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Investigation on Laser Assisted Micro Ball Milling of Inconel 718

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Abstract. Micro milling of super alloy materials such as nickel based alloys 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 pre-heating the workpiece's surface to reduce its strength. Determining the processing parameters and their effects to the processing characteristics are crucially important. However, not only the micro-milling parameters need to be considered, but the pre-heating parameters are also need to take into consideration as well. These parameters are expected to improve the machinability. In this study, the experiment of LAMM in Inconel 718 was conducted with considering laser power, cutting speed, depth of cut, feed rate and laser-to-cutting tool distance. From the result, the effectiveness of laser assisted and cutting parameter in term of cutting force and tool wear was identified by comparing between conventional and LAMM. Finally, the optimum range of machining parameters can be determined.

Introduction

Inconel 718 is categorized as super alloy or nickel base alloy materials. It has excellent mechanical properties such as high heat resistance, high material strength, high corrosion resistance and high resistance for chemical degradation. It is widely used in many industries such as aerospace, nuclear and oil and gas to produce turbine component, jet engine, nuclear fuel element and high-strength bolting. However, high challenging involves producing part from this material because of the mechanical properties where it can increase the tool wear and shorten tool life.

Appropriate parameter must be obtained to ensure the machining process in the higher performance to produce the micro part and the high machining accuracy can be produces. Arif et al. [1] was investigated the effectiveness inclination of micro tool ball mill and it was reveal that lower feed rate produce rougher surface. Otherwise, Daymi et al. [2] study effect of the workpiece inclination angle on the surface roughness in ball end milling and it highlight the importance of determining effective cutting velocity based on the effective tool diameters in inclination condition. The results also indicate that low cutting speed generate bad surface quality due to much vibration during cutting process. Kuram and Ozcelik, [3] investigated the effect of spindle speed, feed rate and depth of cut on the tool wear. The result specifies that the feed rate give the significant impact on tool wear and the best combination parameter was obtain when using spindle speed (10000 rpm), feed per tooth (0.5 µm/tooth) and depth of cut (50 µm).

The increasing demand on the super alloy especially Inconel 718 was significantly increased in various heavy and micro scale industries. It is a one of the challenging to determine the best method and optimum parameter that will be able to improve the machinability of super alloy materials in the micro ball end mill process. Anderson et al. [4] show the significant benefit of LAM over the conventional machining in turning process where it was reduce 25% of total cutting energy and increase tool life up to 200%. Navas et al. [5] also proved that with applying laser preheating method can reduce the yield strength of material and also reduces the cutting force.

In this study, micro milling experiments were carried out to investigate the influence machining parameter of the micro milling process with considered the effective cutting tool diameter in 10° tool inclination and the performance of coating in the machining of Inconel 718 nickel alloy. Additionally, wear mechanism and effect of reduction of tool diameter on machine slot geometry was discussed. Finally, result from these investigations will be used in a LAMM to identify the effectiveness of laser preheating in the micro milling of Inconel 718.

Methodology. A AlTiN two flute coated carbide ball mill with maximum tip diameter of 300 µm was used to performed linear groove on 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. 1). 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. 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 as shown in Fig. 2. In the case of LAMM, the laser beam-to-cutting tool distances, $X_{t\text{-}b}$ was fixed at 600 µm in order to avoid the the laser beam irradiate into the cutting tool. Furthermore, the worn tool was inspected using a scanning electron microscopy (SEM).

