Chip pattern, burr and surface roughness in laser assisted micro milling of Ti6Al4V using micro ball end mill

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ABSTRACT

The effectiveness of laser heating could easily fluctuates when the uncut chip thickness are extremely inconsistent. In the case of using micro ball end mill tool, rubbing mechanism is inevitable due to its radial shape geometry. Furthermore, the scenario could be worst when the workpiece is a ductile material which has low thermal conductivity such as Ti6Al4V. Thus, characterization study was carried out to evaluate the feasibility of micro ball end mill in laser assisted micro milling operation. The chip, burr and surface roughness from conventional and laser assisted micro milling were compared and discussed. It is understood that the chip pattern indirectly gives significant influence to the effectiveness of laser assisted micro milling technique. With tool edge radius of 2×10^{-3} mm, feed value of 3.0×10^{-3} mm produced more consistent surface roughness compared to feed value of 2.1 and 4.2×10^{-3} mm. The machining parameters which produced continuous and conical chips ended up with sever burr formation and surface roughness inconsistency.

Keywords: Laser assisted micro milling; chip pattern; burr; surface roughness; Ti6Al4V

INTRODUCTION

Laser assisted machining technique combines heating process and milling process to allow the removal process to be done under preheated state [1, 2]. This technique is reported effective in machining of difficult-to-machine materials with high hardness [3, 4]. Heating the workpiece helps to reduce the hardness and maximum temperature increment caused by shearing and friction mechanisms. The workpiece properties are temporarily modified, allowing the milling process done under lower mechanical and thermal load. The machining process managed to be done under lower cutting force and cutting temperature [5, 6], thus improve machining surface quality and tool life.

However, this technique has comparatively larger number of process influencing factors which leads to performance inconsistency [4]. The machining performance could fluctuates by two major categories of parameters namely laser heating and milling process. Laser heating parameters such as laser power, laser beam diameter and power intensity distribution modes contribute largely to temperature distribution characteristics [7]. The achievable heating temperature at cutting area will finally determine the level of softening effect at cutting area. On the other hand, Milling parameters such as feed per tooth (f), depth of cut (t_c) and

cutting speed (v_c) determine the removal process mechanism by altering the value of uncut chip thickness and the temperature at the cutting area [8, 9].

Laser assisted milling/ micro milling on various materials including titanium alloy has been reported with significant improvement. Most of the study used flat end mill and insert cutting tools [10-14] and generally focused on the cutting force and tool wear characteristics. Recent study in laser assisted milling using ball mill tool were also reported but using macro size tools and not focused on titanium alloy as the workpiece [14-18]. Furthermore, less has been reported on the effect of machining parameters to the chips formation mechanism and machining quality in laser assisted micro ball milling process.

The study on laser assisted micro machining performance using micro ball end mill tool was firstly reported by Melkote et al. [1]. In the study, Ytterbium doped continuous wave near IR (1.06 μm) fibre laser with diameter and laser power of ~ 0.16 mm and 7 W respectively was used as the laser source. Four flutes micro ball mill with diameter of 0.25 mm was used to perform machining on hardened A2 steel. Lower surface roughness, lower tool wear rate and better dimensional accuracy were obtained with the assist of laser heating.

In the case of micro ball end mill, geometrical factors expose the removal process to intense rubbing and ploughing effect [19, 20]. Furthermore, the chips evacuation efficiency in laser assisted micro milling could be worst when the material is heated, softened and more ductile [8]. Due to the tool geometrical factor, the chips are formed in complicated shapes by multiple of strain vectors and tends to remain in the cutting area. Forces act in multiple directions and the high gradient of cutting velocity produces variant of strain rate in the cutting zone leading to poor surface roughness [21]. In addition, tool size effect and minus rake angle [8] predominantly give influence to chip formation characteristics and cutting performance when the tool is in micro scale size.

Long chips should be avoided to prevent entanglements around the cutting area which could lead to cutting tool and cutting surface damages [22]. Continuous and excessive ploughing mechanism promotes temperature rise at the cutting zone which consequently increases the tool wear rate [23]. Burr formation is another problem that need to be considered when the material is heated and softened due to tearing failure during the removal process [24]. At the tool bottom, comparatively large cutting edge radius induce peculiar effects, erratic force variation and causing extensive burr formation [25].

