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Experimental Investigation of the Micro-Milling of Additively Manufactured Titanium Alloys: Selective Laser Melting and Wrought Ti6Al4V

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Abstract

In recent years, additive manufacturing (AM) has gained popularity in the aerospace, automobile, and medical industries due to its ability to produce complex profiles with minimal tolerances. Micro-milling is recommended for machining AM-based parts to improve surface quality and form accuracy. Therefore, the machinability of a titanium alloy (Ti6Al4V) manufactured using selective laser melting (SLM) is explored and compared to that of wrought Ti6Al4V in micro-milling. The experimental results reveal the surface topology, chip morphology, burr formation, and tool wear characteristics of both samples. The micro-milling of AM-based Ti6Al4V generates a surface roughness of 19.2 nm, which is 13.9% lower than that of wrought workpieces, and this component exhibits less tool wear. SLM-based Ti6Al4V produces continuous chips, while wrought Ti6Al4V yields relatively short chips. Additionally, SLM-fabricated Ti6Al4V exhibits smaller burrs after micro-milling than wrought Ti6Al4V. Despite the higher hardness of SLM-based Ti6Al4V, it demonstrates better machinability than wrought Ti6Al4V, resulting in better surface quality with lower tool wear levels and shorter burr heights. This study provides valuable insights into future research on postprocessing AM-based titanium parts, especially using micro-milling.

Keywords Micro-milling, Additive manufacturing, Titanium alloys, Surface morphologies, Chip morphology

1 Introduction

Titanium grade 5 (Ti6Al4V) is an alloy with excellent properties, including a high strength-to-weight ratio, good durability, excellent corrosion and erosion resistance, and a low elastic modulus. Moreover, this alloy is

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³ School of Fashion and Textile, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China nonreactive and ductile [1-6]. All of the abovementioned characteristics make this alloy superior to nickel-based alloys for critical applications; thus, it has been used for decades [7, 8]. The nonmagnetic nature, corrosion resistance, and other mentioned properties of Ti6Al4V have attracted attention in regard to application in the fields of health care and medicine in recent years [9]. This alloy has a wide range of potential applications, including medical endoscopes, dental optical instruments, and peep inspection mirrors [1, 2, 7, 10]. Furthermore, astronomical instruments, whether used on the ground or in space, require optical mirror surfaces. Due to weight constraints, these mirrors should have low mass-tostrength ratios. Titanium alloys are good materials with these qualities [11]. However, traditional methods for manufacturing titanium alloy parts often have significant



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challenges, including complex processing procedures, poor forming effects, high processing costs, and substantial material waste yields. These issues can hinder efficiency and increase the overall cost of production, making titanium alloys less economically viable than other materials [12–14].

Additive manufacturing (AM), often referred to as 3D printing, has attracted significant attention because of its efficiency, adaptability, cost-effectiveness, and environmental sustainability. In this process, a laser beam is utilized to melt metallic powder, which solidifies according to a design outline obtained from a computer-aided design (CAD) model [15, 16]. AM obviates the need for dies and specialized tooling; thus, it can be implemented to fabricate intricate geometries without additional equipment. This technique results in shorter production times and less material waste than traditional manufacturing methods [17–20]. Current AM technology can produce thin walls and features at the 0.2-mm level [21].

Because of its numerous advantages, selective laser melting (SLM) is the preferred method for fabricating Ti6Al4V components. These advantages include rapid production, diverse material options, direct CAD production, intricate geometry adaptability, and internal structure formation. Furthermore, the rapid cooling and solidification inherent in SLM not only refines microstructures but also induces the formation of a martensitic α phase, significantly improving various mechanical properties, such as mechanical strength, hardness, and corrosion resistance [22]. However, precision and surface roughness are characteristics that need further optimization [22-24]. The roughness values of SLM metal parts range from approximately 5 μ m to 10 μ m, even after process optimization [25]; therefore, post-machining is necessary for AM-based components [23, 26]. Micromilling, which is a type of precision machining process and is a promising technology for fabricating products with high precision, can address these shortcomings [22, 26]. Micro-milling can be used to generate precise details on parts and improve surface characteristics [22, 27]. This technology removes a small amount of material, leading to high geometrical precision and low surface roughness [27].

