On the Effect of Layer Thickness and Cutting Orientation of Laser Powder Bed Fused Ti6Al4V Parts during Wire Electric Discharge Machining

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Abstract

Machining additively manufactured parts to improve surface finish is, sometimes, a challenging process because different manufacturing orientations and process parameters result in different machined surfaces. Extensive research has been devoted to additive manufacturing (AM) technologies and their abilities to produce end-use parts. However, post processing such as machining is still required for many applications. In this paper, non-traditional machining, Wire Electric Discharge Machining (WEDM), is used to study the result of WEDM on the surface roughness and machining time when the layer thickness and cutting orientation are changed. In this study, three layers' thicknesses (LT = 60, 80, 100 µm) and three orientations of cut are considered; wire cuts in a perpendicular plane to a layer (Ori-1), wire cuts in a parallel plane to a layer (Ori-2), and wire cuts all layers at the same time (Ori-3). Surface profilometry, scanning electron microscope (SEM), and machining time are used to evaluate the machining performance. The results show that the variation of the machining time for all layer thicknesses on Ori-1 and Ori-2 was minimal, except for Ori-3. Similarly, better surface quality could be achieved when the WEDM cuts along the Ori-2, whereas the variation of surface roughness (S_a) increases for the Ori-3. LT is also found to affect machining performance. For instance, when LT = 100 µm is employed, the roughness variation among different orientations increases up to 22.36%. On the other hand, roughness variation among different orientations reduced to 2.42% and 10.7% for LT of 60 µm and 80 µm, respectively. Overall, it was found that the WEDM along the Ori-2 yields improved surface roughness for any layer thickness. Similarly, the SEM results also show that improved surface morphology with less redeposited material could be achieved when the parts are machined along the Ori-2 as compared to Ori-1 and Ori-3.

Keywords
Laser powder bed fusion, wire electric discharge machining, surface roughness and Ti6Al4V

1. Introduction
Since Titanium was produced commercially in 1948, there are more than 100 Titanium alloys have been developed, which are categorized according to the nominal compositions (Donachie 2000). The popularity of Titanium alloys is due to their excellent properties such as corrosion resistance and high-strength-to-weight ratio. One of the most common Titanium alloys is Ti6Al4V alloy which dominates more than fifty percent of the usage of Titanium, especially in aerospace industries (Leyens and Peters 2003), automotive industry (Veiga et al. 2012), and medical applications (Li et al. 2005), (Jorge et al. 2013) and (Wally et al. 2015). Due to the diverse industrial applications of Ti6Al4V, it has received significant attention from the developers and users of additive manufacturing (AM) technologies compare to all other metallic materials. For instance, the laser powder bed fusion (L-PBF) process is one of the AM technologies that fabricate parts by selectively melting consecutive layers of powder using a laser beam as a source of energy. The L-PBF technology can be used to manufacture complex shapes with satisfying mechanical properties (Frazier 2014) and (Gokuldoss et al. 2017). Sometimes, the built parts need post processing, such as heat treatment and machining, to tailor specific characteristics, remove unwanted phenomena (e.g. residual stress) or improve the surface roughness. Due to low thermal conductivity, low elasticity modulus and highly chemical reactiveness with cutting tool materials, titanium alloys are considered difficult-to-machine materials (Paulo Davim 2014).

Researchers tried different methods to improve the surface roughness of AM parts during the fabrication process. Snyder and Thole (2020) studied the factors and process parameters that may result in different surface roughness during the L-PBF process. Understanding and controlling the melting-process physics and melt-pool geometry could help to predict the surface roughness for the built parts and, therefore, fatigue performance, as commented by (Snyder and Thole 2020) and (Eidt et al. 2019). Other researchers used the re-melting process (Alrbaey et al. 2014), pulsed laser (Gharbi et al. 2014) or AM-post chemical treatment (Pyka et al. 2013) to improve the surface roughness.

However, improving poor surface quality requires post machining. Therefore, many research works have been conducted to study the effect of the machining on the resulted surface roughness for additively manufactured parts. Al-Ahmari et al. (2016) studied the effect of end milling process parameters on the surface roughness for the titanium alloy parts produced by an AM technology, electron beam melting (EBM). They found that there is a strong correlation between surface roughness increase and the increase of the feed rate and depth of cut. However, increasing spindle speed resulted in a decrease in surface roughness reading. Milling operation was also used for machining parts built using L-PBF technology. The result showed that change in surface roughness is based on cutting and feed directions (Milton et al. 2016). The surface roughness for AM parts obtained after turning operation was reported to be dependent on the process parameters and also the tool-workpiece compatibility (Oyelola et al. 2016). Increasing the depth of cut and/or feed rate would increase the surface roughness with a coated and uncoated tool. However, increasing the cutting speed resulted in improved surface roughness. Further increase in cutting speed led to an increase in surface roughness, which is related to the excessive generated temperature that adversely affects the machined surface (Anwar et al. 2020). Dabwan et al. (2020) investigated the effect of the EBM parts orientation during the milling operation. The milling tool was fed into three different planes: in a layer plane, perpendicular to layers' planes, and parallel to layers' planes. They found that the average surface roughness was lower than machining on the other orientations when the tool was machined perpendicular to layers' planes. The cutting forces were also affected while machining along these three orientations.

