Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 71 (2018) 500–504

www.elsevier.com/locate/procedia

4th CIRP Conference on Surface Integrity (CSI 2018)

Finish machining-induced surface roughness, microhardness and XRD analysis of selective laser melted Inconel 718 alloy

Yusuf Kaynak[a]*, Emre Tascioglu[b]

[a]Department of Mechanical Engineering, Technology Faculty, Marmara University, Goztepe Campus, Istanbul, 34722, Turkey
[b]Department of Mechanical Engineering, Technology Faculty, Marmara University, Goztepe Campus, Istanbul, 34722, Turkey

* Corresponding author. Tel.: +90 216 336 5770; *E-mail address:* yusuf.kaynak@marmara.edu.tr

Abstract

Selective laser melting (SLM) is one of the most commonly used additive manufacturing (AM) techniques to manufacture metal components; however, during building process partially melted powders and/or pores on the outer surface of metallic parts results in very high surface roughness and eventually poor surface quality of components manufactured by selective laser melting. Thus, post-processing is needed to improve surface quality and also control subsurface characteristics. Hence, this study presents the effects of finish machining process on surface integrity characteristics including surface roughness, microhardness and XRD analysis of selective laser melted (SLMed) Inconel 718 alloy. In machining process of SLMed Inconel 718 alloy, the effect feed rate on measured outputs was also examined. Besides, the role of cold air on surface integrity characteristics was also presented in this study. This study reveals that arithmetic average surface roughness of as-built SLMed Inconel 718 can be lowered more than 90% with finish machining post processing operation. Increased feed rate results in work hardening on the surface and subsurface and eventually microhardness of surface and subsurface increases notably as compared to as-built SLMed Inconel. Finish machining process deeply influences XRD patterns of SLMed Inconel 718 alloy.

Selection and peer-review under responsibility of the scientific committee of the 4th CIRP Conference on Surface Integrity (CSI 2018).

Keywords: Additive Manufacturing; Selective Laser Melting; Finish Machining; Inconel 718 alloy; Surface integrity

1. Introduction

Nickel-iron based superalloys are widely used in applications that require remarkably high strength and high corrosion resistance at elevated temperatures, such as jet engine components, aerospace parts, and fossil fuel and nuclear power plant components [1]. Components made of Inconel 718 alloys have generally complex geometry and complicated parts particularly considering components used in aircraft engine such as spool, shaft, turbine disc etc. Although all these components have been manufactured using conventional manufacturing methods, considerable difficulties during fabricating processes of this alloy due to its thermal and mechanical properties are faced with.

Selective laser melting (SLM) process is the most widely used process for additive manufacturing (AM) of complex and customized parts in different industries, such as aerospace and automotive sectors and in the medical field [1]. Taking advantages of manufacturing capability of any complex geometry and form of SLM process into account, SLM can be considered as one of the most promising manufacturing approach to produce components made of Inconel 718 alloy. Available literature reports that manufacturing Inconel 718 components through SLM process is successfully achieved by obtaining comparable mechanical properties [2], fatigue [3]and creep resistance[4] with fabricated Inconel 718 using conventional manufacturing methods. However, main challenge is that surface quality of SLMed Inconel 718 components are not comparable with the surface quality of Inconel 718 fabricated by conventional manufacturing approaches[5]. This fact indicates that post-processing is inevitable to obtain expected surface quality of SLMed components. According to the literature, electrochemical polishing[5], milling[6] and laser polishing[7] were used as post-processing operation for SLMed Inconel 718 parts and some progress were reported. Although these few studies

Selection and peer-review under responsibility of the scientific committee of the 4th CIRP Conference on Surface Integrity (CSI 2018).
10.1016/j.procir.2018.05.013

contributes the understanding current issue with surface quality of SLMed Inconel 718, but further studies is needed to better understand the role of the effects of various parameters on surface improvements during post-processing operation.

