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EVALUATION OF EFFECT OF PARAMETER ON SINGLE POINT INCREMENTAL FORMING OF TITANIUM

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ABSTRACT

Single Point Incremental Forming (SPIF) has emerged as a promising technique for shaping complex geometries in various materials. This study investigates the influence of process parameters, specifically step size and tool diameter, on the SPIF of titanium sheets. The experiment comprises three different step sizes (0.2, 0.4, and 0.6 mm) and three tool diameters (6, 10, and 14 mm), applied to titanium sheets. The research focuses on evaluating the impact of these parameters on three crucial aspects of SPIF: thickness reduction, fracture depth, and forming angle in the fracture zone. Through a series of experiments, the relationship between step size, tool diameter, and these performance indicators is thoroughly examined. Results indicate that smaller step sizes lead to higher thickness reductions and more precise forming angles in the fracture region and smaller tool diameters also increased fracture depths. Understanding the interplay between these parameters is vital for optimizing SPIF processes in titanium sheet forming applications, offering insights for enhanced production efficiency and quality in industries relying on advanced forming techniques. The CNC forming process took about 10 hours.

KEYWORDS: SPIF, Titanium, Step Size, Tool Diameter, Sheet Forming, Hardness, Forming Parameters.

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1. INTRODUCTION

These days, the demand to improve both processes and components has coincided with the need to lose weight. Although for diverse reasons, most industrialized nations have followed this tendency.

Domains, especially aeronautics and transportation (trains, trucks, and vehicles), resulting in the appropriate blending of cutting-edge technologies and materials (Jeswiet et al., 2008). Titanium (Ti), one of the cutting-edge elements, offers the possibility of making lightweight parts, which unquestionably represents a realistic option for lowering pollution and petroleum consumption, whose price is always rising. Other benefits of titanium alloys include their compatibility with CFR composites, which is crucial for aircraft applications, and their greater specific strength and stiffness.

On the contrary, the main disadvantage of Ti is its high cost or, at the very least, extreme cost fluctuation (Swale et al., 2010); however, thanks to innovative extraction and fabrication techniques, costs are decreasing, determining a renewed interest not only in the aerospace but also in the automotive fields for producing components assembled on commercial vehicles (Froes et al., 2004; Governale et al., 2007). Another significant limitation of Ti alloys is their poor formability in comparison to steel, which is caused by the high degree of spring-back, high flow stress, and low ductility caused by the HCP structure of the a-phase (Odenberger et al., 2008). appropriate process conditions and/or proper manufacturing techniques are thus required to overcome such a limitation.

Regarding the first approach, namely the use of proper process conditions, temperatures greater than room temperature allow for improved material formability: Vanderhasten et al. (2008) conducted tensile tests on the Ti-alloy Ti-6Al-4V, which demonstrated that the deformation behavior of this alloy may be categorized into four major domains: Room temperature to about 650 °C (characterized by no dynamic recrystallization or grain boundary sliding regardless of strain rate); temperatures between 725 °C and 950 °C and strain rates less than (5 x 10^{-3} s^{-1}) (the material exhibits superplastic behavior in this domain); temperatures above 950 °C and strain rates less than 5 x 10^{-3} s^{-1} (dynamic grain growth causes the disappearance of superplasticity); above 750 degrees Celsius and a high strain rate (traditional hot deformation mechanisms mixed with dynamic recrystallization are thought to occur).

When it comes to the second solution, which is the use of proper manufacturing techniques, when equipment is capable of reaching high temperatures (greater than 725 °C), the Super Plastic Forming (SPF) process certainly provides the possibility of producing components with a high degree of complexity (Tsuzuku, 1999; Hefti, 2010; Ho-Sung et al., 2010), but both the very high temperature level and the requirement of using low strain rates are the main limitations of such process. Another option for forming Ti alloy might be the Incremental Forming (IF) technique, which can fully answer the demands for flexibility and affordability, as well as the need to reduce tool costs. Asymmetric IF (often conducted on a CNC) in particular enables the fabrication of any shape and almost any material (Franzen et al., 2009) utilizing a single tool and, in most cases, without the use of a support die. The greatest advantage of the IF process is thus its high flexibility (the shape of the part is defined simply by controlling the movement of the forming punch): this methodology is known in literature as Single Point Incremental Forming (SPIF), in order to distinguish it from the process using a partial or full die (Two Point Incremental Forming, TPIF), which is sometimes used to improve the accuracy of the formed part (Jeswiet et al., 2005). The most important parameters affecting the SPIF process are well detailed in the widely cited work of Jeswiet et al., (2005) (the sheet thickness, the step down or pitch, the dimension of the forming tool, and the tool speed); it is important to note that, among them, the effect of the tool speed is studied in depth by few works in literature:

- Durante et al., (2009) discovered a decrease in forming force peaks during SPIF testing on AA7075-O aluminum alloy, notably when increasing the (clockwise) rotation speed, however because low rotation speed values were utilized, the temperature increase was fairly limited.
- Hamilton and Jeswiet (2010) investigated the impact of high feed rates and rotational speeds on AA3003-H14 Al alloy, focusing on roughness and noticing that the thickness distribution remained essentially unaltered as rotation speed increased.
- Ambrogio et al. (2011) focused on process competitiveness by limiting the investigation to feed rates (very high values were achieved using a custom fixture constructed on a lathe), emphasizing that the formability behavior remained intact.

In this research, Studying the ability of the single point incremental forming process to be manufactured in the medical field and examining the effect of the process parameters on both the thickness and the formability of commercial pure titanium grade 1.

2. EXPERIMENTS

2.1. Material and experimental set-up

The test material was a sheet of CP Ti grade 1 with a thickness of 0.7 mm. The following is a list of its mechanical characteristics and composition:

Table 1. Chemical composition.

Element	*Fe %*	*C %*	*N %*	*H %*	*O %*	*Others %*	*Ti %*
Wt%	*0.20*	*0.08*	*0.03*	*0.015*	*0.18*	*0.4*	*99.1*

Table 2. Mechanical properties.

Young modulus(GPa)	*Yield stress $\sigma_{y,}$(MPa)*	*Ultimate tensile stress (MPa)*	*Density(kg/m^3)*
108	*230*	*359*	*4505*

2.2. Plan of experiment

The experimental work was specifically designed to explore the impact of tool diameter and incremental step size on thinning average and hardness generated in SPIF parts.

2.3. Equipment used

The following equipment and devices are used in this work:

1. Fixture + CNC machine
2. Wire cut
4. Digital double point micrometer
5. Micro hardness

A CNC milling machine shown in (Fig. 1a) was used to perform a single point incremental forming process for 9 sheets of commercially pure titanium grade 1 which is shown in (Fig. 2) and the Taguchi design was used to found the process parameters, which are (3 steps size and 3 tools diameter) The tool path in this work was developed by the Cero parametric program, as shown in (Fig. 3).

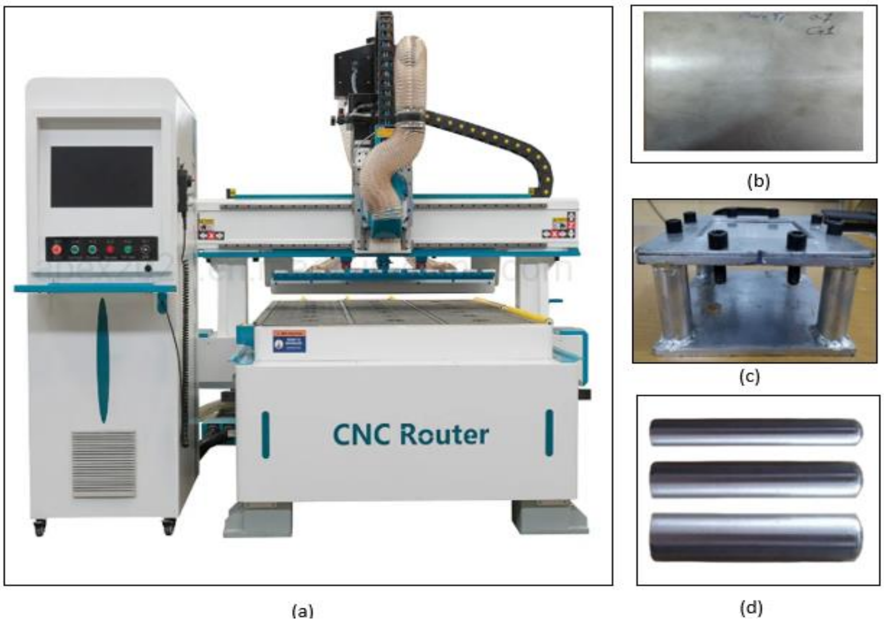


Fig. 1. a) CNC milling machine b) Base sheet of pure titanium c) Fixture d) Tools.

