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Investigating the Influence of Step Size and Tool Diameter on the Microstructure of Incrementally Formed Commercially Pure Titanium

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Abstract

This study examines how the microstructure of pure titanium is affected by Single Point Incremental Forming (SPIF) factors, such as step sizes (0.2, 0.4, 0.6 mm) and tool diameters (6, 10, 14 mm). According to the research, increasing step sizes cause more material to deform with each stride, which increases the accumulation of strain over shorter distances. By encouraging grain refinement and resulting in smaller, more evenly dispersed grains, this strain can improve mechanical qualities. Furthermore, localized heating is produced by the increased friction brought on by bigger step sizes, which further influences microstructural alterations.

The results show that, with respect to tool diameter, larger tools provide greater friction, which might lead to localised heating and encourage grain recrystallisation. This therefore has an impact on the material's residual stresses, which are crucial to the final microstructure. The study highlights the connection between tool diameter and microstructural evolution by analysing four different sections from each sample and observing significant changes in grain size and distribution along the sample wall. The findings highlight how crucial it is to optimise SPIF parameters in order to enhance the material's performance properties.

The analysis of fracture behaviour sheds light on the change from brittle to ductile fracture. SEM study of the fracture surfaces demonstrates that the number of pits increases as tool diameter and step size decrease, influencing the fracture behaviour.

Keywords: Titanium, SPIF, Microstructure, Fracture surface

دراسة تأثير حجم الخطوة وقطر الأداة على البنية المجهرية للتيتانيوم النقي المُشكَّل تزايديا

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المستخلص

تبحث هذه الدراسة في تأثيرات معلمات عملية التشكيل التزايدي بنقطة واحدة (SPIF)، بما في ذلك أحجام الخطوة (0.2، 0.4، 0.6 مم) وأقطار الأدوات (6، 10، 14 مم)، على البنية المجهرية للتيتانيوم النقي. تكشف التجارب أن أحجام الخطوة الأكبر تؤدي إلى تشوه أكبر للمادة في كل خطوة، مما يؤدي إلى تراكم إجهاد أعلى عبر مسافات أقصر. يعزز هذا الإجهاد تنقية الحبيبات، منتجًا حبيبات أصغر وأكثر توزيعًا منتظمًا، مما يمكن أن يحسن الخصائص الميكانيكية. بالإضافة إلى ذلك، يؤدي الاحتكاك المتزايد المرتبط بأحجام الخطوة الأكبر إلى توليد تسخين موضعي، مما يؤثر بشكل إضافي على التغيرات في البنية المجهرية.

وفيما يتعلق بقطر الأداة، تشير النتائج إلى أن الأدوات الأكبر تولد مزيدًا من الاحتكاك، مما يسبب تسخينًا موضعيًا يمكن أن يعزز إعادة تبلور الحبيبات. وهذا بدوره يؤثر على الإجهادات المتبقية في المادة، والتي تلعب دورًا مهمًا في البنية المجهرية النهائية. من خلال فحص أربع مناطق مميزة من كل عينة، تلاحظ الدراسة تغييرات واضحة في حجم الحبيبات وتوزيعها على طول جدار العينة، مما يبرز العلاقة بين قطر الأداة وتطور البنية المجهرية. تؤكد النتائج على أهمية تحسين معلمات SPIF لتحسين الخصائص الأداء للمادة.

يتم ايضاً فحص سلوك الكسر ،مما يوفر نظرة ثاقبة للانتقال من الكسر الهش الى الكسر المرن .يؤدي الانخفاض في قطر الاداة وحجم الخطوة الى زيادة عدد الحفر ،مما يؤثر على سلوك الكسر ،كما يتبين من تحليل SEM لاسطح الكسر

الكلمات المفتاحية: التيتانيوم، البنية المجهرية، عملية التشكيل التزايدي بنقطة واحدة، سطح الكسر

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Importance of the Research and Its Objectives:

Titanium's remarkable mechanical qualities and biocompatibility make it the perfect material for use in aerospace, medicine, and other fields. Conventional forming methods, however, have drawbacks such as material waste, exorbitant expenses, and difficulty creating thin sheets. Although Single Point Incremental Forming (SPIF) is a viable substitute, process optimisation is limited because of the lack of knowledge on the impact of critical parameters, such as step size and tool diameter, on the microstructure of pure titanium. This study aims to investigate the effect of step size (0.2, 0.4, 0.6 mm) and tool diameter (6, 10, 14 mm) on the microstructure of commercially pure titanium. It seeks to optimize SPIF conditions by examining the influence of these parameters on grain refinement, residual stresses, and mechanical properties.

Introduction

These days, the urge to reduce body weight has coincided with the need to improve components and processes. The majority of developed countries have followed this trend, albeit for different reasons **[1]**. domains, particularly transportation (trucks, trains, and automobiles) and aviation, which leads to the proper mixing of advanced materials and technology [1]. One of the innovative materials is titanium, which provides the potential to create lightweight components. This is undoubtedly a practical solution to reduce pollution and the use of petroleum, whose price is always rising. Additional advantages of titanium alloys include their increased specific strength and stiffness, and compatibility with Carbon Fibre Reinforced Composites (CFRC), which is essential for aircraft applications [2].

On the other hand, titanium's high cost, or at the very least, its notable vulnerability to large price swings, is a considerable disadvantage [2]. However, cost-cutting trends brought about by improvements in extraction and fabrication techniques have rekindled interest in the aerospace and automotive industries for the production of parts used in commercial vehicles [3, 4].

