INVESTIGATION ON THE INCONSISTENCIES OF CUTTING FORCE WHEN LASER ASSISTED AND HIGH SPEED MICRO BALL MILLING OF INCONEL 718

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ABSTRACT

Inconel 718 is one of the extremely difficult to cut materials at room temperature due to the excessive tool wear and poor surface finish. Previous researchers has reported that the laser assisted machining (LAM) offers the ability to machine Inconel 718 more efficiently by providing the local heating of the workpiece prior to material removal. With increasing material removal temperature using a laser preheating technique from room temperature to 700 °C indicated the reduction of yield and materials strength at a certain depth in underneath surface. However, in laser assisted micro milling (LAMM) preheating temperature shall be reviewed to ensure that the resulting temperature does not worsen the properties of materials. By using higher preheating temperature the material becomes softer and it will result in the cutting process more difficult with increasing cutting force and this promotes higher tool wear. Moreover, the application of the micro ball mill needs deeply study due material removal mechanism is more complicated in groove cutting compare to side cutting. Generally, ball end mill is designed for lower depth of cut. In this study, the cutting force, chip formation and tool wear of conventional and LAMM on Inconel 718 have been measured and compared. Result of preheating technique using a laser beam shows an improvement in cutting force when ball milling of shallow groove. However, inconsistence force results were produced for the deep groove ball milling due to the ineffective materials removal and adhesion phenomenon on the rake surface of cutting tool. It also demonstrated that the application of preheating in softening the workpiece has consequently initiated the formation of connected chip, build up edge and the undeformed chip also piled in the up milling area. Lower preheating temperature is recommended in micro cutting compared to the macro cutting process because of tool size and cutting depth applied. Machining with lower spindle speed is more preferable to prevent the formation of connected chip and build up edge.

Keywords: laser assisted micro milling, inconel 718, chip formation.

INTRODUCTION

The miniaturized part demand is increasing significantly in several industrial fields particularly in medical, electronic, aerospace and automotive industries. It required a rapid manufacturing through high precision component with low cost, large volume and capability on machining advanced material properties. Moreover, to increase the machinability of difficult-to-cut material new approach was introduced with merging preheating method and cutting process. This process can be categories as a hybrid machining process and also well known as hot machining.

Due to the excellent material properties of nickel based alloy, they are widely utilized in important fields of industries. Currently, these materials are being used in gas turbine, the aviation industry, nuclear sectors and many applications where high temperatures are used (Liao *et al*. 2007). However, thermal and mechanical properties of nickel based alloy were limiting the machinability of these materials. The higher material strength, high resistance of the materials which occurs during processing and low thermal conductivity coefficient affect the tool negatively during cutting process. A main issues were identified were given a significant effect on the cutting performance which is localized temperature generated and deformation hardening during cutting contribute to the reduction of cutting tool performance and inconsistency of cutting force. In order to solve the problems, many researchers come up with many suggestions for machining technique such as diversified cooling technique, preheating and coating of cutting tool. Preheating technique most significant where it will reduce the yield strength which is a main cause of the temperature generated during cutting process (Rahim *et al*. 2015) (Mohid,*et al*. 2014).

The demand on nickel based alloy materials in aerospace and power plant industries was increase expressively due to the advantages in terms of strength, high mechanical and chemical properties and high corrosion resistance at elevated temperature. Among nickel based alloy, Inconel 718 is a most widely material used and because of that it has been studied extensively for analysis the surface integrity, machinability and residual stress (Rahim *et al*. 2014). In hot machining process, previous researchers was proved that with increase the preheating temperature to 700 to 900°C it will decrease the material and yield strength. However, with uncontrolled the preheating temperature effectively will cause the material become softer encourage rubbing and ploughing against cutting process.

Various type of heat source as a preheating method was used such as laser, gas flame, electricity and plasma. Each type have an advantage and disadvantages need to be consider as well to maximize the preheating performance and minimize the effect on material

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properties changes due to heating process was using diode laser to conducted experiment on laser assisted turning of Inconel 718 (Anderson *et al*. 2006). Results showed that with an increasing of preheating temperature up to 620°C, specific cutting energy decreases up to 25% and increases of 200-300% in terms of tool life. It also supported by (Shi *et al*. 2008) and (Germain *et al*. 2011). They have revealed that the laser preheating improves the machining performance especially on turning process. The result shows that the cutting force and surface quality were improved when turning of Inconel 718. Moreover, (Wang *et al*. 2003) using plasma as a heat source medium on turning process. It shows an improvement of surface roughness and prolongs tool life approximately 250% and 170% respectively. In another method, (Amin *et al*. 2008) investigated the effectiveness of induction heating by using coil in milling of D2 hardened steel. The result shows the temperature induced by the coil into the workpiece subsequently soften and altered the mechanical properties. Therefore, it provides beneficially in reduction of chatter and vibration phenomenon subsequently improve the surface quality.