To produce machining surface with a consistent and small roughness, understanding the actual mechanism occur during the machining process is crucially important. Small uncut chip thickness tends to produce inconsistent surface roughness due to ploughing and elastic recovery which finally generate uneven plastic flow [26]. Considering that titanium alloy possesses low thermal conductivity, machining this alloy using laser assisted micro ball end mill could adversely worsen the machining performance. Localised heat increment could promotes tool wear rate when the heat is continuously conducted from the workpiece to the cutting tool [27-29].

This study was carried out to investigate the feasibility of laser assisted micro milling when using micro ball end mill on ductile (Ti6Al4V) material. A new approach was implemented to minimise the effect of ploughing and rubbing mechanism and to eliminate large temperature gradient at the machining area. The tool was set in tilted orientation and relatively large laser irradiation spot diameter was applied. The

feasibility of micro ball end mill in laser assisted micro milling operation through chip pattern, burr and machining surface condition. The effect of laser heating to the chip formation and machining surface conditions were evaluated by comparing between conventional and laser assisted micro milling.

EXPERIMENTAL SETUP

Laser beam head is placed at the inclination angle (θ_i) of 55° from X-Y plane in Y-Z plane direction as shown in Figure 1. A laser focusing head with focal length and focusing diameter of 60 mm and 0.700 mm respectively was applied. The tool was placed at the inclination of 80° from X-Y plane in X-Z plane direction to minimise the forces generated during the cutting process [30]. All experiments were conducted under stagnant air and controlled room temperature of 28°C .

Figure 1. Micro milling tool and laser beam orientation

Table 1. Milling parameters

$f \times 10^{-3}$ (mm/flute)	t_c (mm)	$[v_c \text{ (m/min)}/f_r \text{ (mm/min)}]$
2.1, 3.0 & 4.2	0.020	[7.6/52.5],[10.6/74] & [15.1/105]
	0.045	[9.7/75],[13.6/105] & [19.4/150]
	0.070	[10.9/105],[15.3/147] & [21.8/210]

In this study, two flute TiAlN coated cemented carbide micro ball mill with diameter of 0.3 mm was used to produce grooves. Linear groove machining with length of 25 mm/path was performed on Ti6Al4V plate with thickness, width and length of 1.8, 25 and 40 mm respectively. The machining process were performed using variable feed (f), cutting speed (v_c) and depth of cut (t_c) in both machining techniques; conventional (Conv. μMill) and laser assisted micro milling (LA μMill) (Table 1). In Conv. μMill , the workpiece temperature was controlled at 28°C , while the workpiece temperature in LA μMill varied by the laser heating parameters applied.

The 80° of tool inclination from X-Y plane has made the tool effective diameter ($\phi_{t\_effect.}$) become 0.193, 0.247 and 0.248 mm at t_c of 0.020, 0.045 and 0.070 mm respectively (Figure 2). To perform machining with three levels of f of 2.1, 3.0 and 4.2

$\times 10^{-3}$ mm/flute, three spindle rotation (N) of 12.5, 17.5 and 25.0×10^3 rpm were applied. The value of v_c were taken from the maximum values obtained from calculation using the ϕ_{t_effect} and N applied. This configuration has made the v_c varied by t_c values. At t_c of 0.020 mm, different N values of 12.5, 17.5 and 25.0×10^3 rpm has made the machining process performed at three different v_c of 7.6, 10.6 and 15.1 m/min respectively. At N of 12.5, 17.5 and 25.0×10^3 rpm, increasing the t_c to 0.045 mm has increased the v_c to three different value of 9.7, 13.6 and 19.4 m/min respectively. At t_c of 0.070 mm, three different v_c of 10.9, 15.3 and 21.8 m/min were recorded.