This study focuses on the finish machining-induced surface integrity characteristics including surface roughness, microhardness, and XRD analysis of SLMed Inconel 718 alloy. This study demonstrates that finish machining is an effective post processing operation to improve surface and subsurface characteristic of SLMed Inconel 718 alloy.

2. Material and Method

The workpieces used in this study were Inconel 718 as round bars of 16 mm diameter and 80 mm length, and manufactured by selective laser melting method by Renishaw. SLM process parameters used to build these samples is illustrated in Table 1. Fig. 1 shows microstructure of as-built SLMed Inconel 718 alloy including melting pools, building direction and scanning plane.

Table 1. Selective Laser Melting process parameters

Particle size of powder	14-45 μm	Point Distance	70 μm
Layer Thickness	60 μm	Exposure Time	80 μs
Power	200 W	Hatch Distance	90 μm

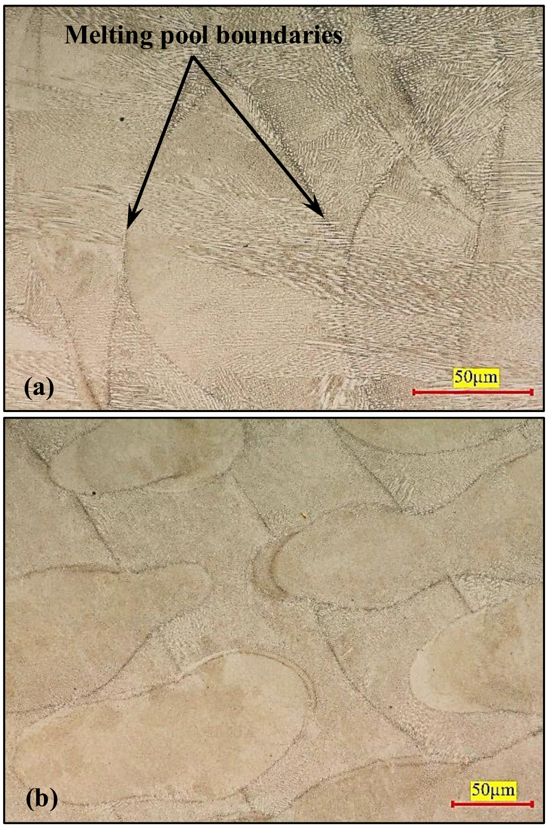


Fig. 1. Optical microscope image of Inconel 718 a) build direction and b) scanning plane

As a post processing operation, finish machining operations were conducted. Machining conditions were dry and cold air. Experimental setup for dry and cold air is shown in Fig.2. In finish machining operations, cutting speed and depth of cut were kept constant as 60 m/min and 0.4 mm, respectively. Three different feed rate values that are 0.08, 0.16, and 0.2 mm/rev were used.

