

Numerical Analysis of Laser Preheating for Laser Assisted Micro Milling of Inconel 718

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Abstract. Micro milling of super alloy materials such as nickel based alloys such as Inconel 718 is challenging due to the excellent of its mechanical properties. Therefore, new techniques have been suggested to enhance the machinability of nickel based alloys by preheating the workpiece's surface to reduce its strength and ductility. The prediction of fluctuated temperature distribution generated by pulsed wave laser in laser assisted micro milling (LAMM) is crucial. The selection of processing parameter by minimize the effect on the processing characteristic is decisive to ensure the machining quality is high. Determining the effect of heat generated in underneath surface is important to make sure that the cutting tools are able to cut the material with maximum depth of cut and minimum defects in terms of tool wear and tool life. In this study the simulation was carried by using Ansys APDL. In order to confirm the actual and distribution irradiation of temperature from simulation, an experimental was done to validate the results. The experiment was conducted by using Nd:YAG laser with wavelength 1064 nm.

Introduction

Laser technology has increased the requirement due to its demands in material processing and manufacturing. Laser material processing includes various applications like cutting, welding, drilling, cladding and laser assisted machining (LAM). In LAM, laser is used to preheat the workpiece material before milling process. It pursues to reduce the material strength. However, important to control the preheating temperature to avoid the significant changes on mechanical properties and microstructure on the irradiation area especially on Inconel 718 nickel based alloy material.

Prediction on laser irradiation by using finite element analysis (FEA) software has widely reported in many researchers. Saodari and Majumdar [1] were using FEA to analyze the heating rate, heat affected zone and the shape and size of the molten pool using Gaussian laser beam. It also analyse the effect of mesh size on heat distribution. Mohid et al. [2] we're investigating the effect of absorptivity, A and constant, K value on pulsed laser by using Gaussian beam distribution. The investigation shown that the A and K value has a significant effect on the determination of melting pool and heat effected zone (HAZ) pattern. Otherwise, Ren et al. [3] was using FEA to analyses the effect of heat generated on residual stress during laser shock processing.

In LAM, the determining of melting pool and HAZ region create by laser irradiation is crucially important. It is intended to confirm that the selection of laser beam-to-cutting tool distance and depth of cut is able to reduce cutting force, tool wear and increase tool performance. Mohid et al. [4] was predicting the temperature distribution on pulsed laser mode by using ANSYS APDL software. From the result, it was concluded that by using laser power 140 W laser beam-to-cutting tool distance between 0.8 to 1.9 mm and depth of cut is 0.005 to 0.117 mm respectively. Yang et al. [5] was developed 3D transient finite element

method to predict the depth and width of HAZ on TiAl4V material. It was found that the laser parameter especially laser power has strongly influenced on depth and width of HAZ. In addition, Kim and Lee [6] were using FEA to predict the preheating temperature on Inconel 718 and AISI 1045 material to obtain the depth of cut.

Thus, it is important to determine the possible distance between laser beam-to-cutting tool and depth of cut with minimum effect on cutting tool and workpiece properties changes. Besides that, laser irradiation has a significant role important in determining the distance and depth of cut. In this study, the FEA model was developed by using ANSYS APDL software to predict the heat distribution and HAZ pattern during laser irradiation. Finally, the appropriate laser beam-to-cutting tool distance and depth of cut will be used in the actual machining process. The result of surface roughness was compared to obtain the effectiveness of laser preheating method. The micro milling experiments were carried out considered the effective cutting tool diameter in 10° tool inclination and the performance of coating in the machining of Inconel 718 nickel alloy.

Numerical Analysis

In the simulation, the heat flux was obtained from equation (1) where A is absorption rate (%), K is intensity distribution constant. S is irradiated surface area (mm^2) and b is the laser beam radius (mm). Mohid et al. [2] reveal that the K value of Nd:YAG pulsed laser is 2.5. Meanwhile, the value of A might be changed due to material surface conditions and in this study the value of A for Inconel 718 workpiece are 40% with the impression that the heat was generated by laser on the workpiece surface only. Therefore, the heat flux on the internal can be neglected. For the calculation of the moving heat flux, the position and magnitude of the heat flux are confirmed every time. The distribution of heat flux is depending on the pulsed length time. When the heat flux moved to the next step with different element, the latter distributed heat flux step is deleted. The moving laser beam heat source with depending on pulsed length is applied in order to simulate laser pulsed scanning as shown in Fig. 1 (b). When $t=t_o$, the laser beam was moving in the element between x_1 and x_2 while when $t=t_o+t_p$, it moving from X_1+1 to X_2+1 element. The time t_p (ms) at every element can be expressed as equation (2).

