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Experimental investigation of micro-milling of selective laser melted and wrought titanium alloys

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Abstract

Selective laser melting (SLM) is commonly used for Ti6Al4V parts because it allows for more complex shapes. This study uses micro-milling of SLM Ti6Al4V to investigate surface characteristics, tool wear, and chip morphology. The results of SLM Ti6Al4V are compared with those of wrought Ti6Al4V. SLM titanium alloys achieve surface roughness of 25nm, which is 37.5% lower than wrought Ti6Al4V. However, the tool processed with SLM Ti6Al4V showed higher wear than the tool for micro milling wrought Ti6Al4V. Surface roughness increased in direct proportion to the depth of cut. The chips produced by SLM Ti6Al4V are long and continuous, as opposed to wrought Ti6Al4V, which is discontinuous. This study compared the micro-milling results of SLM Ti6Al4V and wrought Ti6Al4V, demonstrating the influences of micro milling on surface features, tool wear, and chip morphology.

Selective laser melting; Additive machining; Titanium alloys; micro-milling; precision machining

1. Introduction

Selective Laser Melting (SLM) is a cutting-edge technique in the field of Additive Manufacturing (AM), known for its precision and adaptability in producing intricate metallic components with high structural integrity. Machining AM metallic parts presents more formidable challenges than wrought alloys, owing to the intricate dynamics entailed by interactions between the powder bed, molten pool, powder, and laser beam inherent in AM processes [1, 2]. These complexities impede a thorough understanding of the thermophysical and metallurgical phenomena occurring within AM. Subsequent post-processing of metallic AM parts becomes extremely complex, especially in the context of micromachining. Micromachining must contend with factors such as tool-workpiece interactions, machine tool vibrations, and the size effect [3, 4]. The unique characteristics of SLM technology cause the formation of elongated columnar grains oriented in the build-up direction within AMed materials. In addition to the inherent challenges of AM parts, micromachining processes are influenced by the size effect, machine tool vibrations, tool-workpiece interactions, and chip formation, all of which have a significant impact on their behavior [5, 6]. According to the research findings, SLM Ti6Al4V responds differently than conventional Ti6Al4V during micro-machining. There is very little research available comparing SLM Ti6Al4V to wrought Ti6Al4V for micro-milling. The goal of this work is to close this gap. This study examines the micro-milling of SLM Ti6AL4V in terms of surface roughness and topography. Furthermore, tool wear and chip morphology are studied. The results are compared to wrought Ti6Al4V.

2.Methodology

Experiments were conducted on two types of specimens: 3D printed (fabricated using SLM) and wrought titanium alloys. The SLM part was generated using powder particles sized between 15-53µm, with process parameters including a laser power of 340W, scanning speed of 1250mm/min, hatch spacing of .3mm, and layer thickness of 60µm. Experiments were conducted using the high-precision five-axis Toshiba UVM-450C(V2) machine, as shown in Figure 1. This machine has extremely precise movements at increments as fine as 0.01µm along the X, Y, and Z axes. To investigate the machinability of SLM Ti6Al4V, a series of micro-grooves measuring 10 mm in length and matching the tool diameter were machined. Micro-slots were generated at varying depth of cut (20µm ,35µm, 50µm) whereas spindle speed and feed rate are kept constant i.e., 60k rpm and 3µm/flute respectively. The experiments were conducted using two fluted CBN micro-flat end mill cutters with a cutting diameter of 900µm and a length of 1.5mm each. Each sample was treated with a new tool to ensure consistency and precision. Prior to the micro-milling experiments, the workpiece was plane milled with a standard 2mm diameter, two-fluted end mill cutter to ensure precise depth of cut and removal of the oxide layer. Lubrication during experimentation was provided by Klubercut CO (6-102), a biodegradable vegetable oil. Assessment of surface roughness and topography was performed using an optical profiling system (Zygo NexviewTM), while a Hitachi tabletop microscope (TM3000) was utilized for the analysis of tool wear and chip morphology.

