Experimental Evaluation of Surface Quality Characteristics in Laser Machining of Nickel-based Superalloy

Adam Khan M[1] and Kapil Gupta[1*]

[1]Mechanical and Industrial Engineering Technology, University of Johannesburg,
Johannesburg, South Africa
*Corresponding Author- kgupta@uj.ac.za; +27-011-5599081
7225 John Orr Building, University of Johannesburg (DFC)
Doornfontein, Johannesburg- 2028 (South Africa)

Abstract

This paper reports the investigation results of CO_2 laser cutting of Inconel 718 superalloy. Investigation on the effects of the two important laser parameters power and travel speed on machinability i.e. material removal rate, kerf wall inclination, and average surface roughness of Inconel 718 has been conducted. Increased kerf wall inclination has been found with slow travel speed and increasing power. Low power and high travel speed produced maximum material removal rate and minimum surface roughness. Premature state of fusion has advanced dross regime at a slow cutting speed of 3.3 m/min and leading to a surface roughness of 9.3 microns maximum. Dendrite structures were formed and changes in surface hardness were observed due to high travel speed. Therefore, based on the investigation, slow travel speed with appropriate laser power is recommended for the improved machinability and surface quality of Inconel 718 superalloys.

Keywords: kerf; laser; microstructure; roughness; superalloy; surface; wear

1. Introduction

The demand on nickel-based superalloys has been tremendously increased during last two decades. Inconel 718 superalloy is an important type, extensively employed in jet engine and other parts for aerospace applications due to its superior mechanical properties and metallurgical qualities [1]. But, Inconel 718 is also known as difficult-to-machine (DTM) material due to inherent properties such as low thermal conductivity and high work hardening rate [2,3]. Machining Inconel718 is a challenging task with an existing edge cutting process and the results are rapid tool wear, surface deterioration, machining cost and consumption of cutting fluid. Thus, advanced machining process has to be explored for Inconel 718 superalloy type sensitive materials. Laser cutting or Laser based machining (LBM) is one of the advanced machining processes identified for cutting wide range of engineering materials with high dimensional accuracy and good surface quality [4-6]. It makes use of a high-intensity laser beam to cut the desired amount of material by melting and vaporization [7]. The CO_2, Nd:YAG, fiber and ultra-short pulse (femtosecond) lasers are the most common source used in machining process.

In a detailed literature study, authors found some past work on machining of various materials by CO_2 laser. Nitrogen as an assisted gas was used in a research work conducted by Cekic et al. (2014) on CO_2 laser cutting of alloy steels [8]. The best surface roughness (Ra- 1.67 μm) was obtained for high alloy steel at gas pressure- 15 bar, focus- 1 mm, and cutting velocity- 1000 mm/min. Certainly, low thickness of the workpiece was recommended for better quality. In a novel investigation, different gases such as argon, helium, and nitrogen are used while machining sheet metals with pulsed CO_2 laser [9]. Low pulse and helium gas system has resulted machined surface with low heat affected zone and free from dross. A recent study informs about the capability of laser for machining of hard materials such as granite [10]. Some more important research studies evaluated the machinability of steels at high laser power, low speed, and moderate gas pressure [11,12]. There is a very limited research conducted and reported on laser machining of nickel-based superalloys [13-15]. Thus, in the present research work, an attempt has been made to machine nickel-based superalloy i.e. Inconel 718 by CO_2 laser cutting process and study its machinability. Geometric accuracy in terms of kerf wall inclination, surface roughness, and wear characteristics of the laser machined surface are investigated.

2. Experimental Procedure

Inconel718, a nickel-based superalloy has been machined with gas assisted CO_2 laser cutting process using TRULASER 3040 (Make: TRUMPF, German) laser machine. Figure 1a shows the photo image of TruLaser cutting machine used in the present research and Fig. 1b schematically illustrates CO_2 laser cutting of Inconel 718 material sheet (50 x 50 mm^2) of 6 mm thickness.

Fig. 1. a) Photo image of TruLaser 3040 cutting machine.