Figure 2. Relation between cutting speed (v_c) and depth of cut (t_c)

Table 2. Laser heating parameters in LA μ Mill

Items	Values
Laser average power, P_{avg} (W)	3.4
Pulse on time, t_p (ms)	1.0
Pulse repetition rate, f_p (Hz)	100
Tool to laser beam distance, X_{t-b} (mm)	0.6
Tool orientation angle, θ_t ($^\circ$)	80
Feed rate, f_r (mm/min)	Refer Table 1

In LA μ Mill, the laser setting parameters are shown in Table 2. To avoid the workpiece from the creation of heat affected zone (HAZ) and melted zone (MZ) in LA μ Mill, a constant P_{avg} , t_p and f_p of 3.4 W, 1 ms and 100 Hz respectively were applied. This laser heating parameters was confirmed applicable to heat the workpiece with maximum temperature not exceeding 950 $^\circ$ C which is the Ti6Al4V phase transformation temperature.

The distance between the laser beam centre and the cutting tool centre (X_{t-b}) was set at 0.6 mm. A gap of 0.1 mm between the laser irradiated area and tool outer diameter was applied to avoid direct laser irradiation onto the cutting tool, workpiece drastic temperature fluctuation and workpiece material sputtering effect.

The temperature of the area which has direct contact with the micro ball milling cutting edges were determined by finite element method (FEM) simulation.

The simulation model was validated by results comparison with the experiment using thermocouple embedded 0.05 mm under the workpiece surface at three different laser irradiation feed rate of 52.5, 105 and 210 mm/min. Using the validated model, the temperature history and distribution of the heated surface at the centre line of the irradiation path were recorded and used to estimate the maximum temperature at the cutting area. The results has shown that at three levels of t_c , f and v_c , the workpiece top surface temperature at the cutting area in LA μ Mill were estimated between 128 and 178 °C. The estimated workpiece temperature at different f_r and t_c are plotted in Figure 3.

Figure 3. Estimated workpiece temperature at the cutting area in LA μ Mill under different f_r and t_c .

The chips produced and scattering on the workpiece were collected using double side tape and carbon tape after the first machining path (X_c of 25 mm). High magnification micro scope was used to observe the chips pattern differences between different machining parameters. Scanning electron microscope was used for better image quality and larger magnification ratio. The width and length of single chips were measured randomly from the chips with good orientation and measurable. The chips thickness was not able to be measured due to the difficulty to get the measurable orientation.

The burr and cutting surface topography were observed under SEM while the cutting surface roughness was measured using table top roughness measuring machine. Sampling length (λ_c), sampling size (I_n) and stylus tip radius (r_{tip}) of 0.08, 0.4 and 0.002 mm respectively were applied for the roughness measurement, according to the EN ISO 4288 standard. The surface roughness of three locations at the machining groove (entrance, middle and exit side) were measured and averaged.

RESULTS AND DISCUSSION

Chip Formation Characteristics

Table 3 shows the distribution of each different chips pattern. Based on the observation on chips produced from different machining parameters and methods, the chips can be divided into three main categories: loose arc, conical and continuous.

From the table, it can be seen that at t_c of 0.020 mm, loose arc chips were produced when the feed (f) was 0.003 mm/flute. When the t_c was 0.045 and 0.070 mm, all f values produced chips mixed with continuous and conical chips. Less connected chips were produced from Conv. μ Mill process when the f were 4.2×10^{-3} mm/flute. In addition, at f of 4.2×10^{-3} mm/flute, Conv. μ Mill produced continuous chips only at t_c of 0.020 mm (Figure 4-a and Figure 5-b). Increasing the f value has consequently increased the uncut chip thickness and reduced the swept angle [31]. At t_c of 4.2×10^{-3} mm/flute, the chips were formed with larger thickness and stiffer. As a result, the chips were produced with consistence shape and less connected compared to the lower f value. Even though the ball milling tool perform interrupted cutting, the chips were connected by compression and heat generated during the cutting process [32]. The connected chips become longer until certain length and flew away for the increasing of weight and collation with work piece or other chips.