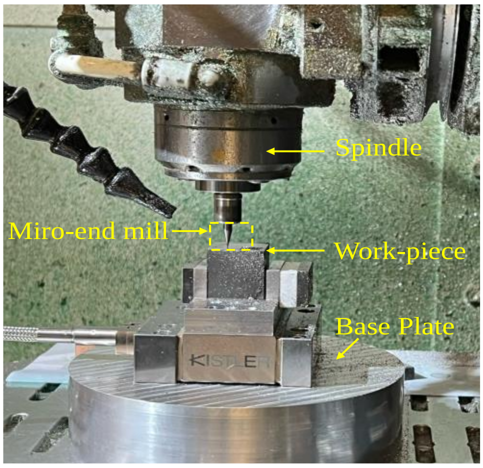

Figure 1. Micro-milling experimental setup

2.Results and Discussions

2.1. Surface Roughness

Exploring surface roughness in the micro-milling of SLM Ti6Al4V provides essential insights crucial for comprehending material behavior and machining effectiveness. The identification and examination of surface roughness are pivotal in evaluating the excellence and accuracy of machined parts [7, 8]. Micro-milling, particularly on intricate materials such as SLM Ti6Al4V, poses distinct challenges influenced by a myriad of parameters. Factors like tool geometry, cutting conditions, material properties, and machining dynamics intricately collaborate to define the ultimate surface finish [9, 10]. Five readings of surface roughness (R_a) were taken along the central line of machined surface, and the average values are shown in figure 2. For each trail, SLM Ti6Al4V has a lower surface roughness than wrought Ti6Al4V. Wrought Ti6Al4V is more ductile; during cutting, the heat generated causes more plastic flow of material than harder SLM Ti6Al4V, resulting in a rougher surface [11]. At a cut depth of 20µm, SLM Ti6Al4V has a 37.5% lower surface roughness than wrought material. As the depth of cut increased, the surface roughness increased. Surface topography is primarily captured from the center of each slot. Figures 3a,b, and c show the surface topography for SLM Ti6Al4V, whereas the peaks in wrought Ti6Al4V are dense and numerous, whereas the surface produced by SLM Ti6Al4V is less dense and far fewer in number. Figures 3c&f show dense marks and more peaks. It can be said that as the depth of cut increased, the surface degraded due to increased heat generation caused by excessive material removal.

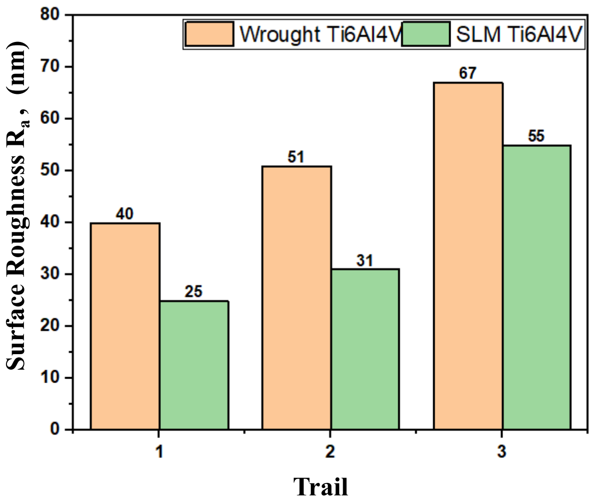

Figure 2. Comparison of surface roughness between SLM Ti6Al4V and Wrought Ti6Al4V

2.2. Tool Wear

The influence of tool wear on the micro-milling process of Ti6Al4V represents a pivotal determinant affecting machining efficiency and surface integrity. This phenomenon emerges as a result of the continuous engagement of the cutting tool with the workpiece, gradually experiencing wear under high loading and unloading machining conditions. The ramifications of tool wear are substantial, notably impacting critical aspects of the machining process, including alterations in cutting forces, chip formation dynamics, and surface quality. As tool wear progresses, discernible changes in tool geometry ensue, leading to notable variations in fundamental cutting parameters, encompassing cutting forces, surface roughness characteristics, and chip morphology [12, 13]. Figure 4 shows the post-machining condition of the tool face. SLM Ti6Al4V shows more wear having adhesive wear and micro chips welded on cross section as compared to wrought Ti6Al4V, showing no prominent adhesive wear, due to a variety of factors. Differential micro-hardness between the materials plays a significant role, with SLM Ti6Al4V having a higher hardness, resulting in increased cutting forces and tool wear. The non-uniform microstructure amplifies the effects of fatigue loading during micro milling, resulting in increased wear. Furthermore, higher ultimate tensile strength and yield influence the tool-workpiece interaction, resulting in plastic deformation. This accelerates plowing force and promotes tool wear in SLM Ti6Al4V when compared to wrought Ti6Al4. Sharma and Meena [11] discovered a strong correlation between work material microstructure and tool degradation during micro-scale machining. Because of its laminar grains, SLM Ti6Al4V has a higher hardness and lower ductility.