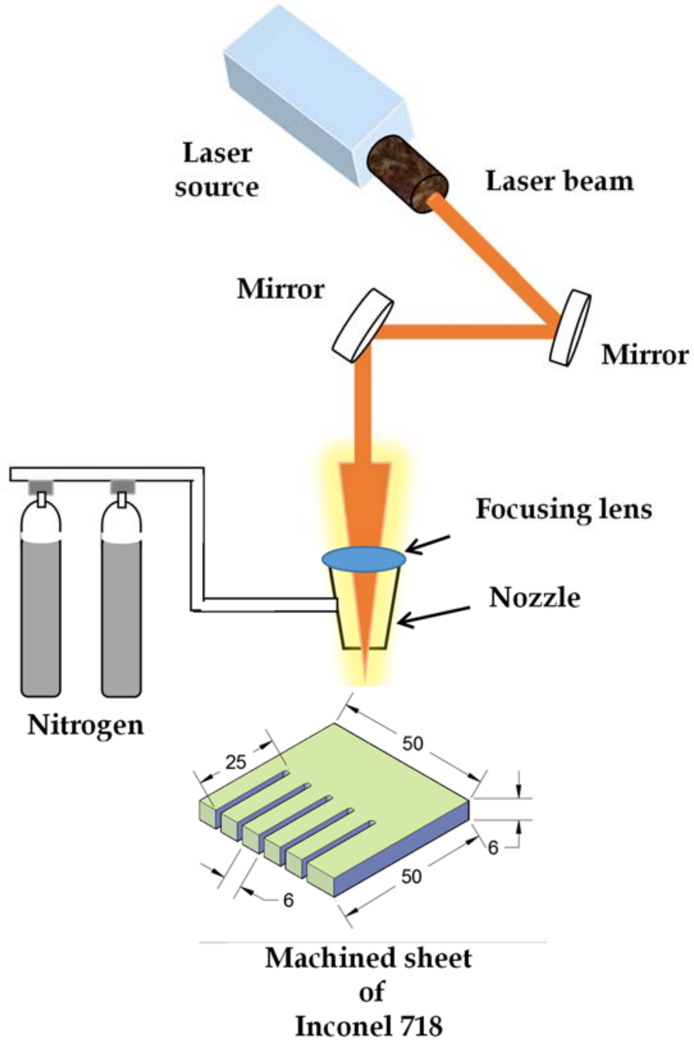


Fig. 1. b) Schematic representation of laser cutting of Inconel 718 sheet (all dimensions are in mm).

As shown in Table 1, two important laser machining process parameters namely laser power and laser travel speed were varied, whereas other parameters were kept constant based on the machine constraints and results of some preliminary experiments. Table 2 presents the composition of raw material Inconel 718. Kerf wall inclination, material removal rate, average surface roughness and topography, and wear characteristics were the major responses considered to evaluate quality of the machined surface and machinability of the laser cutting process.

Table 1 Laser cutting process parameters used to machine Inconel 718 superalloy.

Parameter	Range	Units
Laser power	3500, 3600, 3800 and 4000	*W*
Laser travel speed	3 and 5.0	*m/min*
Nitrogen gas pressure	16	*bar*
Nozzle diameter	0.26	*mm*
Nozzle standoff distance	1.6	*mm*
Focus position	-6	*mm*

Table 2 Chemical composition of Inconel 718 superalloy.

Element	Ni	Fe	Cr	Nb	Mo	Ti	Al	Si	C	Co	Cu and W
Wt.%	52.44	19.78	17.13	4.77	3.38	1.11	0.59	0.13	0.05	0.16	Traces

Light spectroscope and electron microscope were used for surface topography analysis. Kerf wall inclinations and material removal rate were calculated using empirical relation with reference to the difference in band gap width (kerf gap) and thickness of the plate (Equations 1 and 2).

$$Kerf\ wall\ inclination = \frac{(W_t - W_b)x180}{2t\ x\ \pi} \qquad \ldots (1)$$

$$MRR = h_t d_i v_f \qquad \ldots (2)$$

Where;

W_t – kerf top width (mm)

W_b – kerf bottom width (mm)

t – thickness of the job (mm)

h_t – depth of penetration (mm)

d_i – average focused diameter (mm) $[d_i = \frac{W_t + W_b}{2}]$

v_f – laser nozzle travel speed (mm/min)

Contact type roughness meter (Make: SJ410, Mitutoyo, Japan) was used to measure the average roughness value and the same was compared with the white light spectroscope (Make: RTEC, USA). The surface contours and the machined surface profiles were interpreted for discussion. Further the metallurgical analysis was also made through scanning electron microscope.