All the literature mentioned above considered traditional machining processes to improve the surface roughness. In this research, the surface quality of the L-PBF printed Ti6Al4V parts is attempted to be improved by employing a non-traditional machining process, namely, wire electric discharge machining (WEDM). The parts used in machining are built with different layers' thicknesses using the L-PBF process. Also, the effect of different parts' orientations with respect to the wire feed direction is also considered during the WEDM process.

2. Materials and Methods

Gas-atomized Ti6Al4V ELI powder was used to manufacture the parts using the laser powder bed fusion (L-PBF) process. The particle size of the powder D_{10}, D_{50} and D_{90} is 20.6 µm, 32 µm and 48.6 µm, respectively. The weight percentage of the nominal chemical compositions is shown in Table 1.

Table 1: Chemical composition of all powder in weight percentage (wt. %)

Element	***AL***	***V***	***O***	***N***	***C***	***H***	***Fe***	***Ti***
wt. %	6.5	3.9	0.11	0.03	0.01	<0.01	0.2	Bal.

Table 2: Process parameters used in the experiments to investigate the effect of layer thickness (LT)

Parameter	*Value*
Layer Thickness, LT - (µm)	60, 80, 100
Laser Power, LP – (W)	200
Exposure Time, ET (µs)	70
Point Distance, PD – (µm)	50
Hatching Distance, HD - (µm)	65

10 mm × 10 mm × 10 mm cubes were manufactured using a Renishaw laser melting machine model AM250 equipped with a 200 W fiber laser (Figure 1). The laser beam had a minimum diameter of 70±5 µm and a wavelength of 1070 nm. The build envelope of the machine was 250 mm × 250 mm × 300 mm. The L-PBF process parameters used in

this study are shown in Table 2. The build platform was pre-heated up to 170°C in line with the standard build procedure recommended by the manufacturer, and all builds were fabricated under Argon atmosphere with an oxygen level below 0.1%. The process parameters employed here were originally found in a previous study (Alfaify et al. 2018). However, for the purpose of the current investigation, the layer thickness was changed, as shown in Table 2.

Figure 1: (a) Renishaw AM250 laser powder bed fusion machine, (b) as-build L-PBF parts

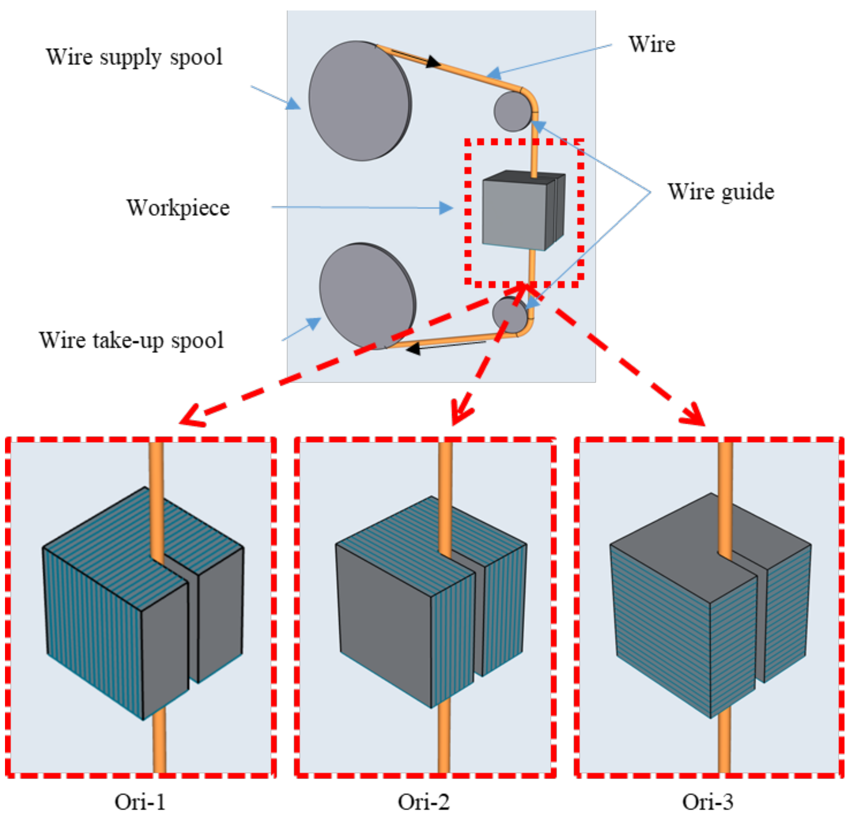

Figure 2: Schematic of WEDM process and the cutting orientations: Ori-1 - “wire cuts in a perpendicular plane to a layer”, Ori-2 - “wire cuts in a parallel plane to a layer” and Ori-3 - “wire cuts all layers at the same time”

