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ORIGINAL ARTICLE

Evaluating productivity characteristics of laser engineered net shaping titanium alloy

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Abstract
Advances in Additive Manufacturing (AM) technologies have made it possible to reduce the design and prototyping costs to a minimum especially for a low-productivity material like titanium. Titanium alloys are commonly and widely used alloys in the aerospace and biomedical sector due to their advantageous material properties. This paper is an evaluation study of factors affecting the productivity characteristics of Laser Engineered Net Shaping (LENS) titanium alloy (Ti-6Al-4 V) using face milling. Some of the productivity challenges associated with titanium such as rapid tool wear, poor surface finish, and high-power consumption are explored in this paper. All materials processed using AM face the same critical problem that the manufactured part requires a post machining since AM produces relatively poor surface finish. Machining trials are conducted using the combinations of machining parameters such as spindle speed of 800 and 1600 rev/min; feed rate of 50 and 100 mm/min; and a constant depth of cut of 1 mm, respectively. Titanium being a poor thermal conductivity material, the effect of coolant was investigated using wet/dry machining. Data related to the productivity factors and material behavior under a milling trial was recorded and analyzed. The obtained data from the trials include productivity factors such as Metal Removal Rate (MRR), power consumed, and the surface finish for each plate/trial. The power consumed in dry milling was observed to be lower than that in wet milling which is contrary to the observations from conventional wet milling. The paper concludes the trends observed for LENS titanium are opposed to the trends in conventional machining such as increasing cutting speed will result in lower cutting force and power consumed.

Keywords Machining · Milling · LENS · Titanium alloy Ti-6Al-4 V · Additive manufacturing · Productivity

1 Introduction

In general, the production rates associated with titanium alloy components are low due to the cost involved and challenges in machining. Due to the low thermal conductivity of the material, the cutting tool wear rate is high resulting in frequent tool changes, increased setup time, and lower material removal rate [1]. Titanium alloys are used to manufacture components, where the requirements of design reliability and superior material properties such as creep resistance, high corrosion, and high strength to weight ratio are a priority [2]. Titanium alloys have a wide range of application base such as automobile, aerospace, and biomedical industry. Contrarily, some of the material properties of titanium such as low thermal conductivity and high chemical reactivity lead to poor productivity characteristics [3–5]. With additive manufacturing (AM) technology, it has been made viable to reduce the cost, energy consumptions, and carbon footprint that are associated with traditional manufacturing. However, the downside of an AM-produced part is its relatively poor surface finish, inconsistent strength, and dimensional inaccuracy which prioritize the need for secondary machining. Understanding the machining behavior of an AM titanium alloy can provide further insights on how to increase the production rates. Metal removal rate is a good indicator of productivity as there exists a direct proportionality between the metal removal rate and the number of parts produced in a given time.

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Tool wear has an inverse proportionality with productivity as a worn-out cutting edge will increase the machine downtime and reduce the capacity to produce more components in a given time. Power consumed is higher for a worn-out tool as it struggles to cut the material leading to an increase in machine time to produce a component. These are some of the factors analyzed in this paper to understand the machining behavior of titanium alloys and to suggest measures to improve the productivity of titanium alloys.

1.1 Laser engineered net shaping

Laser Engineered Net Shaping (LENS) also known as laser cladding by powder injection is a form of an AM process and an extension of other laser cladding processes in which metals in forms of tiny powders are deposited layer by layer until the predefined object is completed [6]. LENS can utilize various materials such as steel, titanium-based alloys, aluminum, nickel-based alloys, and even various ceramics. LENS has a lot of similarities to other laser processes like the Selective Laser Sintering/Melting (SLS/SLM). A typical microstructure of LENS Ti-6Al-4 V is shown in Fig. 1. Laser, powder, and laser-powder interaction in both the LENS and SLS are typically the same. However, the only major difference is that LENS is a blown-powder technique while SLS is a powder bed technique. LENS utilizes higher laser power and larger spot size which make it have higher deposition rate compared to SLS. Moreover, LENS allows for modification, repair, and addition of new features to existing parts of various geometries by using the same material or even a far better material [7]. Furthermore, LENS can fabricate parts using materials with high melting points, which have a greater tendency to oxidize with traditional manufacturing methods.