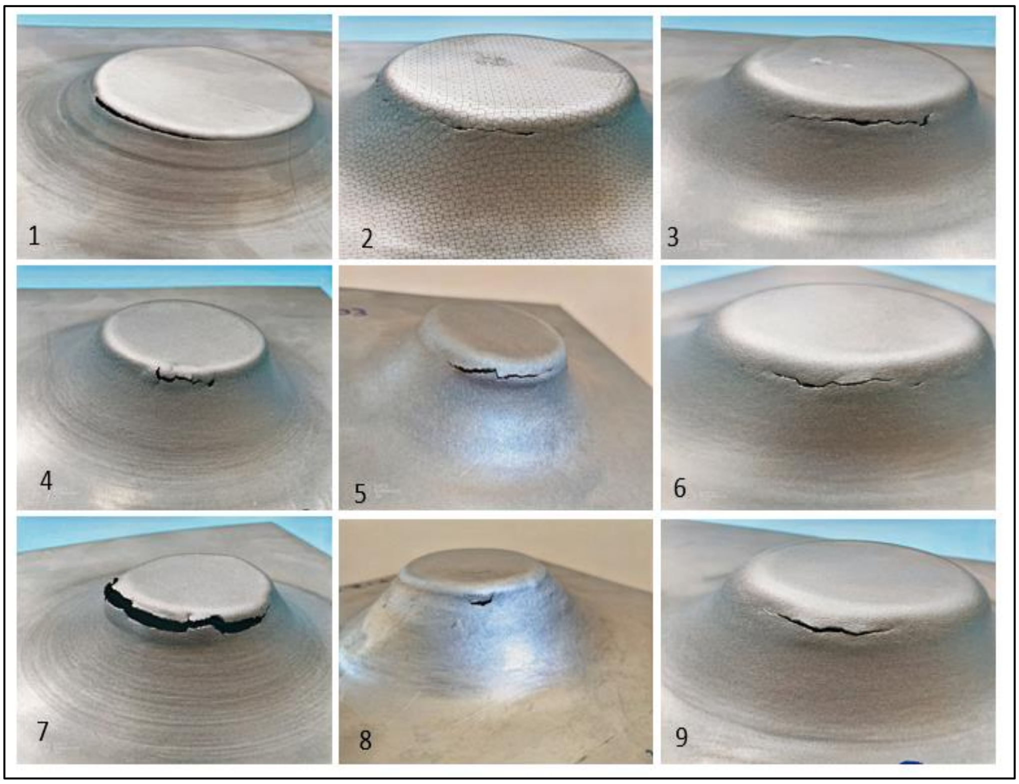


Fig. 2. Manufactured pure titanium sheets.

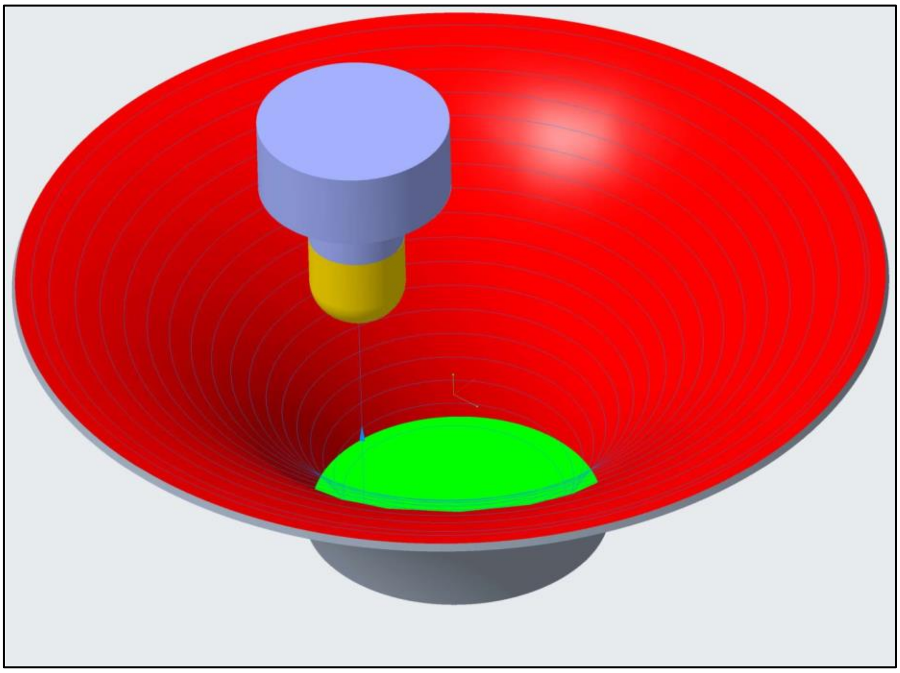


Fig. 3. Tool path creation.