In this study, the significant factor that contributes to the inconsistency of cutting force in high speed LAMM and the mechanism of chip formation was investigated. Observation on the chips and the tool after machining was conducted and the effect of preheating temperature on chip formation and cutting force was explained.

METHODOLOGY

A dynamometer Kistler type 9317B with charge amplifiers along with computer were used to measure and record the cutting forces during the LAMM process. The air bearing spindle with the maximum rotational speed of 60,000 rpm was mounted into the micro milling machine. All the laser assisted micro milling tests were carried out on an Inconel 718 plates (21-22 HRC) with 15 mm length, 45 mm width and 6 mm thickness. A commercially available AlTiN coated carbide ball end mills (two flutes) with a diameter of 300 µm was used in cutting tests. The workpiece surface was preheated using a Nd:YAG pulsed laser with 1064 nm. Table-1 provides the parameters for ball milling process. Figure-1 shows the schematic diagram of the LAMM setup. In addition, the air bearing micro spindle was tilted into 80° to increase the effective diameter during cutting. The laser head was inclined to 55° to avoid the deflection of laser irradiation on the cutting tool. The irradiated heat into the cutting tool will alter its properties. In the case of LAMM, the laser beam-to-cutting tool distances, Xt-b was fixed at 600 µm in order to avoid the laser beam irradiate into the cutting tool. Based on FEA analysis, the initial temperature generated by the laser is approximately 700 K (Rahim *et al*. 2015). Furthermore, the chip pattern was inspected using an optical microscope. Meanwhile, the groove quality was observed using a scanning electron microscopy (SEM).

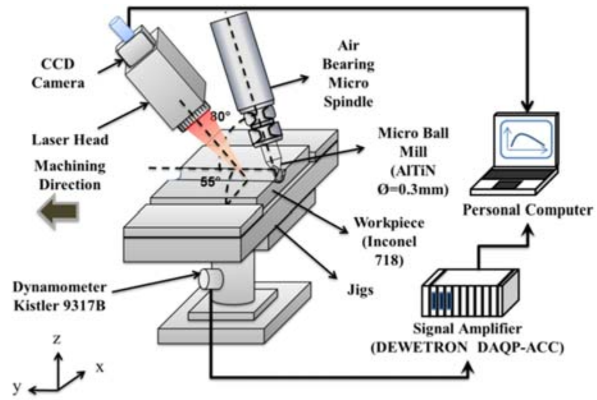

Figure-1. Machine setting layout.

Table-1. Cutting parameters.

Laser Parameters		
Parameters	**Conventional**	**LAMM**
Average laser power, P_{avg} (W)	-	4.16
Laser pulsed width, t_p (ms)	-	1
Pulsed repetition rate, f_p (Hz)	-	100
Laser beam-to-cutting tool distance, D_x (µm)	-	600
Machining Parameters		
Depth of cut, t_c (µm)	20	40
Spindle speed, N x10^3 (rpm)	12.4, 17.4, 22.4	10.0, 14.0, 18.0
Feed, f (µm/flute)	2, 3, 4	
Cutting speed, v_c (m/min)	7.5, 10.5, 13.5	

RESULT AND DISCUSSION

Cutting force

The overall result shows the cutting force was inconsistence between conventional and LAMM, and at various cutting speed, v_c, feed, f , spindle speed, N and depth of cut, t_c. Increasing of cutting speed from 7.5 to 13.5 mm/min subsequently intensified the thrust force, F_z in the range of 5 to 12 %. Higher cutting speed generates higher dynamic effects and elastic deformation (Ucun *et al*. 2013).

