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Influence of Build Orientation on Machinability of Selective Laser Melted Titanium Alloy-Ti-6Al-4V

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***Abstract*—**Selective laser melting (SLM), a promising additive manufacturing (AM) technology, has a huge potential in the fabrication of Ti-6Al-4V near-net shape components. However, poor surface finish of the components fabricated from this technology requires secondary machining to achieve the desired accuracy and tolerance. Therefore, a systematic understanding of the machinability of SLM fabricated Ti-6Al-4V components is paramount to improve the productivity and product quality. Considering the significance of machining in SLM fabricated Ti-6Al-4V components, this research aim is to study the influence of build orientation on machinability characteristics by performing low speed orthogonal cutting tests. In addition, the machinability of SLM fabricated Ti-6Al-4V is compared with conventionally produced wrought Ti-6Al-4V to understand the influence of SLM technology on machining. This paper is an attempt to provide evidence to the hypothesis associated that build orientation influences cutting forces, chip formation and surface integrity during orthogonal cutting of SLM Ti-6Al-4V samples. Results obtained from the low speed orthogonal cutting tests highlight the practical importance of microstructure and build orientation on machinability of SLM Ti-6Al-4V.

***Keywords*—**Additive manufacturing, build orientation, machinability, titanium alloys (Ti-6Al-4V).

I. INTRODUCTION

TITANIUM alloys stand out primarily due to properties such as high specific strength, bio-compatibility and corrosion resistance. Ti-6Al-4V, an (α+β) titanium alloy with a balanced set of mechanical properties, is often referred to as the "work horse" of titanium alloys and is preferentially used in a variety of applications in the aerospace, chemical, medical engineering and automotive industries among others [1]-[4]. Despite their superior properties, their extraction, fabrication and production are expensive due to the requirement of a protective environment, high energy consumption and various other manufacturing associated problems [5]-[8]. To decrease the overall cost of production and to improve productivity, research has therefore been focused on alternative manufacturing methods. In recent years, AM has been widely used for fabricating near-net shape titanium alloy (Ti-6Al-4V) products due to its advantageous features like freedom of design, on-demand manufacturing and high productivity. SLM is emerging as a promising AM technology for fabrication of high quality end components. However, poor surface finish in SLM components requires finish machining to achieve desired accuracy and tolerances. Hence this research focuses on machinability studies of SLM fabricated Ti-6Al-4V components.

Build orientation plays a major role in influencing the microstructural and mechanical characteristics of SLM Ti-6Al-4V. Although several research studies focus on the effect of build orientation on microstructure and mechanical characteristics of AM (or SLM) titanium alloys [9]-[12] , there is no existing literature exploring the influence of build orientation on machinability of SLM titanium alloys. The research described in this chapter was undertaken to study the influence of build orientation on machinability characteristics such as cutting forces, chip formation and surface integrity.

Orthogonal cutting was performed on the SLM fabricated Ti-6Al-4V after heat treatment in three cutting directions based on the build orientation. These cutting directions include movement of cutting tool a) perpendicular to the build direction (along Y direction in the XY plane of case 1 sample); b) perpendicular to the build direction (along Y direction in the ZY plane of case 2 sample); and, c) parallel to the build direction (along X direction in the YX plane of case 3 sample). Cutting forces, machined chips and surface topography were analyzed to study the influence of build orientation on machinability of SLM Ti-6Al-4V.

II. EXPERIMENTAL PROCEDURE

The samples required for the orthogonal cutting tests were fabricated using three different build strategies (see Fig. 1) in the SLM machine using optimized process parameters. All SLM Ti-6Al-4V samples were fabricated in an argon protective atmosphere. After fabrication, the samples were carefully cut from the build substrate of the SLM machine using a wire-EDM machine. The samples were then carefully polished using silicon carbide paper of grit sizes 220, 400 and 600 for orthogonal cutting experiments.

Slow orthogonal cutting tests were performed on the SLM Ti-6Al-4V with different build orientations in a Spinner U-620 5-axis vertical machining centre. SLM Ti-6Al-4V fabricated samples were fitted firmly on the Kistler dynamometer (9257B) that was bolted to the milling machine bed. For this study, a specially designed cutting tool was used to carry out the orthogonally cutting process on the work material. The geometric dimensions of the tool used for these experiments and the experimental details are shown in Fig. 2. Orthogonal cutting tests were carried out at constant cutting speed Vc = 1 mm/sec, uncut chip thickness = 0.05 mm and width of cut =1 mm. During orthogonal machining of these materials, the

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cutting forces were monitored using the Kistler dynamometer. The obtained chips and machined surface after orthogonal machining trials were studied using an optical microscope.