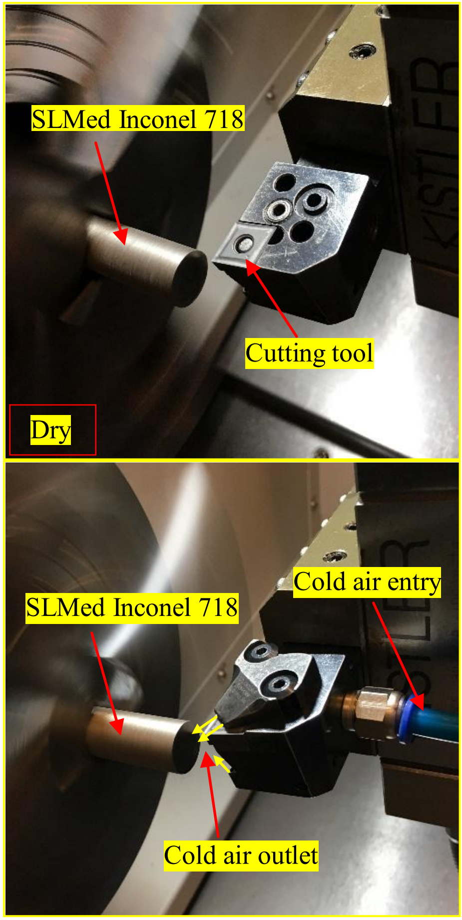


Fig. 2. Experimental setup

To examine the surface characteristics (microhardness, microstructure, etc.), machined specimens were cut with diamond cutting disk followed by cold-mounting in acrylic and polishing using 60, 30 and 15 μm grit magnetic discs. Specimens were etched using a solution of 15 ml HCI, 10 ml Glycerol and 5 ml HNO3 to review the microstructure. Surface roughness values were measured by average of four measurements by using Mitutoyo SJ210. Surface topography and microstructure of etched specimens were examined by Keyence Digital Optic Microscopy. Microhardness of workpiece was measured by using Future-Tech FM310e. Hardness of specimen was determined by average of four measurements after applying 50 gf during 15 second to each specimen. X-ray diffraction (XRD) was used by Bruker XRD device to analysis the phase transformation of machined specimens.

3. Results and discussions

3.1. Surface roughness and topography

As stated in literature review in introduction section of this study, one of the major shortcomings of additively manufactured metal parts is poor surface quality as compared to the conventionally manufactured components.Fig.3 shows the topography of as-built SLMed Inconel 718. It is apparent that surface is extremely rough because of partially melted powers presents on the surface of part.

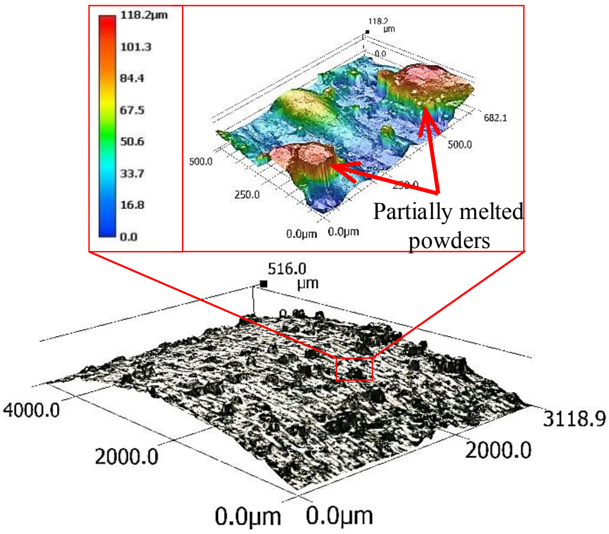
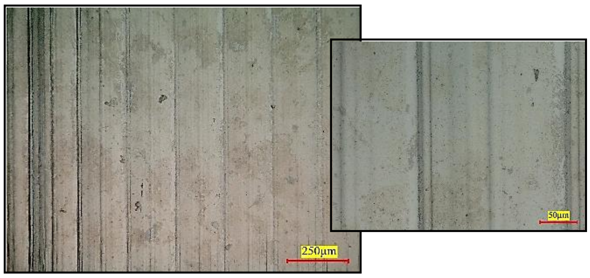
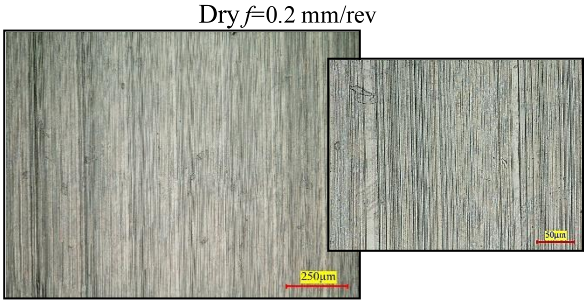


Fig. 3. Surface topography of as-built SLMed part

The surface topography of finish machined SLMed Inconel 718 for 0.2 mm/rev feed rate value is illustrated in Fig. 4. Both dry and cold air-assisted finish machining process at higher feed rate value produce improved surface.



