Applied Mechanics and Materials Vol. 660 (2014) pp 55-59
© (2014) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.660.55

Submitted: 26.06.2014
Revised: 14.08.2014
Accepted: 14.08.2014

Laser Assisted Micro-Groove Ball Milling of Ti6Al4V

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Key words: Titanium alloy, cutting force, inclination angle, Laser assisted micromilling

Abstract: In micro scale, the size of cutting tool and shape significantly contributed to the machining performance. Many studies have been done to improve the cutting tool life and machined surface quality. Problems could become more severe when the workpiece has a low thermal conductivity while having high level of ductility such as titanium alloy. In this study, micro ball mill cutting tool is selected to produce a linear groove on a titanium alloy plate. The process is integrated with a laser source as a pre-heating element on the work piece surface. The condition of the flank surface of the tools and cutting force were observed and discussed. The influence of tool orientation and laser heating parameters in laser assisted micro ball milling (LAMM) were also discussed. It was found out that adhesion is the dominant tool wear mechanism thus fluctuate the cutting force value.

Introduction.

In machining process, the mechanical properties of the work material are apparently influence its performance. Low thermal conductivity could promote to high temperature increment at tool-work-piece interface [1]. Generally, cooling medium such as flood coolant, minimum quantity lubricant (MQL) or at least air blow were employed to reduce the cutting temperature to prolong the tool life and cutting quality [2, 3]. However, in micro milling, small amount of external forces from cooling medium supplied could vibrate the tool. In dry cutting, by applying the appropriate machining parameters, subsequently better performance can be obtained. To enhance the machining performance of dry cutting, heating up the workpiece such as in laser assisted machining is proven to be effective [4].

In laser assisted machining, the selection of parameters became more complex when pulsed laser is used as the heat source. The pulsed laser tends to create deep penetrated melted zone rather that wide and shallow heat affected zone for the high peak power compared to continuous wave laser. Excessive laser power will promote to lower cutting force but adversely increase the tool wear rate [5]. However, with appropriate machining parameters, past research has proven that the tool life can be extended to approximately 15% compared to conventional machining [5]. Total machining cost can be saved by 50% for its higher machining speed and lower wear rate [6]. Applying laser to heat the material has sufficiently improve the cutting accuracy, consistent surface roughness and dimensional accuracy [7].

It is reported that minimum undeformed chip thickness of Ti6Al4V can be estimated to be 10-20% of radius edge [1]. The size of radius edge plays an important role in determining the cutting force as well as the tool wear rate. In milling process, the tool cutting edge intermittently interacts with the workpiece with fluctuating undeformed chip thickness. Even though it is commonly known that unsuitable undeformed chip thickness leads to high tool wear ratio, it is inevitable in the case of end milling process. In the case of micro ball mill, this effect becomes more obvious where the undeformed chip thickness also differ with radial distance.

In this study, the capability of AlTiN coated carbide micro ball milling in single groove cutting are investigated. The influence of tool orientation, laser heating and machining parameters were studied an attempt to improve the machinability of Ti6Al4V.

Methodology.

Linear groove machining was performed on a titanium alloy Ti6Al4V plate with the thickness 1.8mm. Two flutes AlTiN coated carbide micro ball milling with maximum tip diameter 0.3mm was used to produce the linear groove. The cutting tool was clamped on an air bearing spindle and rotates in range of 12,000 to 35,000 rpm rotating speed (*N*). The spindle assembly and cutting tool were set with two different inclination angles (θ_t), 90 and 80 degree as shown in Figure **1** (a) and (b). Cutting forces were measured and recorded using a tool dynamometer connected through a signal amplifier to a computer. The experiment parameters were set as the values shown in Table 1 and 2. In the case of laser assisted micro ball milling, the distance between cutting tool and laser beam $X_{t\text{-}b}$ was fixed to 0.600 mm.

