced part has failed to reach the desired profile. In contrast, the positive values indicate that the produced part has exceeded the designed profile.

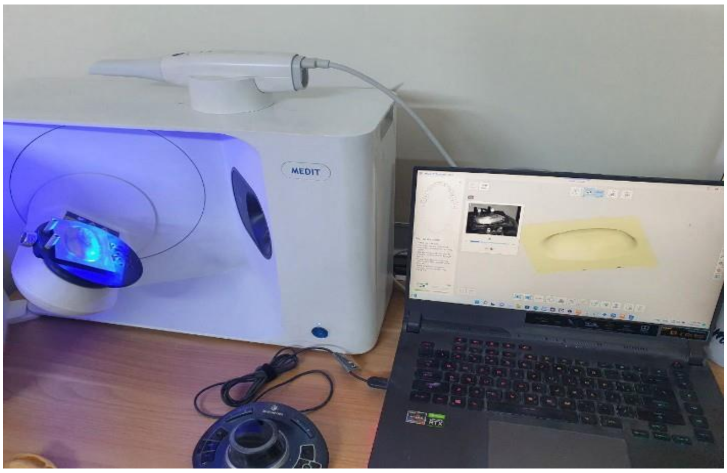


Fig. 9. Scanning process of the manufactured part.

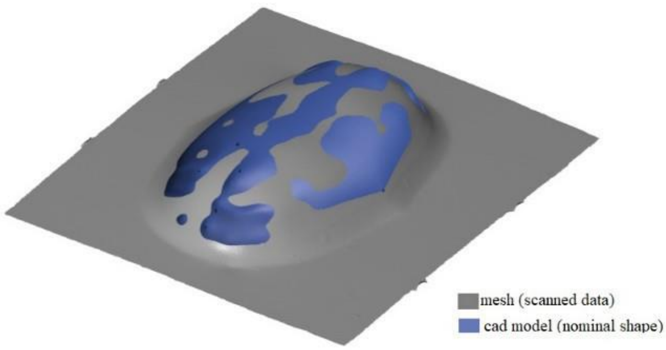


Fig. 10. Alignment between the scanned data and CAD model.

4. Results and Discussion

4.1. Geometrical accuracy

Denture fit is an essential aspect that determines the quality of the produced denture, as it ensures the patient's comfort with wear and reduces or prevents traumatic ulcers in the mouth. Thus, manufacturing a denture plate with satisfactory dimensional accuracy is essential to ensuring the patient's comfort [27]. In our study, both stainless steel prototypes (304 and 316L) showed similar results, as shown in figures 11 and 12. The deviation between the developed and actual models primarily ranged between ±0.25 mm. The obtained results are considered within the clinically acceptable tolerances of 0.311mm [28]. Therefore, the obtained results are judged to be satisfactory. Furthermore, in comparison to the traditional method (lost wax technique), the results are similar to those obtained by [29], who measured the average dimensional gaps of the conventionally fabricated models with the reference model to be between 0.15 to 0.28mm. In addition, the results are also comparable to the most common CAD-CAM techniques that are currently being used in the fabrication of denture prosthetic bases, such as the subtractive milling process (primarily ranging around 0.2 mm) and the additive manufacturing method (3D printing) (primarily ranging around 0.16mm) [30]. Taking these facts into account, it can be considered that SPIF technology has the potential to be applied in dentistry to fabricate metal dental prostheses. In addition, the manufacturing time is highly reduced (1 hour) compared to the milling process (5 hours), and 3D printing (1.3hours) [31].