3. Results and Discussion

The effect of laser power on kerf wall inclination at two sets of laser travel speed is shown in Figure 2. The laser power and its scan rate has highly influenced the kerf inclination. Minimum kerf of 0.5 to 0.6 was measured in both speed conditions for lower values of laser power. Kerf has gradually increased for 3.3m/min and found unstable for 5m/min travel speed. Subsequently, the removal of material from the bulk is more with high speed machining. Figure 3 shows the variation of material removal rate with laser power at two sets of travel speed. At slow travel speed, material removed due to diffusion is in the range of 193-199 mm^3/s and 250-307 mm^3/s at high speed. Under the condition of metal diffusion, the resistivity of the material and applied power are the predominant factors affecting the machinability of nickel-based superalloys. Thus, the machinability of Inconel 718 is better at high speed laser cutting.

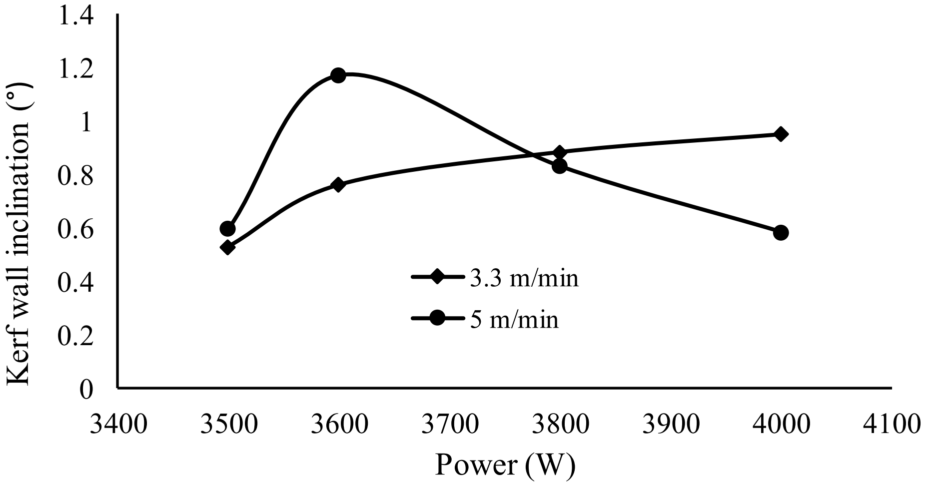


Fig. 2. Kerf wall inclination with reference to applied power and laser travel speed.

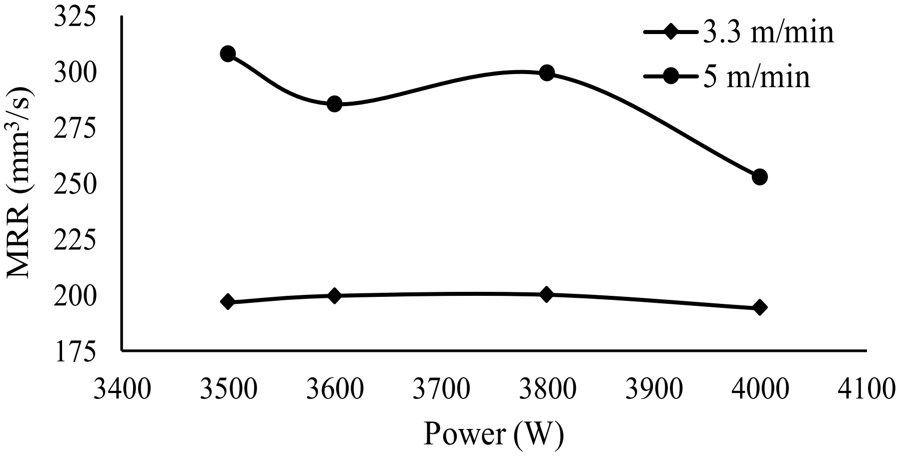


Fig. 3. Variation in material removal rate (MRR) with reference to applied power and laser travel speed.

In laser cutting process, machined surfaces are subjected to face high heat energy produced for metal fusion. To understand the effect of heat energy and surface finish, diamond indentation technique is used to measure the hardness (HRC). Maximum surface hardness of 51HRC was observed in both the speed while machining with a laser power of 3500 W and slight variation with respect to laser power and travel speed as shown in Figure 4. Rapid solidification of fused metal surface led to severe metallurgical changes and surface hardening. Figure 5 presents the effect of laser power on surface roughness. Minimum roughness Ra value (of 3-4μm) was observed for low laser power (3500W). There are no drastic changes with respect to change in power, however the roughness value has been increased with slow travel speed. That is, the material surface has undergone severe metallurgical changes on slow movement of laser torch. To realize surface profile and to justify the average surface roughness, samples are investigated to observe the wear scars using white light spectroscope.