Table 3. Chips pattern mapping

t_c (mm)	Machining technique	$f1$			$f2$			$f3$		
		$N1$	$N2$	$N3$	$N1$	$N2$	$N3$	$N1$	$N2$	$N3$
0.020	Conv. μ Mill	⊙	⊙	⊙	L	L	L	C	C	○
	LA μ Mill	○	○	○	○	L	L	⊙	⊙	⊙
0.045	Conv. μ Mill	C	C	C	⊙	⊙	⊙	C	L	C
	LA μ Mill	○	○	○	⊙	⊙	⊙	⊙	⊙	⊙
0.070	Conv. μ Mill	⊙	⊙	⊙	C	C	C	C	C	C
	LA μ Mill	⊙	⊙	⊙	C	C	C	C	C	⊙

$N1, N2, N3$: $12.5 \times 10^3, 17.5 \times 10^3, 25.0 \times 10^3$ (rpm)

$f1, f2, f3$: $2.1 \times 10^{-3}, 3.0 \times 10^{-3}, 4.2 \times 10^{-3}$ mm/flute

○ : mixed with continuous chips

⊙ : mixed width continuous and conical chips

C : conical chips

L : only loose arc chips

Conv. μ Mill, $f = 2.1 \times 10^{-3}$ mm/flute

LA μ Mill, $f = 2.1 \times 10^{-3}$ mm/flute

Figure 4. Chips pattern from Conv. μ Mill and LA μ Mill under different t_c and v_c when f is 2.1×10^{-3} mm/flute

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Conv. μ Mill, $f = 4.2 \times 10^{-3} \text{ mm/flute}$

LA μ Mill, $f = 4.2 \times 10^{-3} \text{ mm/flute}$

Figure 5. Chips collected from Conv. μ Mill and LA μ Mill under different t_c and v_c when f is $4.2 \times 10^{-3} \text{ mm/flute}$

On the other hands, when the f was 2.1×10^{-3} mm/flute, the uncut chip thickness were approximately equal to the tool tip radius. When the uncut chip thickness is equal or less than tool tip radius, the chips will be formed under uneven plastic flow with high ratio of rubbing and ploughing effect due to minus rake angle cutting edge [26, 33]. Ploughing and rubbing effect has consequently produced thin and connected chips, and inconsistent in shape and size. Generally, increasing the f value from 0.0021 to 0.0042 mm/flute has changes the chips from continuous to conical.

Increasing the v_c in the range between 7.6 m/min to 21.8 m/min was unable to show different chip formation characteristics as reported by Sun et al. [29]. No sharp-teeth and sharp segmented chip were identified. The v_c increment were found does not have significant relation with the chip creation characteristics. The chips produced in this study were comparatively too thin and small. The chips were formed under intense plastic deformation and the segmentation distance was independent from cutting speed changes.

It is also observed that the chips were also produced in the similar shape, regardless to the v_c applied in LA μ Mill. It is suggested that the temperature increment initiated by the v_c increment were not significant to give influence onto the chip formation behaviour between the both machining techniques (Conv. μ Mill and LA μ Mill). The shear and plastic deformation zone were extremely small and unable to generate sufficient heat which can give influence to the workpiece physical properties during the removal process.

Figure 6. Chip formation in micro ball milling

The variation shapes of chips produced under different t_c has a strong relation with the cutting edges location (Figure 6). In this study, the smallest t_c of 0.020 mm was used which is capable to produce two chips patterns (Figure 6-a and Figure 6-b). When the t_c is increased to 0.045 mm, the chips shown in Figure 6-b dominated the total chips produced. Groove machining using higher t_c of 0.070 mm produced a higher ratio of conical chips (Figure 6-c).

Since the cutting edges are in radial shape, the chips thickness increases with the t_c . Unevenly distributed built up edges and comparatively rough tool surface roughness initiate crack and break the chips into smaller pieces. This mechanism has eventually produced chips with pattern as shown in Figure 6-a and Figure 6-b. Increasing the t_c to

0.070 mm has further increased the chip thickness and made the chips become larger and stiffer. Consequently, the chips turn to conical as their length and width become too large to fit in the space in front of the tool rake face. At this conditions, the chips were compressed and bent by mechanical force to conical shapes.

LA μ Mill produced conical and elemental arc shape chips at t_c of 0.045 and 0.070 mm. It is obviously can be seen that the chips produced form LA μ Mill is larger and curlier compared to Conv. μ Mill (Figure 4-a). Larger chip size is one of the evident that the chips flow out more easily due to lower tensile strength at higher workpiece temperature [28].