The deviation map shows that the maximum errors are located at the edge of the parts in the regions closest to the clamping plate, which can be ascribed to the sheet bending during the forming process, as these regions are under excessive bending stress since they are the nearest to the backing plate and the farthest from the tool. Geometrical inaccuracies caused by the bending effect during the forming process are one of the primary origins of geometrical errors in the SPIF process. However, from a dental perspective, high dimensional error in this region is not of significant concern since artificial teeth, and acrylic resin will further pad them [19]. One possible way to minimize the bending effect and improve the overall geometrical accuracy is the application of double-sided incremental forming (DSIF), in which an additional supporting tool is utilized during the forming process. In contrast, regions located at the bottom part and the walls of the denture plate have a slight and uniform geometrical deviation. As geometrical deviations in these regions are commonly affected by the pillow effect, it can be concluded that the pillow generation was minimized and didn't produce significant inaccuracies. Furthermore, the dimensional discrepancies detected in the prototype made from 0.5mm 304 stainless steel showed a slight improvement in dimensional accuracy compared to the 0.8 mm 316L prototype, which can be attributed to the lower sheet thickness, which exhibits less spring-back.

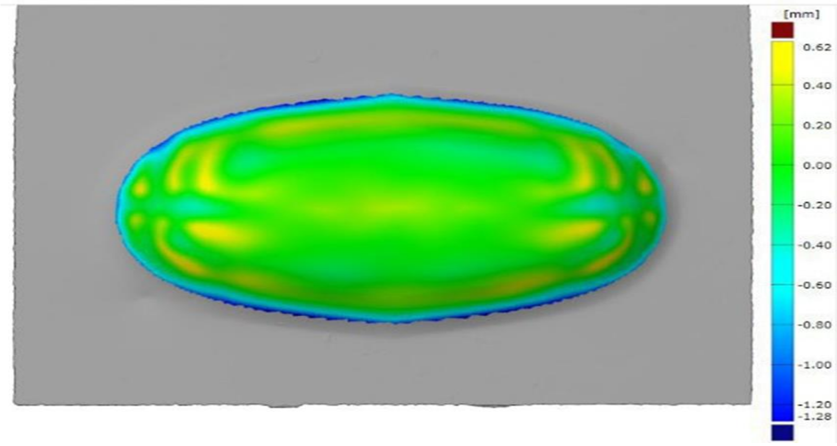


Fig. 11. Geometrical deviation accuracy map for (0.5mm) stainless steel 304 denture plate.

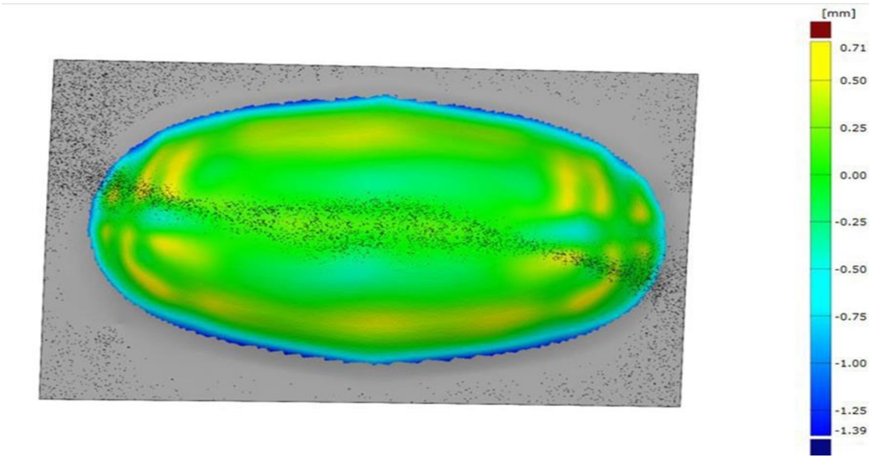


Fig. 12. Geometrical deviation accuracy map for (0.8mm) stainless steel 316L denture plat.

4.2. Thickness distribution

One of the significant drawbacks of incremental sheet forming is sheet thinning, which has an adverse effect on the formed parts in terms of geometrical accuracy, formability, and strength. In fact, when the formed part reaches its forming limit, thinning can lead to its cracking. Thus, it is crucial to evaluate the thickness distribution of the formed components.