Dry *f*=0.2 mm/rev



Cold air *f*=0.2 mm/rev

Fig. 4. Surface topography of finish-machined SLMed Inconel 718

Fig. 5 shows measured arithmetic average surface roughness values of machined SLMed Inconel 718 alloy as a function of various feed rate under dry and col air conditions. It should be noted that average surface roughness values of as-built SLMed Inconel 718 parts varied from 19 to 24 µm. After finish machining process, the surface roughness shows substantial reduction when compared with as-built SLMed parts. Among all cutting conditions and parameters, measured largest surface roughness value is 1.85 µm. Finish machining process is resulted in 92 % lower when compare to surface roughness of as-built SLMed Inconel 718. This percentage is increased when feed rate is reduced, as shown in Fig.5.

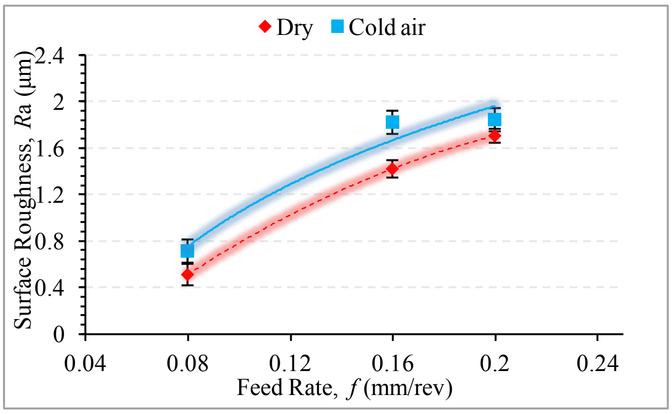


Fig. 5. Surface roughness of finish-machined SLMed Inconel 718 as a function of feed rate

From the recorded results, it is an obvious that increased feed rate in both conditions leads to increased surface roughness. The lower the feed rate, the smaller the arithmetic surface roughness. This is expected results, but the notable difference is the effects of cutting condition on arithmetic surface roughness. In all three different feed rate values, dry cutting results in lower surface roughness than cold air. Compare to different post-processing operations such as laser polishing that is capable of reducing arithmetic surface roughness up to 5 µm [7], and electro polishing operation capable of reducing arithmetic surface roughness up to 4 µm [5]. Compared to these post-processing operations, finish machining is the most promising post processing operation to control surface roughness.

3.2. Microhardness

Fig. 6 shows surface and subsurface microhardness of the SLMed Inconel 718 samples finish machined under dry conditions at various feed rate and its comparison with as-built SLMed Inconel 718 sample. It needs to be noted that as built sample has average 322 HV. Finish-machining conditions result in increased microhardness on the surface and subsurface of SLMed Inconel 718, as depicted in Fig.6.

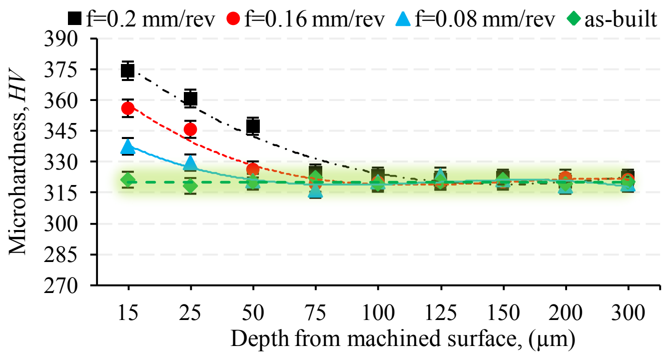


Fig. 6. Microhardness of finish-machined and as-built SLMed Inconel 718 as a function of feed rate (Dry)

The larger the feed rate, the higher the microhardness. The largest microhardness is measured with the sample machined with 0.2 mm/rev feed rate followed by 0.16 and 0.08 mm/rev feed rates values. This trend is consistent throughout the depth of 50 µm from the surface.