In addition, manufactured parts are found to be more robust, less brittle, and less prone to cracking at low stress. This is due to LENS process having a more defect-free interfacial bond between the layers for optimization within a process window [6]. As with all metal advance manufacturing (AM) technologies, it is difficult to predict thermal behavior due to uneven heating and cooling. In the case of LENS, this problem is a lot more prominent due to the layers closer to the substrate having a higher cooling rate compared to the other higher layers. Unlike with Powder Bed Fusion (PBF) processes, LENS cannot use the unmelted powder around the melt pool to assist in creating a more even thermal gradient and reduce residual stresses. This results in residual stress being significantly higher with LENS compared to other laser-based technologies. Higher residual stress leads to work hardening which could affect the productivity regards to dimensional accuracy and metal removal rate [8]. Complex thermal wave effects during deposition combined with irregular build heights can significantly affect the mechanical properties of the printed part [9]. Due to the nature of manufacturing layer by layer in AM, a staircase effect that affects surface roughness is present in the produced part. As LENS is an extension of a Direct Metal Deposition (DMD), there are many partially melted particles which could increase the overall surface roughness of the as-print component. Increasing surface roughness decreases fatigue life as seen on Electron Beam Melting (EBM) fabricated Ti-6Al-4 V parts [10].

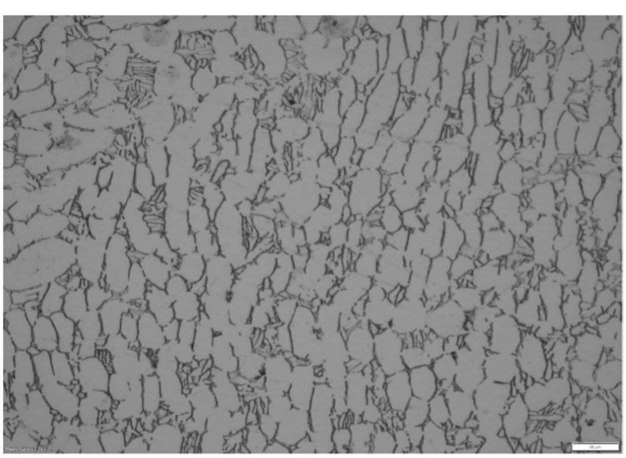

Fig. 1 Typical microstructure of LENS Ti-6Al-4 V from plate 1

1.2 Machining titanium

A paper published by Ezuguwu E.O. and Wang Z. (1995) illustrates why titanium and its alloys are considered as hard-to-machine and the causes such as the elevated temperature and stress in the shear zone. Additionally, cutting tools are subjected to severe thermal and mechanical loads due to the intense heat and stresses generated during the machining process. The severe thermal and mechanical loads affect the wear rate of the tool which results in lower tool life. Use of cutting fluid helps reduce the thermal build up and prolongs tool life [11]. Sun et al. (2009) convey that the amplitude of the cutting forces decreases as the cutting speed is increased. Furthermore, Sun et al. (2009) stated that the variation of the cutting force in reaction to cutting speed is far more complicated. In his results, the cutting force increased at a low cutting speed due to strain hardening, and then, the cutting force drastically decreased with a cutting speed from 21 to 57 m/min. The drastic decrease in cutting force is attributed to thermal softening due to the intense increasing cutting temperature. Sun et al. (2009) concluded that cutting forces generally decrease with increasing cutting speed due to thermal softening [12].

2 Experimental design

The experimental design for this paper consists of face milling LENS plate to the selected cutting parameters. The variable cutting parameters selected for the eight trials are shown in Table 1. A two set of plates to machine with coolant on and off condition was used.