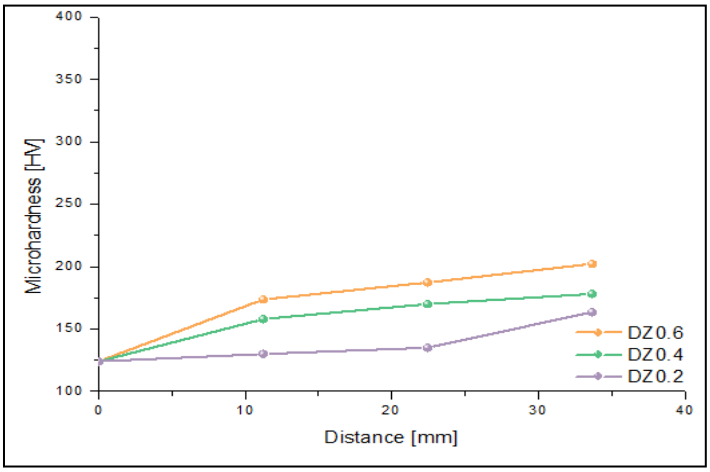
3. RESULTS

3.1. Effect of step size

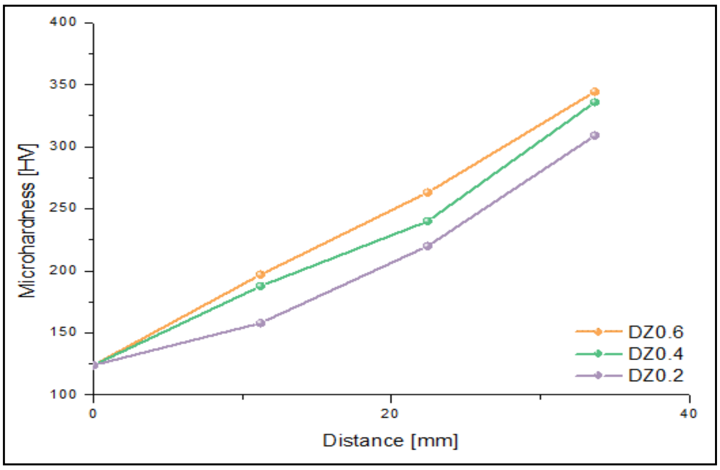
Three values were chosen for the step size: 0.2, 0.4, and 0.6mm. Table 3 lists the experimental results for the hyperbolic truncated cone's maximum wall angle (fracture angle) and fracture depth for various step sizes and tool diameters. The below table and Fig. (4 a, b, c) make it evident that when the step size is decreased from 0.6 mm to 0.2 mm, the influence of parameters on the formability (maximum wall angle) and fracture depth of grade 1 pure Ti. Hyperbolic truncated cone increases by 6.8.

Table 3. Effect of step size and tool diameters on the formability and fracture of pure Ti grade 1.

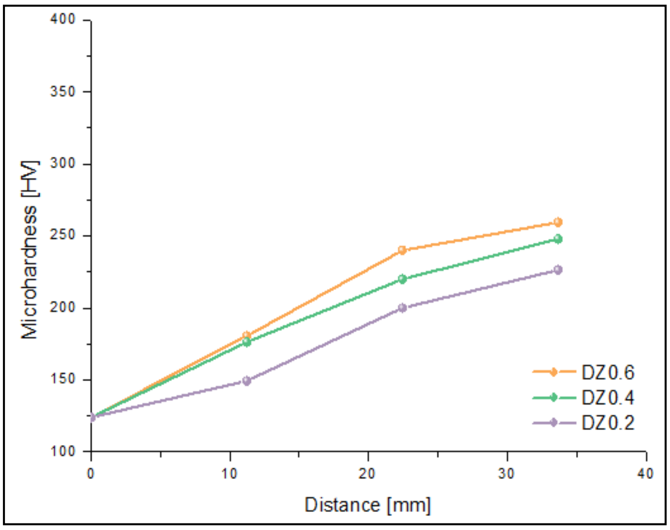
No.	*Tool Diameter. (mm)*	*Step Size. (mm)*	*Fracture Depth. (mm)*	*Wall Angle*
1	*6*	*0.2*	*33.66*	*77.6*
2	*6*	*0.4*	*31.5*	*74.6*
3	*6*	*0.6*	*28.54*	*70.8*
4	*10*	*0.2*	*33.2*	*76.8*
5	*10*	*0.4*	*30.05*	*72.8*
6	*10*	*0.6*	*27.591*	*69.6*
7	*14*	*0.2*	*28.93*	*71.3*
8	*14*	*0.4*	*28.5*	*70.8*
9	*14*	*0.6*	*24.528*	*65.5*