Despite the numerous benefits and potential applications of Ti6Al4V, its low heat conduction, strain hardening, high strength at elevated temperatures, and high chemical activity make machining of titanium alloys extremely difficult [28–31]. Furthermore, the machining AM-based metallic parts presents unique challenges not experienced by wrought alloys. The dynamics of the powder bed, molten pool, and laser beam components during AM complicate the understanding of the underlying thermophysical and metallurgical phenomena [32, 33]. Micromachining exacerbates these issues due to increased sensitivity to changes in the AM process parameters and cooling rates, which impact the delicate microstructure. Furthermore, micromachining encounters issues regarding size effects, machine tool vibrations, and tool–workpiece interactions. Size effects are caused by a variety of factors, such as workpiece and microstructural characteristics, process variables, and tool geometries. Chip formation in micromachining alters process behavior as well [32, 34].

AM-based titanium alloys currently face several challenges associated with precision machining, limiting their applicability [11, 35, 36]. Numerous researchers have investigated the micro-milling performance characteristics of selective laser melting (SLM) and wrought Ti6Al4V by utilizing various experimental methodologies. The results have shown that the machining of titanium alloy specimens prepared by selective laser melting using micro-milling techniques can be highly accurate. Airao et al. [23] conducted a comparative analysis that focused on tool wear and surface characteristics. The investigation revealed that wrought Ti6Al4V, characterized by equiaxed grains, exhibits a ductile nature, resulting in adhesive tool wear, built-up edge (BUE) formation, and a suboptimal surface topography. Conversely, SLM-based Ti6Al4V, featuring a lamellar microstructure with a relatively high hardness, demonstrates reduced levels of adhesive tool wear and BUE formation; however, it shows increased levels of tool abrasion and surface roughness. Le Coz et al. [37] examined the micro-machinability of Ti6Al4V produced through casting and SLM utilizing a TiAlN-coated tool. The scholars observed greater cutting feed forces in SLMbased Ti6Al4V than in cast Ti6Al4V, despite both materials exhibiting similar chip morphologies and subsurface microstructures. In a study conducted by Campos et al. [22], the researchers examined the effects of micro-milling on both conventional and SLM-based Ti6Al4V. They found that SLM-based Ti6Al4V exhibits a lower cutting force and burr formation level than conventional Ti6Al4V, which is attributed to its unique microstructure. During their research, the scholars analyzed the milling quality of SLM-fabricated and cast titanium alloys. Their findings revealed that the surface finish qualities of the samples are influenced by both tool wear and milling feed. Overall, the SLM samples display relatively smooth surfaces, highlighting the benefits of their microstructures. Shi et al. [38] developed a reliable model for analyzing the milling force of SLM-based Ti6Al4V based on extensive experiments, providing a theoretical framework for predicting tool loads. Similarly, Karakılınç et al. [39] conducted micro-milling experiments on both SLM-based and wrought Ti6Al4V, revealing that despite their higher strength and hardness, SLM-fabricated Ti6Al4V exhibits lower cutting forces than

Element		Ti	AI	V	Fe	с	0	N	Н
Percentage Composition	Wrought	Balance	6.28	4.05	0.18	0.032	0.159	0.006	0.0021
	AM	Balance	6.01	4.08	0.042	0.006	0.097	0.005	0.003

Table 1 Compositions of wrought and Ti6Al4V alloys fabricated by AM

wrought Ti6Al4V. In a related study, Zhu et al. [19] developed a comprehensive model for simulating the directed energy deposition process. This model offers valuable insights into optimizing subsequent subtractive manufacturing processes, thereby maximizing the benefits of both additive manufacturing and micro-milling. These studies highlight the exciting possibilities of combining AM with micro-milling to achieve exceptional results.