Another significant drawback of titanium alloys is that, in comparison to steel, they are not as formable. This discrepancy results from elements like strong spring-back behaviour, increased flow stress, and decreased ductility that are caused by the alpha-phase's Hexagonal Close-Packed (HCP) structure. [5]. To address this constraint, precise process conditions or appropriate manufacturing techniques must be employed.

Regarding the first strategy, which is process condition optimisation, it has been shown that raising temperatures above room temperature improves material formability. for example [6] tested the titanium alloy Ti-6Al-4V for tensile strength. Their investigation uncovered unique deformation patterns in the four primary temperature domains: The range of 725 to 950 oC with strain rates below 5 × 10-3 S-1 (displaying superplastic behaviour); temperatures above 950 oC with strain rates below 5 × 10-3 S-1 (causing the disappearance of super plasticity due to dynamic grain growth); and temperatures above 750 oC coupled with high strain rates (thought to involve conventional hot deformation mechanisms interspersed with dynamic recrystallisation) are the following temperature ranges: room temperature to about 650 oC (marked by the absence of dynamic recrystallisation or grain boundary sliding regardless of strain rate) [7].

When equipment can reach high temperatures (over 725 ºC), the Super Plastic Forming (SPF) process becomes relevant in the second solution, which involves appropriate production processes. This technique offers the possibility of producing components with complex shapes. [7, 8]. The requirement for extremely high temperatures and the application of low strain rates, however, are the main limitations that hinder the process. As an alternative, the Incremental Forming (IF) method shows promise in shaping titanium alloys, meeting the need for cost-effectiveness and flexibility as well as the need to reduce tool-related costs.

Notably, the ability to shape a variety of materials with no need for support dies is provided by asymmetric incremental forming, which is frequently carried out using Computer Numerical Control (CNC), highlighting its versatility [9].

The main benefit of the IF method is its exceptional versatility, as part shapes are mostly controlled by adjusting the forming punch action. This process is called Single Point Incremental Forming (SPIF) in the literature to distinguish it from the partial or complete die variant known as Two Point Incremental Forming (TPIF), which is sometimes used to increase the precision of manufactured parts [10] as shown in figure (1) The study [10] provides a complete explanation of the key parameters impacting the SPIF process, including sheet thickness, step down or pitch, forming tool size, and tool speed as shown (2). It is important to emphasize that of these factors, only a small body of literature has thoroughly examined the impact of tool speed.

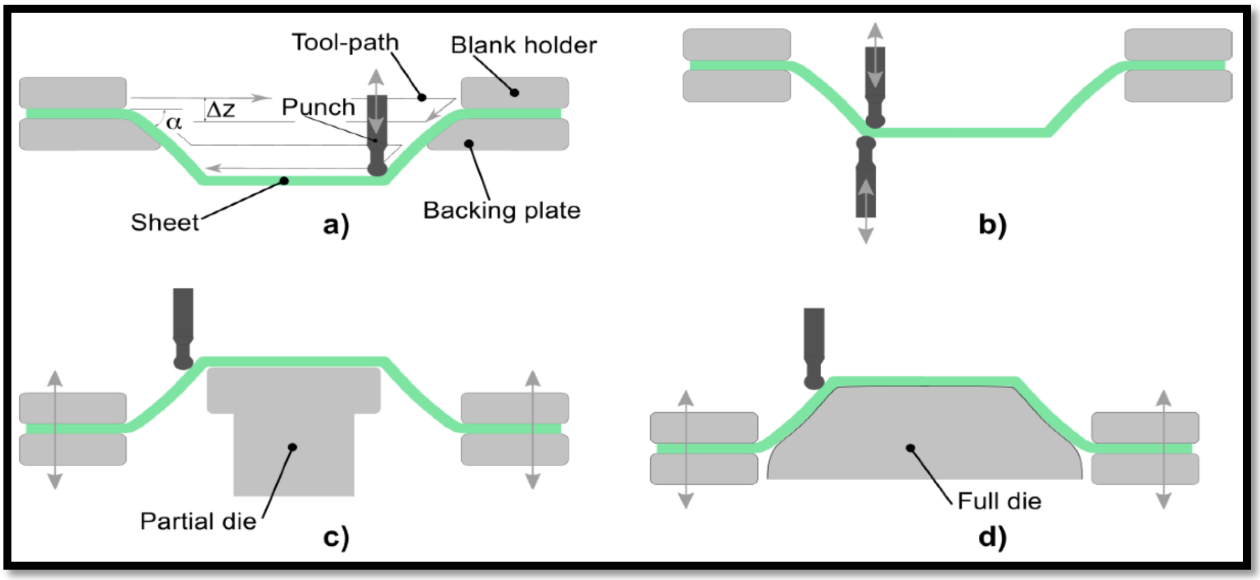


Figure (1): **Main incremental sheet forming (ISF) procedures. There are four types of incremental forming: (a) single point, (b) two points, (c) double-sided with partial die, and (d) double-sided with full die [11]**