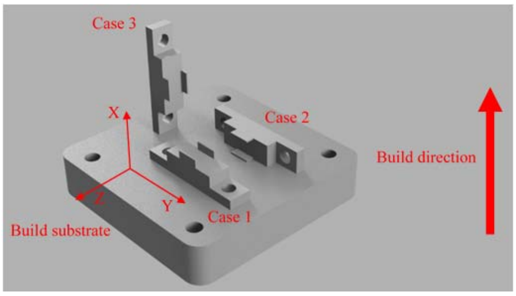

Fig. 1 Three different samples fabricated using different build strategies

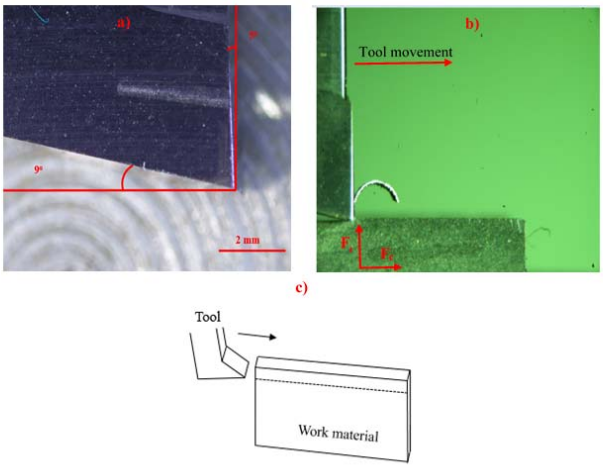

Fig. 2 Cutting tool used for orthogonal cutting operation and b, c) Illustration of orthogonal cutting in SLM Ti-6Al-4V

III. Results and Discussions

A. Microstructural Characteristics and Orthogonal Machining Strategy

Microstructure of additive manufactured titanium alloys is highly dependent on building direction due to layered deposition of materials and vertical heat conduction [13], [14]. This microstructural variation in titanium components is observed in various AM processes [15], [16]. Fig. 3-5 illustrate the microstructure of fabricated SLM Ti-6Al-4V in three different build orientations (case 1, case 2 and case 3) in their respective cutting plane (XY, ZY and YX). Orthogonal cutting was performed on these different planes as described below.

The microstructure of the XY plane in the case 1 SLM Ti-6Al-4V sample (Fig. 3) consisted of vertical columnar prior β grains oriented in the direction of building. These prior columnar β grain boundaries were formed during the solidification of Ti-6Al-4V in the β phase field combined with vertical heat conduction [17]. The cutting tool was moved across the prior β grains (i.e. perpendicular to the direction of building), as shown in Fig. 3 in this machining strategy.

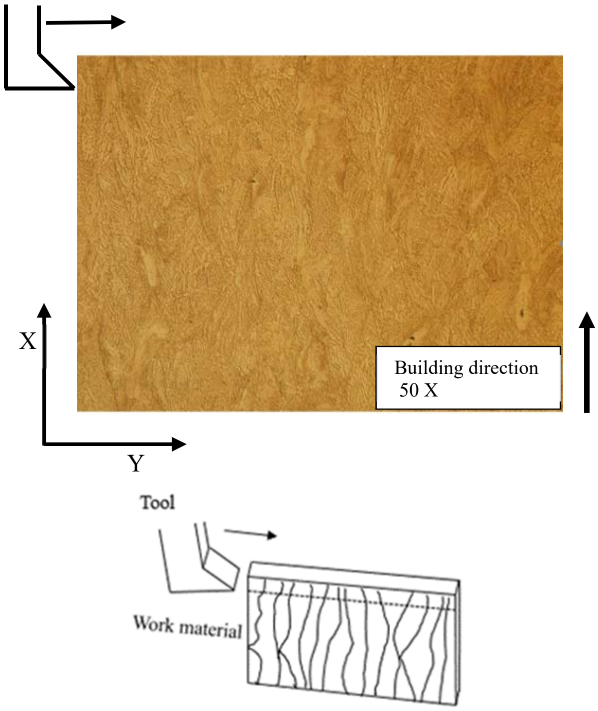

Fig. 3 Microstructural features and the orthogonal cutting strategy employed in machining the case 1 SLM Ti-6Al-4V sample

The microstructure of the ZY plane in case 2 SLM Ti-6Al-4V samples reveals the cross-sections of columnar prior β-grains. In this case, orthogonal cutting was performed perpendicular to the build direction along the cross-section of the prior β-grains (i.e. along Y direction in the ZY plane), as shown in Fig. 4.