$$q(x, y) = \frac{AKP}{S} \exp\left[-\frac{x^2+y^2}{b^2}\right] \quad (1)$$

$$t_p = \frac{x}{V_s} = 1 \text{ Step} \quad (2)$$

Where x is the element size in the x axis direction, and V_s (mm/min) is the scanning speed. Basically, when the element sizes sufficiently small, the moving of the laser beam will have precision and recorded heat distribution is more accurate. Several assumptions must be considered to facilitate the simulation work. The assumption consists of (i) the material is homogenous (ii) simulation is work on transient mode and (iii) the key hole formation can be neglected.

Methodology. Model Development, Validation and Laser Assisted Micro Milling

Finite Element Analysis. In this study, the laser inclined 55° is developed to simulate the actual simulation. A finite element analysis (FEA) model with the width, length and thickness of 2 mm, 4 mm and 1 mm respectively was developed. It was prepared in half of the total width to reduce the total number of element and computational processing time. Fig. 1 (a) shows the half model generated using ANSYS software. The total number of element is 70503. To obtain an accurate result, element size in the centre of the model (L1) (scanning path) must be fine compare to conduction area (L2 to L7). Triangle element shape is used due to the conduction process.

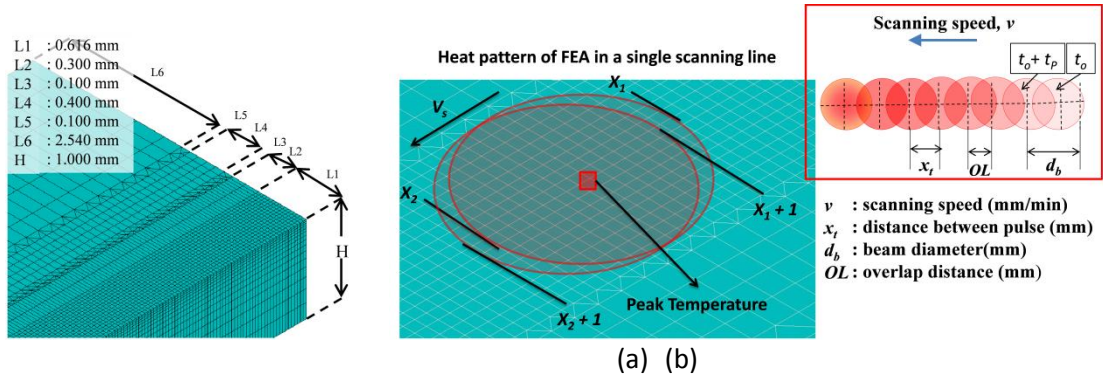


Fig. 1: Mesh and element distribution for FEM model

A three-dimensional finite element model was performed using ANSYS Parametric Design Language (APDL). APDL allows the user to compute the data using transient heat solution, which provides a convenient means of numerical modeling, especially in laser welding processes. In this case, the thermal history of a welded bead is generated by using equation (3) and (4) [7] is required to indicate the accurate thermal distribution during the process. It requires integration between heat conduction with the respect of time. The program is automatically time stepping with consider the different between two point and it also depending on the pulsed length was applied.

$$\text{Thermal conductivity, } K = 0.015x + 11.002 \quad (3)$$

$$\text{Specific heat, } C_p = 0.0002x + 0.4217 \quad (4)$$

Validations. The model can be assumed precise when the depth and width of the melting pool in the numerical simulation are comparable with actual experiment. In this case, the error of less than 10% in melting and HAZ geometry compared to substantial geometry is acceptable to validate the model. The recorded melting temperature in the simulation was ranging from 1250 to 1533 K. It represents the borderline of melting point. The HAZ border lines were defined by face transformation temperature from γ' to γ'' is 800 K.