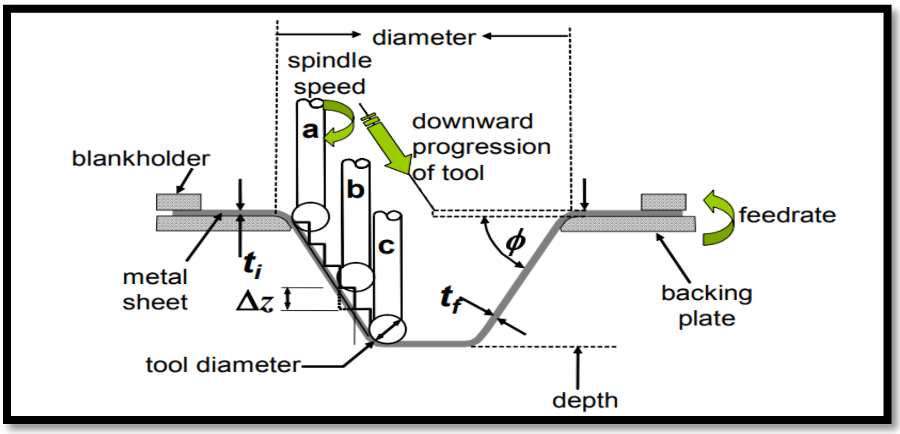


Figure (2): The deformed portion displays the SPIF terminology [12]

Single Point Incremental Forming (SPIF) has been investigated in the manufacturing sector as a result of the search for economical and effective techniques. The impact of process variables on the performance of commercially pure titanium in single-point and incremental sheet forming processes has been the subject of numerous investigations. used SPIF to examine how process variables affected the formability of commercially available pure titanium sheets [13].

Their results shed light on the process's limitations and ideal parameter combinations. [14] focused on the behaviour of fractures in Titanium Grade 2 sheets, emphasising that the highest tool diameter (12 mm) caused the greatest deformation fracture strain. [15] examined the effects of important ISF factors on the formability and fracture behaviour of Grade 1 and Grade 2 titanium sheets, including step-down, feed rate, and tool diameter. They came to the conclusion that Grade 2 titanium was more susceptible to process changes because of its decreased ductility. Moreover, [16] examined the surface roughness of a hyperbolic truncated cone created by SPIF using Grade 1 pure titanium and discovered that areas with low equivalent plastic strain and high equivalent stress had rougher surfaces. In order to improve knowledge of parameter impacts on grain refinement and deformation behaviour, this study builds on previous research by examining the impact of step size and tool diameter on the microstructure of commercially pure titanium.

Experiments

Material and experimental set-up

The test material used was a commercially pure titanium (CP Ti) Grade 1 sheet with a thickness of 0.7 mm. The chemical composition and mechanical properties of the pure titanium are detailed in Tables (1) and (2), respectively.

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 σy, (MPa	Ultimate tensile stress (MPa)	Density (kg/m^3)
108	230	359	4505

Plan of experiment

The experimental work aimed to investigate the effects of tool diameter and incremental step size on the average thinning and surface roughness of components produced via Single Point Incremental Forming (SPIF). A CNC-1325 Router Machine was used to perform SPIF on nine sheets of commercially pure titanium, secured with a custom fixture. After forming, the samples were longitudinally cut using a wire cutting technique for accurate measurement. The experimental design followed the Taguchi method, and the tool path was created using Creo Parametric software, as shown in Figures (3) and (4).

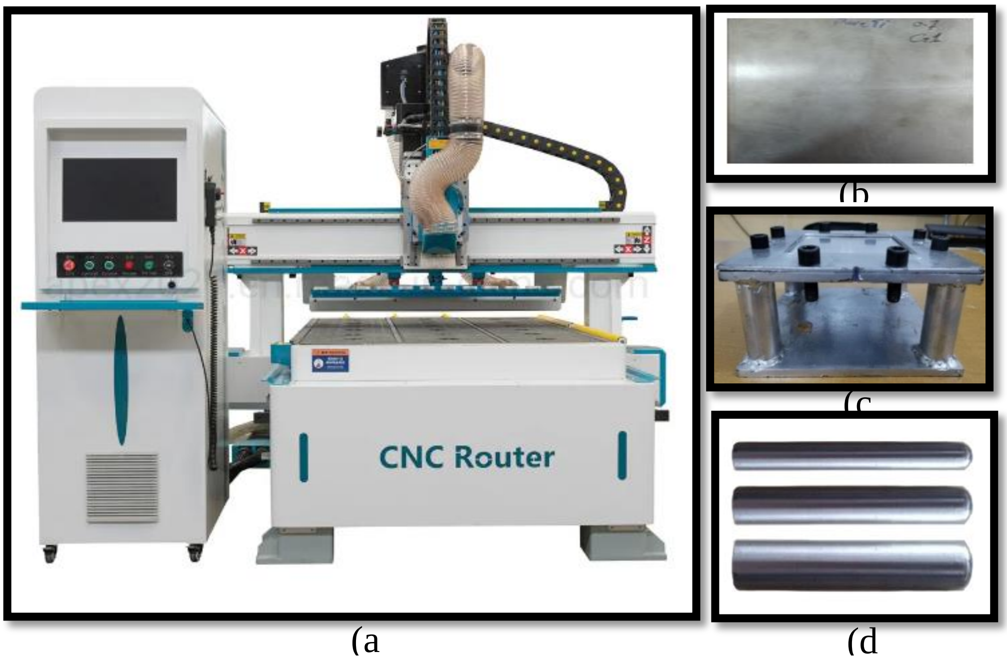


Figure (3): a) CNC milling machine b) Base sheet of pure titanium c) Fixture d) Tools