To study the effect of the non-conventional machining (wire electric discharge machining, WEDM) on surface roughness when the build layer thickness and cutting orientations planes are changed, the manufactured samples were cut in three different orientations: wire cuts in a perpendicular plane to a layer (Ori-1), wire cuts in a parallel plane to a layer (Ori-2), and wire cuts all layers at the same time (Ori-3) (see Figure 2). The machining was conducted on the Electronica ECOCUT CNC wire electric discharge machine manufactured by Electronica Machine Tool Ltd., India. The material of the wire was hard brass and had a diameter of 0.25 mm. Deionized water is continuously flushed on both sides of the workpiece. Closed flow rate values of the deionized water were used to reduce the wire vibration as recommended in the literature (Ishfaq et al. 2018). The length of the cut was 4 mm and the average machining speed was calculated by dividing the machining length by the machining time, which was obtained from the stopwatch during machining. The process parameters that were used in the WEDM operation are illustrated in Table 3.

Table 3: WEDM process parameters' values

Parameter	*Value*
Pulse-On Time, TON - (machine unit, MU)	5
Pulse-Off Time, TOFF – (machine unit, MU)	3
Average Gap Voltage, VGAP - (v)	50
Wire Feed, WF – (m/min)	6
Dielectric Flow Rate Upper nozzle, UFR - (l/min)	6
Dielectric Flow Rate lower nozzle, LFR - (l/min)	5

The machined surfaces were examined by using a tabletop scanning electron microscope (SEM) from JCM-6000 Plus from Jeol, Japan. Surface roughness measurements of the samples were performed using a 3D optical profilometer Contour-GTK from Bruker, USA. Three reading were taken to identify the average and the standard deviation of the readings.

3. Results and Discussion

3.1 Machining Time

Machining time for the WEDM operation in a plane that is perpendicular to the layer (Ori-1) for all the samples was remarkably close. While the machining time for the sample built with LT of 100 µm maintained the same time for the machining in Ori-2, there was a modest increase in the machining time for the samples built using LT of 60 µm and 80 µm at the same orientation (Ori-2). The variation in machining time for the three orientations was notable during the machining along the Ori-3. At this orientation, machining time for the samples built with LT of 80 µm and 100 µm was approximately increased by 6.9% and 4.3%, respectively, compared to the machining time of Ori-1. However, the machining time of Ori-3 for the sample built with LT of 60 µm decreased dramatically by 10.24% compared to the machining time of Ori-1, as shown in Figure 3. Samples built with LT of 60 µm had higher density and fewer voids, while the samples that were built with thicker layers (80 µm and 100 µm) had more voids between layers due to lack of fusion, as demonstrated by Wang et al. (2017). Voids in a sample could result in slower WEDM operation. On the other hand, cutting a layer at a time (Ori-1) and through a layer plane (Ori-2) using WEDM was more stable, possibly because there are a smaller number of pores (voids) compared to the voids between multilayers orientation (Ori-3).