The actual specimens that exposed to the laser irradiation were cut perpendicular to the scanning direction at the distance of 15 mm from the starting point. The location is basically based on the stability of heat generated and heat absorption into materials during the irradiation process. After that, the specimen has undergone hot mounting process and subsequently through grinding and polishing. Finally, the specimen must immediately be etched with a comprising solution (20 ml HCl + 10 ml HNO₃ + 20 ml H₂O + 10 ml H₂O₂) [8]. Optical microscope is used to measure the melted and heat affected zone.

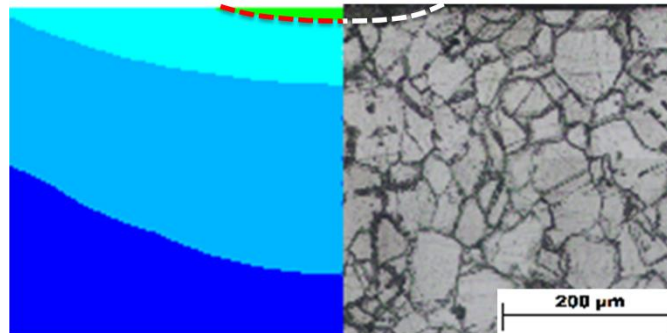


Fig. 2: Comparison of melted zone and HAZ size ($P_{avg} = 5.65$ W, $A = 32\%$ and $K = 2.5$)

In this study, inclination 55° laser was used to validate the model. An average power (P_{avg}) of 4.16 W, laser absorption rate of A 32% and K value of 2.5 were applied into the FEA model in order to validate and compare between actual and simulation. The simulation can be accepted if the percentage error on the melting width and depth is less than 10% as shown in Fig. 2.

Laser Assisted Micro Milling. A AlTiN two flutes coated carbide ball mill with the maximum tip diameter of $300\ \mu\text{m}$ were used to performed linear groove on an Inconel 718 (21-23 HRC) plate. The plate has a thickness of 6 mm. The cutting tool was clamped on air bearing spindle with maximum rotational speed, (N) of 60,000 rpm (Fig. 3). A piezoelectric dynamometer (Kistler type 9317B) with charge amplifiers was used to measure and record the cutting forces data during the machining process. It was connected to the DAQ-Charge B collect the signal and converted it into the data format. Table 1 show the machining parameters used to conduct the experiment. To increase the effectiveness of cutting for ball milling process, the cutting tool was tilted to 10° from Z axis in order to increase the effective cutting diameter. In the case of LAMM, the laser beam-to-cutting tool distances, X_{t-b} was fixed at $600\ \mu\text{m}$ in order to avoid the laser beam irradiate into the cutting tool. Furthermore, the worn tool was inspected using a scanning electron microscopy (SEM).

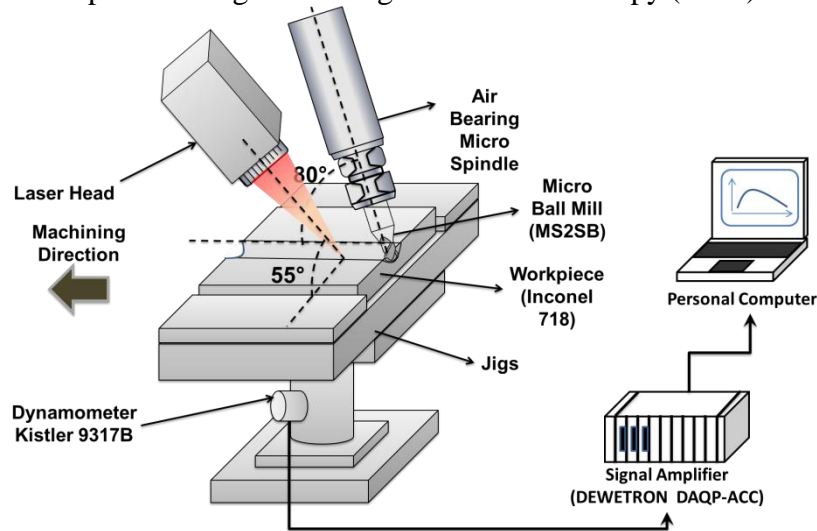


Fig. 3: Machining setup for micro milling process

Table 1: Machining parameters

P_{avg} (w)	v_f (mm/min)	N (rpm)	θ_t ($^\circ$)	t_c (mm)	ϕ_{t_effec} (mm)	v_c (mm/min)	f (mm/tooth)	X_{t-b} (μm)
4.16	70	7500	10	0.020	0.193	4.5	0.0050	600
		12500		0.020	0.193	7.6	0.0030	
		15000		0.020	0.193	9.1	0.0020	
		17500		0.020	0.193	10.6	0.0020	
		7500		0.040	0.293	5.6	0.0050	
		12500		0.040	0.293	9.4	0.0030	
		15000		0.040	0.293	11.3	0.0020	
		17500		0.040	0.293	13.1	0.0020	