(a)Tool 6mm



(b)Tool 10 mm



(c) Tool 14 mm

Fig. 4. effect of step size on microhardness (a, b, and c tool diameters using).

The reason of that, smaller step sizes results in a more refined and localized deformation of the material during the forming process. As a consequence, the strain becomes more uniformly distributed over the entire hyperbolic truncated cone (Fig. 5). This improved strain distribution helps prevent strain localization and reduces the likelihood of localized deformation, such as necking or fracture initiation, which could occur when using larger step sizes.

Fig. 5. presents the target model, a hyperbolic truncated cone, optimized for a) three dimensions and b) two dimensions. The figures showcase the ideal dimensions for the cone, offering valuable insights for design and analysis purposes while the Fig. 6. illustrates the impact of step size on the hyperbolic truncated cone's thickness distribution at fracture. The graph reveals a consistent increase in sheet thinning across the transition region between the contact and non-contact zones before reaching the maximum value, which represents the fracture thickness.

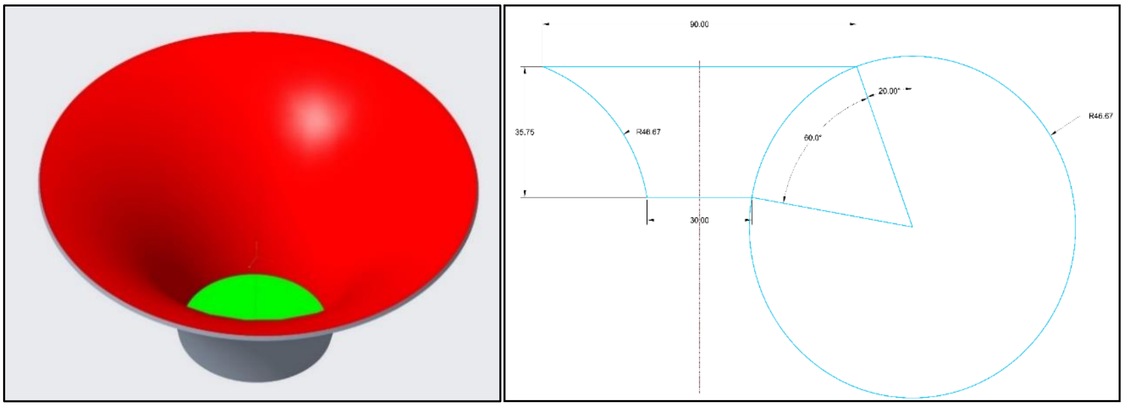
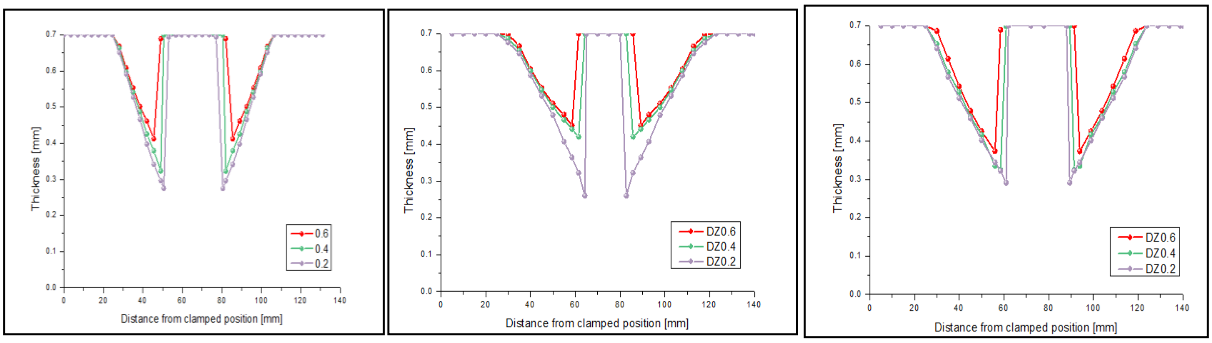


Fig. 5. Target Model: Hyperbolic Truncated Cone with Optimal Dimensions a) three dimensions, b) two dimensions.