Similar to the microstructure in the XY plane of case 1 SLM Ti-6Al-4V samples as described earlier, the YX plane of case 3 SLM Ti-6Al-4V samples exhibited columnar prior β grains. However, in this case, the direction of cutting tool movement was parallel to the prior β grains and build direction (along X direction in the YX plane of case 3 SLM Ti-6Al-4V sample), as shown in Fig. 5.

B. Cutting Forces in Orthogonal Cutting

Forces measured during the orthogonal cutting tests are reported in Fig. 6. It should be noted that only two forces operate during orthogonal cutting, one being parallel to the specimen surface cutting force (Fc), and the other normal to the specimen surface and termed thrust force (Ft). Statistically significant variations in forces during orthogonal cutting tests were observed. The highest cutting force of approximately 172 ± 3 N was observed during orthogonal cutting in the case 1 SLM Ti-6Al-4V sample. That is when the cutting tool movement was perpendicular to the build direction and prior β grains as illustrated in Fig. *3*. The next highest cutting force was observed when the orthogonal cutting was performed parallel to the prior β grains as illustrated in Fig. *5*. The lowest cutting force in SLM Ti-6Al-4V sample (of about 156 N) was observed during orthogonal cutting of the case 2 sample, when the cutting tool movement was across the cross-section of the columnar prior β grains (Fig. 4). The significant variations observed in cutting forces shows that build orientation and prior β grain boundaries influenced the cutting forces during orthogonal cutting of SLM Ti-6Al-4V. Orthogonal cutting tests also illustrated that wrought Ti-6Al-4V requires significantly lower cutting forces, approximately 13%, for shear deformation and chip formation as compared to SLM Ti-6Al-4V, irrespective of the build orientation. The higher cutting forces observed during orthogonal cutting of SLM Ti-6Al-4V as compared to conventionally produced wrought Ti-6Al-4V are consistent with the turning test force results [18]. Similarly, Wilms and Aghan [19] found an influence of microstructural directionality (or anisotropy) on cutting forces during machining of steel plates. They observed high cutting forces during orthogonal cutting along the ferrite-pearlite bands.

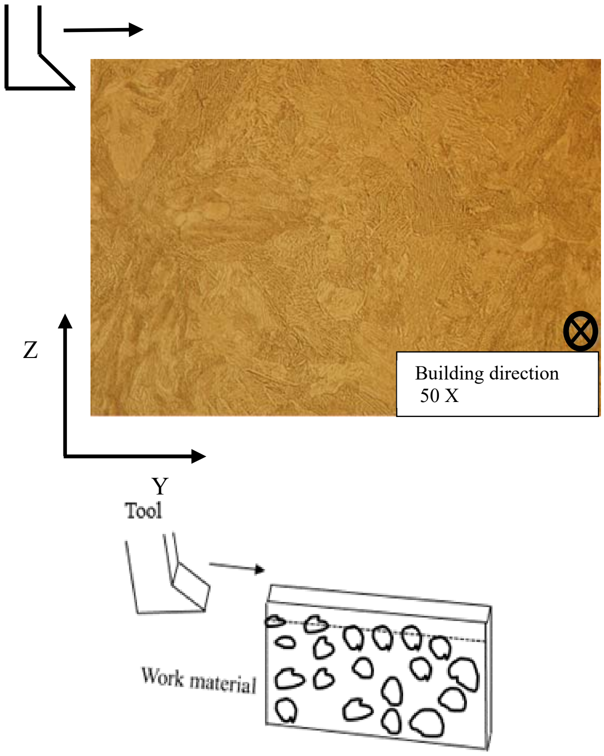

Fig. 4 Microstructural features and the orthogonal cutting strategy employed in machining the case 2 SLM Ti-6Al-4V sample