Result and Discussion

Numerical Analysis. Laser spot-to-cutting tool distance is determined by referring to the temperature generated at the centre irradiation line in FEA. Pre-heating process using pulsed wave laser creates massive fluctuation of temperature value as shown in Fig. 4 (a). Cooling time between pulsed was sufficient for specimen to chill down. Therefore, equation 5 can be used to determine the laser spot-to-cutting tool distance (μm). Cooling period from peak temperature to deformation temperature of Inconel 718 was recorded as a time different, T_d (min). Total cooling time taken must be multiplied by the scanning speed, V_s to obtain the laser spot-to-cutting tool distance.

$$\text{Laser - to - tool Diastance, } x_{t-b} = T_d(v_s) \quad (5)$$

Based on the calculation, with applied P_{avg} is 4.16 W and constant t_p and A of 1 ms and 32 % respectively, the laser spot-to-cutting tool distance was determined approximately 240 μm . Meanwhile, the distance can be increased when the laser power increase due to the increment of preheated temperature generated during the laser irradiation process. Mohid et al. [4] revealed that higher laser power and pulsed width will generate higher temperature at the workpiece surface.

In addition, determination of initial temperature on the tool engagement is crucially important to identified as shown in Fig. 4 (b). This is intended to ensure that the preheating temperature will not reduce tool performance. This argument is supported by Kim and Lee [6] reveals that with applying temperature between 650 to 900 $^{\circ}\text{C}$ will reduce the material strength significantly. Otherwise, Rahim et al. [9] shows the prominence effect on cutting force and tool wear define by laser spot-to-cutting tool distance and its importance to control the irradiation temperature. However, in this study the laser beam-to-cutting tool distances, X_{t-b} was fixed at 600 μm in order to avoid the the laser beam irradiate into the cutting tool and the workpiece temperature during cutting process was obtain approximately 400 K.

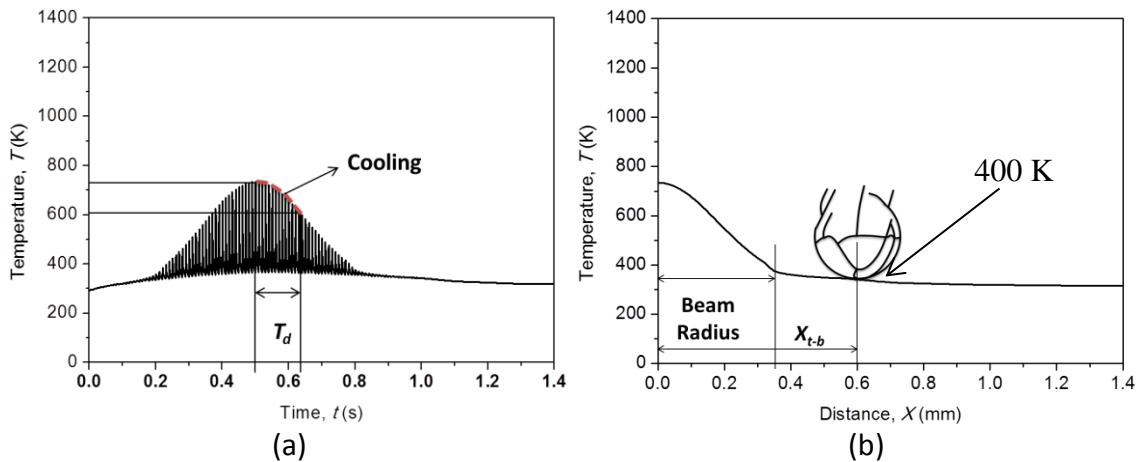


Fig. 4: Result of temperature distribution when applied $P_{avg} = 4.16$ W, $T_p = 1$ ms and $v = 70$ mm/min (a) recorded temperature at the centre irradiation line (b) determination of initial temperature at the first contact of cutting tool