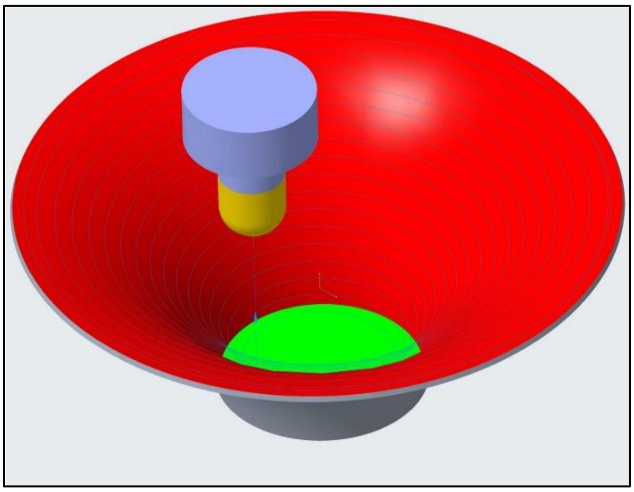


Figure (4): Tool path generation

Discussion

1. Microstructure:

a. Effect of step size on microstructure

The step size in SPIF plays a pivotal role in shaping the microstructure of titanium sheets, with larger step sizes having discernible impacts on the material's characteristics. Microstructure, encompassing grain size, grain orientation, and the distribution of grain boundaries, is a key determinant of a material's mechanical properties, including strength, ductility, and toughness. Understanding how step size influences the microstructure is crucial in optimizing SPIF processes for specific applications.

A larger step size results in more material deformation with each incremental step of the process. This translates into an increased accumulation of strain over shorter distances. Consequently, the greater strain can lead to grain refinement, where grains become smaller and more uniform in distribution. Smaller grains typically enhance the material's mechanical properties. However, the impact of a larger step size extends beyond grain size. The friction generated by larger step sizes can lead to localized heating in the material.

High temperatures during the forming process have the ability to significantly alter the microstructure by influencing the recrystallisation of grains. Additionally, a bigger step size causes the material to experience higher residual stresses. The grain structure and, in turn, the characteristics of the material can be greatly impacted by these residual stresses. To analyze the effects of step size, pictures from four distinct areas of each sample are employed (see Figures 5 and 6 This approach enables the observation of how the microstructure evolves along the wall of the samples as the SPIF process unfolds.

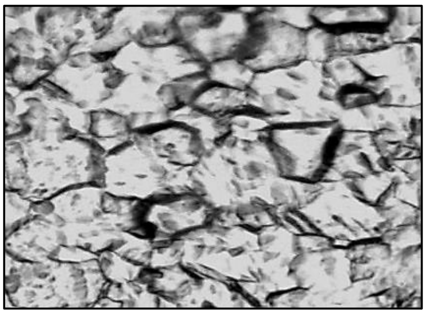


Figure (5): Microstructure of pure titanium

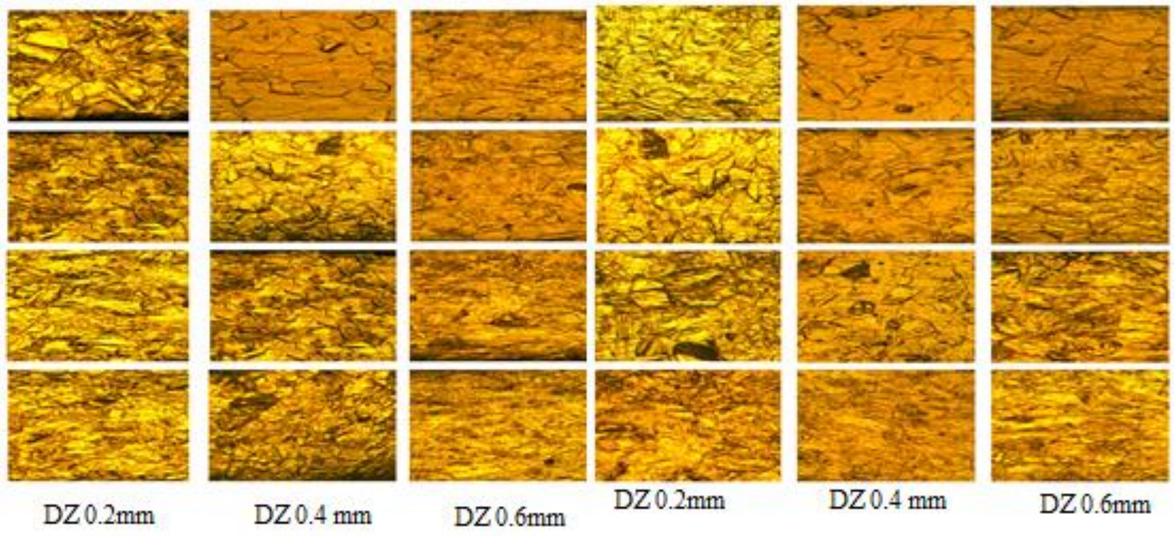
Effect of Tool Diameter on Microstructure

The step size in SPIF significantly influences the microstructure of titanium sheets, affecting grain size, orientation, and boundaries, which determine mechanical properties like toughness, ductility, and strength. Larger step sizes cause greater deformation and strain, leading to grain refinement and improved mechanical properties. However, they also generate friction-induced localized heating, affecting grain recrystallization, and result in higher residual stresses, which impact the grain structure. Microstructure changes are analyzed across four regions of each sample, reveal variations along the sample wall during SPIF. Figure 7 highlights the relationship between tool diameter and grain size in pure titanium.