The demand for titanium parts in the precision industry is increasing, but there are still numerous difficulties associated with producing precision parts using both additive manufacturing and machining processes [22-24, 27]. The main goal of current research is to address these challenges and improve the manufacturing of Ti6Al4V for precision applications. In this study, an integrated micro-milling and AM method is proposed that combines the benefits of both strategies to overcome their limitations. Micro-milling is used as a post process after SLM to improve the surface characteristics and dimensional tolerances associated with additive manufacturing. Furthermore, this approach will increase machining flexibility while addressing the issue of extensive tool wear in micromanufacturing. This research is focused on micro-milling AM-fabricated Ti6Al4V with cubic boron nitride (CBN) micromillers. The results are compared to those of commercially available wrought Ti6Al4V in terms of surface roughness, tool wear, burr formation, and chip morphology. The results validate the concept of combining two advanced machining methods. Compared to that of common wrought Ti6Al4V, the machining performance of the AM-based component is noticeably improved, resulting in a better surface and lower tool wear.

2 Material Preparation and Experimental Setup

To assess the ease of machining of titanium grade 5 (Ti6Al4V) via additive manufacturing, two types of samples were used: 3D-printed specimens created using selective laser melting (SLM) and commercially available wrought titanium alloys. Comparative experimental tests were then carried out. A wrought titanium alloy specimen was selected for the control group due to the casting process for titanium alloys being well-established and the widespread use of wrought titanium alloy specimens in comparative analyses by researchers. Each specimen had dimensions of 25 mm \times 25 mm \times 25 mm. The chemical compositions of both materials are listed in Table 1. The

powder particle sizes used to generate the SLM-fabricated specimens were 15–53 μ m. Other manufacturing process parameters included a laser power of 340 W, a scanning speed of 1250 mm/min, a hatch spacing of 0.3 mm, and a layer thickness of 60 μ m. The prepared part was subjected to post heat treatment, i.e., vacuum annealing at 800 °C for 3 hours in an inert argon atmosphere to eliminate residual stresses, ensuring that it did not influence the machining results [22, 40].

A five-axis high-precision machine, Toshiba UVM-450C(V2), was used to conduct the experiments. The resolution of the machine was 0.01 µm along the X, Y and Z axes. To investigate the machinability of SLM-based Ti6Al4V, multiple microgrooves with a length of 10 mm and a width equal to the tool diameter were machined. The cutting parameters along their lengths are given in Table 2. Two fluted CBN microflat end mill cutters were used. These milling tools each had a cutting diameter of $600 \ \mu\text{m}$ and a cutting length of 1.5 mm. The cross section of the tool was observed under SEM (Hitachi -TM3000) at different magnifications, and the images are shown in Figure 1 for reference. To maintain the same experimental conditions, a new tool was utilized for each sample. Before the experiments, the surface of the workpiece was plane milled using two 2-mm-diameter fluted end mill cutters for standardization. These cutters helped to produce a precise depth of cut for the experiments and remove the oxide layer. Klubercut CO (6-102), a biodegradable vegetable oil, was utilized as a lubricant. An X-ray diffractometer (Rigaku SmartLab) equipped with a 9-kW rotating anode X-ray source ($\lambda \sim 1.54$ Å) was used for XRD analysis (phase identification). Each groove was observed under an optical profiling system (Zygo NexviewTM) to measure surface roughness and generate surface topography, whereas a Hitachi tabletop microscope (TM3000) was used to examine the tool edge, machined surface, and chip geometry. A noncontact measurement method using an optical profiling system was adopted to

Table 2 Machir	ig parameters	of micro	o-milling
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Cutting parameters	Values			
Spindle speed (r/min)	60 K, 65 K, 70 K, 75 K			
Depth of cut (µm)	10, 15, 20, 25			
Feed rate (µm/flute)	1, 2, 3, 4			



Figure 1 Experimental setup and milling paths

study the surface roughness of each groove. Five readings were taken for each groove, and the average is reported here. Approximate measurements were taken along the centerline of each groove. Figure 1 shows the machining setup, cutting sequence, and tool geometry.