C. Chip Formation

Chips were collected after orthogonal cutting of SLM Ti-6Al-4V in different orientations to examine the microstructural deformation and chip formation characteristics. Different types of chips were generated for different machining cases as shown in Fig. 7. The chips obtained during orthogonal cutting of the case 1 SLM Ti-6Al-4V samples were flat with less chip curling. Chips produced during orthogonal cutting of the case 2 SLM Ti-6Al-4V samples exhibited a slightly curled structure as compared to case 1. On the other hand, chips obtained from orthogonal cutting of case 3 samples exhibited severe curling compared to chips obtained in other cutting conditions. Similar to case 3, a high degree of chip curling was also observed during orthogonal cutting of conventionally produced wrought Ti-6Al-4V. Joshi et al. [20] found that chip curling increases with ductility during machining of Al/SiCp composite materials. In agreement with their work, the highest amount of chip curling was observed during machining of wrought Ti-6Al-4V as compared to SLM Ti-6Al-4V, owing to its highly ductile nature. However, the chip curling did not correlate with the ductility during orthogonal cutting of SLM Ti-6Al-4V samples. Generally, during tensile testing of AM titanium components ductility was found to be highest in vertically built samples and was lowest in the horizontally built samples. Poor ductility in the horizontally oriented samples is attributed due to smaller α colony size and the high number of grain boundaries that possibly act as a failure site during tensile loading [11], [13]. Despite of the smaller α colony size in case 2 samples, high chip curling was observed (Fig. 7), indicating chip curling of SLM Ti-6Al-4V did not correlate with microstructural feature or ductility. In addition to the above observations, it can also be seen that high cutting forces are required to form flat chips, whereas, low cutting forces are required to form curled chips. This is in agreement with the work of Wilms and Aghan [19] during orthogonal cutting of steel samples.

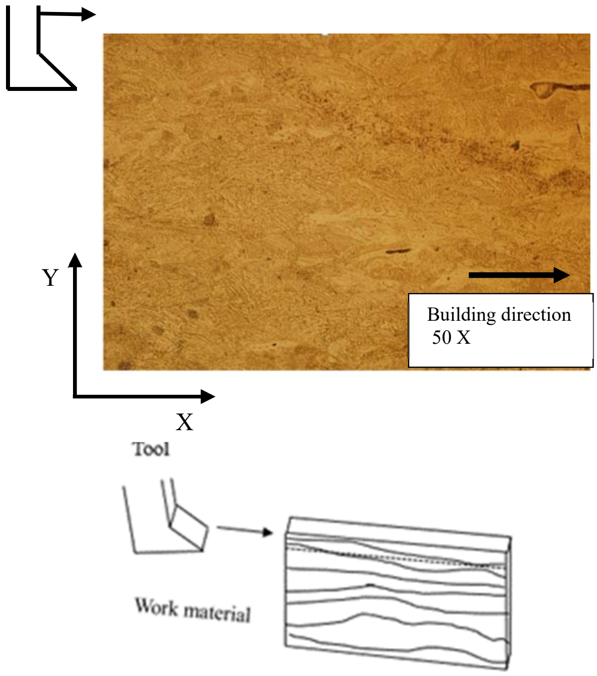

Fig. 5 Microstructural features and the orthogonal cutting strategy employed in machining the case 3 SLM Ti-6Al-4V sample

Overall, the effect of microstructural anisotropy in SLM Ti-6Al-4V was also observed in the chips produced from the orthogonal cutting tests, illustrating that the build orientation had strong influence on the nature of chip formation.

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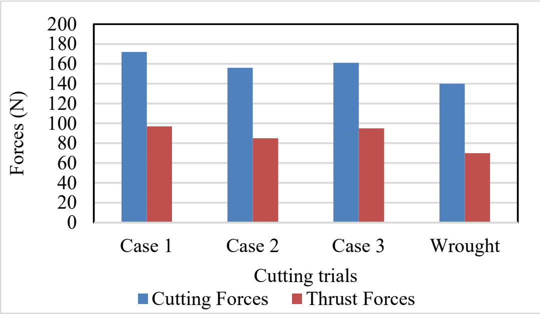