2. Fracture surface:

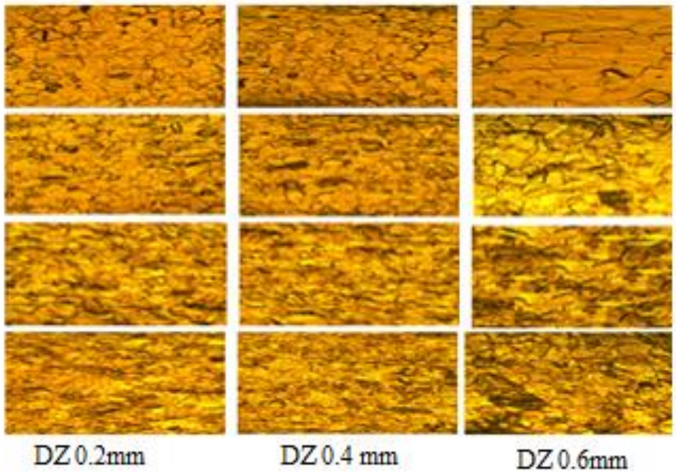
a. Effect of step size on fracture surface:

More dimples on the fracture surface are produced by smaller step sizes (0.2 mm), as shown in Figure (8), suggesting a higher degree of ductile deformation before fracture. Localised shear stress, which encourages ductile fracture properties, is responsible for this behaviour. Although their size and density are different from those seen with the 0.2 mm step size, fracture features in intermediate step sizes (0.4 mm) fall between the extremes of smaller and bigger step sizes. Some dimples are also visible. More brittle fracture behaviour and less plastic deformation are indicated by bigger step sizes (0.6 mm), which, on the other hand, result in fewer or no dimples on the fracture surface. The lack of sufficient plastic deformation at larger step sizes limits the time required for dimple formation, as evidenced in Figure (6).



