View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Universiti Teknologi Malaysia Institutional Repository

Jurnal Teknologi

Full paper

Influence of Cutting Conditions on Surface and Sub-Surface Quality of High Speed Dry End Milling Ti-6Al-4V

H. Safari, S. Sharif*, S. Izman

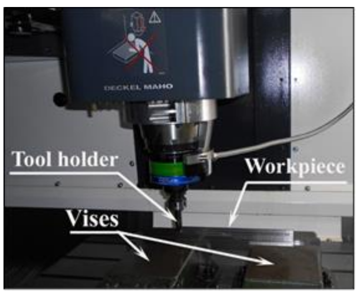
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

*Corresponding author: safian@fkm.utm.my

Article history

Received :23 October 2013
Received in revised form :
14 December 2013
Accepted :10 January 2014

Graphical abstract



Abstract

Surface quality is one of the most critical restraints for determining cutting parameters and selecting of machining process in metal cutting process. In this study, the effects of cutting parameters and tool wear on the surface and sub-surface quality of high speed dry end milling Ti-6Al-4V were investigated. PVD Coated carbide tools were used under different high cutting speeds and feed rates. The quality of the machined surface and corresponding alteration on the sub-surface and entry/exit edges were characterized through scanning electron microscopy. The results showed that the better surface quality was obtained when machining at higher cutting speeds and feed rates. High speed dry end milling using the worn tool causes to plastic deformation of the alloy which is resulted in developing the lamellae on the surface and causing poor surface finish. Worn tools with the uniform tool wear land generated better surface quality compare to those with chipping and flaking on the tool edge surface. Tool wear is suggested as the other contributing factor in developing entry and exit edge damages. The results of sub-surface alteration measurement revealed that the worn tool enhanced the sub-surface alteration resulted in 45% increase in plastic deformation compare to the new tool.

Keywords: Surface quality; high speed; dry end milling; titanium alloy; sub-surface

Abstrak

Kualiti permukaan merupakan satu kekangan kritikal dalam menentukan parameter pemotongan dan pemilihan proses pemesinan pada pemotongan logam. Dalam kajian ini, kesan pemotongan parameter dan kehausan mata alat pada permukaan dan kualiti sub-permukaan kelajuan tinggi akhir pengisaran Ti-6AL-4V telah dikaji. Mata alat PVD bersalut karbida telah digunakan pada kelajuan pemotongan yang tinggi dan kadar suapan yang berbeza. Kualiti permukaan yang dimesin dan pengubahan dicirikan berdasarkan pengimbasan elektron mikroskop. Hasil kajian menunjukkan bahawa kualiti permukaan yang lebih baik apabila pemesinan pada kelajuan pemotongan dan suapan yang lebih tinggi. Kelajuan tinggi pengisaran kering akhir menggunakan mata alat haus menyebabkan perubahan bentuk plastik aloi yang membentuk lamela di permukaan dan menyebabkan kemasan permukaan yang teruk. Mata alat haus menghasilkan kualiti permukaan yang lebih baik berbanding dengan yang bertatal dan sumpek. Mata alat haus adalah faktor yang menyumbang dalam suapan. Data keputusan menunjukkan bahawa mata alat yang haus mengakibatkan peningkatan 45% dalam mengubah bentuk plastik berbanding dengan mata alat baru.

Kata kunci: Kualiti permukaan; kelajuan tinggi; pengisaran kering akhir; titanium aloi; sub-permukaan

© 2014 Penerbit UTM Press. All rights reserved.

■1.0 INTRODUCTION

High reliability levels and resistance to failure of the machined components in various engineering applications can be guaranteed by better surface quality. In general, surface quality of a machined part depends on cutting condition, tool material and tools wear. In addition, it is affected by surface alterations such as feed marks, deposited materials, cracks, tearing, burrs and etc.[1]. Therefore, controlling the machining process parameters is essential to produce acceptable machined surface quality. Burrs forming on entry and exit edges of work-piece is a general phenomenon in machining. It affects the performance and dimensional accuracy of the products. In most of the machining operation de-burring has become a secondary operation to complete the machining process, so controlling of the burr is the key technologies in precision machining. Burrs are varying in size and shape caused by different formation mechanisms [2]. Burrs are positioned at the edges of the work-piece so it can be divided to entry burr, exit burr and side burr. It may be formed in positive or negative shape, which negative burr called fracture. Initiate work on the burr formation in interrupted cutting was conducted by Pekelharing [3]. In milling process burrs are shaped mostly at exit edge of work-piece [4]. The load conditions during entry and exit of the tool are adverse to tool life. During entry, the dangerous load conditions will merely be caused by remnants of previous chips which stuck to the tool. However tools show a greater brittle fracture during exit the work-piece than entering it [3]. Unattractive burrs are always formed in milled surface at the exit side of the work-piece. Burr formation alters the nature of the chip formation and the related forces towards the exit. This can have a negative effect on the chipping of cemented carbides tool during milling of difficult to cut materials at high speed milling (HSM) [5]. Clean tool faces and rounded cutting edges will substantially reduce the risk of chipping and breakage.