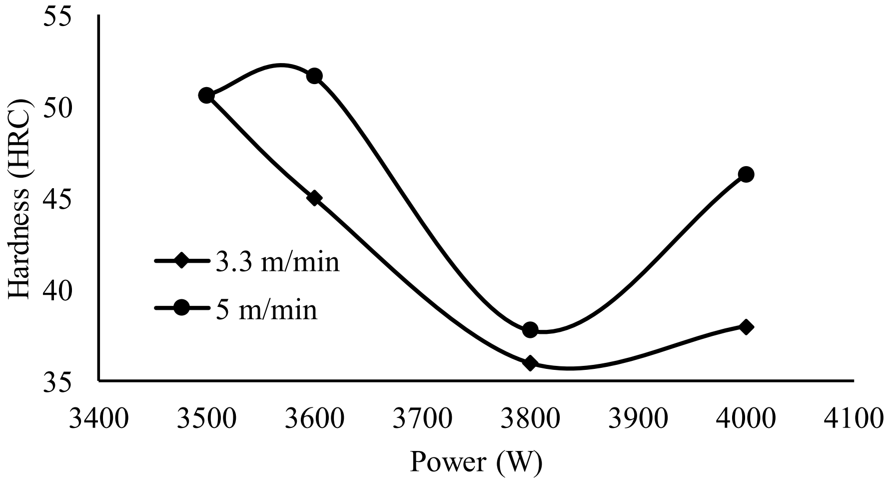


Fig. 4. Hardness on the machined surface of the laser machined samples, with reference to the applied power and laser travel speed.

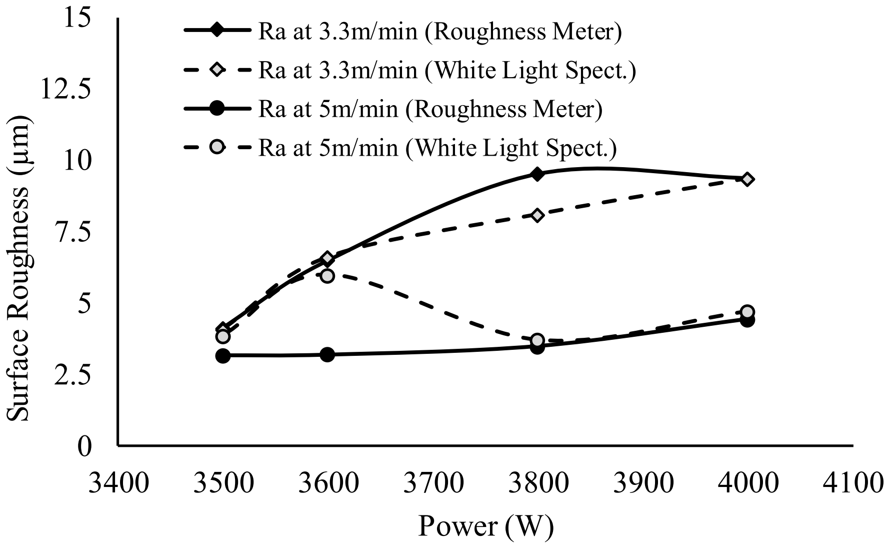


Fig. 5. Effect of laser power on surface roughness.

Figure 6 shows the 3D profile of the surfaces machined at different combinations of laser power and travel speed. The surface wear scars are similar to valley tracks with sharp peaks reflecting destructive surfaces. Surface profile was rougher at slow travel than the higher travel speed. The fusion rate of metal remains maximum at low travel speed and leads to form uneven recast layer. Further, layer adjunct to recast surface are also highly induced towards catastrophic in diffusion rate.

