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MACHINING CHARACTERISTICS OF LASER ASSISTED MICRO MILLING (LAμM) ON Ti6Al4V USING MICRO BALL MILLING TOOL

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ABSTRACT

Thermal assisted machining has been reported to be effective in machining performance enhancement on wide range of processing materials. It includes polymers, ceramics and metals. The machining performance could differ due to the variation on material behaviour against temperature increment. Among heat induction methods, laser is reported to have high flexibility to be focused and to heat up an extremely restricted area. However, the heat generated by the laser irradiation could give different impact to the machining performance, depends on the laser beam characteristics. Heated workpiece surface behaves differently during the machining process due to softening effect. Furthermore, the workpiece made from metals has a tendency to acts as plastic at micro level than macro level. In this situation, tool design and size exhibit significant effect to the machining characteristics. In this study, micro ball end milling tools were used to produce linear deep groove. The machining performance between laser assisted micro milling (LAμM) and conventional micro milling (Conv. μMill) were compared and discussed. It is found out that these two machining methods produced different chips pattern which has significant relation to the tool wear and cutting force changes.

Keywords: laser assisted micro milling, Ti6Al4V, pulsed mode laser.

INTRODUCTION

Laser assisted machining (LAM) is one of the thermal assisted machining. This heating technique performs well on metals. The attempt of using LAM has been widely reported with significant machining performance improvement.

In material removal process, LAM was formerly introduced in turning process. The workpiece was heated at a specific location continuously with certain frequency depends on the rotation speed. Suffecient heating time is essential to the workpiece prior the cutting tool engagement. The workpiece temperature can be adjusted by modifying the laser spot location and material rotation speed.

Laser assisted turning process tends to prolong the tool life and improve the cutting quality. It is reported that the tool used in laser assisted turning preserved twice longer than conventional turning of AISI D2 tool steel(Dumitrescu *et al*., 2006). Improvement also reported forlaser assisted Inconel 718 turning process. Proper and optimized machining parameters managed to increase the material removal rate to 800% and improved surface finish for more than 25% (Attia *et al*., 2010). It is suggested that 250 °Cis the optimum heating temperature for Ti6Al4V with 1.7 times tool life improvement when cutting speed was 107 m/min. The performance became better when the tool is chilled using liquid nitrogen during the machining process(Dendakar *et al*., 2010).

Applying laser as an instrument for heating process in milling process involves slightly different heating fundamentals compared to turning process. Most of the cases, the laser will only passing through the material surface for one time before the tool performs the removal process. All heat energy needed to soften the workpiece need to be supplied in a single irradiation path. In this case, the material thermal properties and laser beam characteristics need to be considered as the first priority before determining the machining parameters. These has made the process of obtaining the best fit of heating and removal process conditions become harder than turning process.

The method of applying laser can be divided into two major categories: external and internal. Internally delivered laser beam is reported to be better for more consistence heating performance (Brecher *et al*., 2011). However, this method only can be applied on macro size cutting tool. In micro milling, the laser is usually supplied directly from external direction.

The attempt of applying a continuous wave laser in laser assisted micro milling (LAμM) process using micro ball end milling tool has been reported by (Melkote *et al*., 2009). They found out that groove machining on A2 tool steel produced better accuracy and surface integrity when applying LAμM. However, it is important to understand that the ratio of laser spot size to tool diameter affects the surface roughness and burr formation. Laser spot size which is larger than the cutting tool diameter produces rough machining surface and higher burr formation(Kumar and Melkote, 2012).

This study is another attempt to apply LAμM on ductile material. A pulsed wave laser is used to study the potential of this type of laser in laser assisted milling process. Machining performance is compared to the conventional micro milling (Conv. μMill) process by referring to the cutting forces and tool wear rate.

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MEHODOLOGY

Actual machining experiments were conducted using AlTiN coated ball end mill with maximum diameter of 0.3mm. Work materials were fixed on a jig mounted on a dynamometer to measure the machining forces. The air bearing spindled which holding the tool was tilted with angle 80° from *X* axis while the laser beam for LAµM experiment was placed with 55° from Y axis in *Y-Z* plane. Linear groove machining with machining length of 25mm/path were performed under different machining conditions. In the case of LAµM, the laser beam is focused at location 0.6mm before the ball end milling tool. The detail machining parameters are shown in Table-1.During the experiment, cutting forces were recorded and the chips produced were collected using carbon tape and double-side tape. The chips were observed using optical microscope and scanning electron microscope (SEM). For the first two lines, the cutting forces were recorded and the flank surface was observed after the second line.