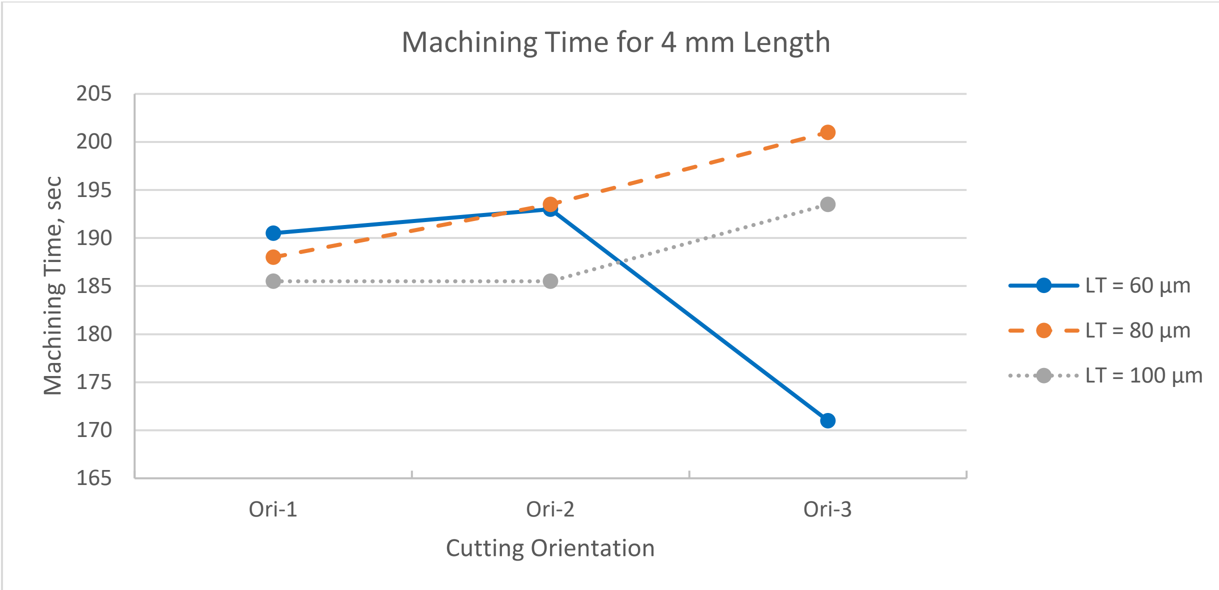

Figure 3: Machining time of WEDM for the samples in different orientations

3.2 Surface Morphology

Surface morphology for the samples built with different layer thicknesses and then machined by WEDM process along three orientations was studied based on SEM images obtained at a magnification of 1000X. The effect of the WEDM cutting orientations on the resulted surface morphology of the samples was prominent. Figure 4 shows the surface morphology for the samples at different orientations. When WEDM processing along the Ori-2, it resulted in improved surface roughness (less redeposited materials and more flat areas) compared to the Ori-1 and Ori-3 for all the L-PBF Ti6Al4V samples with any layer thickness, as shown in Figure 4b, e and h. The region between layers counters many re-melting processes during the L-PBF process. Therefore, cutting along the Ori-2 the wire appears to pass through a smaller number of re-melted regions. This could be a reason for getting better surface roughness along the Ori-2 for all samples printed with any layer thickness. Another possible reason for reduced surface roughness could be the presence of higher voids length along the Ori-2. During the L-PBF process when the layers are deposited on top of each other the porosities are generated due to various reasons such as powder size distribution effect (Alfaify et al. 2018), contraction of the solidifying material (Zhao et al. 2011), lack of fusion (Coeck et al. 2018) (Tang et al. 2017), and heat treatment (Tammas-Williams et al. 2016). These voids are usually longitudinally distributed between the adjacent layers as shown in Figure 5. The generated molten material during the WEDM along Ori-2 settled in these voids as fillers resulting in overall lesser roughness compared to molten settling on top of a surface without voids. On the other hand, WEDM along the Ori-1 and Ori-3 resulted in more redeposited (re-solidified) material on the machined surface due to the lesser voids' length/cross-section along these orientations, which led to a poorer surface finish. It was also observed that the redeposited material resulted from the conducting WEDM along Ori-3 increased for thicker LT. This would definitely result in a poorer surface finish, as shown in Figure 4c, f and i.