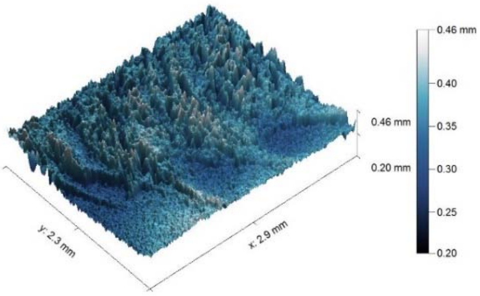
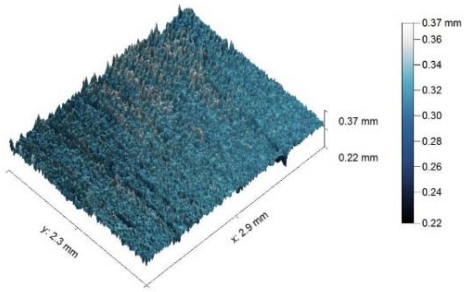
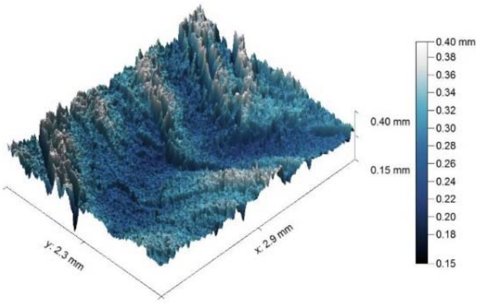
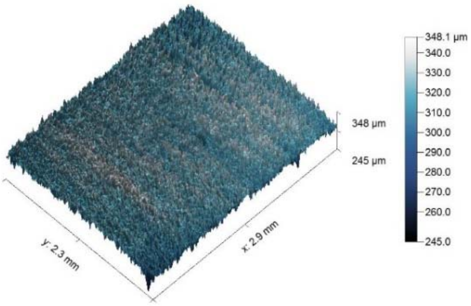
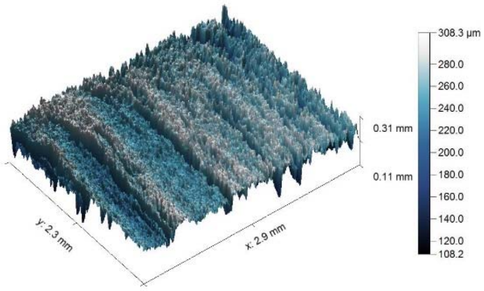
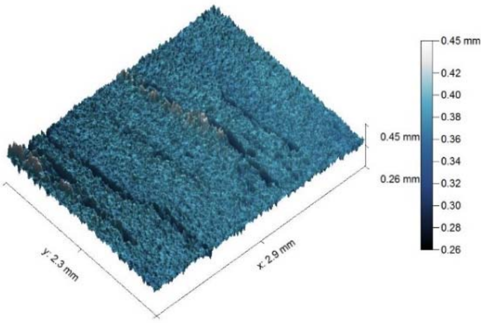
	3.3 m/min	**5 m/min**
3600W		
3800W		
4000W		

Fig. 6. 3D profiles of the laser machined Inconel 718 samples, indicating surface roughness and wear scars.

Figures 7 and 8 are used to compare the surface topographies of the laser machined Inconel 718 superalloy. The surface topography is having three main regions namely; (i) cutting zone; (ii) reflection zone and (iii) dross zone. Surface topography of the material machined at 3800W has proved that the variation in dross is due to the laser cutting speed and the intensity of the laser impingement. At slow speed, the spinning effect is produced with fused metal and the direction of the laser source varies at reflection and dross zone subsequently. Thus, the variation in cutting zone varies with respect to laser travel speed.