In this research, the thickness distribution was measured by scanning the entire part (internal and external surfaces of the formed component). The thickness distribution was measured using the GOM inspection software. The results showed that the thickness remained unchanged at the bottom of the plate for both types of stainless steel (304 and 316L) with initial sheet thicknesses of 0.5mm and 0.8mm. The most affected zones are located along the lateral and front walls of the plate, with a maximum thickness reduction of 50% as thinning intensity has increased at regions with high wall angles. From a dental point of view, this is highly desirable as it ensures mass reduction, which as a result, increases the comfort of wear for the patients [32]. However, additional tests are required to evaluate the strength of the parts to verify if this mass reduction affects the performance of the plate. The early results are promising; Milutinovic et al. [25] performed mechanical tests (stiffness and flexural strength) to evaluate the performance of the SPIF-made denture plate from stainless steel 430 with 0.5mm thickness, in which a thickness reduction of about 60% was recorded. The study's results revealed that the produced denture plate using SPIF technology had satisfactory mechanical properties and even exhibited similar performance to a conventionally produced denture plate (using the lost wax technique) with a thickness of 0.8mm.

In conclusion, additional tests are still necessary to assess the performance of the produced denture plate, especially in the long term. Thickness distribution for the 304 and 316L parts is presented graphically in Figures 13 and 15.

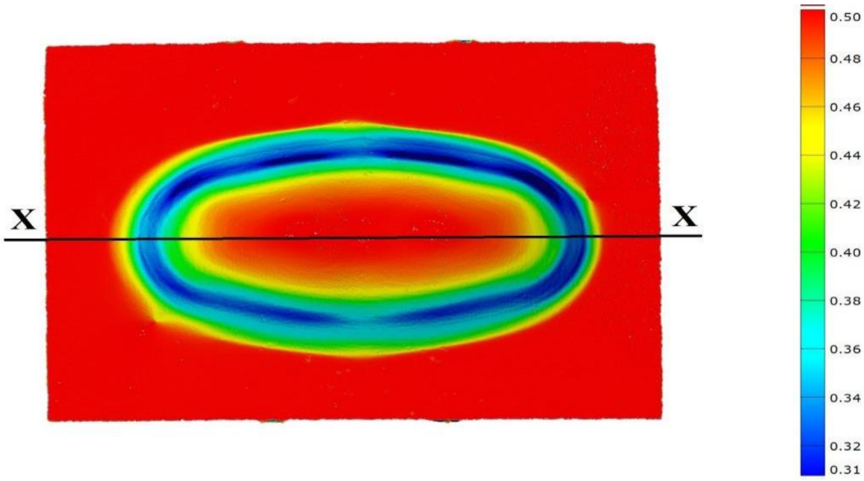


Fig. 13. Distribution of final sheet thickness of (0.5mm) 304 Stainless Steel.

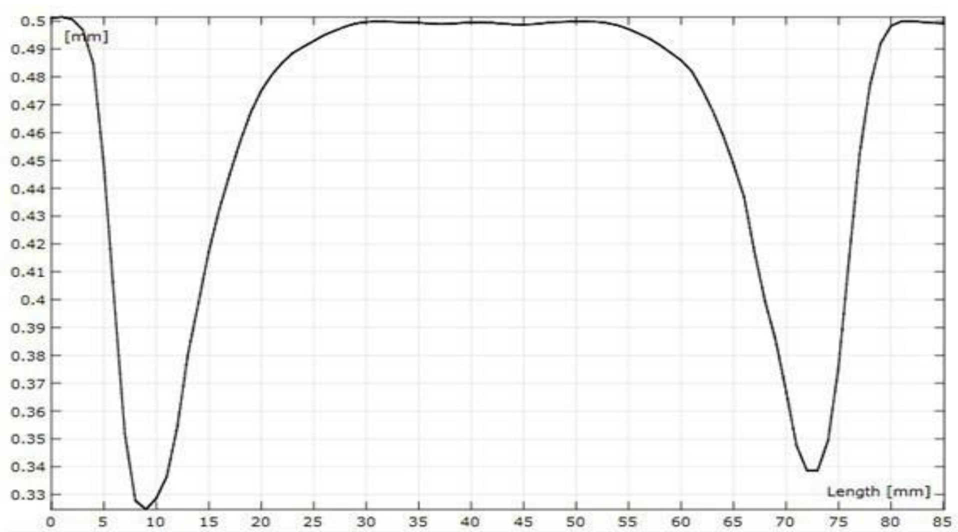


Fig. 14. Sheet thickness distribution along the section (x-x).