Fig. 5, when the cutting tool starts cutting workpiece temperature is approximately 450 K and the laser beam-to-cutting tool distance, X_{t-b} is 600 μm . Shokrani et al. [10] states that the carbide material will experience a reduction in strength when heated above 600 K. Thus, temperature controls are important to ensure the strength of the cutting tool material was unchanged. In addition, temperature control is also important in ensuring the coating material

does not suffer delamination caused by temperature generated by laser. This is to certify that the cutting tools are at the high performance. In this case, the appropriate depth of cut is very shallow due to the lower laser power applied. Otherwise, no significant effect of preheating temperature was observed in the underneath surface in terms of HAZ and microstructure changes. In this case, the depth of cut is determining determined by the affiliation between the temperature distributions on FEA data (Fig. 5) and phase transformation temperature. The depth of cut was obtaining approximately 20 μm .

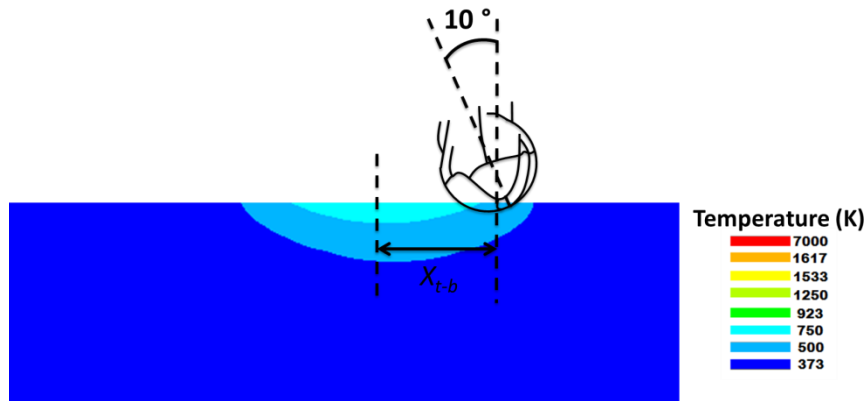


Fig. 5: Prediction of tool location and the depth of cut when using $P_{avg} = 4.16 \text{ W}$, $T_p = 1 \text{ ms}$, $v = 70 \text{ mm/min}$, $A = 32\%$

Surface Roughness. The cutting tests are performed in machining with ball end mill at angle 10° from Z axis in the direction of cutter feed. Ductile fracture was observed with an increase the spindle speed, cutting speed and depth of cut. Fig. 6 shows the comparison between conventional and LAMM process. In all cases, the cutting and spindle speed gives a prominent effect on the formation of undeforms chip thickness. Undeformed chip thickness increases in the down cutting process from the centre to the left side of the groove and decrease in the up cutting process from right side to centre groove. Ono and Matsumura [11] show the undeformed chip thickness are in ductile cutting condition in actual cutting due to a large undeformed chip thickness induced by dynamic displacement of the cutter. In addition, at the bottom groove, rubbing phenomenon was observed and the width of feed mark was increase significantly when the cutting and spindle speed increase.

Overall, LAMM show improvement in the surface texture and the formation of undeformed chip thickness. In case of depth 20 μm showed the effectiveness of laser preheating in the reduction of undeformed chip thickness compared to conventional cutting. While, when the depth of cut increase to 40 μm no significant was observed in both conditions. This phenomenon is due to the effect of the laser preheating does not reach at a depth of 40 μm . Based on the FEA on Fig. 5 shows the effective depth of cut when using P_{avg} 4.16 W is approximately 20 μm . In order to produce batter surface texture in higher depth of cut, the laser power must be increased in line with depth of cut applied. However, the preheating temperature must be controlled effectively to avoid large microstructure changes and reduce cutting tool performance.