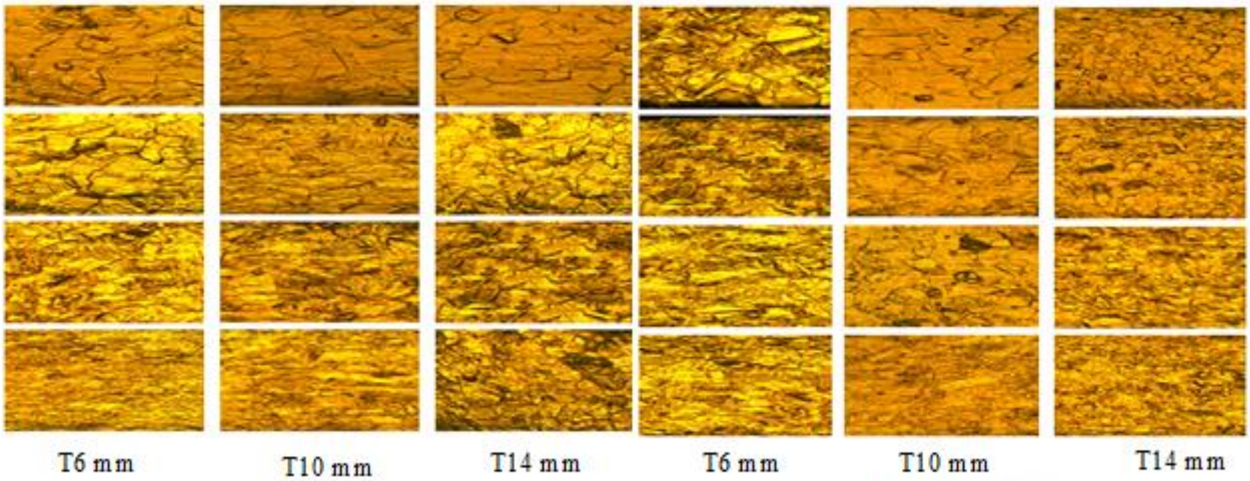
(a) Tool 6mm

(b) Tool 10 mm

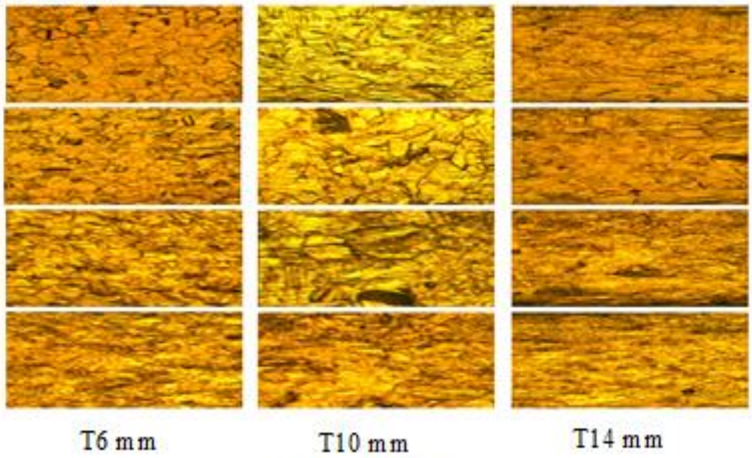


(c) Tool 14 mm

Figure (6): Effect of step size on microstructure of commercially pure titanium

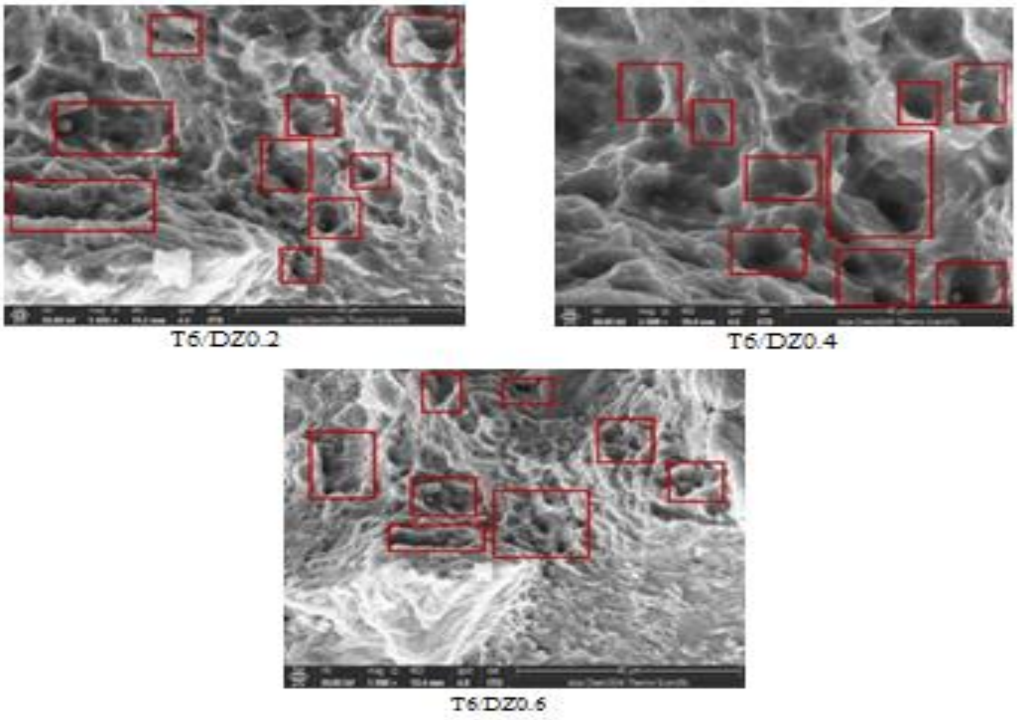


(a) DZ 0.2mm (b) DZ 0.4mm

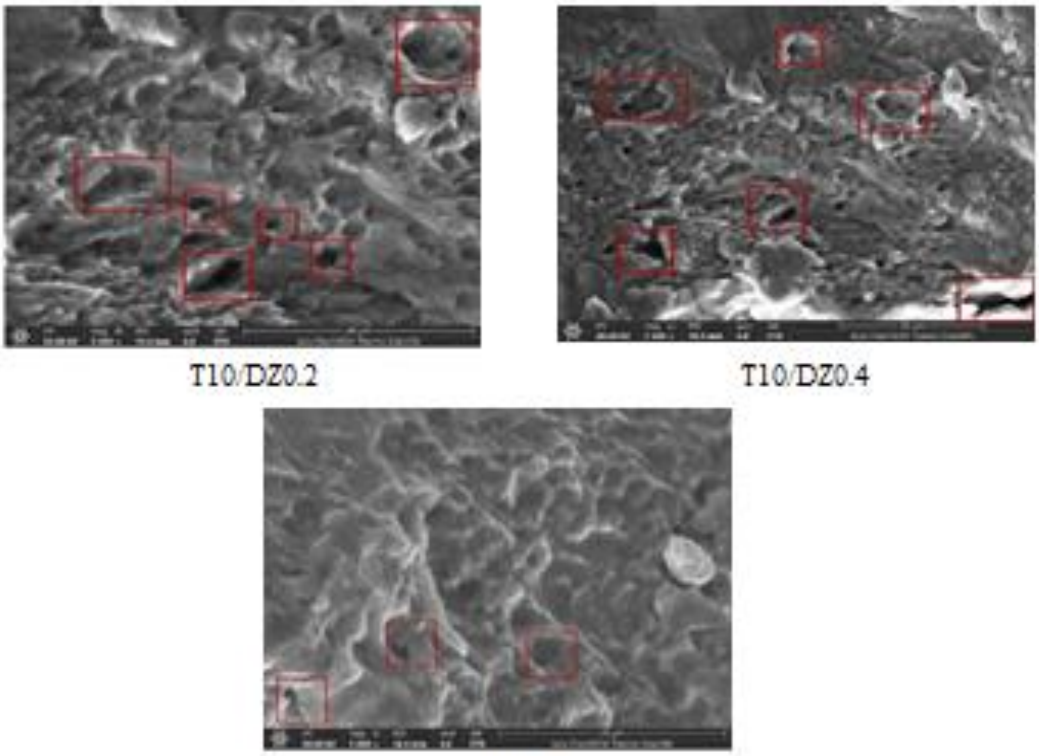


(c) DZ 0.6mm

Figure (7): Effect of tool diameter on microstructure of commercially pure titanium