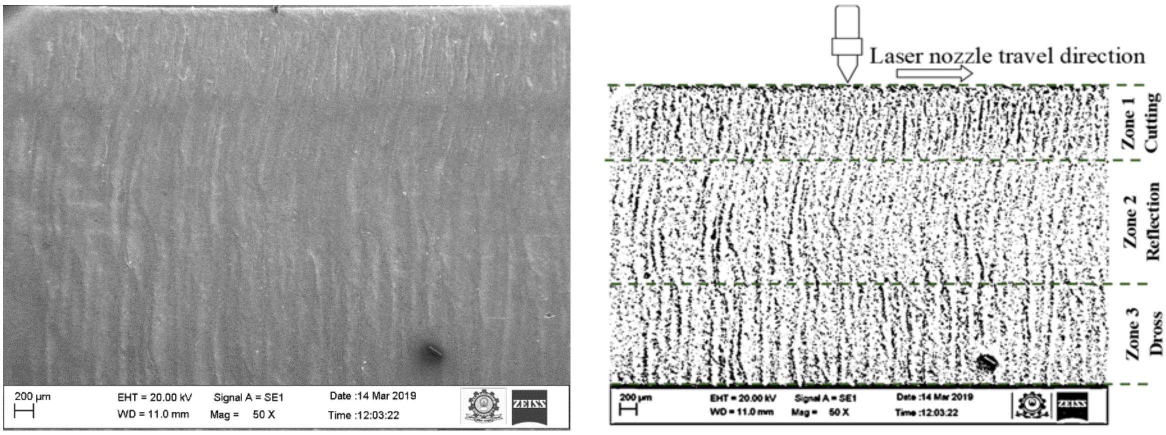


Fig. 7. Microanalysis on the machined surface of Inconel 718 alloy at 3800W and 5 m/min.

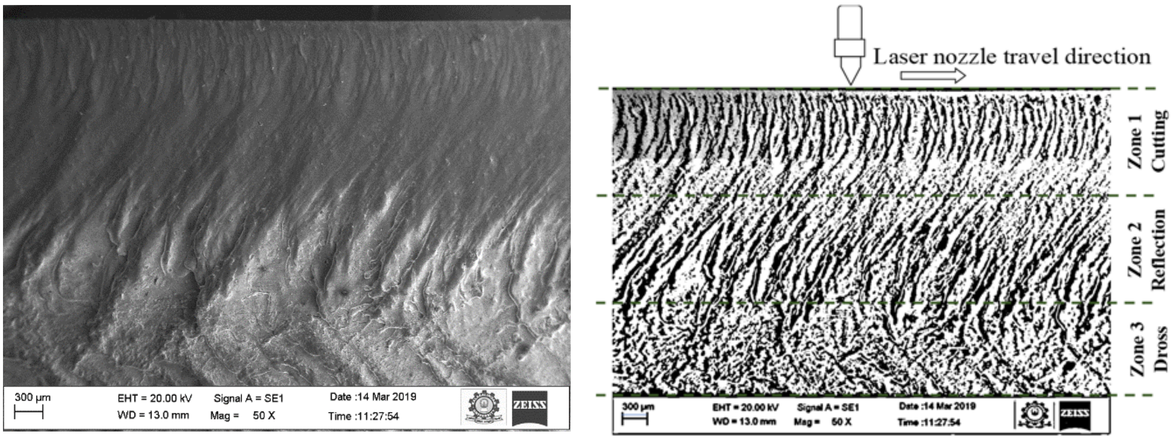


Fig. 8. Microanalysis on the machined surface of Inconel 718 alloy at 3800W and 3.3 m/min.

Figure 9 shows the wear morphology observed at higher magnification of the sample machined at same respective conditions. The material has undergone drastic thermal fusion and metal splats are formed. It is a form of irregular machining that yields rough surface due to rapid movement of the laser beam. However, at same laser power with 5m/min has produced better surface topography than 3.3 m/min. Similar observation are made for other power conditions. Similar results are obtained with 3500W and 4000W laser power for different nozzle travel speed. To study metallurgical changes on the machined surface, higher magnification electron images have been obtained and analysed. The nitrogen gas purged during cutting prompts rapid solidification of fused material and formation of dendrite structure.