The cutting parameters were selected based on earlier research works on titanium machining and considering the CNC capacity and limits. To maintain a consistent effect, the parameters were selected in a 2:1 ratio. The trials were conducted using a combination of cutting conditions which include two cutting speeds of 1600 and 800 rev/min and two feed rates of 100 and 50 mm/min, respectively. Depth of cut of 1 mm remains constant for all trials. Each LENS plate was printed to a size of 50 mm in length and 27 mm in width. All plates were cut along the width lasting 60 s. To maintain consistency, all eight trials were done in a single setup and instance. The cutting tool used is a 6-mm solid carbide end mill. The zero-reference tool wear condition was maintained by using a new tool for each trial. Kistler dynamometer was used to measure the cutting force during the trials as shown in Fig. 2. The surface roughness measurements for each trial were evaluated using a Taylor Hobson surface profilometer. The speed at which the stylus moves is set at 0.25 mm/s with a measuring length of 20 mm along the cut direction. The machined plate is shown in Fig. 3. Power consumed and metal removal rate (MRR) for each trial were calculated. The trends observed for each factor were used to evaluate the productivity of LENS titanium.

Table 1 Cutting parameters table

Plate	Trial number	Cutting speed (rev/min)	Feed rate (mm/min)	Depth of cut (mm)	Coolant
1	1	1600	100	1.0	On
1	2	800	50	1.0	On
1	3	1600	50	1.0	On
1	4	800	100	1.0	On
2	5	1600	100	1.0	Off
2	6	800	50	1.0	Off
2	7	1600	50	1.0	Off
2	8	800	100	1.0	Off

3 Results and discussion

The results obtained from the experiments are tabulated, analyzed, and discussed in this section. The outputs from the trails are used to estimate the productivity of LENS titanium. Productivity factors such as power consumed, MRR, surface roughness, and tool wear are used for productivity evaluation as shown in Table 2. The machining time for each trial was measured to be used for MRR and power consumed calculations. As observed from Table 2, the overall machining time is heavily influenced by the feed rate whereas cutting speed and depth of cut had a minimal effect. This trend can be confirmed by comparing the machining time for plate 1, trial 1 (1600 rev/min and 100 mm/min) and trial 3 (1600 rev/min and 50 mm/min), where for a coolant on condition, similar cutting speed and reduction in feed rate by 50% led to doubling up of the machining time. The same can be observed from trial 5 (1600 rev/min and 100 mm/min) and trial 7 (1600 rev/min and 50 mm/min), conducted on plate 2 under coolant off condition.

3.1 Cutting power analysis

The selected cutting speed and the feed rate influence the power consumption during the milling process. As observed from Fig. 4, trials with high cutting speed consumed more power than trials with low cutting speed. During the milling experiments, it was noted that the cutting forces reduced with the increase in spindle speed.