Recently, dry machining is progressively becoming more popular as it contributes to cleaner environment and reduces manufacturing cost [6-7]. However, the absence of cutting fluids results in high mechanical and thermal loads on cutting tool-workpiece interface. This leads to tool wear deterioration and surface integrity alteration.

Titanium alloys are widely used in the aerospace industry for manufacturing structural components, hydraulic tubing, compressor and gas turbine engine [8]. These alloys are also used in automotive, offshore and marine, chemical and petroleum industries as well as medical implants [9-10]. This is due to their superior strength-to-weight ratios, excellent mechanical properties at elevated temperatures, high corrosion resistance and compatibility with composite structure. There are a number of investigations [11-12] conducted on milling process to explore the surface integrity of titanium alloys. It has been reported that due to the poor thermal conductivity, surface quality of titanium alloys can easily be affected during milling operation [10]. On the other hand, it is known that the heat generated at the cutting zone is the main reason for surface damage [13]. Therefore, bulk of the heat is evacuated out with chips during HSM. In addition, HSM provides a cleaner cutting process which results in better machining quality because of having cooler tooling and lower machining forces. However, limited results have been reported on surface quality and sub-surface alterations of titanium alloys during HSM. In the present research the effect of different high speed dry end milling (HSDEM) conditions on surface quality of Ti-6Al-4V alloy using PVD coated carbide tool are investigated. Surface roughness values, surface quality and sub-surface alterations were also analyzed.

2.0 EXPERIMENTAL PROCEDURE

CNC milling machine designated Deckel Maho 835 V with the maximum spindle speed of 18000 rpm was used for the HSDEM experiments, the high speed end milling set up is shown in Figure 1. For aerospace materials such as titanium alloys conventional cutting speed ranges from 30 to 100 m/min when using carbide tools [14]. In this study high cutting speeds of 100, 200, and 300 m/min were employed. Based on supplier catalogue feed rates of 0.03 and 0.06 mm/tooth together with axial depth of cut 5.0 mm, and radial depth of cut 1.5 mm were employed as the cutting parameters.

A TiAlN/TiN PVD coated carbide milling insert known as Nano Turbo from SECO with designation XOMX060204R-M05 F40M was used and mounted onto a tool holder type R217.69-1616.0-06-4A. Table 1 provides the specifications of the cutting tool insert and the holder. Figure 2 displays the images of tool holder and inserts used throughout the investigation. To avoid the influence of the tool run-out on surface quality analysis all the experiments were completed using single cutting insert.

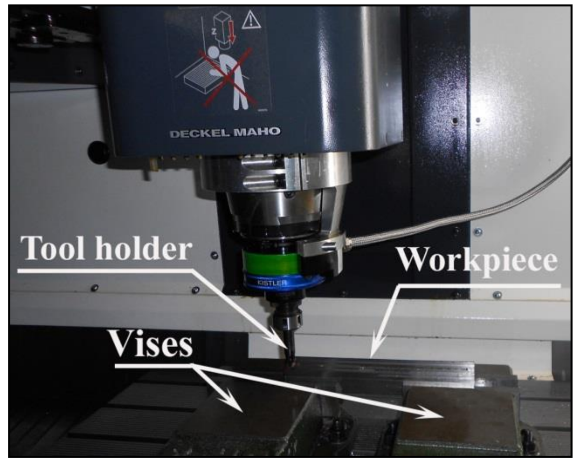


Figure 1 HSDEM experimental setup

A work-piece of Ti-6Al-4V alpha-beta titanium alloy sized 270 ×58 × 25 mm was used for the experimental trials. Tables 2 and 3 show chemical composition and mechanical properties of the investigated material received as hot rolled at the temperature of 925˚C and air cooled, respectively. A Handy-surf E-35 surface roughness tester was used to determine the average surface roughness value of the machined parts at different machining conditions. An average of four readings of surface roughness for each machined surface was recorded. Subsequently, surface of the work-pieces after machining was characterized using scanning electron microscope (SEM, Philips XL40).