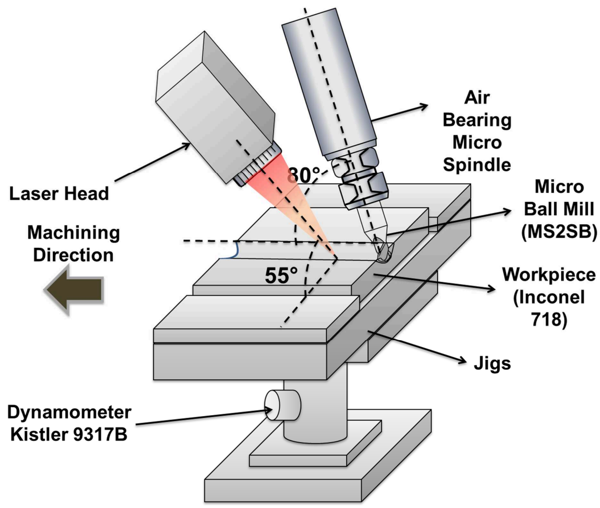

Fig. 1: Machining setup for micro milling process

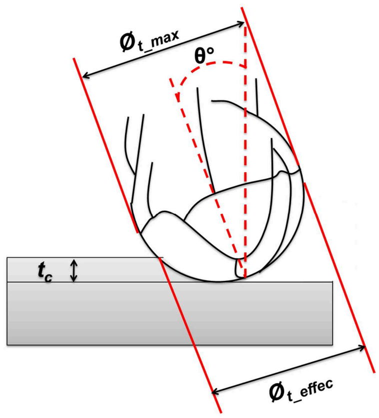

Fig. 2: Tool orientation with 10° inclination

The machining parameters were described in Table 1. The cutting speed (v_c) can be calculated by considering the effective cutting tool diameter ($\emptyset_{t\_effect}$) at 10° inclination from Z axis and spindle speed (*N*) as written in equation 1.

$$v_c = \frac{N.\pi.\emptyset_{t\_effect}}{1000} \quad (1)$$

When the tool orientation angle Θ (Fig. 2) is known, the $\emptyset_{t\_effect}$ can be calculated using equation 2. Equation 3 can be used to measure the feed rate, f (mm per tooth). Where v_f and Z were feed and number of flute respectively.

$$\emptyset_{t\_effect} = \emptyset_{t\_max} \text{ X Sin}[\theta + Cos^{-1}\left(\frac{\emptyset_{t\_max} - 2\,.(t_c)}{\emptyset_{t\_max}}\right)] \quad (2)$$

$$f = \frac{v_f}{N.Z} \quad (3)$$

Result and Discussion

Cutting Force. Figs. 3 and 4 showed the result of cutting force at all tested conditions. The measurements indicated that the trend was depending on spindle speed, *N*, cutting speed, v_c and depth of cut, t_c. Increasing the spindle speed from 12500 to 17500 rpm and depth of cut from 20 to 40 µm subsequently intensified the thrust force, F_z approximately 10%. High rotational of spindle speed generated higher dynamic effect and elastic deformation [6]. Furthermore, the reduction of spindle speed significantly reduces the total thrust force, F_z because of the effectiveness material removal rate and larger tool contact area at slower rotational speed.

Table 1: Machining parameters

P_{avg} (W)	v_f (mm/min)	N (rpm)	Θ_t (°)	t_c (mm)	$Ø_{t\_effec}$ (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	

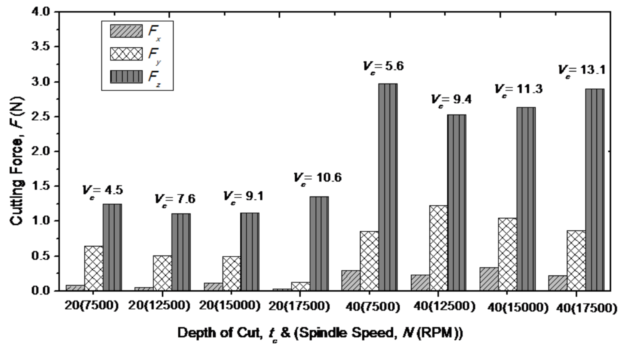

Fig. 3: Result of cutting force in different cutting speed, v_c, depth of cut, $t_c$and spindle speed, N in conventional micro milling process.

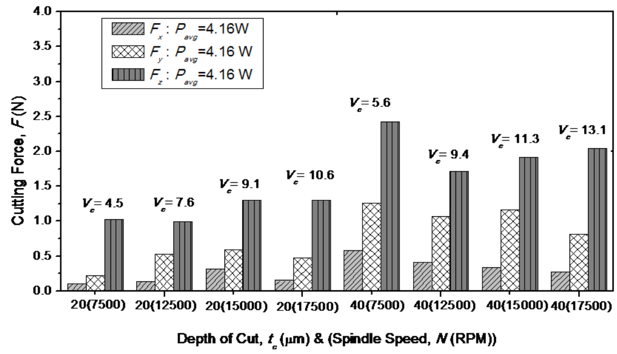

Fig. 4: Result of cutting force in different cutting speed, v_c, depth of cut, $t_c$and spindle speed, N in LAMM process.