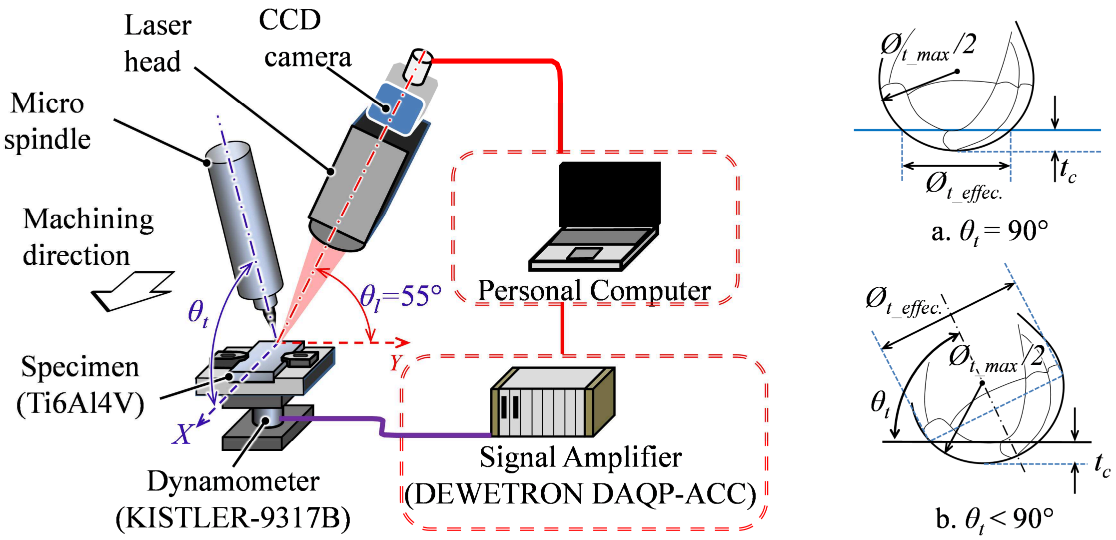


Figure 1: Laser beam and tool orientation

Table 1: Machining parameters for tool inclination angle effect determination

$\{P_{avg}$ (W), t_p (ms), f_p (Hz)$\}$	v_f (mm/min)	N (rpm)	Z	θ_t (°)	t_c (mm)
{0,0,0}	210	35000	2	80, 90	0.030, 0.070, 0.110

Table 2: Machining parameters for comparison between conventional and laser assisted micro milling under different cutting speed and feed.

$\{P_{avg}$ (W), t_p (ms), f_p (Hz)$\}$	Z	θ_t (°)	t_c (mm)	v_c (m/min)	f (mm/tooth)
{0,0,0}, {3.4,1,100}	2	80	0.070	10.9, 15.3, 21.8	0.002, 0.003, 0.004

Results and Discussions.

Figure 2 compares the cutting forces obtained from the experiment using different cutting tool inclination angles. There were no significant differences between the feed forces (F_x) and tangential forces (F_y). However, the thrust forces (F_z) decreased when the tool orientation angle was at 80° compared to 90°. In the case of ball mill cutting tool, the cutting force decreases and then increases with the increment of tilting angle [8]. It is suggested that the bottom part of the tools which does not have cutting edge contribute to high thrust force. By tilting the tool in the feed direction, rubbing process can be avoided and effectually reduce the thrust force. However the thrust force reduction percentage decreased as the depth of cut increased. The thrust forces reduced for 300%, 100% and 20% when the depth of cut was 0.030 mm, 0.070 mm and 0.110 mm respectively. Longer chips were produced when the depth of cut is increased. This has made the chips easier to stick at the tool rake surface since the chips were not efficiently evacuated from the tool-to-work piece contact area. The tools become blunt as the cutting edges are largely covered by the chips adhesion. Figure 3 compares the average cutting forces measured from conventional micro ball milling and laser assisted micro ball milling. Under constant t_c but different v_c and f_v, the effectiveness of laser heating was evaluated. In the case of f of 0.002 mm/tooth, thrust force (F_z) reduces as the cutting speed v_c is increased for both conventional and laser assisted micro-milling. Additionally, the value of F_z slightly reduced when laser is applied during the milling process.