In the other side, the formation of feed mark also increases when the cutting and spindle speed increase. This is proved when the surface roughness was measured by using atomic force microscopy (AFM). The data was recoded and graph was plotted as shown in Fig. 7. Good agreement was found in LAMM method where it produces a fine surface finish compares to the conventional cutting. The effective laser beam-to-cutting tool distance and lower power average create appropriate preheating temperature to reduce the yield strength in

depth of cut, t_c 20 μm . The changes will produce finer cutter mark at the bottom groove. Otherwise, lower spindle and cutting speed also produce batter surface roughness. According to Kiswanto et al. [12] feed rate and machining contribute the significant effect on the surface roughness and burr formation. Longer machining will effect on the tool condition and performance due to wear or delamination. Therefore, it drives resulting poor surface finish produce at cutting groove.

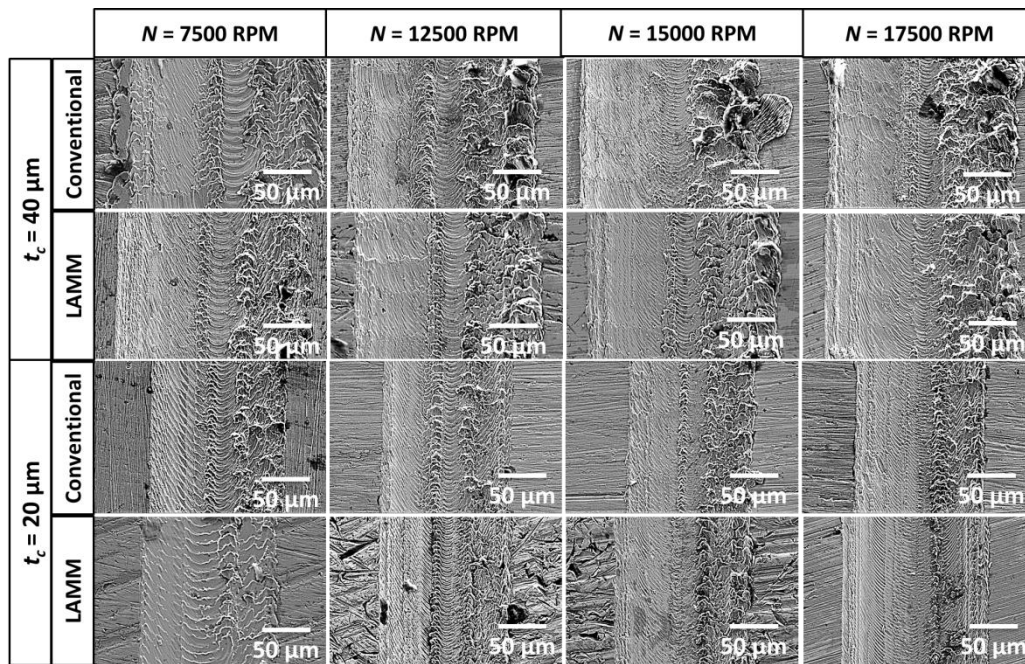


Fig. 6 : SEM image of groove after cutting process with 500X magnification

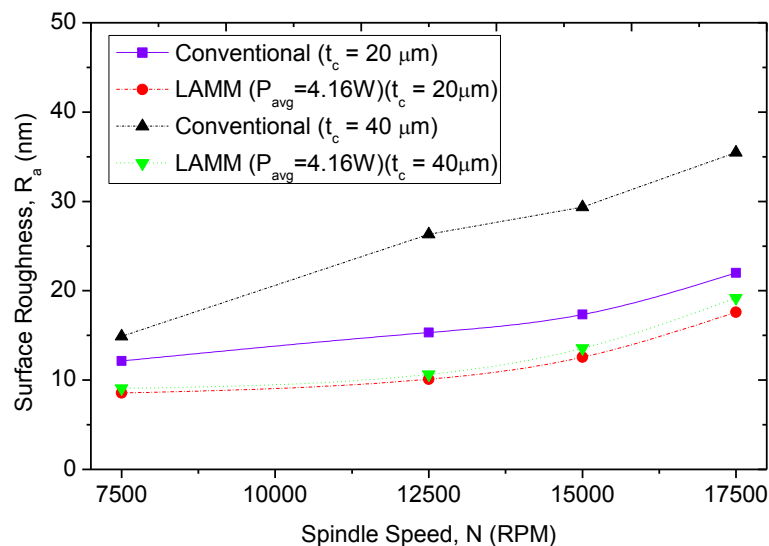


Fig. 7: comparison of surface roughness between LAMM and conventional cutting process.