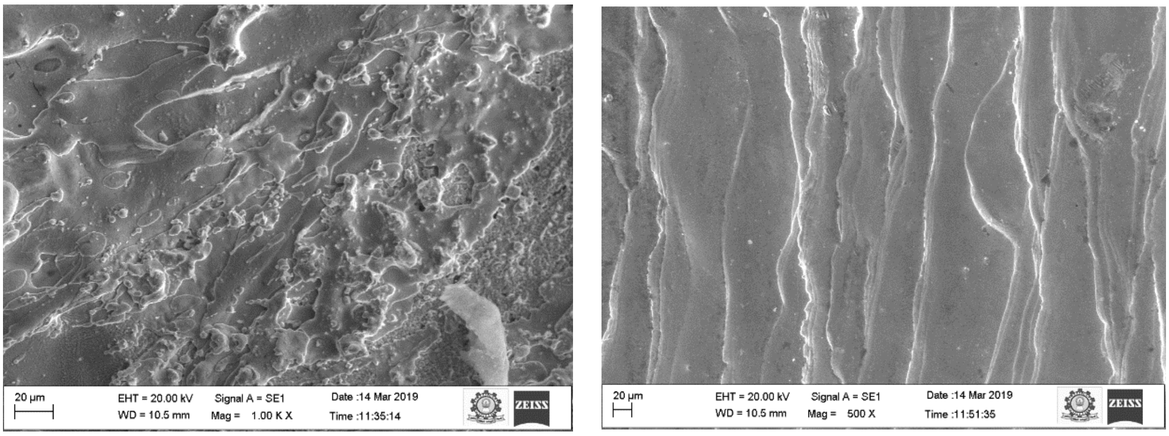
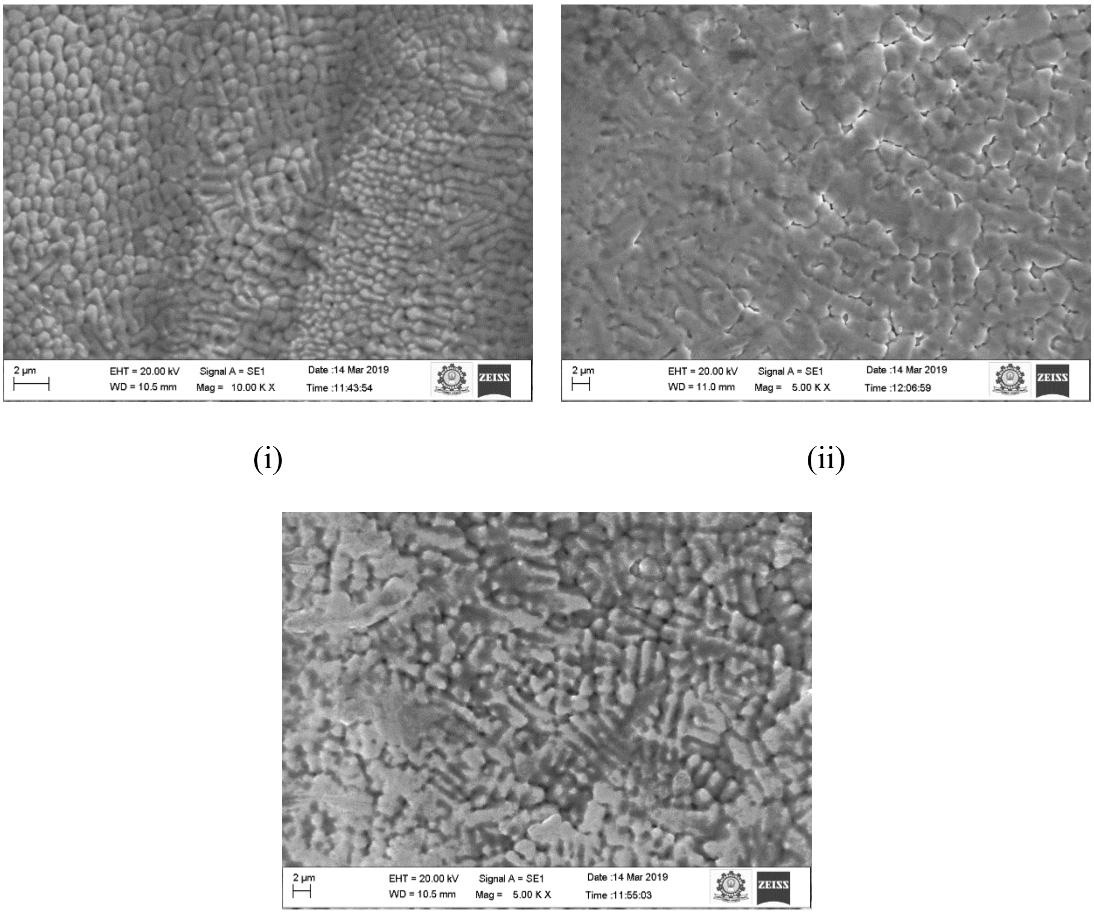


Fig. 9. Wear morphology of the machined surface of Inconel 718 alloy at 3800W at 3.3 m/min and 5m/min.



(i) (ii)

(iii)

Fig. 10. SEM image of Inconel718 indicating metallurgical changes involved during laser cutting at a power source and travel speed of (i) 4000 W and 5 m/min, (ii) 3800 W and 5 m/min; and (iii) 3500 W and 5 m/min respectively.