The largest feed rate results in approximately 16 % increase when compared to the microhardness of as-built samples. Altered depth from the surface of samples is also affected from feed rate value used in finish machining. Larger feed rate has much deeper effect from the surface as compared to smaller feed rate in dry finish machining. When cold air is used in finish machining process of SLMed Inconel 718 alloy, the microhardness trend does not show considerable difference. It is more or less similar to the microhardness trend obtained from dry finish machining, as illustrated in Fig. 7. Increased feed rate leads to increased hardness values on the surface and subsurface of finish machined SLMed Inconel 718 alloy. In cold air condition, depth of machining-induced layer is approximately 50 µm that is almost same as the results obtained from dry machining.

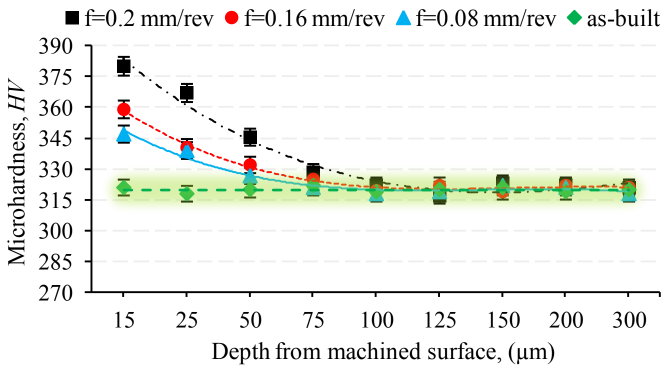


Fig. 7. Microhardness of finish-machined and as-built SLMed Inconel 718 as a function of feed rate (Cold air)

The comparison of microhardness values of dry and cold air-assisted finish machined taking all feed into account is presented in Fig. 8. The results show that cold air-assisted finish machining leads to slightly higher hardness when compared to hardness of dry finish machining in all three feed rate values. Cold air reduces cutting temperature and thus mechanical effect is much dominant than the thermal effect; this eventually resulted in slightly increased microhardness.

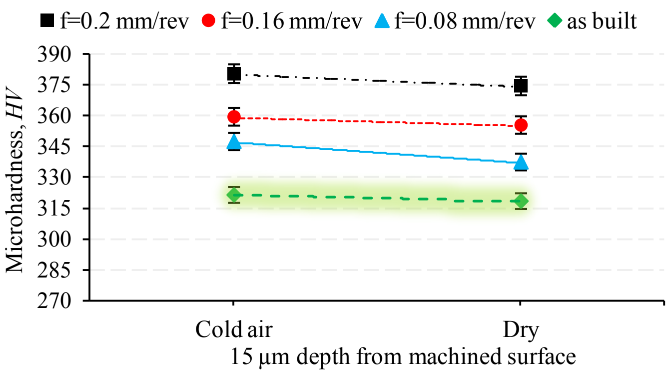


Fig. 8. Microhardness of finish-machined and as-built SLMed Inconel 718 as a function of feed rate

Microhardness measurement result indicates that finish machining process causes work hardening on the surface and subsurface of machined SLMed Inconel 718 and thus microhardness increases after finish machining process. The depth of work hardened layer from the machined surface is approximately 50 µm. Feed rate in finish machining process has direct effect on microhardness of SLMed Inconel 718. Increased feed rate results in increased microhardness. Furthermore, cold air assisted machining produces slightly higher hardness than dry machining process.

3.3. XRD analysis

Fig. 9 shows comparison of XRD patterns of as-built SLMed and finish machined SLMed Inconel 718 alloy. Two different feed rates (0.08 and 0.2 mm/rev) in dry and cold air conditions are considered for XRD pattern analysis. Large difference is recorder in between machined samples and as-built sample when XRD patterns of (111) and (200) textures are examined. As-built sample has weak (111) texture and relatively strong (200) texture. Strong (200) texture in as-built SLMed are also reported in literature [8]. However, after machining process XRD patter shows substantial changes.