Figure 7. Chips formation in LA μ Mill
($f = 3.0 \times 10^{-3}$ mm/flute, $t_c = 0.020$ mm, $f_r = 52.5$ mm/min)

Figure 7 shows the evident of how the chips were formed in LA μ Mill. Commonly, chips in LA μ Mill were created in ununiformed shapes. Higher percentage of continuous and conical chips were produced and they were larger in size compared to Conv. μ Mill. Even though the size of the chips was larger when the t_c is increased, less chips were produced in elemental arc shape. The conical chips were connected to form continuous and thin chip. The thin and continuous chips adhered on the cutting edge which performing the cutting process and they were located near to the chisel area. From a single cutting edge, the chips were formed in various thickness and patterns. When the material is heated, the chip size and shape can be more inconsistent due to the increment of plastic behaviour and ductility. Elastic recovery thickness is suggested one of the major reason [31]. Certain thickness of workpiece were left over during the previous cut and removed together with the next tool engagement and created thicker and different chip size and pattern. This phenomenon can be seen obviously at the f of 2.1×10^{-3} mm/flute which is near to cutting tool tip radius ($1 \sim 2 \times 10^{-3}$ mm). In addition, the heated workpiece has a higher tendency to produce continuous and snarled

chips [34]. This type of chips frequently interfere the cutting process and gave significant influence on the overall chips pattern.

Figure 8. Comparison of adhesion condition between LAMμMill and Conv. μMill
($f = 2.1 \times 10^{-3}$ mm/flute, $t_c = 0.070$ mm)

At higher workpiece temperature, the adhesions on the cutting tool edges were accumulated more easily and consequently constructed a new cutting edge geometry [35, 36]. The condition of tool with adhesion can be seen in Figure 6. The height of adhesion increases with the radial distance from the tool rotation centre. Comparison between LAMμMill and Conv. μMill has shown different amount of chip adhesion (Figure 8). In LAMμMill, the built up edges formed by adhesion can be seen along the cutting tool edge and sometime larger chip adhere near the tool rotation centre and upper location of the cutting edges. As a result, the chips flow out in front of the rake surface in conical shape. As a result, LAMμMill produced larger amount of conical chips compared to Conv. μMill.

Burr Formation Characteristics

Figure 9 shows the condition of the grooves machined by different f , t_c and machining methods. The direction of the tool movement is shown in the figure. Left and right side of each grooves were processed by down and up milling respectively.

Both machining methods (Conv. μMill and LAMμMill) produced grooves with slot base burr on the up milling cutting surface. The location of slot base burr has shown that the chips were torn and separated from the base material under proper cutting speed and good cutting edges [24]. In this study, the slot base burrs were formed on the up milling surface when the chips adhered on the cutting tool rake surface were compressed during the tool entrance. When the f is increased to $4.2 \times$

10^{-3} mm/flute, less slot base burr created (Figure 10). Ticker and stronger chips were produced and flowed out from the cutting area more efficiently is suggested to be the main reason. In addition, the milling process was performed under less elastic deformation effect when the uncut chip thickness is larger than minimum chip thickness [8] which need to be in range of 5 % to 38 % of the cutting edge radius [37]. Consequently, fewer chips adhered on the up milling side surfaces.

Figure 10 shows the grooves fabricated using higher v_c which ranged from 15.1 to 21.8 m/min. The groove conditions were not much different compared to Figure 9 which were produced under lower v_c . Ploughing and rubbing effect dominated the removal process mechanisms in the both v_c ranges which consequently worsen the cutting surface appearance [23, 38] at lower cutting speed, in LA μ Mill process and Conv. μ Mill. Increasing the v_c does not give significant effect on the burr condition at t_c of 0.020 and 0.045 mm. The amount of slot base burr at the up milling regions were considerably equal.