Figure 10, represents the metallurgical changes involved during rapid solidifications. The metallurgical changes revealed columnar dendrite structure (with average dendrite size 0.5-1 μm) from austenitic phase. Intensity of the heat source is less at a minimum laser power of 3500W and dendrite formation was also controlled. It has also influenced to produce best qualified surface finish in the range of 3.1-4.1 microns.

4. Conclusions

The results of experimental investigation on CO_2 laser machining of Inconel 718 superalloy are reported in this paper. The following conclusions can be drawn from this research work:

1. Laser power and travel speed significantly influenced kerf wall inclination and material removal rate.
2. Surface roughness of the laser machined surface was improved with a minimum laser power of 3500W in the range of 3-4.7μm.
3. Metal diffusion during machining has been highly influenced by travel speed. At 3800W with 5 m/min has produced good surface compared to other cutting conditions.
4. The rapid solidification of diffused metal has led to form dendrite structure.
5. All the above, laser cutting with slow travel speed at optimal input power can be used to machine Inconel 718 superalloy type DTM material with good geometric accuracy and surface quality.

References

1. A.P. Mouritz, Introduction to Aerospace Materials, Woodhead Publishing Limited, Cambridge UK, 2012.

2. Y.B. Guo, W.Li, I.S. Jawahir, Surface integrity characterization and prediction in machining of hardened and difficult – to – machine alloys; a state-of-the-art research review and analysis, Mach Sci Technol, 13 (2009) 437 – 70.

3. D.G. Thakur, B. Ramamoorthy, L. Vijayaraghavan, Study on the machinability characteristics of superalloy Inconel 718 during highspeed turning, Mater Des, 30 (2009) 1718–1725.
4. E. Haddadi, M. Moradi, A.K. Ghavidel, A.K. Ghavidel, S. Meiabadi, Experimental and parametric evaluation of cut quality characteristics in CO2 laser cutting of polystyrene, Optik, 184 (2019) 103–114.
5. M. Sharifi, M. Akbari, Experimental investigation of the effect of process parameters on cutting region temperature and cutting-edge quality in laser cutting of AL6061T6 alloy, Optik, 184 (2019) 457-463.
6. Y. Xing, L.Liu, X. Hao, Z. Wu, P. Huang, X. Wang, Micro-channels machining on polycrystalline diamond by nanosecond laser, Opt Laser Technol, 108 (2018) 333 – 345.
7. B.S. Yilbis, The laser cutting process: Analysis and Applications, Elsevier, USA, 2017.
8. A. Cekic, D.B. Hajdarevic, M. Kulenovic, A. Omerspahic, CO2 Laser Cutting of Alloy Steels using N2 Assist Gas, Procedia Engineer, 69 (2014) 310 – 315.
9. B.T. Rao, R. Kaul, P. Tiwari, A.K. Nath, Inert gas cutting of titanium sheet with pulsed mode CO2 laser, Opt Lasers Eng, 43 (2005) 1330–1348.
10. A. Riveiro, A. Mejías, R. Soto, F. Quintero, J. del Val, M. Boutinguiza, F. Lusquiños, J. Pardo, J. Pou, CO2 laser cutting of natural granite, Opt Laser Technol, 76 (2016) 19–28.
11. A. Parthiban, M. Chandrasekaran, V. Muthuraman, S. Sathish, Optimization of CO2 Laser Cutting of Stainless-Steel Sheet for Curved Profile, Mater Today - Proc, 5 (2018) 14531–14538.
12. R. Karthikeyan, V. Senthilkumar, M. Thilak, A. Nagadeepan, Application of Grey Relational Analysis for Optimization of Kerf quality during CO2 laser cutting of Mild Steel, Mater Today - Proc, 5 (2018) 19209–19215.

13. A. Hascalık, M. Ay, CO2 laser cut quality of Inconel718 nickel – based superalloy, Opt Laser Technol, 48 (2013), 554 – 564.

14. P.K. Shrivastava, A.K Pandey, Optimization of Machining Parameter during the Laser Cutting of Inconel-718 Sheet Using Regression Analysis based Particle Swarm Optimization Method, Mater Today - Proc, 5 (2018) 24167 – 24176.

15. D.G. Ahn, K.W. Byun and M.C. Kang, Thermal Characteristics in the Cutting of Inconel 718 Superalloy Using CW Nd:YAG Laser, J Mater Sci Technol, 26:4 (2010), 362-366.