Figure 2 Tool holder and insert used for HSEM

Table 1 Specification of the insert and the tool holder

Tool holder			**Insert**	
Cutting rake (°)	Axial rake (°)	Radial rake (°)	Max. Depth of cut (mm)	Cutting rake (°)
–12 - –5	+3 - +8	–12 - –5	5	21

Table 2 Nominal chemical composition of Ti-6Al-4V alloy

Element	Al	V	Fe	N_2+ O_2	H_2	Ti
Wt. %	5.5-6.75	3.5-4.5	0.03 (Max.)	0.25 (Max.)	0.0125 (Max.)	Balance

Table 3 Mechanical properties of Ti-6Al-4V alloy at room temperature

Tensile strength (MPa)	**Yield strength (MPa)**	**Elasticity modulus (GPa)**	**Elongation (%)**	**Area reduction (%)**	**Hardness (HV)**
960-1270	885	100-130	8	25	330-370

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Surface Roughness

The results of surface roughness measurements at both feed and stepover directions at different cutting speed, feed rate and tool condition during HSDEM of Ti-6Al-4V alloy are illustrated in Figure 3 (a-d). It was observed that in general, high quality surface finish was obtained for the milled work-pieces for the investigated conditions. As shown in Figure 3 (a), a significant improvement in the values of surface roughness up to 50% was achieved with recorded surface roughness of 65 nm using new tool at the highest cutting speed of 300 m/min in the feed direction. Similar behaviour was observed for the stepover directions; however the measured surface roughness values were notably higher than those obtained in the feed direction. In general, increasing feed rate results in increased surface roughness of the machined parts. Result in Figure 3 (a, b) indicates that increasing feed rate from 0.03 to 0.06 mm/tooth during HSDEM of Ti-6Al-4V, not only reduces the surface roughness, but surprisingly the improvement was remarkable significant, especially for those machined under lower cutting speed. This can be attributed to the combined effect of milling conditions and tool geometry used during milling process.