Maximum flank wear (VB_{MAX}) was measured from a direction with angle 30° from tool center line. This angle was choosen by referring to the tool effective diameter. The measurement was done on all cutting flute (2 flutes) to get the average VB_{MAX} value.

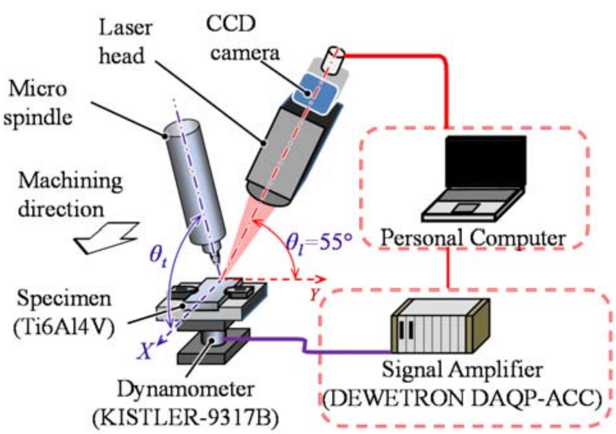

Figure-1. Experimental setup.

Table-1. Machining conditions**.**

Items	Values
Machining methods	**Conv. µMill &LAµM**
Feed, f (µm/flute)	2.1, 3.0, 4.2
Spindle rotation speed, $N \times 10^3$(rpm)	12.5, 17.5, 25.0
Depth of cut, t_c(µm)	20, 45, 70

Further machining experiments were done on selected cutting conditions to observe the tool wear increment with machining distance. The maximum cutting tool flank wear (VB_{MAX}) from various machining conditions were compared to evaluate the effectiveness of pulsed wave LAµM process.

RESULTS AND DISCUSSIONS

Figure-2 to Figure-4 showed the maximum flank wear after of 50 mm of machining length. From these results, it can be concluded that the LAµM with the selected machining parameters does not effectively improve the machining performance. The maximum flank wear after 50mm machining length was significantly larger compared to Conv. µMill.

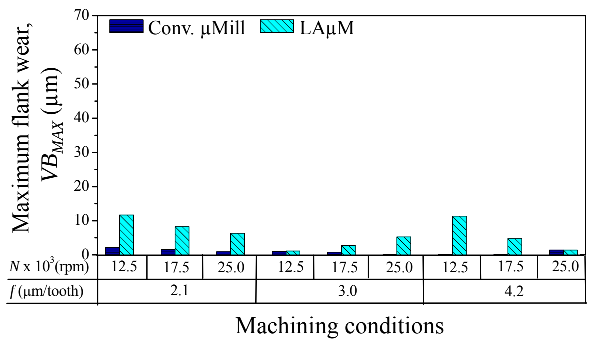

Figure-2. Maximumflank wear, VB_{MAX} after machining length 50 mm when t_c=20 µm.

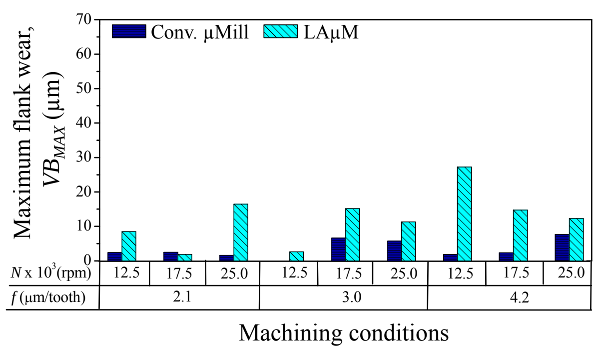

Figure-3. Maximum flank wear, VB_{MAX} after machining length 50 mm when t_c=45 µm**.**

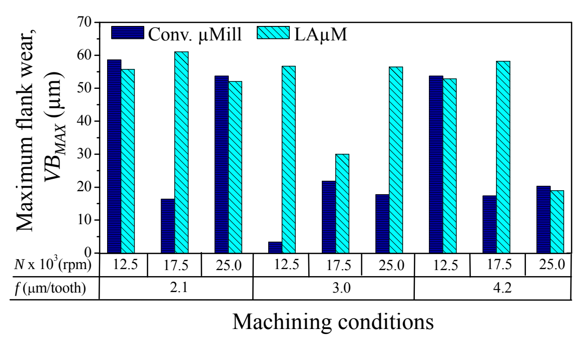

Figure-4. Maximum flank wear, VB_{MAX} after machining length 50 mm when t_c=70 µm.