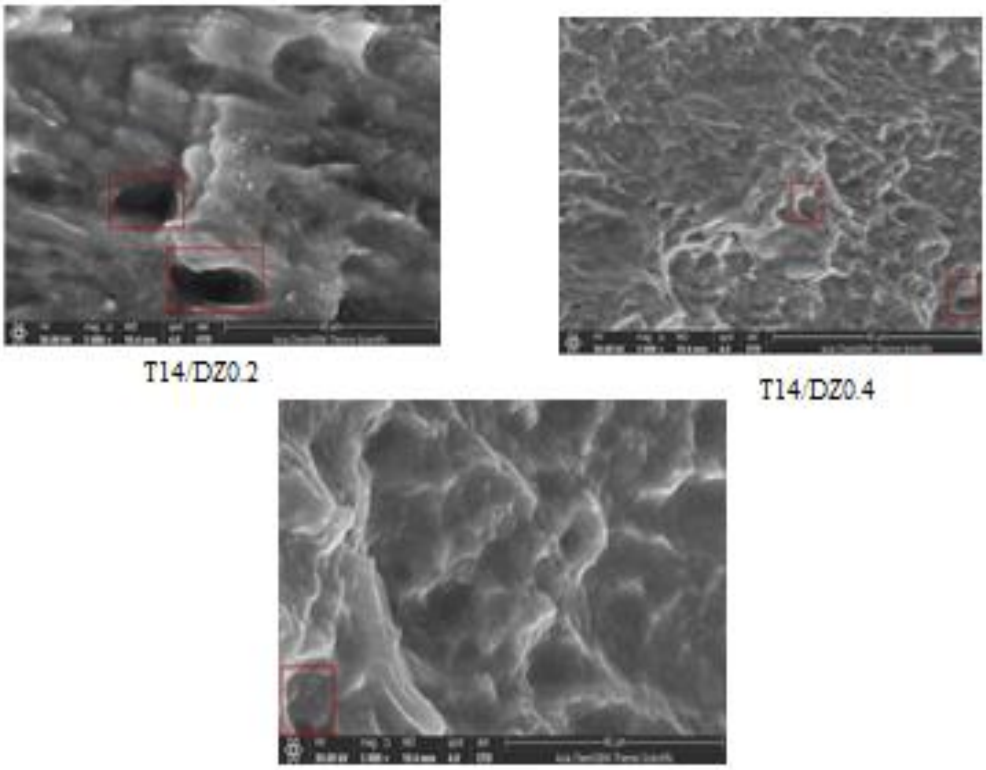
(a)Tool 6 mm



T10/DZ0.2 T10/DZ0.4

T10/DZ0.6

(b) Tool 10



T14/DZ0.2 T14/DZ0.4

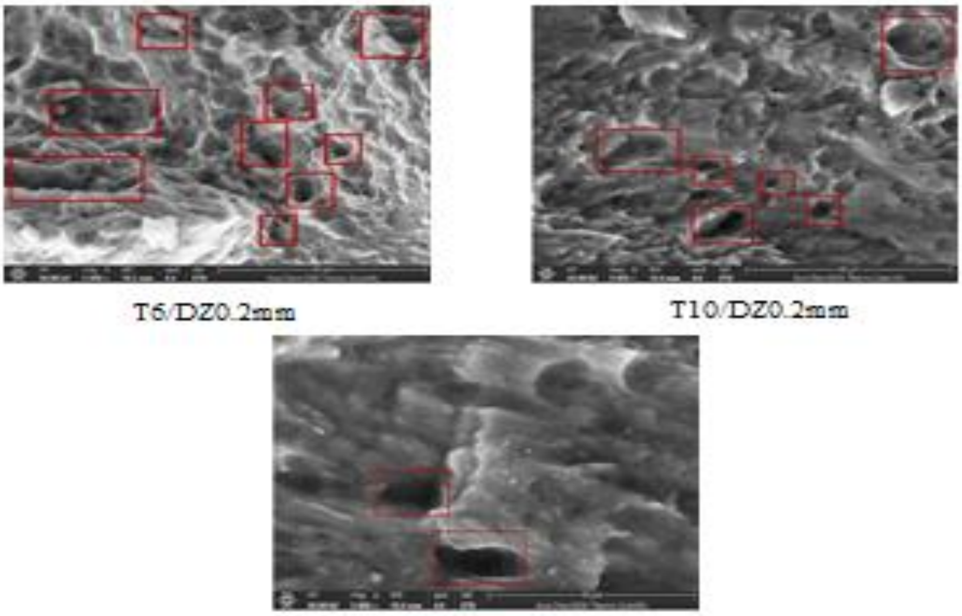
T14/DZ0.6

(c) Tool 14 mm

Figure (8): SEM images showing the effect of tool diameter on fracture morphology: (a,b,c)

b. Effect of tool diameter on fracture surface:

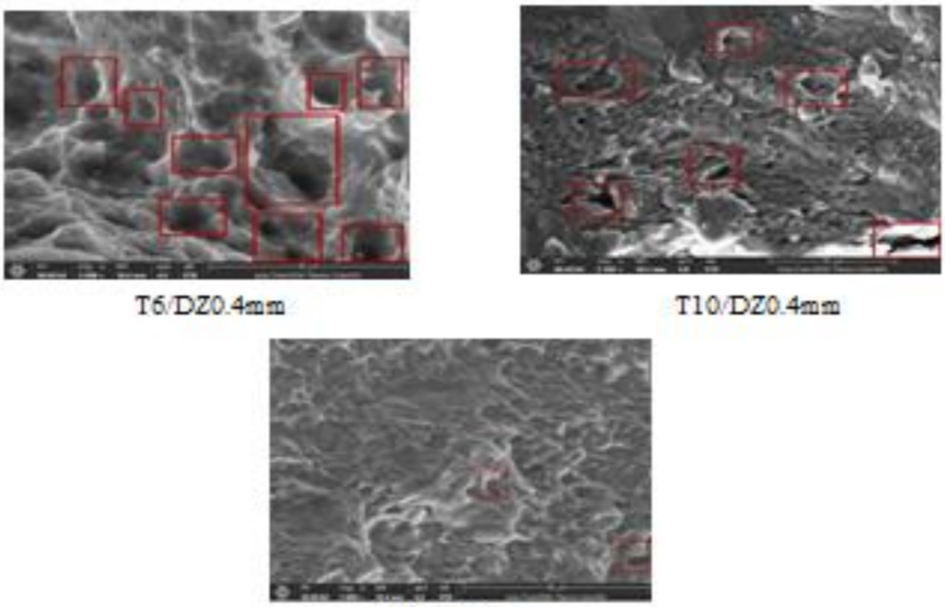
Figure (9) illustrates that smaller tool diameters (6 mm) lead to more dimples on the fracture surface, indicating a greater degree of ductile deformation before fracture. This is associated with localized shear stress that promotes ductile fracture behavior. For intermediate tool diameters (10 mm), the characteristics lie somewhere between the extremes of the smaller and larger tool diameters. It represents a transition zone where some dimples are present, but their size and density might be different from those observed with the 6 mm tool diameter. Larger tool diameters (14 mm) result in fewer or no dimples, suggesting reduced plastic deformation and a more brittle fracture behavior. With less plastic deformation, there may be insufficient time for the development of dimples.



T6/DZ0.2mm T10/DZ0.2mm

T14/DZ0.2mm

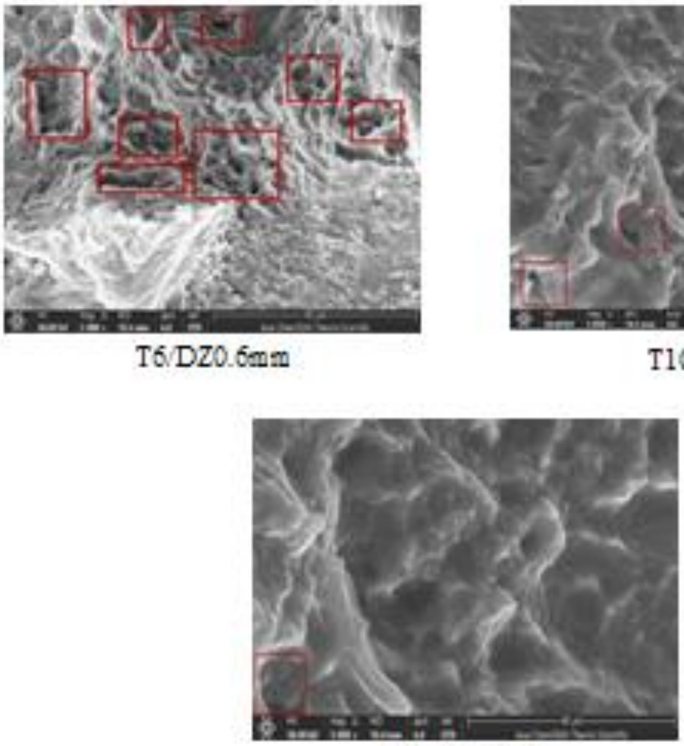
(b) Step size 0.4 mm



T6/DZ0.4mm T10/DZ0.4mm

T14/DZ0.4mm

(b) Step size 0.4 mm



T6/DZ0.6mm

T10/DZ0.6mm

T14/DZ0.6mm

(c) Step size 0.6 mm

Figure (9): SEM images showing the effect of step size on fracture morphology: (a,b,c)

Conclusions

This work investigates how the microstructure of commercially pure titanium formed progressively using Single Point Incremental Forming (SPIF) is affected by both step size and tool diameter. The findings show that differences in tool diameter and step size have distinct impacts on fracture behaviour and grain distribution.

1. Effect of Step Size on Microstructure: The findings demonstrated that increasing the step size promotes grain refining by causing more strain accumulation over shorter distances. Nevertheless, this procedure may also result in increased residual stresses, which could impact the structure's mechanical stability and grain distribution. Grain recrystallisation is facilitated by the localized heating brought on by increased friction with larger steps, which enhances material characteristics but may also result in unanticipated changes in particular sample locations.
2. Effect of Tool Diameter on Microstructure: The study demonstrates that greater friction caused by bigger tool diameters promotes localised heating and grain recrystallisation. This may, however, also result in higher residual stresses, which could affect the material's stability over time. On the other hand, smaller tools result in more uniform grain distributions and fewer localised heating effects, which enhance mechanical characteristics.

- Behavior of Fractures: Smaller steps (0.2 mm) result in more dimples on the fracture surface, suggesting greater ductile deformation prior to fracture, according to an analysis of the impact of step size and tool diameter on fracture behavior. Conversely, larger steps (0.6 mm) cause less plastic deformation and more brittle fractures.

While larger tool sizes exhibit more brittle fracture characteristics, smaller tool diameters produce more ductile fracture features.

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