3 Results and Discussion

3.1 Surface Morphologies and Material Properties of The Specimens

As mentioned previously, two specimens manufactured using different manufacturing methods—an SLM-based alloy and a wrought alloy—are used in this study. The surface morphologies, X-ray diffraction (XRD) patterns and -structures of both types of specimens as-received before processing are shown in Figure 2. Crystal impact match software is used for phase detection. This software is instrumental in identifying and analyzing the crystallographic phases present in samples. For the surface morphology, a wavy pattern featuring dimples and bumps of varying sizes can be observed for the SLMbased part, differing from the linear pattern with spikes that is observed for the wrought specimen. This phenomenon is attributed to differences in the manufacturing technique and posttreatment, i.e., heat treatment for the SLM-based part and machining removal for the wrought part.

The XRD results show that only the α -phase is prominent in the SLM-fabricated Ti6Al4V, whereas the α +



Figure 2 Surface morphologies of a SLM-based Ti6Al4V and b wrought Ti6Al4V, XRD patterns of c SLM-based Ti6Al4V and d wrought Ti6Al4V, microstructures of e SLM-based Ti6Al4V and f wrought Ti6Al4V

 β -phase structure is prominent in wrought Ti6Al4V. A high cooling rate during SLM results in the development of the martensitic α' phase during solidification; thus, both α' and α are present. Since α' + and α have similar crystalline structures, i.e., hexagonal close packed (HCP) and similar lattice parameters, XRD cannot distinguish them [32, 37]. According to a comparison of the proportions of the β phase and α phase in wrought Ti6Al4V, the quantity of the β phase is negligible. Therefore, compared with that of wrought Ti6Al4V, the crystalline structure of SLM-based Ti6Al4V is relatively uniform with $\alpha' + \alpha$ phases and traces of β phase (bodycentered cubic (BCC)). These findings are consistent with previous research. The crystalline structure has a direct impact on the mechanical properties of materials. The tensile strength, microhardness, and yield strength values of the two types of specimens differ slightly. The investigation of the microstructure involves sectioning the workpiece using wire electro discharge machining, followed by its preparation through polishing and etching with Kroll's reagent (HF + HNO₃ + H_2O) for subsequent microscopic examination. The obtained microstructure, depicted in Figure 2, reveals distinct characteristics. In wrought Ti6Al4V, the microstructure exhibits both α and β phases. A notable feature of SLM-based Ti6Al4V is its fine needle-like microstructure, which is attributed to the rapid cooling rates inherent in the SLM process. The microhardness of each specimen is measured using

a universal microhardness tester with a 1-kgf load and a 10-second dwell time. The microhardness values of the SLM-based Ti6Al4V and wrought Ti6Al4V alloys are 370 HV and 325 HV, respectively. Carroll and Palmer [35] stated that the mechanical properties and microhardness are directly related; specifically, the ultimate tensile strength and yield strength of SLM-based Ti6Al4V are greater than those of wrought Ti6Al4V. The comparatively high hardness of the SLM-fabricated Ti6Al4V alloy is attributed to its fine $\alpha' + \alpha$ phase structure. The high strength and hardness values of the SLM-based specimens indicate that the AM-based components are resistant to plastic deformation [37, 41].