On the other side, increase in cutting speed (v_c) from 7.6 to 10.6 mm/min and 9.4 to 13.1 mm/min for t_c 20 and 40 µm produced higher thrust force. Moreover, at the minimum cutting speed, v_c of 4.5 and 5.6 mm/min, the cutting force increased. This trends has comprehensively explained by Arndt [7]. He mentioned that higher cutting speed produces higher shear resistance, however at slower cutting speed, higher temperature was generated thus produced strain hardening effect. It can be noted that, the cutting force was reduced by LAMM compared to conventional machining. It can be suggested that the combination of pre-heating process on the workpiece surface and the generation of heat during the machining process, in turn reduces the shear resistance when the temperature approaching the workpiece melting point temperature.

In general, it can be observed that the recorded cutting force for LAMM condition was much more lower compared to conventional machining as shown in Fig. 5. It indicates that workpiece surface pre-heating process using laser source has significantly impaired the material strength and shear resistance during the machining process. The recorded workpiece temperature during the process was approximately 800K. At this temperature, the workpiece experienced from the deformation phase thus accelerating the thermal softening effect [8]. Furthermore, the workpiece loss its ductility due to the heating and cooling process [9].

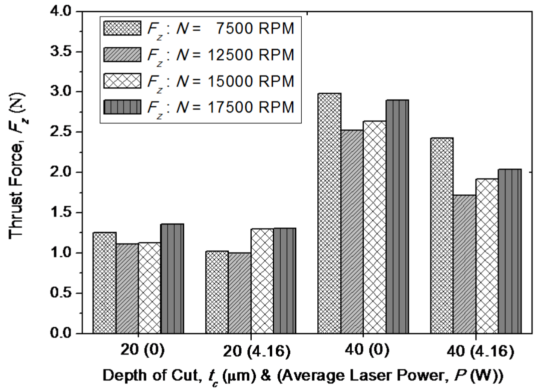

Fig. 5: The comparison between conventional micro milling and LAMM

Tool Wear. It can be seen in Fig. 6 that serious adhesion was occurred in conventional machining process due to the higher ductility of Inconel 718. Meanwhile, at lower spindle speed, the chips tends to adhered and remain on the ball mill cutting edges especially at the higher cutting temperature and larger chip size. According to Kuram and Ozcelik [10], most of the dominant wear mechanism during micro milling of ductile material is abrasion and adhesion. The materials adhered to the cutting tool and built up edge was due to the ductile nature of workpiece material.

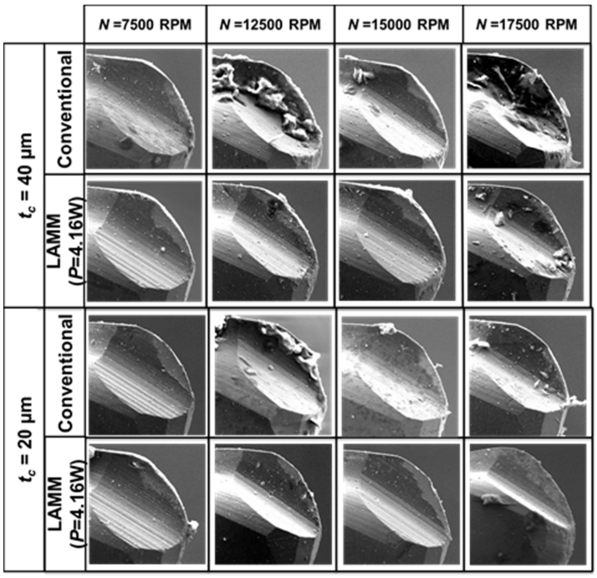

Fig 6: Tool wears

In the case of LAMM, at the applied laser power, P_{avg} of 4.16W was significantly reduced the thrust force. Furthermore, it can be observed that the occurrence of adhesion on cutting tool was minimized. It shows that the preheating process using laser source method is tends to reduce the ductility and yield strength of the workpiece materials. The workpiece material suffered from surface modification at the certain depth. However, this modification demonstrated positive effect where the strain hardening can be avoided during the machining process. It can be observed that the cutting tool coating was delaminated at all tested conditions. Larger delamination area was observed when the depth of cut, t_c increases from 20 to 40 µm. It was due to the increasing of cutting temperature over the melting temperature of coating materials build up edge. Therefore, the appropriate cutting parameters must be well selected to prolong the tool life and improve the cutting performance.

Conclusion

In the present work, the machining performance of Inconel 718 was compared between conventional and LAMM condition. The following conclusions can be drawn from this work:

i) It was proven that LAMM technique significantly improved the cutting force, tool wear and tool life performance.
ii) Workpiece preheating method can be able to reduce the ductility and yield strength of Inconel 718. Furthermore, LAMM can be able to minimizing the quantity of chip adhesion on the cutting tool.

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