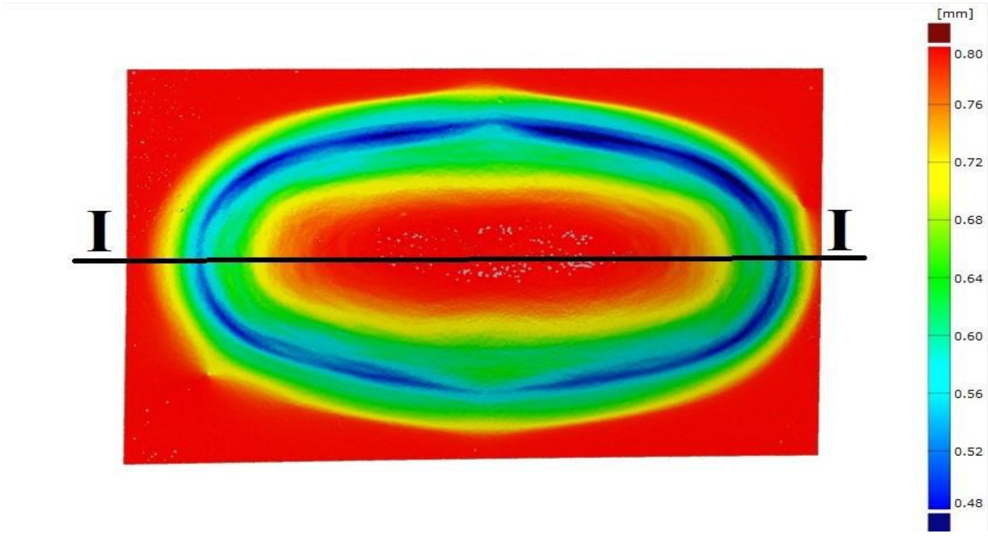


Fig. 15. Distribution of final sheet thickness of 316L Stainless Steel.

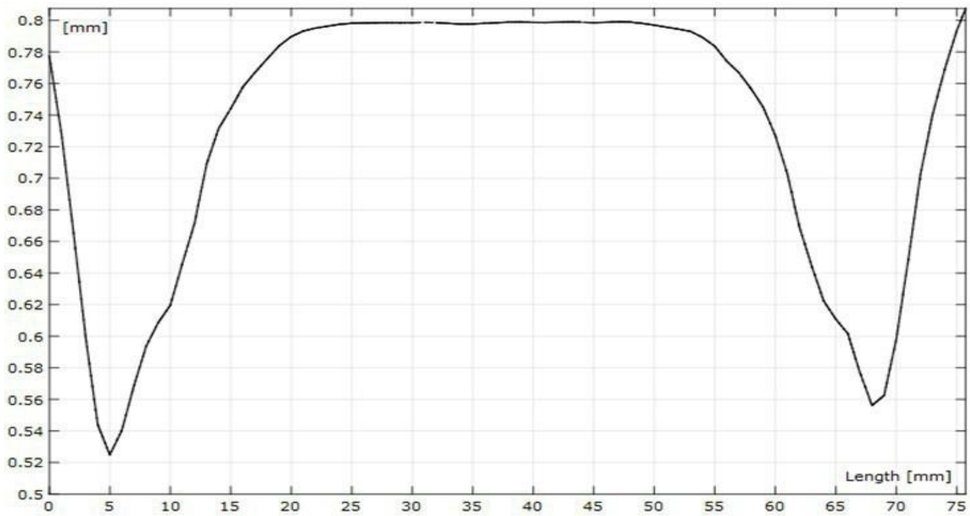


Fig. 16. Sheet thickness distribution along the section (I-I).