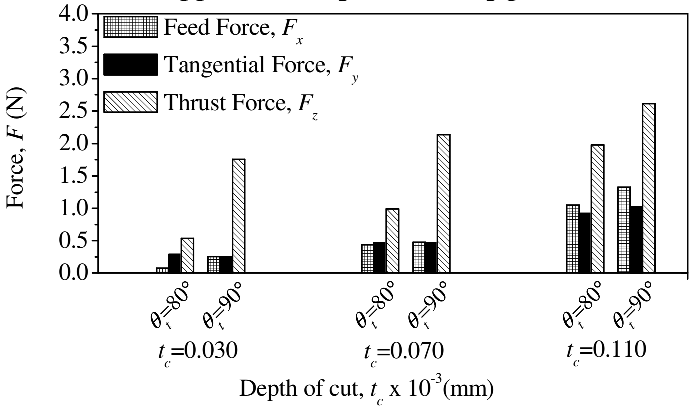
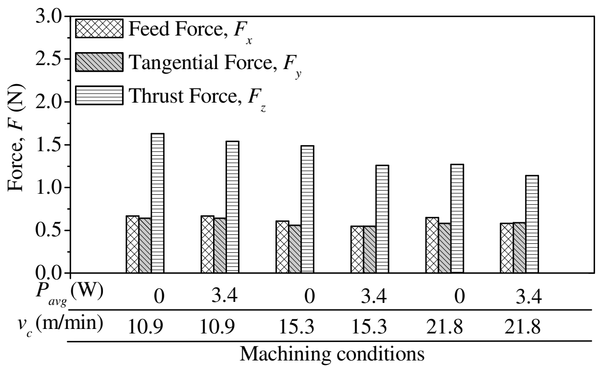
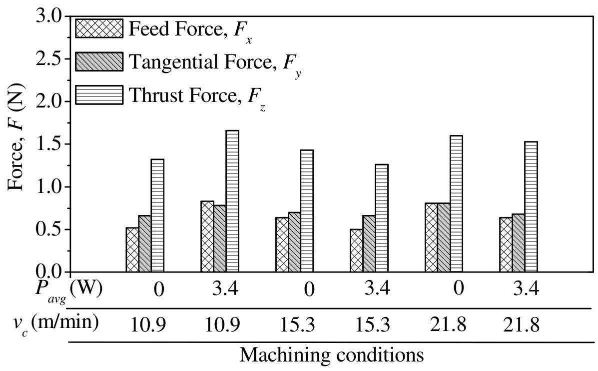


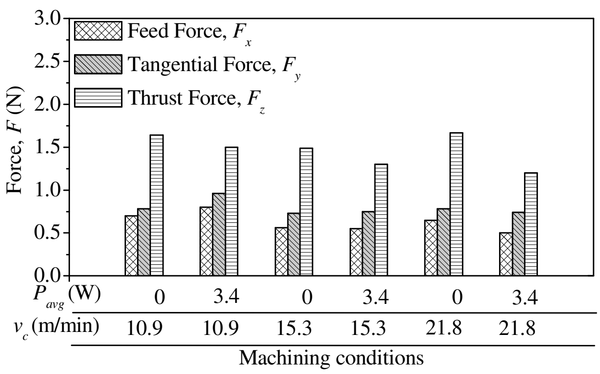
Figure 2: Comparison of average cutting forces between different tool inclination angles and depth of cut. (f_r = 210 mm/min, f_p = 100 Hz, t_p = 1 ms, Without laser, θ_t = 80° and 90°)