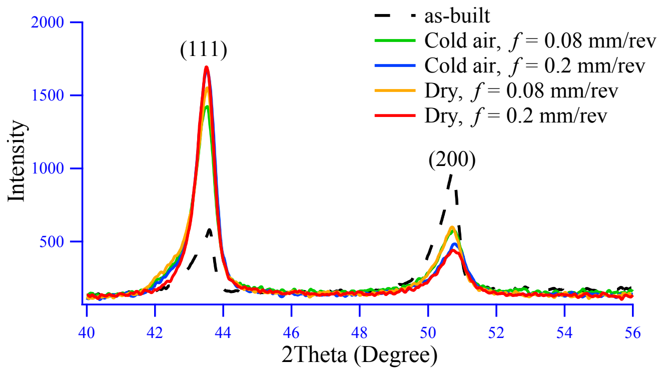


Fig. 9. Comparison of XRD profiles of finish-machined and as-built SLMed samples

While as-built has weak peak intensity at (111) texture, after finish machining processes, this texture become much stronger than (200) texture that is the one of the most significant results demonstrated in this section. Peak intensity of as built sample at (111) texture is much lower than peak intensity of machined samples, as shown in Fig. 10. Machining results in approximately 200 % increase in intensity of (111) texture when compared to as-built sample. When the effects of feed rate on intensity of (111) texture is examined, consistent trend is observed. Increasing feed rate during both dry and cold air finish machining process results in increased intensity at (111) texture.

Furthermore, finish machining processes also broadens the (111) peaks remarkably. However, it should be noted that varying feed rate or cutting conditions does not show any noticeable difference in peak broadening. All presented machining conditions and parameters causes more or less same broadening at this peak. Broadening of this peak indicates formation of small sized crystalline grains of SLMed Inconel 718 parts [2].

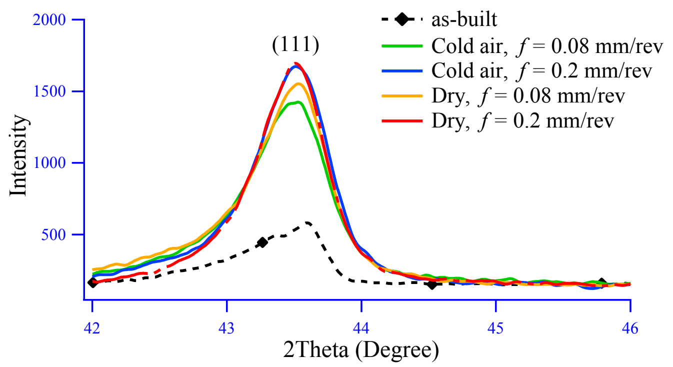


Fig. 10. (111) textures of XRD profiles of finish-machined and as-built SLMed samples

Machining process adversely affected the intensity of (200) texture, as shown in Fig.11. Machining process results in approximately 55% lower intensity of (200) texture when compared to the intensity of as-built sample. The effects of feed rate on intensity of (200) texture is apparent. The higher the feed rate, the lower the peak intensity of (200) texture. It should be also noted that the effects of cold air on peak intensity is negligible.