The VB_{MAX}decreases with the decrement of t_c. This is a normal trend where the tool effective diameter decreases with t_c, which consequently reduces the cutting speed and cutting force.

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When t_c is increased from 20 µm to 70 µm, the flank wear increased exponentially (Figure-4). The average thrust force, F_z also have the same trend of increment (Figure-9). This is because of the tool radial shape where the uncut chip cross sectional area increases exponentially with t_c (Figure-5).

VB_{MAX} fluctuates randomly and does not have any significant trend similarity with F_z. This indicates that the tools worn out not purely initiated by the forces reacted on the tool cutting edges. It is well known that titanium alloy is a ductile material and behave more ductile in higher temperature due to thermal softening effect. The chips tend to adhere on the cutting tool. At the lowest art of the cutting tool, the chip thickness is far smaller than the cutting edge radius (approximately 2µm) and tends to perform plunging rather than cutting process. It is suggested that the chips adhered and accumulated at the bottom area has caused the F_z to fluctuate during the machining process.

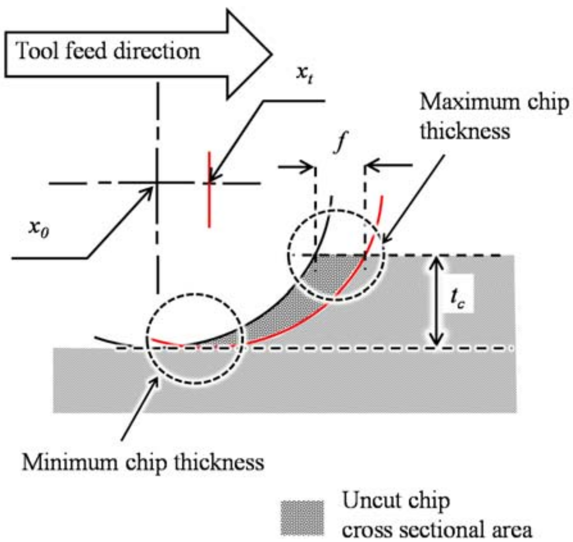

Figure-5. Ball milling chip cross sectional area.

Meanwhile, adhesion on flank and rake face also contributed to the variation of tool wear rate. Continues chips were observed in certain machining parameters. These chips remained for a certain period. In LAµM, these continues chips were heated up by the laser radiation and transfer the heat to the cutting tool and initiated thermal effect.

Figure-6. and 7 show the major chips pattern from various machining parameters and techniques. The symbols only represent the chips pattern but not the size or the thickness. Conical and continuous chips are comparatively thicker than the continuous chips. Loose arc chips are comparatively smaller and thinner than conical chips. From the figure, it can be seen that LAµM produce more continuous chips than Conv. µMill. Even though the materials were heated up and became softer, the continues

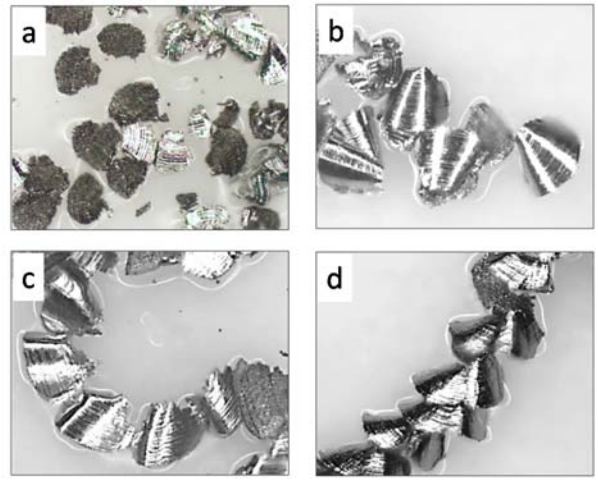

Figure-6. Chips pattern produced from micro ball end milling process, a) loose arc chips, b) conical chip, c) continuous chips, d) continuous and conical chips.

		f1			*f2*			*f3*		
		N1	*N2*	*N3*	*N1*	*N2*	*N3*	*N1*	*N2*	*N3*
t_c = 20µm	Conv. µMill	●	●	●	L	L	L	C	C	○
	LAMM	○	○	○	○	L	L	●	●	●
t_c = 45µm	Conv. µMill	C	C	C	●	●	●	C	L	C
	LAMM	○	○	○	●	●	●	●	●	●
t_c = 70µm	Conv. µMill	●	●	●	C	C	C	C	C	C
	LAMM	●	●	●	C	C	C	C	C	●