Figure-2 shows the result of cutting force at lower depth of cut, t_c of 20µm and at various feeds. The effectiveness of laser preheating was evaluated at the constant t_c and various v_c and f. In the case of f is 2 µm/flute (Figure 2 (a)), the thrust force F_z increases as a cutting speed was increased for both conventional and LAMM. However, the variation of results were recorded for both conventional and LAMM. In some cases, the value of thrust force of LAMM is higher than conventional

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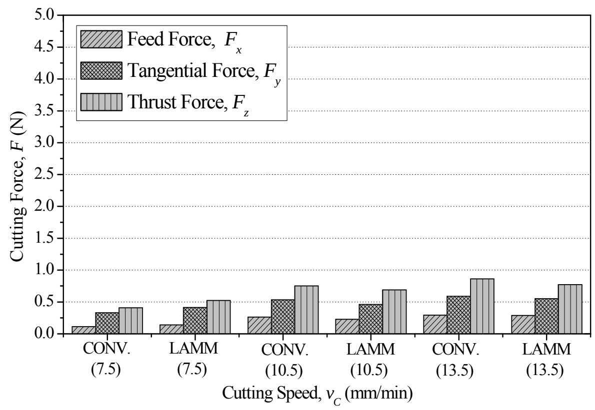
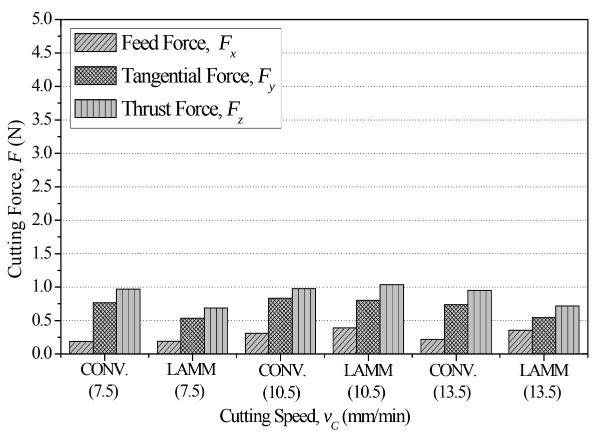
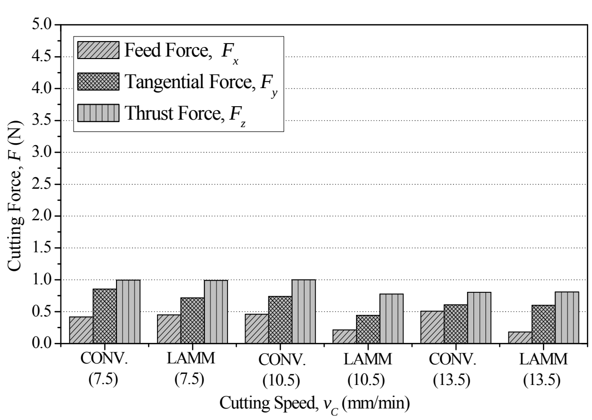
machining. This can be explained by the thinner and connected chips were produced in LAMM. As a consequence, the chip remains in the cutting zone. Furthermore, when the workpiece material is preheated using laser, the softening effect was taken placed and indirectly the chip was adhered on the tool rake face.



(a)Feed, f = 2 µm/flute.



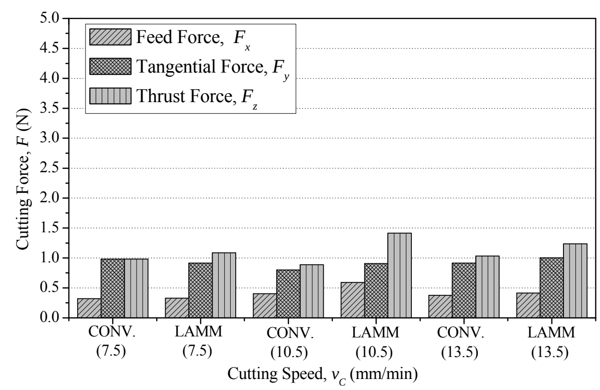
(b)Feed, f = 3 µm/tooth.



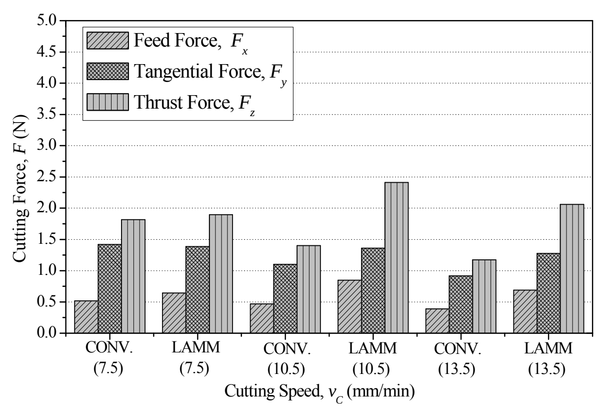
(c)Feed, f = 4 µm/flute.