Additionally, smaller step sizes can lead to an overall increase in strain within the material, enabling it to undergo more significant plastic deformation without fracture or failure (Fig. 6). This can result in a higher maximum wall angle (fracture angle) and deeper fracture depth, indicating better formability of the material.



(a) **(b)** **(c)**

Fig. 6. Effect of step size on thickness; a. *T6 mm, b. T10 mm and c. T14 mm*.

Furthermore, the graph demonstrates that using a smaller step size allows for greater thickness reduction compared to larger step sizes. Additionally, the data shows that a smaller step size results in a larger wall angle, indicating improved formability. In summary, the figure provides visual evidence that reducing the step size leads to more significant thinning of the sheet, particularly in the transition region, and enables achieving higher wall angles. This emphasizes the importance of the step size as a crucial parameter in the forming process to enhance the material's formability and achieve desired outcomes.

Fig. 7 illustrates the correlation between step size and hardness of CP (Commercially Pure) titanium sheet during the SPIF (Single Point Incremental Forming) process. The findings reveal that larger step sizes correspond to higher hardness values in the formed sheets.

This phenomenon can be attributed to several factors. Firstly, larger step sizes lead to a more significant accumulation of strain in the material, resulting in increased dislocation density within the crystal structure and consequently higher hardness. Secondly, higher strain rates during deformation caused by larger steps can contribute to enhanced strain hardening and elevated hardness levels.

Moreover, larger step sizes may induce more frictional heating at the tool-sheet interface, allowing for slower cooling rates, which can promote the development of a coarser grain structure and subsequently higher hardness. However, it is essential to consider that these hardness gains may be accompanied by potential drawbacks, such as reduced ductility and formability in the material.

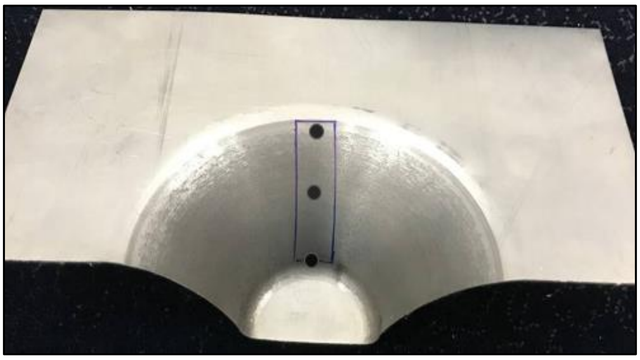


Fig. 7. Half of the produced design with hardness measurement places marked.

On the other hand, using smaller step sizes typically leads to more uniform deformation and improved material properties like ductility and formability. However, the hardness values might be relatively lower due to reduced strain accumulation and milder deformation. It can be seen from the Fig. 4 the distribution of hardness values across the formed CP titanium sheet, with indicated measurement points for analysis."

3.2. Effect of tool diameters

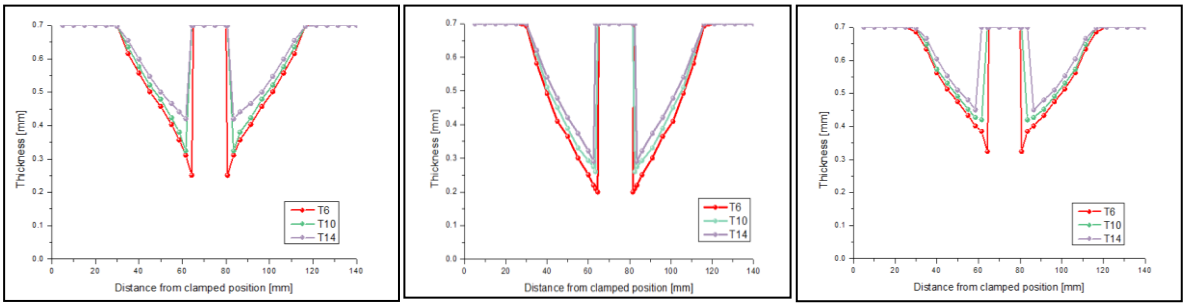
From Table 3 it is evident that changing the tool diameter has a notable impact on the formability of the material. Specifically, when the tool diameter is reduced from 14 mm to 6 mm, the maximum wall angle (fracture angle) of the hyperbolic truncated cone increases. The reason behind this improvement in formability with smaller tool diameters lies in the way the material undergoes deformation during the forming process. With smaller tool diameters, there is a more refined and localized deformation of the material.