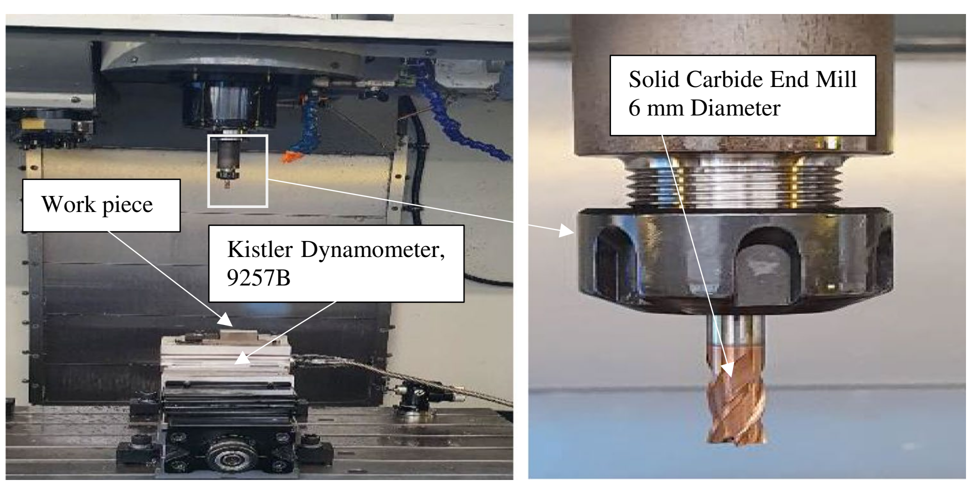

Fig. 2 Experimental setup and cutting tool

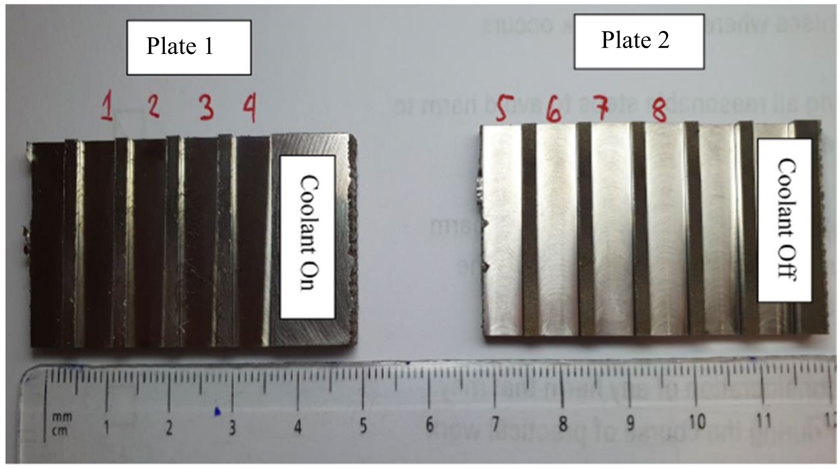

Fig. 3 Machined plates—plate 1 and plate 2

Table 2 Results associated with productivity factors

Trails	Machining time (s)	MRR (mm^3/min)	Power (watts)	Surface roughness (µm)
1	16	11,286	53	0.389
2	32	1411	31	0.482
3	32	2810	45	2.210
4	16	5646	40	0.362
5	16	11291	47	0.149
6	32	1411	26	0.175
7	32	2818	36	0.168
8	16	5626	33	0.258

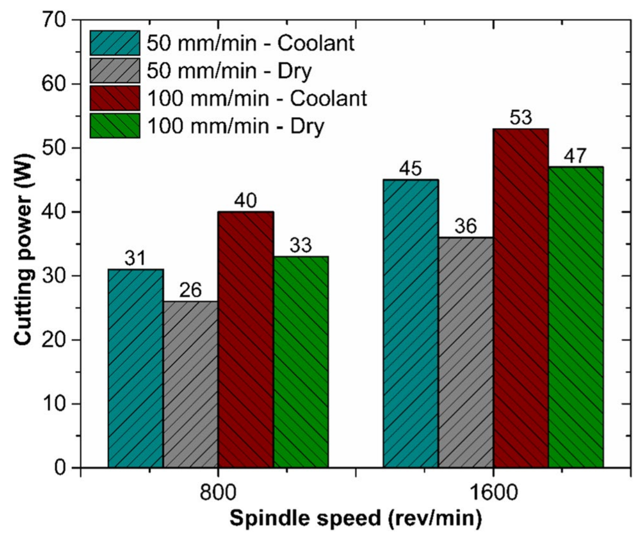

Fig. 4 Influence of milling process variables on cutting power

However, the reduction in the cutting force with the spindle speed is quite small. Moreover, the cutting power is dependent on selected spindle speed. For example, when milling with a fixed feed rate of 50 mm/min and a spindle speed of 800 rev/min, a power requirement of 31 W was recorded. However, with the increase in the spindle speed to 1600 rev/min, the cutting power increased to 45 W. Since the spindle speed is doubled during the trials, the cutting power shows an increasing trend, doubling the power rating. A similar trend was noted with the other feed and speed combinations. As denoted in Eq. 1, the cutting power (P_c) is the function of the cutting force (F_c) and spindle speed (N) and tool diameter (D).