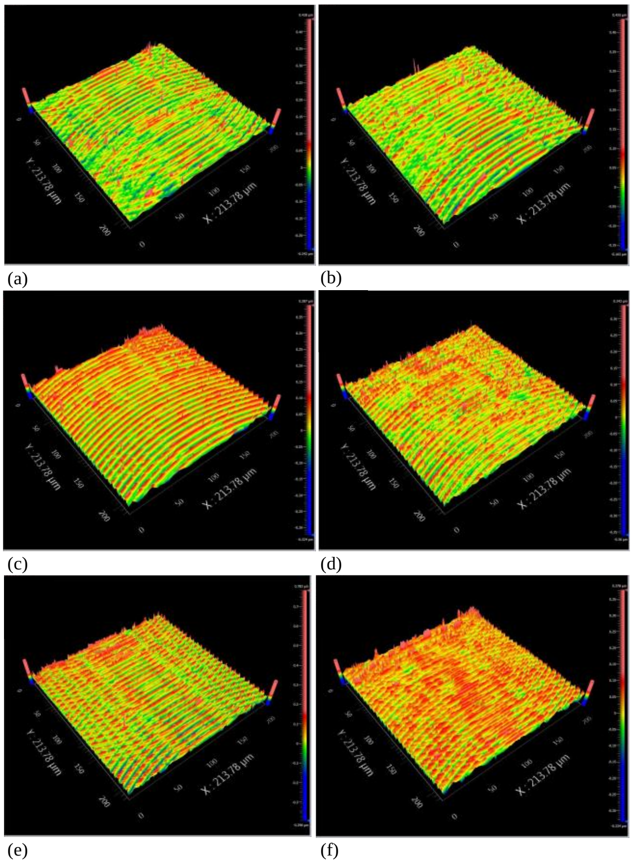

Figure 3. Surface Topography of SLM Ti6Al4V (a)20µm (b) 35µm (c) 50µm; and, wrought Ti6Al4V (d)20µm (e) 35µm (f) 50µm

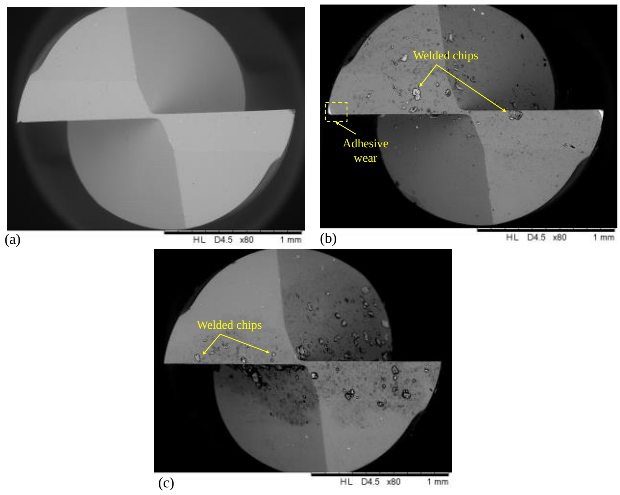

Figure 4. Tool cross section; (a) new tool, (b) tool processed on SLM Ti6Al4V, (c) tool processed on wrought Ti6Al4V