3.2 Tool Wear

This part of the study is related to an in-depth evaluation of the impacts of fabrication methods, i.e., SLM and hammering, on tool wear. Figure 3 shows the SEM images of the milling tools after the micro-end milling of SLM and wrought Ti6Al4V. Prior to the experiment, the cutting edge of each cutter is smooth and sharp, as shown in Figure 1. However, after machining of slots, the cutting tool is subjected to mechanical and thermal loading, which causes wear. The SEM images show that tool wear is concentrated around the cutting edge in each image. The results show that there is no catastrophic tool failure during the experiments on either specimen, although tool wear is visible at the end of each set of grooves. The



Figure 3 Cutting tool processed on SLMTi6Al4V: a left flute, b cross section, and c right flute. Cutting tool processed on wrought Ti6Al4V: d left flute, e cross section, and f right flute

extent of tool wear is not very severe for the SLM-fabricated specimen, but for the wrought specimen, tool wear is greater. These results are supported by the surface generated in each groove. As a result, CBN milling tools have good machining performance for titanium alloys, especially SLM-based Ti6Al4V, in terms of tool wear and surface quality in micro-end milling.

For wrought Ti6Al4V, chipping off from the cutting edge can be observed, and the tool edge loses its sharpness and shape. Tool wear is related to the material hardness and properties. Figure 3(a) and (c) shows minor wear and abrasion at the cutting edges of the tools for the AMbased parts, differing from the wear shown by the tool in Figure 3(d) and (f) used for micro-milling of wrought Ti6Al4V. The difference in the microstructures of the two workpieces can be attributed to differences in the mechanical properties of the two workpieces. The tool for the AM-based part should experience additional wear because the workpiece has relatively great strength and hardness, but the results are contradictory. According to the XRD analysis shown in Figure 2(c), the SLM-fabricated specimen has a more uniform crystalline structure, i.e., $\alpha' + \alpha$ HCP, than the $\alpha + \beta$ of wrought Ti6Al4V, which improves the machinability of the material by reducing plastic during cutting due to its reduced ductility.

Furthermore, some welded micro fragments on the cross-sectional area of each tool can be seen. SLM-based Ti6AL4V (Figure 3(b)) shows the presence of only a few attached segments, whereas wrought Ti6Al4V (Figure 3(e)) has many more attached segments, which can affect the machined surface quality and tool life at later stages. These abrasive particles can scratch the groove surface. These are potentially hazardous enough to break the tool tip. A high temperature during cutting makes a small fraction of β -grains unstable, resulting in soft wrought Ti6Al4V and increased material adhesion on the cross section [23]. When this material is removed from the tool surface, chipping can occur, which is especially noticeable in this case, as shown in Figure 3(d). SLM-based Ti6Al4V is harder and has a lower capacity for material adhesion. This metal resists material adhesion on the surface and shows no chipping on the cutting edge.

3.3 Surface Roughness

Surface roughness is a very important parameter for assessing product quality during the micro-milling process. For precision applications, the product must have a very fine surface roughness, typically measured in nanometers. The surface roughness depends on the machining parameters, specimen material, tool material, tool geometry, lubricating conditions and machining vibrations [42, 43]. Figure 4 shows the average surface roughness obtained in each experiment. The results for SLM-manufactured Ti6Al4V are superior to those for wrought Ti6Al4V. For SLM-based Ti6Al4V and wrought Ti6Al4V, the minimum surface roughness obtained are 19.21 nm and 22.31 nm, respectively. SLM-fabricated Ti6Al4V has a 13.9% lower surface roughness than wrought Ti6Al4V. Throughout the experiments, the surface roughness of the SLM-based Ti6Al4V alloy less than that of the wrought Ti6Al4V alloy. A highly important parameter governing the surface roughness of a micro-milled surface is the condition of the cutting tool edge. Tool wear is not very noticeable in the tools implemented for SLM, as shown in the previous section.

Compared to wrought Ti6Al4V, the lower plastic deformation of SLM-fabricated Ti6Al4V is a result of its higher hardness and lower ductility, and it may be one reason for its excellent surface quality. [44]. The material can deform while being machined in a plane parallel to the cutting edge. During deformation, this lateral plastic flow increases the peak-to-valley height of the machined surface profile. This peak-to-valley height is greater for soft materials and lower for hard materials [45]. As a result of the high hardness of SLM-manufactured Ti-6Al-4V, the lateral plastic flow is reduced, enhancing the surface finish. The lower plasticity of SLM-based Ti6AL4V reduces plastic deformation during micro-end milling and reduces surface roughness during cutting [44].