$$P_c = \frac{F_c \cdot \pi \cdot D \cdot N}{60000} \quad (1)$$

Figure 4 also presents the evolution of cutting power with the feed rate. The cutting power increased with the increase in feed rate. For example, when a lower feed rate of 50 mm/min was considered, a cutting power of 31 W was recorded, while the power increased to 40 W, when a feed rate of 100 mm/min was chosen. The increase in the magnitude of cutting power is ascribed to the increase in cutting force. When lower feed rates are employed, the generated cutting forces are smaller due to the smaller cutter contact with the work material. With higher feed rates, the tool contact length increases, increasing the cutting force and cutting power.

Furthermore, the effect of the coolant use during the milling process was analyzed. When machined under dry environment, due to the absence of the coolant, extremely high heat is generated due to the plastic deformation of the material and friction at the tool-chip interface. Such higher temperatures can soften the material and ease the process of material removal, thus lowering the cutting force and cutting power. However, it must be noted that the additive manufactured titanium alloy exhibits higher hardness and finer microstructure, thereby increasing the brittle characteristic and lowering the plastic flow behavior of the titanium alloy [13]. As a result, with coolant-assisted cutting, the ability of the material to thermally soften is curtailed, thus increasing the cutting power requirement.

3.2 Metal removal rate analysis

Material Removal Rate (MRR) is a measure of the amount/volume of material removed per unit time, which provides a good indication of productivity. In the case of milling operation, MRR can be calculated using Eq. (2).

$$MRR = n \cdot N \cdot f \cdot a_p \cdot a_e \quad (2)$$

N is the spindle speed in rev/min, n is tool flutes, f is feed rate in mm/min, a_p is depth of cut in mm, and a_e is width of cut in mm. Typically, higher cutting parameters result in higher MRR rating and indirectly more components can be produced in a given time. As seen from Fig. 5, the MRR increased with the increase in spindle speed irrespective of the cutting condition (dry/coolant). With the selection of higher spindle speeds, chips removed per unit time increase, thereby increasing the MRR. Also, in the case of feed rate, the MRR increases with the feed value. At a lower feed rate, traverse speed of the end mill will be slower, thereby leading to lower chip removal. However, with the increase in the feed rate, the end mill traverse time is reduced, improving the MRR. Overall, the highest MRR of 11,286 mm^3/min and 11,291 mm^3/min respectively is achieved when the milling operation is performed utilizing a cutting speed of 1600 rev/min and feed rate of 100 mm/min, respectively. However, it must be noted that the trials with the highest MRR rating (trials 1 and 5) display moderate power consumption, while trials (trials 2 and 6) highlighting lower MRR consume higher power. Cutting trials 3 and 7 exhibited the lowest power consumption, which is desirable for any machining practice. However, the rate at which material is removed is too low during these trials, making the selection of high speed (1600 rev/min) and low feed (50 mm/min) combination undesirable for machining the additive manufactured titanium alloy. It is therefore suggested that spindle speed of 1600 rev/min and a feed rate of 100 mm/min can be used for efficient machining of the additive manufactured titanium alloy.