Figure-2. Cutting force result for depth of cut, t_c = 20µm.

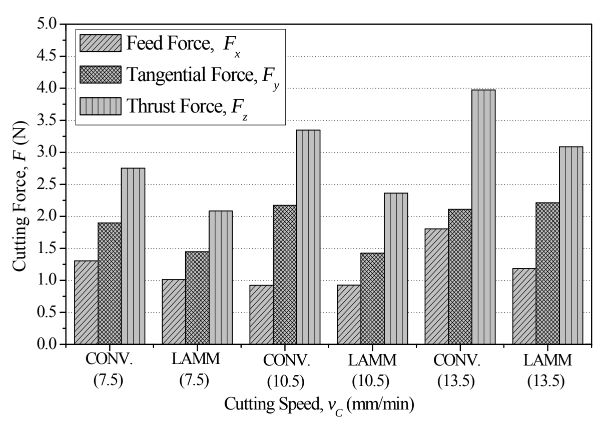
The result cutting force was more consistent as the feed increases. Figure 2 (b) and (c) showed that the effectiveness of LAMM contributes to the reduction of thrust force approximately 5 % for feed, f of 3 and 4 µm/flute. The LAMM was successfully reduces the F_z value as the v_c increases from 7.5 to 13.5 mm/min. Temperature generated by laser and cutting makes an impression for the softening effect on workpiece material.



(a)Feed, f = 2 µm/tooth.



(b)Feed, f = 3 µm/flute.



(c)Feed, f = 4 µm/flute.

Figure-3. Cutting force result for depth of cut, t_c = 40µm.

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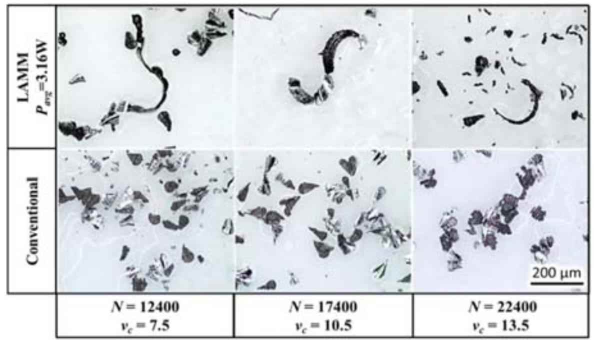
The contradict result was observed at the depth of cut, t_c 40 µm . Most of the result showed the inconsistency of cutting force when compared between conventional and LAMM. The measurement indicated that the increasing of cutting speed consequently increases the average thrust force. Figure 3 (a) and (b) shows that the measured average thrust force produce by LAMM is higher compared to conventional machining. LAMM reduces the yield strength and ductility of Inconel 718 material at the cutting region (Kim & Lee 2014). As a result, the workpiece material becomes softer thus machining process becomes harder (Wang *et al*. 2003). It also creates thinner and connected chip at lower feed. This enable the chips easier to adhere at the tool rake face.There is an evidence showing that the chips were adhered and tangled at the cutting flute. As a result, the cutting tool becomes blunt as the cutting edges were largely covered by the adhesion of chips (Mohid, *et al*. 2014). On the other side, higher feed (Figure-3 (c)) shows that the result of cutting force for LAMM is much better than conventional. It is expected that the increasing of feed produces thicker connected chip, thus enable to evacuate from cutting area.

Chip pattern

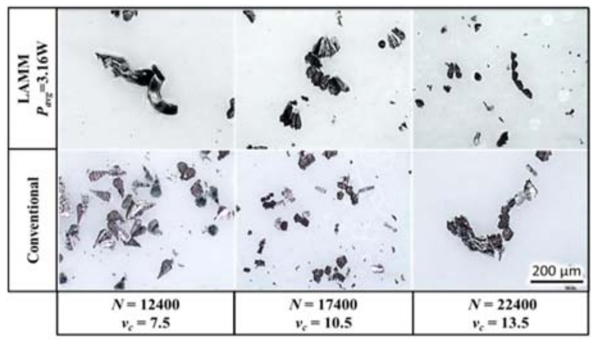
Observation shows that the chips can be categorized into three major categories. Under the lower depth of cut of 20µm, the thinner chips with various shapes were produced. However, increasing the depth of cut to 40µm has consequently increased the ratio of loose arc and connected chips. Further increasing the feed rate at higher depth of cut lead to the creation of conical shape of chip.