Fig. 6 Forces measured during orthogonal cutting trails

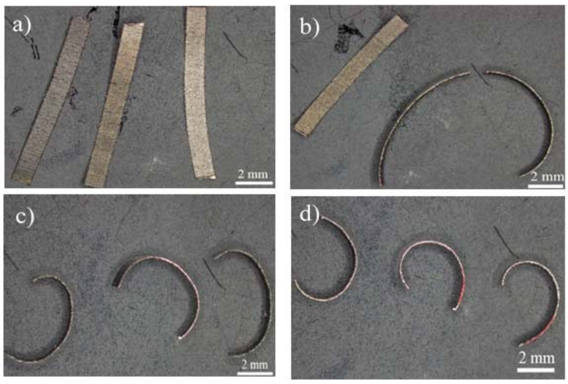

Fig. 7 Macroscopic images of chips obtained from (a) case 1, (b) case 2, (c) case 3 SLM Ti-6Al-4V and d) wrought Ti-6Al-4V samples

D. Surface Topography

The surfaces resulting from orthogonal cutting of SLM Ti-6Al-4V in different orientations and those of the wrought Ti-6Al-4V were studied and compared to understand the influence of build orientation and microstructure on machined surface finish. Images of the machined surfaces are shown in Fig. 8. Case 1 SLM Ti-6Al-4V exhibited a smooth surface compared to the sawtooth surface profile observed in case 2 and case 3 SLM Ti-6Al-4V. In addition, it was observed that the machined surface topography of SLM Ti-6Al-4V was smooth as compared to wrought Ti-6Al-4V.

The unstable BUE commonly formed on the cutting edge during chip formation can be redeposited on the machined surface during machining of titanium, affecting the surface quality. This illustrates that the tendency of BUE formation is higher in wrought Ti-6Al-4V as compared to SLM Ti-6Al-4V as observed in turning tests [21], [22]. Heavy deposition of fragments of work material on the machined surface was observed for wrought Ti-6Al-4V. The differences in surface finish of SLM Ti-6Al-4V with different build orientations can be rationalized by the difference in machined chip types. The flat chip type observed after case 1 SLM Ti-6Al-4V illustrates shear deformation with less tool-chip friction, therefore improved surface quality results.

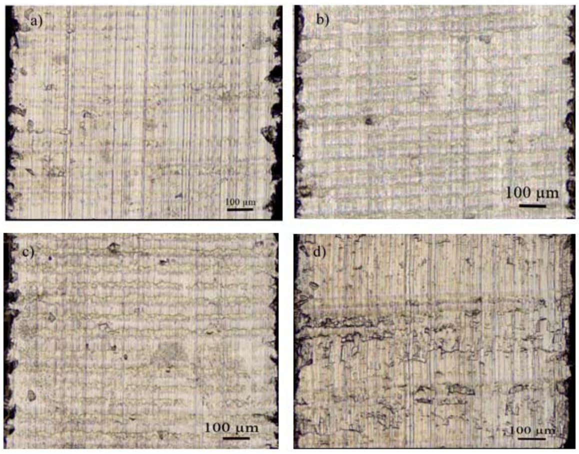

Fig. 8 Optical images of the machined surface of (a) Case 1, (b) Case 2, (c) Case 3 SLM Ti-6Al-4V and d) Wrought Ti-6Al-4V samples

IV. Conclusion

The influence of prior β grain boundaries and build direction on mechanical properties such as the yield strength, tensile strength, ductility and hardness of AM fabricated Ti-6Al-4V components have been the subject of intense research. Despite the consequences of build orientation on mechanical properties, there is no available literature discussing the influence of build orientation on machinability characteristics. This research, primarily undertaken to improve the knowledge on influence of build orientation on machinability found that:

- Cutting forces are higher during orthogonal cutting of case 1 SLM Ti-6Al-4V across prior β grains (or perpendicular to build direction) compared to case 2, case 3 and wrought samples.
- Influence of build orientation resulted in differences in chip curling of SLM Ti-6Al-4V. Heavier chip curling was observed for case 2 and case 3 SLM Ti-6Al-4V indicating that the sticking phenomenon and intense friction occurred between the tool-chip interfaces.
- Machining of SLM Ti-6Al-4V samples across the prior β grains (case 1 SLM Ti-6Al-4V) yielded superior surface finish as compared to other machining strategies due to a lack of intense friction between tool and chip and indicated by flat chips.

Overall, in relation to practical issues, the results obtained in the low speed orthogonal tests highlight the practical importance of microstructure and build orientation effects on the machinability of SLM Ti-6Al-4V. The overall results have potential to play a major role in manufacturing industries to design the machining process and strategy for high quality production of AM components.

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