As a result, the strain becomes more uniformly distributed over the entire hyperbolic truncated cone. The more uniform strain distribution helps in preventing strain localization and reduces the likelihood of localized deformation issues, such as necking or fracture initiation. These problems could occur when using larger tool diameters, where the strain is concentrated in certain regions, making them more susceptible to failure. Moreover, when smaller tool diameters are used, the overall strain within the material tends to increase. This allows the material to undergo more significant plastic deformation without experiencing fracture or failure. Consequently, a higher maximum wall angle (fracture angle) and deeper fracture depth are achieved, indicating an enhancement in the formability of the material.

Fig. 9 illustrates the influence of tool diameters (6 mm, 10 mm, and 14 mm) on the thickness distribution of the hyperbolic truncated cone at the point of fracture. The graph clearly shows how the sheet thickness changes across the transition region between the contact and non-contact zones before reaching the maximum value, which corresponds to the fracture thickness.

Upon analyzing the graph, it becomes evident that using different tool diameters has a significant impact on the sheet thinning process. Specifically, when smaller tool diameters (e.g., 6 mm) are employed, there is a consistent and more pronounced increase in sheet thinning across the transition region compared to larger tool diameters (e.g., 14 mm).

This observation is consistent with the understanding that smaller tool diameters result in a more refined and localized deformation of the material during the forming process. As a consequence, the strain is more uniformly distributed over the entire hyperbolic truncated cone, leading to a greater thickness reduction, particularly in the transition region.



DZ 0.2mm ***DZ 0.4 mm*** ***DZ 0.6 mm***

Fig. 9. Effect of tool diameter on thickness distribution.

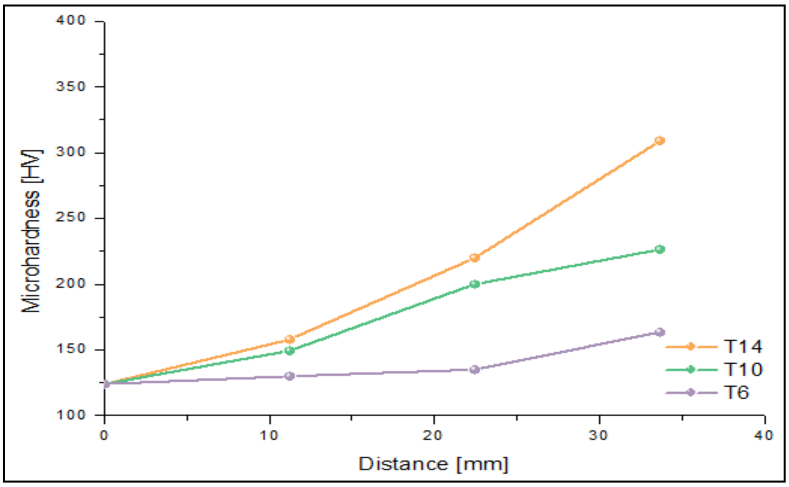
The graph also indicates that as the tool diameter increases (e.g., from 6 mm to 14 mm), the sheet thinning becomes less significant. This can be attributed to the fact that larger tool diameters cause more concentrated strain and deformation, leading to a less uniform thickness distribution and reduced thinning in the transition region

Fig. 10 illustrates the correlation between tool diameter and the hardness of CP titanium sheet during the SPIF process. The findings suggest that the tool diameter plays a significant role in determining the hardness values of the formed sheets. A larger tool diameter can lead to higher hardness values in the formed sheet due to several factors. Firstly, a larger tool diameter results in more material being subjected to deformation in a single pass. This increased deformation can lead to higher strain accumulation and an elevated dislocation density within the crystal structure, contributing to higher hardness levels.