3.3 Surface roughness analysis

Surface roughness represents the irregularities of a processed surface and is a crucial indicator of a part's surface integrity. The anti-corrosion fatigue resistance and frictional wearing characteristics of components are all strongly impacted by surface roughness. Therefore, roughness of the milled surface was analyzed. The selection of spindle speed influenced the surface roughness. As seen from Fig. 6, the surface roughness lowered as the spindle speed increased from 800 rev/min to 1600 rev/min, irrespective of the dry or coolant-assisted cutting conditions. Yield stress of the material is reduced due to the elevated machining temperatures encountered while milling with higher spindle speeds. This makes it easier to reduce friction and milling force, thus enhancing the process stability and surface finish. In the case of feed rate, an interesting trend was observed. The surface roughness in general reduced with the increase in feed rate. When a higher feed rate of 100 mm/min was employed, the plastic deformation of the material increases, resulting in transverse plastic flow of the softened material. Due to the traverse flow, the peaks of the feed marks are blunted, lowering the surface roughness value. However, further exploration is essential to comprehend the effect of feed rate on surface roughness. Due to process errors and limitations, abnormal surface roughness

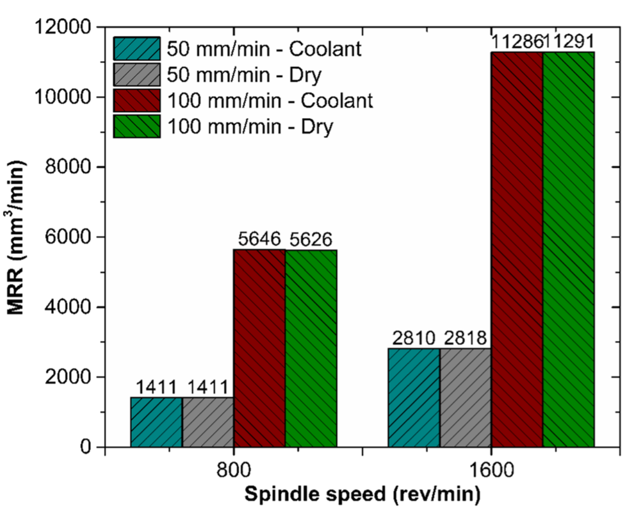

Fig. 5 Influence of milling process variables on MRR

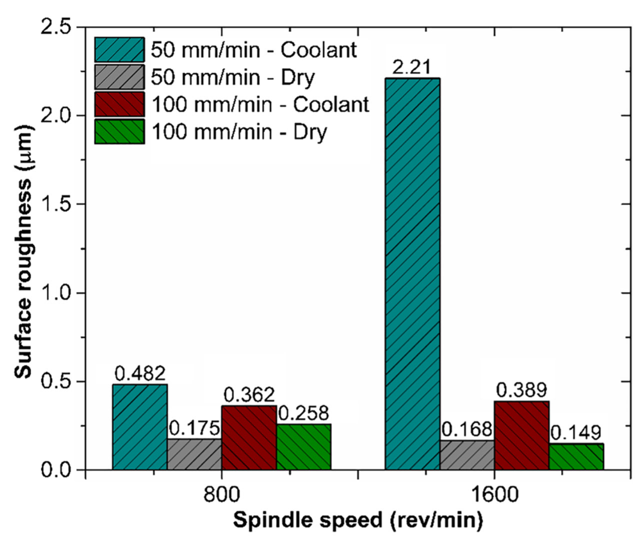

Fig. 6 Influence of milling process variables on surface roughness

was observed in the trial conducted at a speed of 1600 rev/min and feed of 50 mm/min under coolant-assisted cutting condition and can be considered as an outlier. Overall, it can be visualized that the surface roughness improves with the increase in spindle speed and feed rate. The highest roughness magnitude of 0.482 μm was noted when milling was performed at a spindle speed of 800 rev/min and feed of 50 mm/min under coolant-assisted cutting condition. The lowest surface roughness of 0.149 μm was recorded in the slot milled with a spindle speed of 1600 rev/min and feed of 100 mm/min under dry condition.

Furthermore, the presence or absence of the coolant affected the surface roughness. Higher surface roughness was observed in trials conducted with the help of coolant, while dry milling resulted in lower surface roughness. For a material like titanium especially an additive manufactured titanium having a low thermal conductivity and exposed to frequent fluctuations in thermal loads during the print process leading to accumulation of residual stress at specific areas. When the cutting tool encounters these specific areas, it leads to release of the residual stress thereby causing anomaly in the surface properties.