However, significant difference on slot base burr condition between high and low v_c was observed at t_c of 0.070 mm. The chips were produced in continuous and conical shapes, and significantly larger than t_c of 0.045 mm and 0.020 mm. At t_c of 0.070 mm, the large size of chips compressed on the machining surface created slot base burr and top burr at the up milling machining surface. Larger size of chip compression at higher v_c has consequently promoted the slot base burr formation due to higher cutting temperature [35] generated via shearing and friction mechanisms adhere on the tool cutting edges. At the same time, the grooves seemed to be larger in LA μ Mill. It means that the grooves were produced deeper in LA μ Mill. The actual t_c become larger for the less tool edge positioning error [39], thus produced larger amounts of conical shape chips. This type of chips were being compressed onto the cutting groove up milling sides and remained as slot base burr.

The top burr at the down milling side was produced larger in LA μ Mill compared to Conv. μ Mill. This burr was formed by plastic deformation during the cutting process. LA μ Mill tends to produce continuous chips and rotating together with the cutting tool. This phenomenon shows that LA μ Mill has a higher tendency for the chips to adhere and blocking the cutting edges which contributes to inconsistency machining performance [40]. The creation of larger top burr at the down milling sides in LA μ Mill is a significant evidence showing that the workpiece being heated has become softer. Consequently, more obvious plastic deformation occurs during the cutting process. The formation of top burr are obvious at t_c of 0.070 mm. It indicates that the t_c value is too large since the ratio of axial depth of cut to ball milling radius need to be considered in micro milling operation with ball end mill tools [24].

Slot base burr were observed in the both machining techniques, Conv. μ Mill and μ LA μ Mill. It is a normal phenomenon in micro machining of metal materials [41]. However in the case of this study, slot base burr which formed by chip compression at the up milling side were found larger in LA μ Mill. It is suggested that, when the workpiece is heated, the workpiece became softer and easier to

Figure 9. Machined grooves comparison between different t_c, f and machining methods with v_c ranged from 7.6 to 10.9 m/min

Figure 10. Machined grooves comparison between different t_c, f and machining methods with v_c ranged from 15.1 to 21.8 m/min

Referring to the thermal dependant properties of Ti6Al4V, heating the material from 20 °C to 200°C will give softening effect to the workpiece. Young's modulus is expected to reduce from 114 to 105×10^5 (N·mm⁻²) [42], while the density will reduce from 4.42 to 4.39×10^3 (Kg·mm³) [7]. Calculation using modified Johnson Cook material model [23] estimated that the flow stress will

resue for approximately 14 % when the material heated from 20 to 200 °C. The properties changes occur during LA μ Mill has caused different chip formation and machining characteristics between the two different machining techniques.

The difference in burr creation has shown that the micro ball end mill is insufficient for deep groove machining. The chips produced at every tool engagement need to be efficiently removed to avoid chip compression at the machining area.

Surface Roughness

Figure 11 shows the surface roughness (R_a) of the groove bottom surfaces. Alphabet C and L represent the machining techniques used in the experiment (C: Conv. μ Mill, L: LA μ Mill). The measurements were taken at three point; entrance, centre and exit part of the machined grooves. The R_a values were compared between different machining techniques under three different depth of cut (t_c), three different feed (f) and various cutting speeds (v_c).

The R_a fluctuated and changed differently at different t_c . At t_c of 0.020 mm, R_a increased with f . However, the increment was not significant. At f of 4.2×10^{-3} mm/flute, the R_a value fluctuated significantly larger than f of 2.1 and 3.0×10^{-3} mm/flute. Larger size of connected chips are suggested to be the major reason. The connected chips generated at t_c of 0.020 mm became thicker when the f is increased. Low chip evacuation efficiency of connected chips is suggested to give influence to R_a by tangling around the cutting area during the machining process.

The relation between f and R_a was unable to be seen at t_c of 0.045 mm. There were also less significant roughness different between f of 2.1 and 3.0×10^{-3} mm/flute. It is suggested that the f values (2.1 and 3.0×10^{-3} mm/flute) were too close to the cutting edge radius ($1\sim 2 \times 10^{-3}$ mm), thus the cutting process was dominated by rubbing and ploughing effect. In the case of t_c of 0.070 mm, when the f was increased to 4.2×10^{-3} mm/flute, the chips became thicker and stiffer which caused the connected chips to be more easily to disconnected and flow out from the cutting area. This has caused the R_a becomes more consistent at f of 4.2×10^{-3} mm/flute compared to 2.1 and 3.0×10^{-3} mm/flute when the t_c was 0.070 mm.