Conclusion

In the present work, FEA used to predict the laser beam-to-cutting tool distance, X_{t-b} and depth of cut, t_c . Furthermore, the machining performance of Inconel 718 was compared conventional and LAMM condition. The following conclusions can be drawn from this work:

- i) Good prediction on laser beam-to-cutting tool distance and depth of cut is crucially important to identify to enhance the machinability of Inconel 718.
- ii) The appropriate laser beam-to-cutting tool distance when applied P_{avg} 4.16 W, scanning speed, v 70 mm/min and pulsed width, t_p 1 ms is approximately 250 μm . However, to avoid laser irradiate into cutting tool due to beam diameter size is 700 μm the distance was fix to 600 μm . Nevertheless, it is able to improve surface quality.
- iii) It was proven that LAMM technique significantly improved the surface roughness and reduces the undeformed chip thickness.
- iv) Workpiece preheating method can be able to reduce the ductility and yield strength of Inconel 718.

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References

- [1] S. Dharani and M. and Pradip, "Finite element analysis of laser irradiated metal heating and melting processes," *Optics & Laser Technology*, vol. 42, pp. 855-865, 2010.
- [2] Z. Mohid, N. M. Warap, M. I. S. Ismail, R. Ibrahim and E. A. Rahim, "Determination of Heat Flux Intensity Distribution and Laser Absorption Rate of AISI D2 Tool Steel," *Applied Mechanics and Materials*, Vols. 465-466, pp. 730-734, 2014.
- [3] X. D. Ren, Q. B. Zhan, S. Q. Yuan, J. Z. Zhou, Y. Wang, N. F. Ren, G. F. Sun, L. M. Zheng, F. Z. Zhai, H. M. Yang and a. W. J. Dai, "A finite element analysis of thermal relaxation of residual stress in laser shock processing Ni-based alloy GH4169," *Materials and Design*, vol. 54, pp. 708-711, 2014.
- [4] Z. Mohid, N. M. Warap, S. Hassan, M. I. S. Ismail, R. Ibrahim and a. E. A. Rahim, "Numerical Analysis of Laser Heating for Laser Assisted Micro Milling Application," *Applied Mechanics and Materials*, Vols. 465-466, pp. 720-724, 2014.
- [5] Y. Jihong, S. Shoujin, B. Milan and Y. and Wenyi, "Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy," *Journal of Materials Processing Technology*, vol. 210, pp. 2215-2222, 2010.
- [6] K. Dong-Hyeon and L. Choon-Man, "A study of cutting force and preheating-temperature prediction for laser-assisted milling of Inconel 718 and AISI 1045 steel," *International Journal of Heat and Mass Transfer*, vol. 71, pp. 254-274, 2014.
- [7] M. Anderson, R. Patwa and Y. C. Shin, "Laser-assisted machining of Inconel 718 with an economic analysis," *International Journal of Machine Tools & Manufacture*, vol. 46, pp. 1879-1891, 2006.
- [8] W. Hongjie, I. Kenji, T. Makoto and I. and Akio, "Microstructure of Inconel 718 alloy subjected to rapid thermal and stress cycle - joint performance controlling factor in friction welding of Inconel 718 alloy," *Welding International*, vol. 26, no. 2, pp. 152-158, 2009.
- [9] E. A. Rahim, Z. Mohid, N. M. Warap, M. R. Ibrahim and a. M. I. S. Ibrahim, "A Prediction of Laser Sport-to-Cutting Tool Distance in Laser Assisted Micro Milling," in *International Conference of Micro Manufacturing*, Singapore, 2014.
- [10] A. Shokrani, V. Dhokia and a. S. Newman, "Environmentally conscious machining of

difficult-to-machine materials with regard to cutting fluids," *International Journal of Machines Tools & Manufacture*, vol. 57, pp. 83-101, 2012.

- [11] O. Takenori and M. and Takashi, "Influnces of tool inclination on brittle fracture in glass cutting with ball end mills," *JOURNAL OF MATERIALS PROCESSING TECHNOLOGY*, vol. 202, pp. 61-69, 2008.
- [12] G. Kiswantoa, D. L. Zariatina and a. T. Ko, "The effect of spindle speed, feed-rate and machining time to the surface roughness and burr formation of Aluminum Alloy 1100 in micro-milling operation," *Journal of Manufacturing Processes* , 2014.