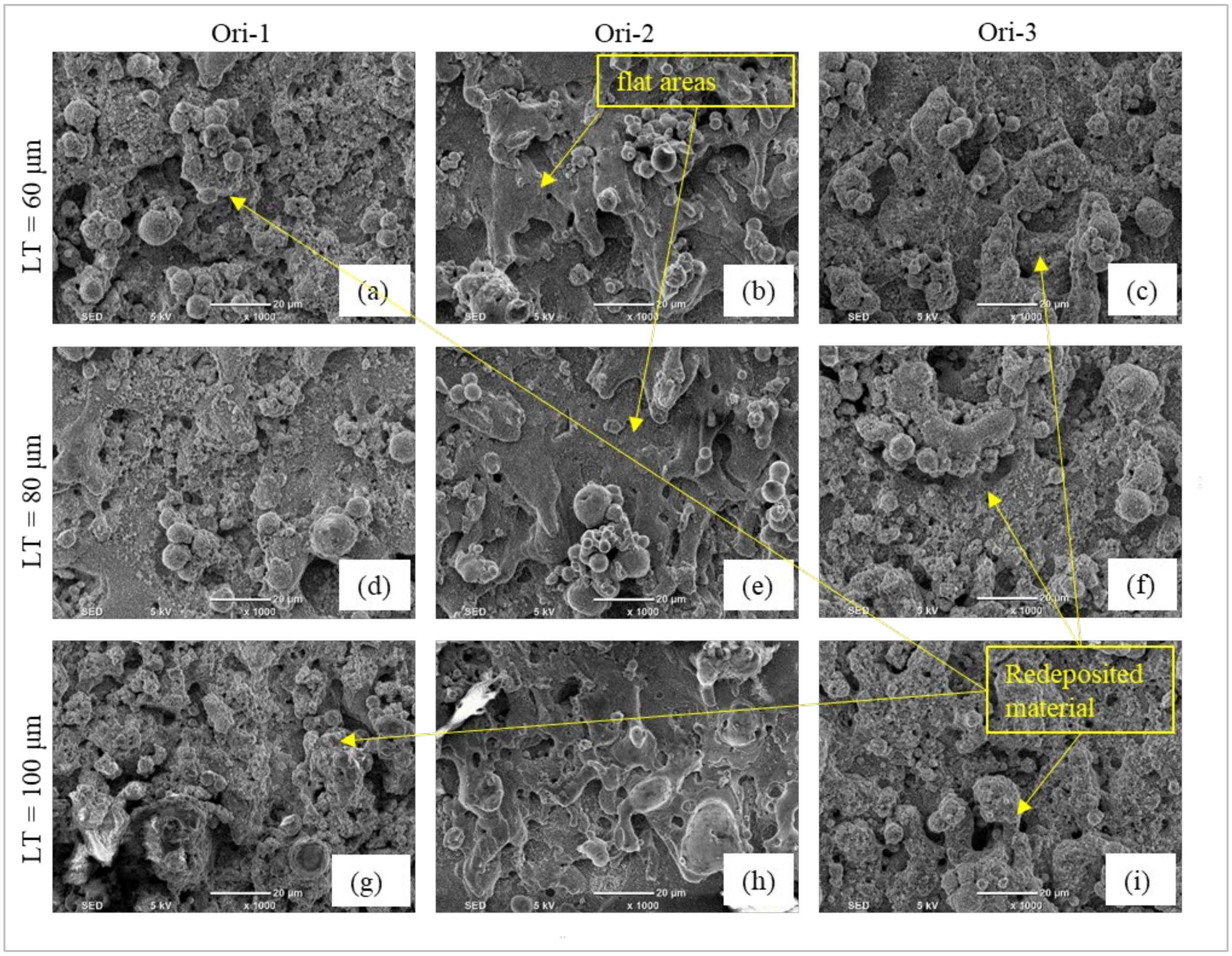

Figure 4: Surface morphology of WEDM Ti6Al4V parts, images (a) – (c) are for Ori-1, Ori-2 and Ori-3, respectively, for the sample built with LT of 60 µm; images (d) – (f) are for Ori-1, Ori-2 and Ori-3, respectively, for the sample built with LT of 80 µm; images (d) – (f) are for Ori-1, Ori-2 and Ori-3, respectively, for the sample built with LT of 100 µm. All images are at a magnification of 1000X and the scale is 20 µm.

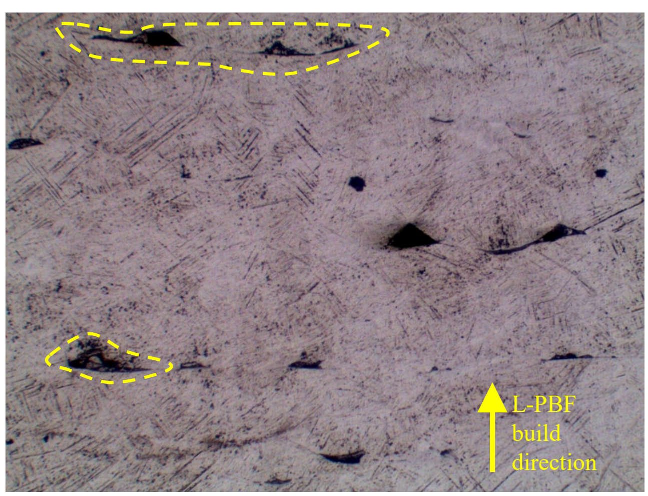

Figure 5: Longitudinally distributed voids between melted layers.

3.3 Surface Roughness

The surface roughness characteristic, arithmetical mean height (S_a), for all the samples processed by WEDM along different orientations were studied. The measurement of the S_a conformed to the surface morphology results observed via SEM. As shown in Figure 6, the surface finish for the WEDM along the Ori-2 gave the smallest values for S_a compared to other orientations. This is because of higher voids length presence along Ori-2. Machining along the Ori-1 revealed no significant variation for machining samples built with different layer thicknesses, while machining along the Ori-3 showed that there is a correlation between layer thickness and the resulted surface roughness for the WEDM process.