The R_a fluctuation range increases with the t_c . Larger volume of chips produce per each tool engagement will consequently increase the forces act on the cutting tool. It is suggested that larger and thicker chips involved in rubbing mechanism has caused ploughing effect to be more influencing the machining surface condition. Rapid flank wear propagation at larger t_c also suggested to give significant effect to the R_a value. As a result, higher t_c produced larger R_a value fluctuation.

Overall, v_c gave less significant influence to R_a value (Figure 11). However, the R_a increases with f_r when the f and t_c were 2.1×10^{-3} mm/flute and 0.070 mm respectively. For the reason that the tool cutting edges radius is approximately 2.0×10^{-3} mm, the process is dominated by rubbing mechanism [31]. Increasing the v_c will consequently enhance the effect of ploughing and plastics deformation. These has caused the R_a value and fluctuation range to increase.

At higher f of 3.0 and 4.2×10^{-3} mm/flute, the increment of v_c from 7.6 to 21.8 m/min did not gave significant R_a changing trend. The machining process was performed under adiabatic shear mechanism which involved poor heat dissipation and intense shear concentration [43-45]. The shear and deformation area is too small and unable to generate significant temperature difference which could bring influence to the R_a value via softening effect. Consequently, the value of R_a were kept approximately at the same level even though the v_c were increased to double.

Figure 11. Surface roughness (R_a) for cutting distance (X_c) between 25 to 50 mm when t_c were 0.020 mm

One quarter of the parameters used in the study has shown larger R_a value when laser heating is applied. LA μ Mill has generally shown larger R_a at t_c of 0.070 mm. Heating process in LA μ Mill has caused the workpiece became more ductile [5, 6] and produced curly chips with inconsistency size and shape. This chips has higher tendency to stick on the cutting surface by rubbing and ploughing mechanisms. A lot of chips

were found sticking on the cutting surface near the groove centre line. This has made the R_a to be larger than Conv. μ Mill.

The effect of laser heating to the reduction of R_a only can be observed at t_c of 0.020 mm when the f were 3.0 and 4.2×10^{-3} mm/flute (Figure 11). The R_a value reduced for approximately 12 % to 20 % when laser heating were applied. It is suggested that lower material strength and better chips flow [46] compared to the t_c of 0.070 mm has contributed largely to R_a reduction. Less R_a reduction was recorded at higher v_c value due to lower workpiece temperature achieved in LA μ Mill.

CONCLUSION

Through the experimental results, the feasibility of micro ball end mill in LA μ Mill was successfully evaluated. LA μ Mill under heating temperature of 130 °C to 180 °C has shown different machining characteristics. From the results of chips formation characteristics, burr and surface conditions, the next conclusions are derived.

Feed of 4.2×10^{-3} mm/flute produced the most consistent chips pattern with less connected chip. In contrast, at feed of 2.1×10^{-3} mm/flute, most of the chips were produced in continuous shape.

Cutting speed in range between 7.6 m/min and 21.8 m/min does not give significant influence to the chip pattern and burr formation characteristics in the both machining techniques (LA μ Mill and Conv. μ Mill).

Chips pattern show a strong relation with the machining surface roughness consistency. Under the depth of cut of 0.020 mm, the feed value of 3.0×10^{-3} mm/flute has shown comparably consistent surface roughness under different cutting speed. Loose arc chips produced at this machining parameter allows the machining to be performed with less chip blocking, ploughing and rubbing mechanism which consequently produced consistent surface roughness.

Machining under the depth of cut 0.045 and 0.070 mm has resulted to inconsistency surface roughness at all feed value and cutting speed applied due to the existence of connected and conical chips.

Laser heating in LA μ Mill promoted the slot base burr creation by increasing the tendency of chip adhesion on cutting tool and the frequency of connected chip creation.

Machining at t_c of 0.045 and 0.070 mm are not recommended for the both machining techniques (Conv. μ Mill and LA μ Mill) due to excessively large chip size. Severe chips compression and poor chip flow led to serious burr formation and poor surface roughness.

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