(a) f = 0.002 mm/tooth



(b) f = 0.003 mm/tooth



(c) f = 0.004 mm/tooth

Figure 3: Cutting forces when t_c = 0.070 mm,

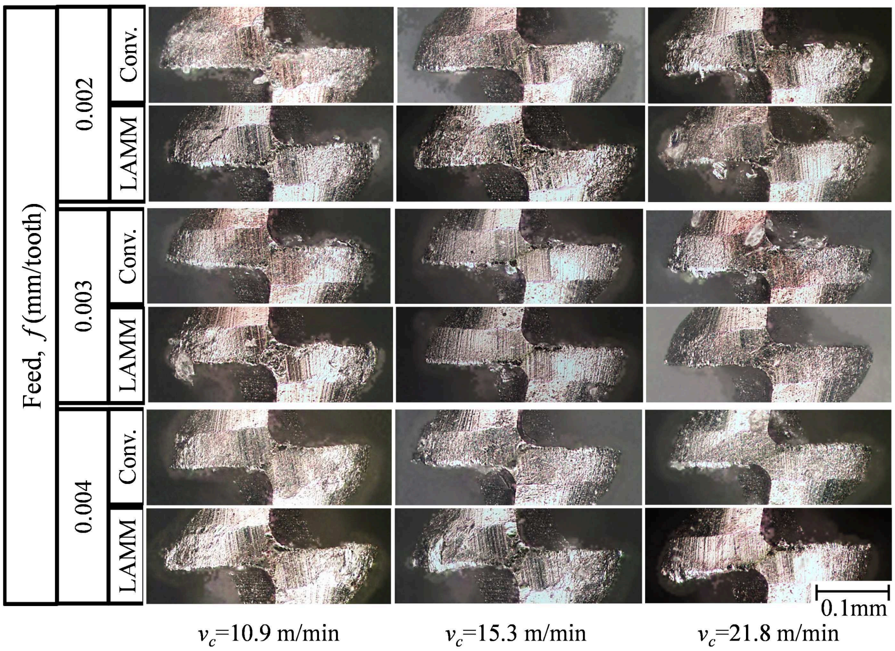


Figure 4: Tool condition after 75 mm of length linear groove cutting

It is suggested that the cutting temperature increased as the cutting speed increases thus reduce the tensile strength. In LAMM, when the material is heated using laser, the material cutting region temperature rises higher. It has consequently produced lower cutting forces compared to conventional micro ball milling for thermal softening.

Increasing the feed (*f*) from 0.002 mm/tooth to 0.003 mm/tooth has slightly increased all cutting forces value. However, the value of F_z changed randomly regardless to the v_c values. The LAMM technique was successfully reduced the F_z value when the v_c was 15.3 mm/tooth. Higher v_c of 21.8 mm/tooth was fail to reduce the cutting forces. Higher *f* means to larger shear area and thicker chip formation. Compared to the tool radius, the cutting depth (t_c) of 0.070 mm means that half of the tool rake surface is rotating under the work piece surface. 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 laser, adhesion occurs randomly thus generate inconsistent cutting force. In titanium alloy high speed machining, cutting force is reported to be highly influenced by the chips evacuation efficiency [9]. This phenomenon also can be seen in machining with 0.004 mm/tooth *f* value. The conventional micro milling produced almost the same cutting forces. The F_z slightly reduced at lower cutting speed but the F_x and F_y remain at approximately the same value with LAMM technique.

The above results show that reducing the *f* does not necessarily reduce the cutting force. The plastic behavior dominates the tool cutting behavior. After 75 mm of deep grove cutting, no obvious wear can be seen from all machining conditions even though the depth of cut was ten times deeper than the recommended value. However, almost all tools has serious adhesion problem at the flank surface (Figure **4**) and it is a normal phenomenon in titanium alloy machining [10].

It is suggested that lower *f* produces thinner and softer chips especially when laser heating is performed during the machining process. These chips have a higher tendency of sticking on the tool flank and rake surface when it's accumulated in the gap between the tool and the work piece. Though, increasing the value of *f* does not necessarily overcome the problem. Thick and long deformed chips collide with the tool flank and rake surface before it separated from the cutting area could generate vibration and promote the *BUE* (built up edges) formation.

Conclusions

Tilting the tool is efficient in reducing the cutting force, especially the thrust force by reducing the tool rubbing effect. In deep groove cutting, the ball mill cutting performance is largely influenced by the chip adhesion problem. Chip evacuations method need to be considered to enhance the capability and to prolong the tool life. In general, laser assisted micro milling performs better than conventional micro milling with lower cutting force. However, chip adhesion problem need to be taken into consideration since the material plasticity increases in higher temperature.

Acknowledgement
Thanks are given to Ministry of Science Technology and Innovation Malaysia (MOSTI) for their support to the research project named “Laser Assisted Micro-Milling of Biomaterial for Implant Parts”,vot number S020.

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