N1, N2, N3 : 12.5 x10^3, 17.5 x10^3, 25.0 x10^3 (rpm)
f1, f1, f3 : 2.1, 3.0, 4.2 (µm/tooth)
○ : mixed with continuous chips
● : mixed with continuous and conical chips
C : conical chips
L : loose arc chips

Figure-7. Chips pattern differences by machining parameters and techniques.

chips that heated around the micro ball transfer heat to the cutting tool and promotes tool wear and tool failure. During the machining, work material could easily adhere on the tool surface because Ti6Al4V is a reactive metal in elevated temperature. This phenomenon also contributes to thrust force increment and attrition wear. Consequently, there is no trend of decrement for the thrust force can be seen from Figure-8 and Figure-9.

It can be observed that, when the t_c is increased from 45µm to 70µm, the chips obtained form Conv. µMill and LAµM were similar in pattern and size. In this case, the value of F_z recorded by the LAµM were smaller than Conv. µMill (Figure-10). It is suggested that the formation of chips produced booth machining techniques gave a comparable effect to the machining performance. The chips were effectively evacuated from the cutting region with the same efficiency.

Further experiment on tool wear wasconducted on the cutting tools used at thet_c 20 µm. The machining

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distance was extended to 1000mm and the VB_{MAX}were measured at the interval of 100, 200, 300, 500, 750 and 1000mm machining length.

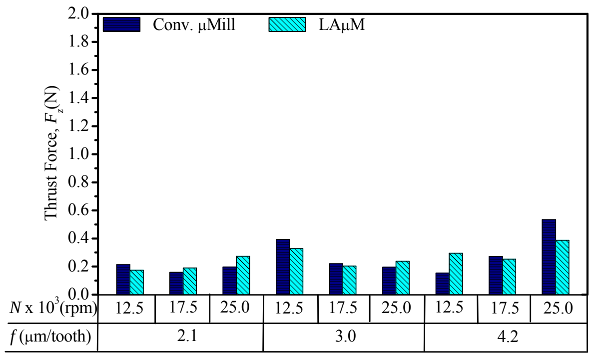

Figure-8. Average thrust force when t_c=20 µm.

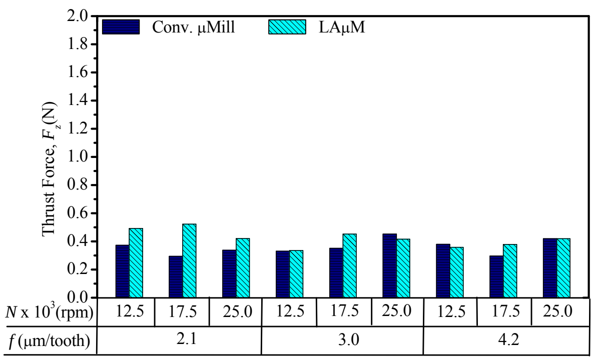

Figure-9. Average thrust force when t_c=45 µm.

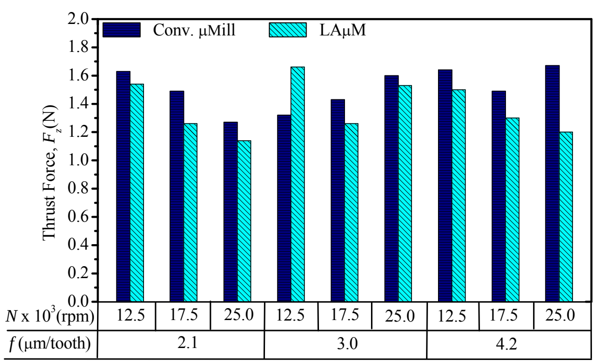

Figure-10. Average thrust force when t_c=70 µm.

Figures 11 to 13 showed the results of VB_{MAX} at various machining parameters and techniques .Conv. µMill has lowertool wear rate compared to LAµMespecially at feed less than 2.1 µm/flute. Furthermore, at the lowest spindle rotation speed of 12500 rpm, the VB_{MAX} of LAµM increases drastically within 500 mm of machining length. It can be observed that at machining length of 300mm, the tool experienced from failure where the coating material at flank surfacewas removed by chipping and flaking mechanism. However, the VB_{MAX} of tools used in Conv. µMill increased linearly only to approximately 5µm even after 1000mm machining length.