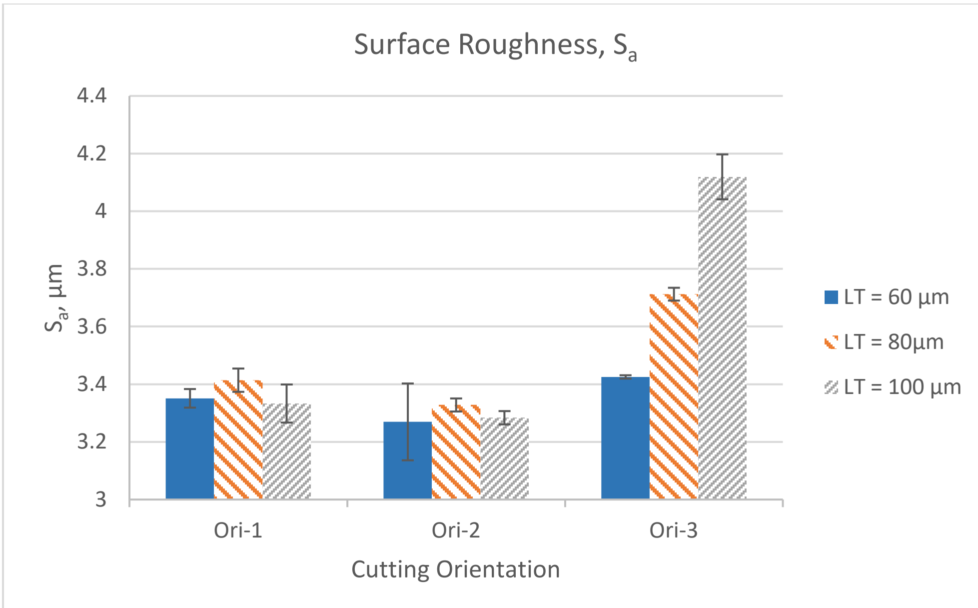

Figure 6: Arithmetical mean height (S_a) for the WEDMed samples in different orientations

Figure 7 shows the 3D scanned contours of the WEDMed surface for three different LTs. It can be seen that peak to valley difference significantly increases for WEDMed surfaces as the LT increases. This is because of the fact that as the LT increases, the randomly distributed porosity in the L-PBF produced samples increases (Alfaify et al. 2018). This leads to non-uniform and discontinuous machining at higher LTs of 80 µm and 100 µm compared with LT = 60 µm. The presence of larger sized pores could be observed in Figure 7b and c. In case of thin layer thickness of 60 µm, these defects were noticed to be not found or very minimal, as shown in Figure 7a. Therefore, improved surface morphology and roughness are observed for LT = 60 µm.