3.4 Chip Morphology

In micro-milling, chip formation is critical; that is, the dimensions of the chip and the depth of the cut are similar to those of the cutting-tool edge and corner radius (re). A tool edge radius smaller than the chip thickness



Figure 4 Surface roughness of the machined grooves during each experiment

results in the absence of chip formation. This phenomenon is termed the size effect in micro cutting processes. The minimum chip thickness is defined as the ratio of feed per tooth to the cutting-tool edge radius, below which no chips form [46, 47]. During milling, as the tool rotates, it encounters a continuously varying chip thickness. Chip formation during micro-milling is described in Figure 5. Plowing occurs when the undeformed chip thickness falls below the minimum required thickness. Plowing negatively impacts surface quality and contributes to burr formation. Based on the uncut chip thickness (*h*) relative to the minimum chip thickness (h_c) , which is determined by various factors, micro-milling can be classified into three scenarios (Figure 5). When $h < h_c$, only plastic-elastic deformation occurs, which worsens the plowing and tool wear. Chip formation begins at h $= h_c$, while at $h \approx h_c$, a mix of plastic–elastic and shear deformation occurs. When h exceeds h_{tar} , the workpiece material is chipped, and the elastic recovery becomes negligible [48, 49]. Hence, determining the minimum chip thickness is crucial before micro-milling the cutting tool and the workpiece.

In micromachining, the morphologies and geometries of chips are dependent on the cutting mechanism, such that when the uncut chip thickness is less than the critical cutting depth, plowing is dominant, and vice versa [32]. The characteristics of chips produced during micromachining depend on several factors, including the workpiece material, tool geometry, cutting speed, cutting depth and lubrication conditions [32, 50]. In this study, SEM is used to examine the chips produced by the microend milling of SLM-based Ti alloys and wrought Ti alloys. Figure 6 shows the chip morphologies of SLM-manufactured Ti6Al4V and wrought Ti6Al4V. The chips have two distinct sides: the free surface (Figure 6(d) and (h)), which usually has a segmented surface, and the contact surface (Figure 6(c) and (g)). As the chip slides over the rack face of the cutting tool, the contact surface becomes relatively smooth and shiny, and the high levels of friction, temperature, and contact pressure soften this side, further smoothing the surface [50].

Figure 6(b)-(d) shows the characteristics of the chips under high magnification. Because of the very fine and uniform $\alpha' + \alpha$ hexagonal close packed (HCP) crystalline structure, the micro-milling of Ti6AL4V by SLM produces chips that are continuous, uniform, and identical. On the chip contact surface, microparticles are welded. The temperature increases during micro-end milling due to frictional heat and stresses, which cause the microparticles to adhere to the surfaces of the chips [32]. On the sides of the chips, continuous ridges are clearly visible due to the high cutting force and intense plastic deformation caused by the high temperature and pressure. The free surface of a chip exhibits a pattern of scales called



Figure 5 Illustration of chip formation during micro-milling



Figure 6 Chip morphologies of SLM-based Ti6Al4V: **a** Long continuous chips, **b** Magnified chip surface, **c** contact surface of chips, and **d** Free surface; chip morphologies of wrought Ti6Al4V, **e** Short, welded chips, **f** Magnified chip surface, **g** Contact surface, and **h** Free surface

lamella. During micro-end milling, high temperature increases ductility and decreases hardness; consequently, high plastic strain causes segments of both types of materials to slide over one another [32, 51, 52].