Larger and thicker chips lead to poor chips evacuation efficiency. The chips remain in the cutting area and interrupt the cutting mechanism by blocking up the cutting edges. It was found that the chips were being compressed and adhered on the tool rake face and groove side surface.

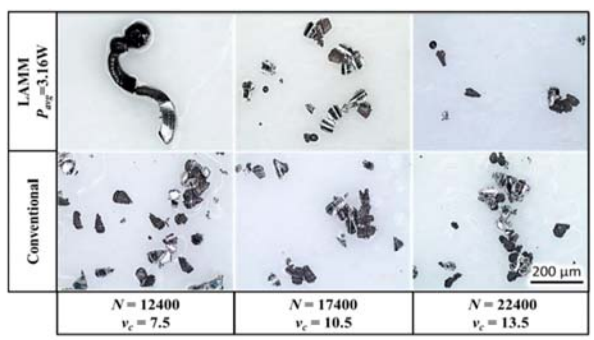
Observation and comparison of chip pattern was conducted between conventional and LAMM as shown in Figures-4 and 5. The creation of connected chip is more severe under the LAMM process due to the thermal softening effect, especially when feed, f increases from 2 to 4 µm/flute in both cutting depth. Meanwhile, dominant loose chip pattern was produced under conventional machining. However, higher feed prones to produce the conical chip with large radius and uneven chip pattern. This phenomena is due to the depth of cut and undeformed chip thickness less than the radii cutting edge. It produces large negative rake angle subsequently more rubbing and compression action was taken place rather than cutting process. In addition, because of the minimum chip thickness effect, when machining at small feed rates, the chip thickness accumulates and the force increases until the chip thickness is greater than the minimum chip thickness (Liu *et al*. 2004).



(a)f = 2µm/flute.



(b)f = 3 µm/flute.



(c)f = 4 µm/flute.

Figure-4. Chip pattern result for depth of cut, t_c = 20 µm.

In case of the higher t_c 40 µm (Figure 5) , the effect tool diameter is increased to 239 µm. The possibility of chips to stick and remain on the ball mill cutting tips increases when the cutting temperature and chips size increase. Even though the work piece is softened by the heat generated by the laser, adhesion occurs randomly thus generate inconsistent cutting force. Figure 5 (a) and (b) shows connected chip is produced at every parameters result in LAMM. Meaning that, the chip pattern changed when the material heat up by laser irradiation during machining.

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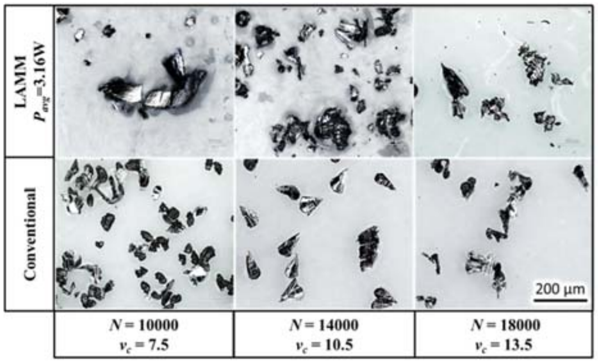
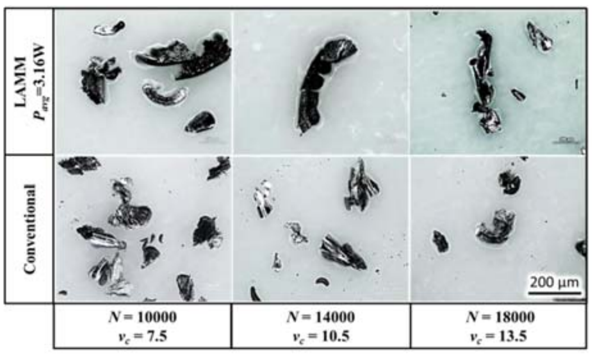


(a)f = 3 µm/flute.



(b)f = 4 µm/flute.

Figure-5. Chip pattern result for depth of cut, t_c = 40 µm.

CONCLUSIONS

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:

- In LAMM, low laser power produces low heating temperature. It is sufficient for micro machining compared to macro machining since the machining area is smaller. Higher preheating temperature provides a negative effect on the changes of material properties.
- The LAMM technique was successfully reduced the material strength due to softening effect. As a consequent the chip was adhered on the tool rake face.
- Chip pattern is a significant contributor on the inconsistency of cutting force during machining. The LAMM produces higher thrust force because of the connected chip and twisted around the cutting tool during the machining process.

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