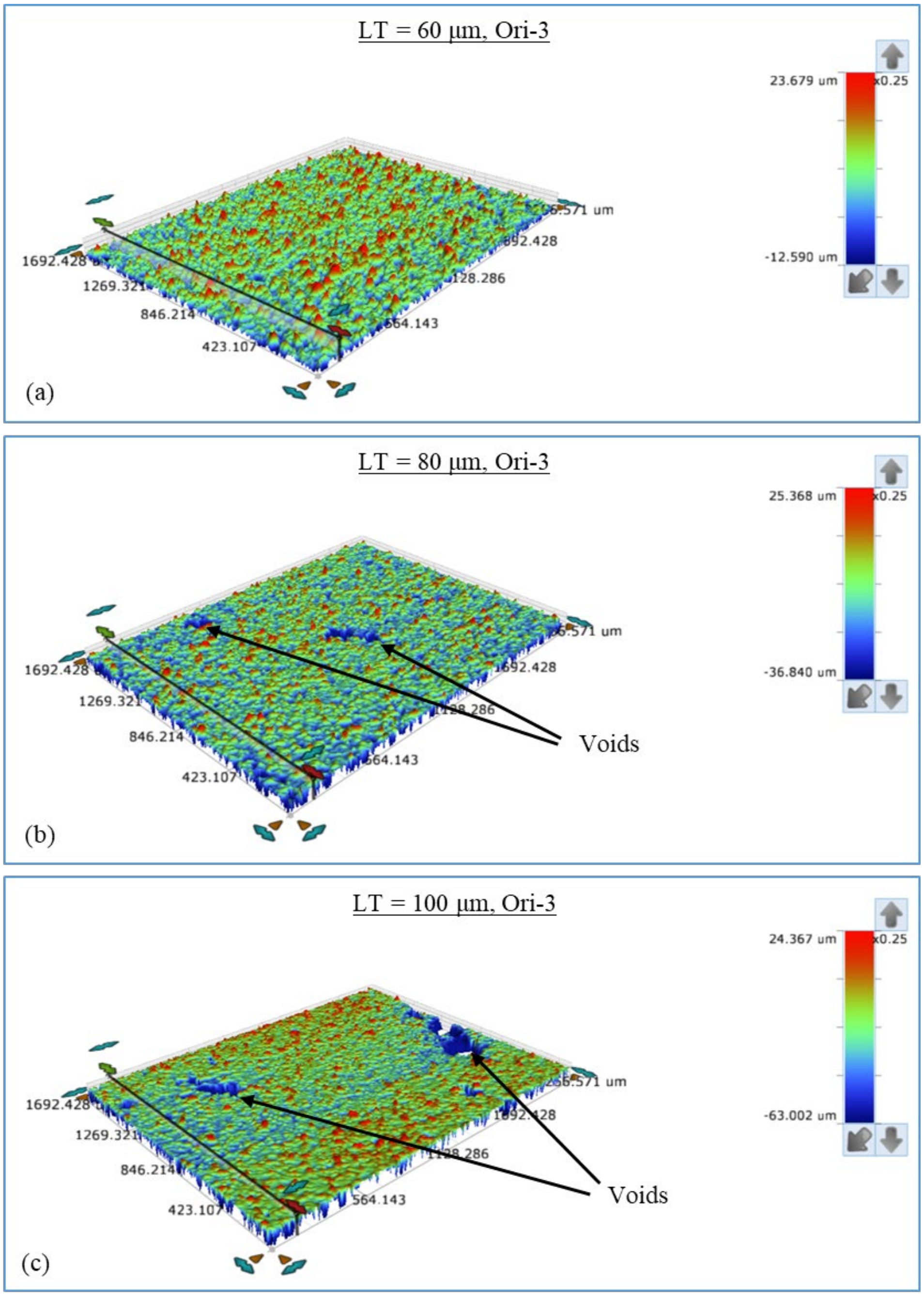

Figure 7: 3D surface plots for the cutting orientation Ori-3 for the samples built with a layer thickness of: (a) LT = 60 µm, (b) LT = 80 µm and (c) LT = 100 µm. Note that the range of the surface roughness on the color bars varies from (a) to (c).

4. Conclusion

Ti6Al4V powder bed fused samples were built with three different layer thicknesses and then machined using the WEDM process in three different orientations to studying the effect of the WEDM on surface roughness. The performance of the WEDM process on the L-PBF fabricated Ti6Al4V samples' surfaces was accessed by using the 3D scanned surface contours and scanning electron microscopy. Based on the results, the conclusions can be drawn as follows:

- The machining speed seems to be influenced by layer thickness when WEDM is conducted along Ori-1. However, it appeared to be independent of the layer thickness on the other cutting orientations (i.e., Ori-2 and Ori-3).
- The surface morphology images indicated that WEDM machining along the Ori-2 would lead to the best surface integrity for all the layer thicknesses.
- Arithmetical mean height (S_a) values confirm the results obtained by SEM images; cutting in Ori-2 would lead to the minimum surface roughness.
- Overall, it could be recommended to fabricate the Ti6Al4V parts with LT of 60 µm and the machining orientation Ori-2 must be preferred during the WEDM process.

References

Al-Ahmari, A., Ashfaq, M., Alfaify, A., Abdo, B., Alomar, A., and Dawud, Predicting Surface Quality of γ-TiAl Produced by Additive Manufacturing Process Using Response Surface Method, *Journal of Mechanical Science and Technology*, vol. 30, no. 1, 2016, doi:10.1007/s12206-015-1239-y.

Alfaify, A. Y., Hughes, J., and Ridgway, K., Critical Evaluation of the Pulsed Selective Laser Melting Process When Fabricating Ti64 Parts Using a Range of Particle Size Distributions, *Additive Manufacturing*, vol. 19, Elsevier B.V., 2018, pp. 197–204, doi:10.1016/j.addma.2017.12.003.

Alrbaey, K., Wimpenny, D., Tosi, R., Manning, W., and Moroz, A., On Optimization of Surface Roughness of Selective Laser Melted Stainless Steel Parts: A Statistical Study, *Journal of Materials Engineering and Performance*, vol. 23, no. 6, 2014, pp. 2139–48, doi:10.1007/s11665-014-0993-9.

Anwar, S., Ahmed, N., Pervaiz, S., Ahmad, S., Mohammad, A., and Saleh, M., On the Turning of Electron Beam Melted Gamma-TiAl with Coated and Uncoated Tools: A Machinability Analysis, *Journal of Materials Processing Technology*, vol. 282, no. February, 2020, doi:10.1016/j.jmatprotec.2020.116664.

Coeck, S., Bisht, M., Plas, J., and Verbist, F., Prediction of Lack of Fusion Porosity in Selective Laser Melting Based on Melt Pool Monitoring Data, *Additive Manufacturing*, vol. 25, Elsevier B.V., 2018, pp. 347–56, doi:10.1016/j.addma.2018.11.015.

Dabwan, A., Anwar, S., Alsamhan, A. M., and Nasr, M. M., On the Effect of Electron Beam Melted Ti6Al4V Part Orientations during Milling, *Metals*, vol. 10, no. 9, 2020, p. 1172.

Donachie, M. J., *Introduction to Selection of Titanium Alloys. Titanium: A Technical Guide*, 2nd Editio, vol. 180, ASM International., 2000, pp. 5–11, doi:10.1361/tatg2000p005.

Eidt, W., Tatman, E. P., McCarther, J., Kastner, J., Gunther, S., & Gockel, J., Surface Roughness Characterization in Laser Powder Bed Fusion Additive Manufacturing, *Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2019*, 2019, pp. 2165–76.

Frazier, W. E., Metal Additive Manufacturing: A Review, *Journal of Materials Engineering and Performance*, vol. 23, no. 6, Apr. 2014, pp. 1917–28, doi:10.1007/s11665-014-0958-z.

Gharbi, M., Peyre, P., Gorny, C., Carin, M., Morville, S., Le Masson, P., Carron, D., and Fabbro, R., Influence of a Pulsed Laser Regime on Surface Finish Induced by the Direct Metal Deposition Process on a Ti64 Alloy, *Journal of Materials Processing Technology*, vol. 214, no. 2, Elsevier B.V., Feb. 2014, pp. 485–95, doi:10.1016/j.jmatprotec.2013.10.004.