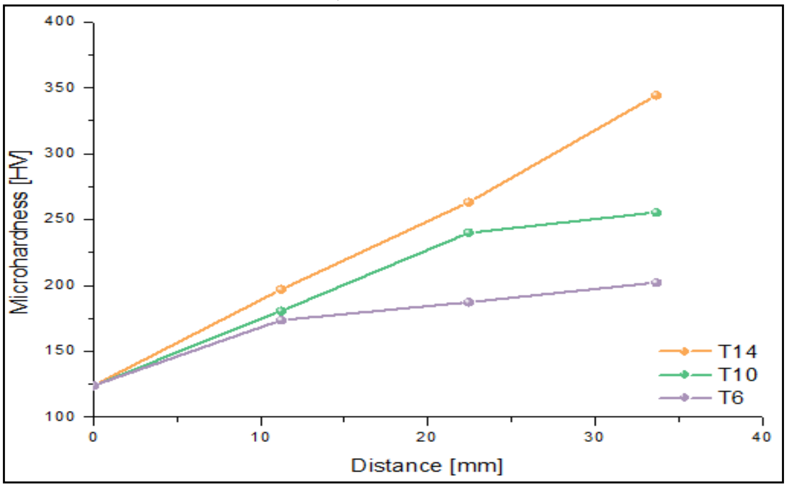
Secondly, the use of a larger tool diameter may also lead to higher strain rates during deformation. The increased strain rates promote enhanced strain hardening, which can further increase the hardness of the material. Moreover, the larger tool diameter can generate more frictional heating at the tool-sheet interface. The slower cooling rates associated with this heating can promote the development of a coarser grain structure in the material. This coarser grain structure is often associated with higher hardness values.

However, it is crucial to consider potential drawbacks associated with using larger tool diameters. While higher hardness values may be achieved, this could be accompanied by reduced ductility and formability of the material. Excessive strain and strain rate during deformation might lead to material embrittlement and limited ability to withstand further forming processes.

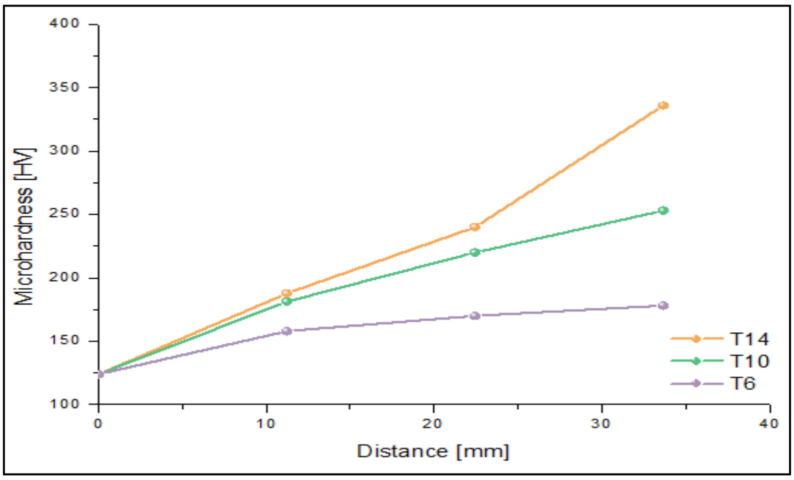
Conversely, using a smaller tool diameter typically leads to more controlled and uniform deformation, which can improve material properties such as ductility and formability. However, the hardness values might be relatively lower compared to larger tool diameters due to reduced strain accumulation and milder deformation.



a) DZ 0.2 mm



b) DZ 0.4 mm



c) DZ 0.6 mm

Fig. 10. effect of tool diameter on microhardness of CP Titanium G1(a, b, c step sizes).

4. CONCLUSIONS

This research demonstrates that careful selection and optimization of step size and tool diameter in SPIF significantly impact the microstructural features, formability, and mechanical properties of implant-grade titanium. These insights are valuable in enhancing the manufacturing process and improving the performance of titanium implants for biomedical applications, ensuring better overall functionality and longevity of implant materials. The findings from this study contribute to the advancement of materials processing techniques and provide a foundation for further research and development in the field of implant manufacturing.

It can be concluded that decreasing the step size and the diameter of the tool leads to an increase in the depth of the fracture and thus a greater decrease in the thickness of the material at the fracture area. It also leads to an increase in the angle of the wall, which means an increase in the ability of the material to form.

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