2.3. Chips Morphology

The characteristics of the chips generated during the cutting process serve as the foundation for evaluating micro-machining performance. Chip morphology reflects surface quality, tool wear, and cutting forces. Chip geometry and morphology in micromachining is dependent upon a mechanism involved in the cutting process i.e., when the uncut chip thickness is lower than critical chip thickness, the plowing dominates the shearing and vice versa [14]. Figure 5 compares the chips produced during micro-groove milling of SLM Ti6Al4V and wrought Ti6Al4V at increasing depths of cut. The two materials exhibit distinct differences in chip morphology. The micro-milling process produces spiral-shaped chips in both materials; however, SLM Ti6Al4V chips have a larger radius of curvature than wrought Ti6Al4V chips, which have a smaller radius. Furthermore, the chips from SLM Ti6Al4V (Figure 5a, b, c) appear longer and continuous, whereas those from wrought Ti6Al4V (Figure 5d, e, f) appear shorter and discontinuous. The observed figures show two distinct sides of the chips: the contact side, which is relatively flat and slides over the tool edge, and the free side, which has a scaly lamella structure. This morphological difference can be attributed to material properties, specifically the brittleness of wrought Ti6Al4V versus the greater hardness of SLM Ti6Al4V [15, 16]. The scaly pattern results from large plastic strain during micro-milling, which causes segment sliding and detachment in both Ti6Al4V due to higher material hardness [12, 17]. Notably, SLM Ti6Al4V chips are broader, which can be attributed to the higher cutting temperature, which causes greater plastic deformation and chip softening[11]. As a result, the welded fragments shown in Figures 5a and 5b are caused by increased heat, which causes chip fragments to adhere to the surface.

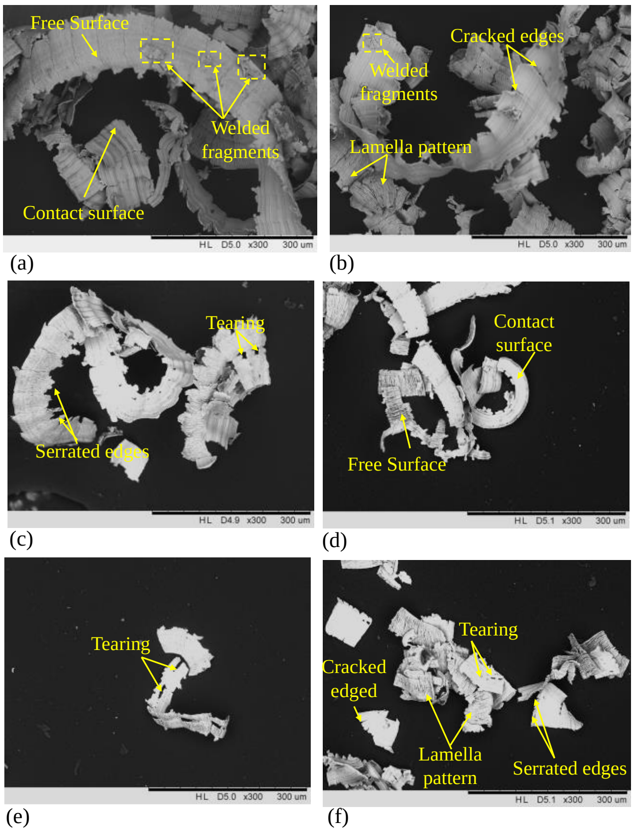

Figure 5. Chip morphology of SLM Ti6Al4V doc(a) 20μm,(b) 35μm, (c) 50μm; and, wrought Ti6Al4V (d) 20μm,(e) 35μm, (f) 50μm

3. Conclusion

This This study is carried out to investigate the micro milling of SLM Ti6Al4V and comparison experimentations were made with the wrought Ti6Al4V using CBN micro end mills. The following conclusions are drawn:

1. At various cut depths, SLM Ti6Al4V had lower surface roughness than wrought Ti6Al4V. A surface roughness of 25nm was achieved at 60K rpm spindle speed, 3μm/flute feed rate, and 25μm depth of cut, a significant 37.5% reduction compared to wrought Ti6Al4V. Surface topography analysis showed fewer defects and peaks in SLM Ti6Al4V, especially at deeper cuts.
2. Machine parameters and material manufacturing methods affect tool wear. Tool wear causes welded fragments on tool surfaces, affecting machined surface quality and tool lifespan, especially when processing softer wrought Ti6Al4V at high cutting temperatures.
3. SLM and wrought Ti6Al4V micro-milled chips show differences. SLM Ti6Al4V produced longer, continuous chips with wider profiles than wrought chips.

Declaration of competing intrest

The authors declare that they have no competing interests.

Acknowledgments

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