Gokuldoss, P. K., Kolla, S., and Eckert, J., Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting-Selection Guidelines, *Materials*, vol. 10, no. 6, 2017, doi:10.3390/ma10060672.

Ishfaq, K., Mufti, N. A., Ahmed, N., Mughal, M. P., and Saleem, M. Q., An Investigation of Surface Roughness and Parametric Optimization during Wire Electric Discharge Machining of Cladded Material, *International Journal of Advanced Manufacturing Technology*, vol. 97, no. 9–12, The International Journal of Advanced Manufacturing Technology, 2018, pp. 4065–79, doi:10.1007/s00170-018-2240-2.

Jorge, J. R. P., Barão, V. A., Delben, J. A., Faverani, L. P., Queiroz, T. P., and Assunção, W. G., Titanium in Dentistry: Historical Development, State of the Art and Future Perspectives, *The Journal of Indian Prosthodontic Society*, vol. 13, no. 2, 2013, pp. 71–77, doi:10.1007/s13191-012-0190-1.

Leyens, C., and Manfred P., Titanium and Titanium Alloys: Fundamentals and Applications, *Titanium and Titanium Alloys*, edited by Christoph Leyens and Manfred Peters, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2003, doi:10.1002/3527602119.

Li, J. P., Li, S. H., Van Blitterswijk, C. A., and De Groot, K., A Novel Porous Ti6A14V: Characterization and Cell Attachment, *Journal of Biomedical Materials Research - Part A*, vol. 73, no. 2, 2005, pp. 223–33, doi:10.1002/jbm.a.30278.

Milton, S., Morandeau, A., Chalon, F., and Leroy, R., Influence of Finish Machining on the Surface Integrity of Ti6Al4V Produced by Selective Laser Melting, *Procedia CIRP*, vol. 45, Elsevier B.V., 2016, pp. 127–30, doi:10.1016/j.procir.2016.02.340.

Oyelola, O., Crawforth, P., M'Saoubi, R., and Clare, A. T., Machining of Additively Manufactured Parts: Implications for Surface Integrity, *Procedia CIRP*, vol. 45, 2016, pp. 119–22, doi:10.1016/j.procir.2016.02.066.

Paulo Davim, J., *Machining of Titanium Alloys*. Edited by J. Paulo Davim, Springer Heidelberg New York Dordrecht London, 2014, doi:10.1007/978-3-662-43902-9.

Pyka, G., Kerckhofs, G., Papantoniou, I., Speirs, M., Schrooten, J., and Wevers, M., Surface Roughness and Morphology Customization of Additive Manufactured Open Porous Ti6Al4V Structures, *Materials*, vol. 6, no. 10, 2013, pp. 4737–57, doi:10.3390/ma6104737.

Snyder, J. C., and Thole, K. A., Understanding Laser Powder Bed Fusion Surface Roughness, *Journal of Manufacturing Science and Engineering*, vol. 142, no. 7, 2020, doi:10.1115/1.4046504.

Tammas-Williams, S., Withers, P.J., Todd, I., Prangnell, P.B., Porosity Regrowth during Heat Treatment of Hot Isostatically Pressed Additively Manufactured Titanium Components, *Scripta Materialia*, vol. 122, Elsevier B.V., 2016, pp. 72–76, doi:10.1016/j.scriptamat.2016.05.002.

Tang, M, Chris Pistoriusa, P., and Beuth, J. L., Prediction of Lack-of-Fusion Porosity for Powder Bed Fusion, *Additive Manufacturing*, vol. 14, Elsevier B.V., 2017, pp. 39–48, doi:10.1016/j.addma.2016.12.001.

Veiga, C., Devim, J. P., and Loureiro, A. J. R., Properties and Applications of Titanium Alloys: A Brief Review, *Reviews on Advanced Materials Science*, vol. 32, no. 2, 2012, pp. 133–48.

Wally, Z. J., van Grunsven, W., Claeyssens, F., Goodall, R., & Reilly, G. C., Porous Titanium for Dental Implant Applications, *Metals*, vol. 5, no. 4, 2015, pp. 1902–20, doi:10.3390/met5041902.

Wang, S., Liu, Y., Shi, W., Qi, B., Yang, J., Zhang, F., Han, D., and Ma, Y., Research on High Layer Thickness Fabricated of 316L by Selective Laser Melting, *Materials*, vol. 10, no. 9, 2017, p. 1055, doi:10.3390/ma10091055.

Zhao, H., Niu, W., Zhang, B., Lei, Y., Kodama, M., and Ishide, T., Modelling of Keyhole Dynamics and Porosity Formation Considering the Adaptive Keyhole Shape and Three-Phase Coupling during Deep-Penetration Laser Welding, *Journal of Physics D: Applied Physics*, vol. 44, no. 48, 2011, p. 485302, doi:10.1088/0022-3727/44/48/485302.

Biography

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