Contrarily, an additional effect during dry milling can be the release of the compressive residual stress due to elevated temperatures in the shear zone which help in surface crack closure or eliminate surface irregularities. The other probable cause of the gradual increase in surface roughness during wet milling can be attributed to the tool wear progression being aggressive.

4 Conclusion

Milling of LENS titanium complied with the notion of increasing cutting speed and feed rate resulted in higher power consumption. Cutting power can be lowered by employing a speed of 800 rev/min and feed of 50 mm/min. However, productivity of LENS titanium with the use of cutting fluid was different to the expectations as suggested in the literature reviews. The power consumed in dry milling is lower than that in wet milling which is contrary to the conventional machining outputs of wet milling.

Notwithstanding, dry milling also performed better in terms of surface quality than wet milling which again is different from the expected standards where the presence of coolant will result in higher surface quality because the coolant helps dissipate heat, flush away chips, and lower tool wear. Surface roughness as low as 0.149 μm can be obtained by employing a spindle speed of 1600 rev/min and feed of 100 mm/min under dry condition. Aside from the points mentioned, LENS titanium did comply with other productivity trends. MRR can be maximized by utilizing higher spindle speeds and feed rates. The authors would recommend a comprehensive study on the costs associated with higher productivity for difficult to machine materials such as titanium alloys.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Polishetty A, Shunmugvel M, Goldberg M, Littlefair G, Singh RK (2017) Cutting force and surface finish analysis of machining additive manufactured titanium alloy Ti-6Al-4V. Procedia Manuf 7:284–289
2. Che-Haron C, Jawaid A (2005) The effect of machining on surface integrity of titanium alloy Ti–6% Al–4% V. J Mater Process Technol 166(2):188–192
3. Polishetty A, Manoharan V, Littlefair G, Sonavane C (2013) Machinability assessment of Ti-6Al-4V for aerospace applications. In: ASME Early Career Technical Journal 2013 ASME Early Career Technical Conference, ASME ECTC November 2 – 3, Birmingham
4. Shunmugavel M (2017) Machinability studies of selective laser melted titanium alloy Ti-6Al-4V. Doctoral dissertation, Deakin University
5. Izadi M, Farzaneh A, Mohammed M, Gibson I, Rolfe B (2020) A review of laser engineered net shaping (LENS) build and process parameters of metallic parts. Rapid Prototyp J 26(6):1059–1078
6. Kumar S (2014) 10.05 Selective Laser Sintering/Melting. In: Hashmi S (ed) Comprehensive Materials Processing. Elsevier, Amsterdam
7. España FA, Balla VK, Bandyopadhyay A (2010) Laser surface modification of AISI 410 stainless steel with brass for enhanced thermal properties. Surf Coat Technol 204(15):2510–2517
8. Wong KV, Hernandez A (2012) A review of additive manufacturing. Int Sch Res Not 2012(1):208760
9. Balla VK, Banerjee S, Bose S, Bandyopadhyay A (2010) Direct laser processing of a tantalum coating on titanium for bone replacement structures. Acta Biomater 6(6):2329–2334
10. Frazier WE (2014) Metal additive manufacturing: a review. J Mater Eng Perform 23(6):1917–1928
11. Ezugwu EO, Wang ZM (1997) Titanium alloys and their machinability—a review. J Mater Process Technol 68(3):262–274

12. Sun S, Brandt M, Dargusch MS (2009) Characteristics of cutting forces and chip formation in machining of titanium alloys. Int J Mach Tools Manuf 49(7–8):561–568
13. Su Y, Li L, Wang G (2022) Machinability performance and mechanism in milling of additive manufactured Ti6Al4V with polycrystalline diamond tool. J Manuf Process 75:1153–1161

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