The right sides of Figure 6(e)-(h) show the chip morphology of wrought Ti6Al4V. The chips are considerably larger in size and have serrated patterns, differing from the chips of SLM-fabricated Ti6Al4V. This phenomenon usually occurs in materials with poor thermal conductivity whose mechanical strengths decrease as the temperature increases. This material property is referred to as thermal softening [32]. The strain produced during machining is not uniform, resulting in regions of high and low shear strains where tearing occurs [53]. This nonuniform strain may be caused by the α + β crystalline structure [54]. On the surfaces of the chips, fine lamella with narrow patterns can be observed, differing from the chip structures produced for the SLM-based sample. Different mechanical properties and microstructures are responsible for this variation in the serration spacing. Specimens with greater ductility and more uniform microstructures undergo greater plastic deformation at elevated temperatures, resulting in a greater distance between serrations [32]. Regardless of the machining parameters, all the chips collected during machining exhibit nearly identical formation characteristics. Short chips are produced for wrought Ti6Al4V, and materials with high hardnesses decrease the plasticity during micro-milling and result in reduced lateral plastic flow, creating discontinuous chips [32]. Some chips are relatively long but have the same shape. Other chips appear to be welded together. A nonuniform strain distribution causes cracking and tearing in the chips. As a result, chip morphology is critical. A minor variation in chip formation can cause variations in tool wear, surface quality, and accuracy. There is more tool wear when milling produces chips that are wider and more discontinuous than in other cases. In the present study, the long continuous chips of SLM-based Ti alloys produce less tool wear and a better surface than the wide and short chips of wrought Ti6Al4V.

3.5 Burr Formation

Burr formation during micro-end milling is another critical issue because it has a direct impact on product efficiency. The material used, the machining parameters, and the tool geometry all impact burr size and formation. In micro-milling, the edge radius of the microtool is a critical factor that cannot be ignored. At low cutting depths, there is substantial friction between the chip and the rake face of the tool, resulting in greater tool wear and deformation of the material due to shearing. Hence, it is advisable to ensure that the cutting depth is greater than the minimum chip thickness to address these concerns effectively [55]. The size and formation characteristics of burrs across the milled area are also directly affected by the conditions of the tool. The worn out tool has a weakened cutting edge, which contributes to burr formation [41, 42]. Hence, burr formation is a critical factor in determining product quality, and it is a critical issue. Burr formation can be controlled or minimized through improved machining strategies and material characteristics. Researchers

have suggested various strategies to address this issue. Kou et al. [55] proposed using adhesive as a supporting material to extend the workpiece boundary, allowing burrs to form on the adhesive rather than on the workpiece. Kumar et al. [56] highlighted the significance of burr modeling for reducing and controlling burrs. Furthermore, to reduce and prevent the formation of burrs, it is essential to optimize the cutting parameters, utilize coatings, implement hybrid cooling-lubrication systems, and employ support materials. Figure 7 shows magnified SEM images of groove surfaces machined by micro-end milling. All the images show that burrs are produced on both sides of the grooves. One side is known as the down milling side (cutting and feeding are in the same direction), while the other side is known as the up milling side (cutting is in the direction opposite to feeding) [57, 58]. Furthermore, the images show that the burr height on the down milling side is greater than that on the other side because of the uneven distributions of forces along the sides during cutting [42].

Figure 7 can be utilized to analyze the surface characteristics of grooves in Experiments 1, 5, 9, and 13. In Figure 7(b), the surface exhibits visible tool marks, while other surfaces appear smooth and devoid of tool marks. Compared with wrought Ti6Al4V burrs (Figure 7(a), (c), (e), and (g)), the SLM-based Ti6Al4V burrs (Figure 7(b), (d), (f), and (h)) are smaller in size. The formation of burrs is influenced by the shear deformation of the material during machining. As the shear deformation increases, wide and thick burrs are generated. Shear deformation and plastic deformation are directly correlated [23, 41]. In contrast to SLM-based Ti6Al4V, wrought Ti6Al4V has a lower hardness. This lower hardness promotes greater plastic deformation of the material, while the Ti6Al4V produced by SLM restricts plastic deformation. Consequently, micro-milling of wrought Ti6Al4V leads to the formation of large burrs, whereas SLM-based Ti6Al4V results in small burrs on its machined surface. Additionally, the sizes and widths of the burrs are directly proportional to the level of tool wear. In our experiments, the tool used for wrought Ti6Al4V exhibits significantly more severe wear than the tool used for SLM-based Ti6Al4V. The burr size increases along the machined surface as cutting-edge wear intensifies.