Once again, the reason of this phenomenon can be referred to the chip pattern shown in Figure-7. Lower N value tends to produce continuous chips. This type of chips will remain at the cutting tool and rotating togather for a certain period. While it rotating, a part of it will have contact with laser beam and heated up. This part will melt and resolidified with different material properties. At the same time, the heat from the chip will also transferred to the cutting tool which could cause thermal effect.

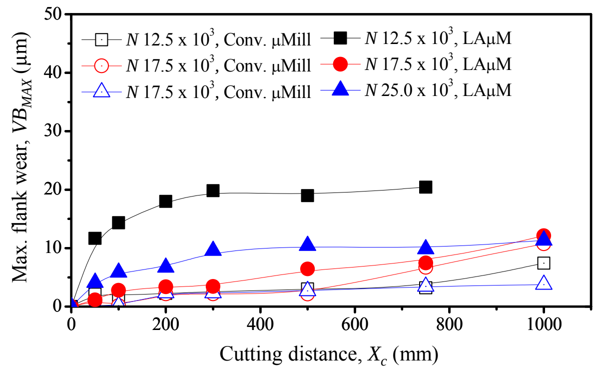

Figure-11. Maximum flank wear against cutting distance when f=2.1µm/flute.

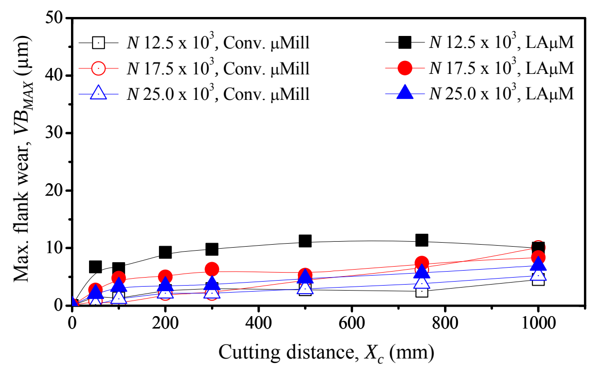

Figure-12. Maximum flank wear against cutting distance when f=3.0 µm/flute.

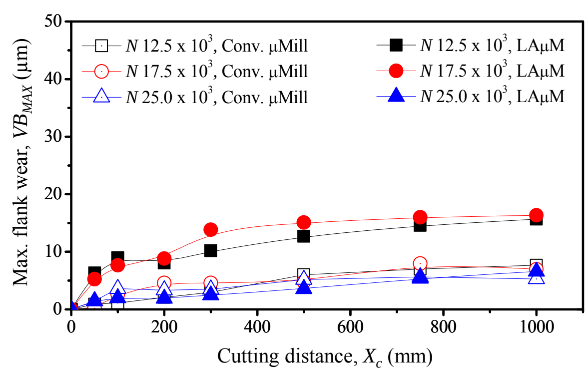

Figure-13. Maximum flank wear against cutting distance when f=4.2µm/flute.

When the feed is increased from 2.1 to 3.0 µm/flute, VB_{MAX} was increased with approximately the same rate in both machining technique. In the case of Conv. µMill, the VB_{MAX} increases linearly to 10 µm within 1000mm machining length. On the other hand, LAµM shows sudden increment of VB_{MAX} at 50mm machining length and then increased with the same rate to Conv. µMill. Among the LAµM tools, with 3.0 µm/flute feed value, the tool used under 12500 rpm experienced the most drastic VB_{MAX} increment. However, it still can be considered better than the value shown in Figure-11 and Figure-13.

As the f is further increased to 4.2 µm/flute, the cutting tool wear rate for LAµM was found lower than when it performed under 2.1 µm/flute but higher than when it performed under 3.0 µm/flute. At this feed rate condition, LAµM under 25000 rpm rotation speed performs slightly better than Conv. µMill.At higher cutting speed, the total time of the cutting tool have contacts with the workpiece was reduced. This condition is better for tool wear rate reduction(Melkote *et al*., 2009).

In general, Figure-11 to Figure-13 indicate that LAµM prone to sustain at higher*f*feed without deteriorating the cutting tool edges thus minimizing the tool wear rate. Furthermore, the consistency of machining performance for LAµM can be obtained by applying higher spindle rotational speed.

CONCLUSIONS

From this study, the next conclusions were drawn.

a. Chip pattern gives substantial influence on the performance of micro machining process.
b. Conv. µMill performs better with less tool wear rate under small feed and tool rotation speed.
c. Tool wear in LAµM does not purely initiated by the cutting forces.
d. The machining performance of LAµM become more stable in larger spindle speed, larger feed and smaller depth of cut.

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