5. Conclusions

Single point incremental sheet forming has been successfully implemented to produce a denture plate from two types of stainless steel, 304 and 316L, with initial thicknesses of 0.5mm and 0.8mm, respectively. The reported results demonstrated that the process is feasible and can be used in real-life medical applications. Compared to the traditional way of impression taking and model waxing, which requires a high degree of skill, high equipment costs, and high processing times, this process can minimize the working hours of dental clinicians and cut production costs significantly. The process was performed using a universal CNC vertical milling machine and required no preparation of shape-specified tools. The main conclusions of this work can be summarized as follows:

1. The process can be realized by developing a 3D model of the biomedical component, tool path generation, G-code transfer to the CNC machine, and the preparation of a customized backing plate to reduce the geometrical deviation.
2. Geometrical deviations between the developed CAD model and the actual model are predominantly in the range of ±0.25mm. The highest geometrical deviation was located at the upper zone of the deformed sheet. This geometrical shift can be attributed to the bending effect during the forming process at regions bordering the backing plate.
3. Thickness distribution was analyzed for both

plates of stainless steel. The thickness was almost unchanged at the bottom of the plates and around the edges. The most critical zones with extensive thinning were located at the lateral and front walls.

Future work and recommendations

1. Similar work can be implemented using biocompatible polymeric materials such as Polyether ether ketone (PEEK) and Polymethyl methacrylate (PMMA), as polymer processing using SPIF is a relatively new technology, and research is scarce regarding these materials.
2. The implementation of double-sided incremental sheet forming (DSIF) as this technology can highly reduce the geometrical deviations caused by the bending effect of the sheet.
3. The performance of a comparison between the SPIF-made denture plate and the commercial one regarding performance, cost, biocompatibility, and accuracy.
4. More work is required to concentrate on the technical parameters used during the manufacturing process to improve the obtained accuracy.

List of abbreviations

ISF	Incremental sheet forming
SPIF	Single point incremental sheet forming
DSIF	Double-sided incremental sheet forming
CAD	Computer-aided design
CAM	Computer-aided manufacturing
STL	Standard triangulation language format
CNC	Computer numerical control
CT	Computerized tomography
MRI	Magnetic resonance imaging

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تصنيع وتحليل لوحة طقم الأسنان باستخدام تشكيل الصفيحة الإضافية بنقطة واحدة

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الخلاصة

تعد عملية التشكيل الصفائحي من التقنيات الحديثة في عملية تشكيل الصفائح المعدنية عن طريق سلسلة من الحركات الدورانية التي تؤديها عدة التشكيل في نقطة تشكيل واحدة وبشكل متسلسل. وتتم حركة هذه العدة من قبل ماكنة التشغيل المبرمج. من خلال هذه العملية يتم تشكيل الصفائح بصورة انية من خلال استخدام عملية السحب النقي. هذا البحث يقوم بالتركيز على استخدام هذا التقنية في مجال عمليات تصنيع التطبيقات الطبية وبالاخص في عملية تصنيع قاعدة طقم اسنان. تم اختيار صفيحيتين من الفولاذ المقاوم للصدأ لأجراء فيما كانت الصفيحة الثانية من نوع (316L) و بسمك كانت من نوع (304) و بسمك (0.5) ملم عملية التصنيع. الصفيحة الاولى (0.8)ملم. تم تصميم النموذج عن طريق القيام بعملية مسح ثلاثي الابعاد 3D) Scanning) لقالب اسنان وبأستخدام برنامج التصميم معان بالحاسوب (EXOCAD). تمت عملية فحص دقة العينات المنتجة عن طريق عمل مقارنة ثلاثية الابعاد بين العينات المنتجة والنموذج المصمم. أثبتت النتائج ان عملية التشكيل النقطي للصفائح ملائمة لهذا النوع من الصناعات الطبية حيث كان التفاوت بين العينات المنتجة والنموذج المصمم يتراوح بين 0.25± ملم

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