Figure 7 SEM images of groove surfaces: a Wrought Ti6Al4V in Experiment 1, b SLM-based Ti6Al4V in Experiment 1, c) Wrought Ti6Al4V in Experiment 5, d SLM-based Ti6Al4V in Experiment 5, e Wrought Ti6Al4V in Experiment 9, and f SLM-based Ti6Al4V in Experiment 9, g Wrought Ti6Al4V in Experiment 13, and h SLM-based Ti6Al4V in Experiment 13

Based on these findings, it can be concluded that the formation of burrs is dependent on the manufacturing method of the workpiece, which is influenced by differences in microstructural characteristics, mechanical properties, and cutting tool conditions. Wrought Ti6Al4V produces wide and uniform burrs, whereas SLM-based Ti6Al4V produces narrow and uniform burrs. In addition, burr formation in micro-milling is attributed to unexpected plastic flow of the material on the sides of the milled slots, which are unresisted free surfaces with low support stiffnesses. The presence of unseparated chips connected to the top of the machined slot significantly increases the number of burrs. To minimize the number of burrs on top, optimal machining strategies should be employed.

4 Conclusions

In conclusion, this study demonstrated that, compared with wrought Ti6Al4V, selective laser melted Ti6Al4V exhibited better machinability when subjected to micromilling. The experimental investigation revealed that the SLM-based Ti6Al4V workpiece achieved lower surface roughness, less tool wear, and less burr formation than its wrought counterparts. Despite the higher hardness of the selective laser melted Ti6Al4V alloy, it displayed improved surface quality with minimal tool wear and burr heights. These findings highlighted the potential of micro-milling as a postprocessing technique for enhancing the surface quality and form accuracy of AM-based Ti6Al4V. The highlights of this work were as follows:

- (1) The tool wear during micro-milling of wrought Ti6Al4V was significantly greater than that of SLM-based Ti6Al4V, with wear being concentrated around the cutting edges.
- (2) Compared with wrought Ti6Al4V, selective laser melted Ti6Al4V exhibited better surface roughness, with minimum roughness values of 19.21 nm for SLM-based Ti6Al4V and 22.31 nm for wrought Ti6Al4V. This difference indicated a 13.9% improvement in surface quality for the SLM-based Ti6Al4V.
- (3) Micro-milling of SLM-based Ti6Al4V resulted in more continuous, uniform, and identical chips, while wrought Ti6Al4V produced larger chips with serrated patterns.

In the future, the findings obtained from this research should facilitate the improvement in postprocessing methods for titanium parts produced through AM. Future work should concentrate on optimizing micromilling parameters to improve surface quality and tool life. Furthermore, the use of advanced monitoring systems to reduce the effects of tool vibrations and improve tool-workpiece interactions may result in even better results than the findings herein. The development of specialized cutting tools tailored to the unique properties of AM materials could help to overcome current machining challenges. By continuing to investigate these possibilities, we can broaden the capabilities of micro-milling as a finishing process for AM-based components, ensuring that they meet the stringent requirements of various industries, such as the aerospace, automotive, and medical device fields.

Author Contributions

MR: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing-original draft; TH: Formal analysis, Investigation, AK: Data curation, Formal analysis, Investigation; WY: Conceptualization, Supervision, Writing-review & editing; ST: Funding acquisition, Project administration, Supervision, resources; DT: writing and editing of manuscript. All authors read and approved the final manuscript.

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Data Availability

All data generated or analyzed during this study are included in this published article.

Declarations

Competing Interests

The authors declare no competing financial interests.

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