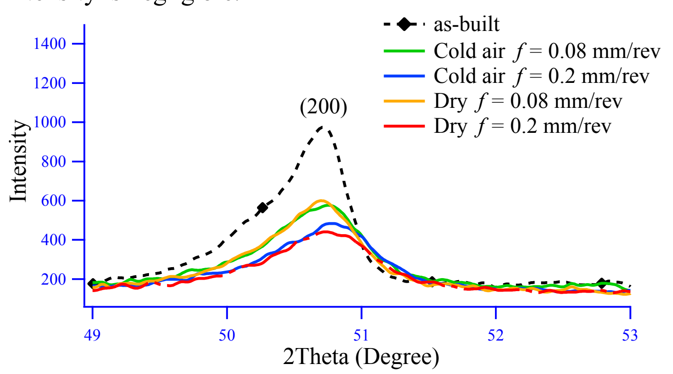


Fig. 11. (200) texture of XRD profiles of finish-machined and as-built SLMed samples

Results clearly show that finish machining processes have substantial effects on XRD pattern of SLMed Inconel 718. The surface and subsurface of samples is both subjected to thermal and mechanical influence during finish machining processes and as a result of this effect, dislocation density increases on the surface and subsurface layer of machined samples [9]. It seems that increased dislocation density alters XRD pattern of SLMed part. SLMed as-built Inconel 718 showed similar intensity response for these texture when they are subjected to different heat treatments [10].

4. Conclusions

This study presents the effect of finish machining process on surface roughness, microhardness and XRD analysis of SLMed Inconel 718 alloy. It is possible to reach following conclusion from this study.

- Finish machining process is very effective post-processing operation to decrease surface roughness of as-built SLMed Inconel 718 alloy. Arithmetic surface roughness of as-built SLMed Inconel 718 can be lowered by 92 % through finish machining operation.
- After finish machining process, the surface microhardness of SLMed Inconel 718 alloy shows approximately 16 % increase mainly due to the work hardening resulting from machining.
- XRD pattern of SLMed Inconel 718 is substantially affected from finish machining operations by showing increased intensity at (111) texture, and decreased intensity at (200) texture.
- Feed rate remarkably affects surface roughness, microhardness and XRD pattern of SLMed Inconel 718; however, the effect of cold air is limited.

Acknowledgements

Authors acknowledge the Renishaw Turkey for providing SLMed Inconel work materials for this this study. Authors also acknowledge the Scientific Research Project Commission of Marmara University for its support to this work.

References

[1] Mostafa A, Picazo Rubio I, Brailovski V, Jahazi M, Medraj M. Structure, texture and phases in 3D printed IN718 alloy subjected to homogenization and HIP treatments. Metals 2017;7:196.
[2] Jia Q, Gu D. Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties. J Alloy Comp 014;585:713-21.
[3] Yoo YSJ, Book TA, Sangid MD, Kacher J. Identifying strain localization and dislocation processes in fatigued Inconel 718 manufactured from selective laser melting. Mat Sci Eng A 2018;724:444-51.
[4] Xu Z, Hyde C, Tuck C, Clare A. Creep behaviour of inconel 718 processed by laser powder bed fusion. J Mate Process Tech 2018;256:13-24.
[5] Baicheng Z, Xiaohua L, Jiaming B, Junfeng G, Pan W, Chen-nan S, et al. Study of selective laser melting (SLM) Inconel 718 part surface improvement by electrochemical polishing. Mater Design 2017;116:531-7.
[6] Brown D, Li C, Liu Z, Fang X, Guo Y. Surface integrity of Inconel 718 by hybrid selective laser melting and milling. Virtual and Physical Prototyping 2018;13:26-31.
[7] Dadbakhsh S, Hao L, Kong CY. Surface finish improvement of LMD samples using laser polishing. Virtual and Physical Prototyping 2010;5:215-21.
[8] Amato K, Gaytan S, Murr L, Martinez E, Shindo P, Hernandez J, et al. Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. Acta Mater 2012;60:2229-39.
[9] Kaynak Y. Machining and phase transformation response of room-temperature austenitic NiTi shape memory alloy. J Mater Eng Perform 2014;23:3354-60.
[10] Mostafa A, Shahriari D, Rubio IP, Brailovski V, Jahazi M, Medraj M. Hot compression behavior and microstructure of selectively laser-melted IN718 alloy. Int J Adv Manuf Techn 2018:1-15.