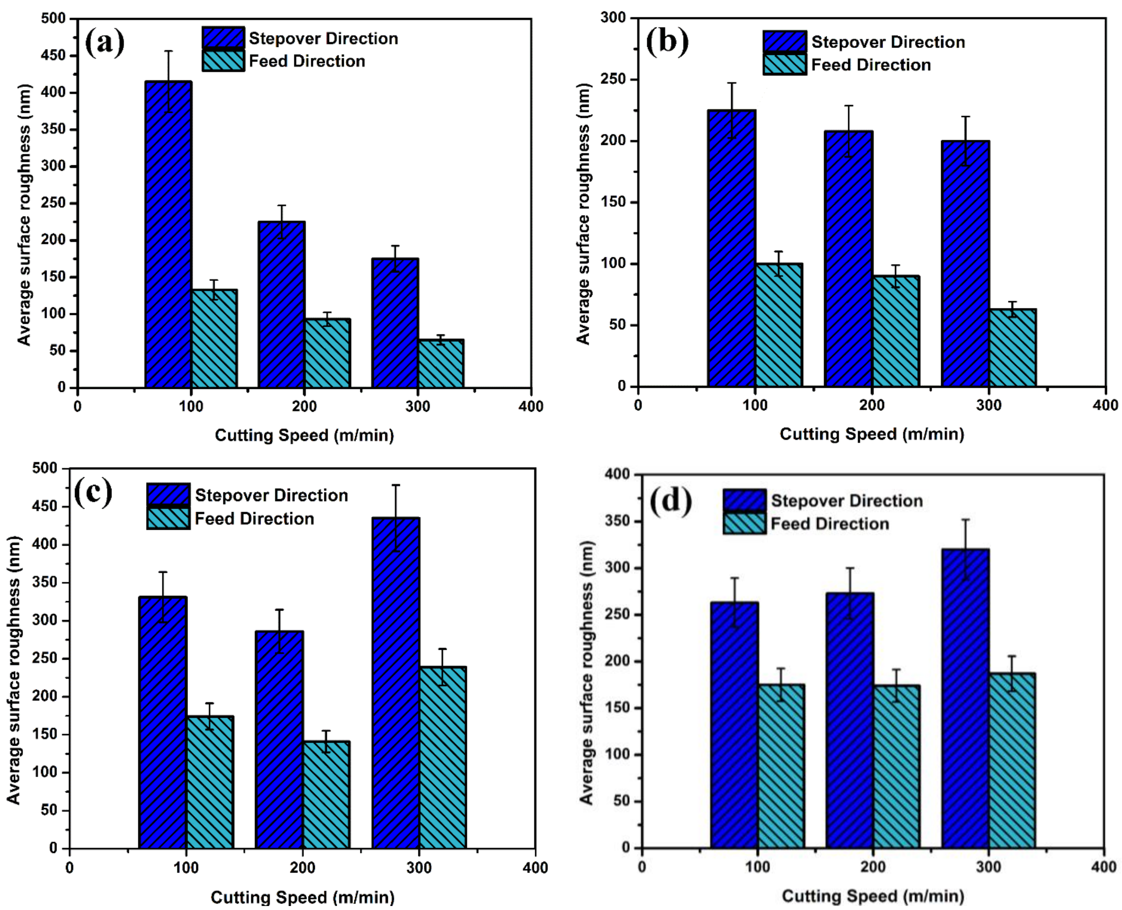


Figure 3 Surface roughness values of the milled Ti-6Al-4V with cutting speed 100, 200 and 300 m/min for different feed rates and tool wears ; (a) new tool at feed rate 0.03 mm/tooth, (b) new tool at feed rate 0.06 mm/tooth, (c) worn tool at feed rate 0.03 mm/tooth, (d) worn tool at feed rate 0.06mm/tooth

3.2 Surface Roughness Micrograph

SEM micrographs of the milled surfaces of Ti-6Al-4V alloy at cutting speed of 300m/min and feed rate 0.06 m/min are shown in Figure 4 (a,b) using new and worn tool, respectively. Figure 4 (a) represents the surface quality of the work-piece after HSDEM process. The surface of the work-piece consists of deformed lamellae caused by the milling process.

Due to the higher quality of the milled surface obtained using new tool, only a feeble lamellae can be observed in Figure 4 (a) whilst it is highlighted by using the worn tool in Figure 4 (b). Worn tool generally causes higher cutting temperature leading to an increase ductility of the chips; therefore, it produces larger lamellae on the surface of the work-piece. It also generates more smeared material particles on the surfaces.

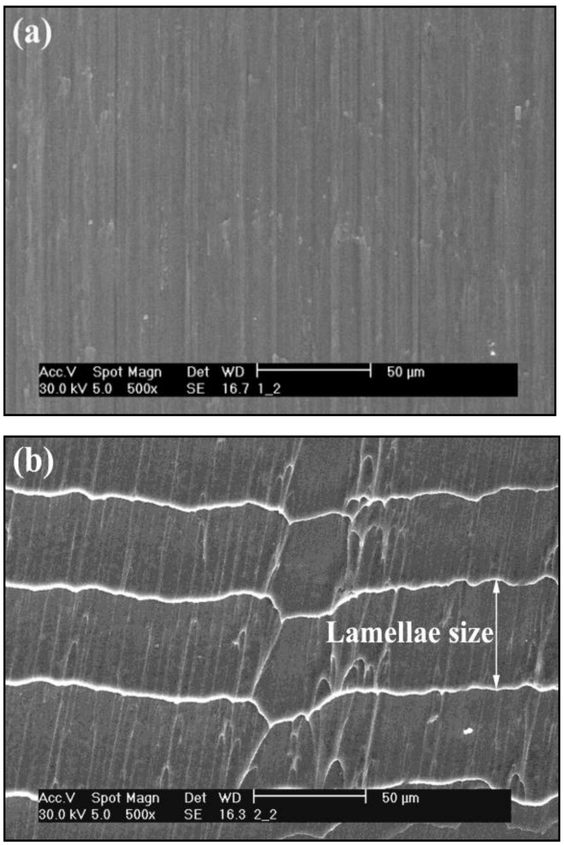


Figure 4 SEM micrographs showing the surface quality of the milled Ti-6Al-4V work-pieces at cutting speed 300 m/min and feed rate 0.06 mm/tooth using (a) new tool (b) worn tool

The analysis of the milled surfaces produced in the present research also showed lower quality surface finish using worn tool. The micrograph also shows that the lamellae are perpendicular to the feed direction with an average size of 60 μm. The measurement was carried out on the edges of lamellae as shown in Figure 4 (b).

The distance represents a single feed band which shows these lamellae are replaced to the feed marks in the other machining operations such as turning. Feed mark is a normal defect emerges on the surface during feeding process. This process brings about plastic deformation of the alloy during the milling resulting in developing the lamellae on the surface and causing poor surface finish.

3.3 Sub-Surface Microstructure Alternations

Figure 5 (a-b) shows the cross-sectional SEM images of sub-surface after milling at feed rate of 0.03 m/min and cutting speed of 200 m/min using new and worn tools respectively. It can be observed that grains deformed immediately beneath the milled surfaces. This behavior was pronounced with using worn tool and the deformed layer grew from approximately 20 to 29 μm in depth. In addition, no sub-surface defects such as cracks or tears were observed after HSDEM process.

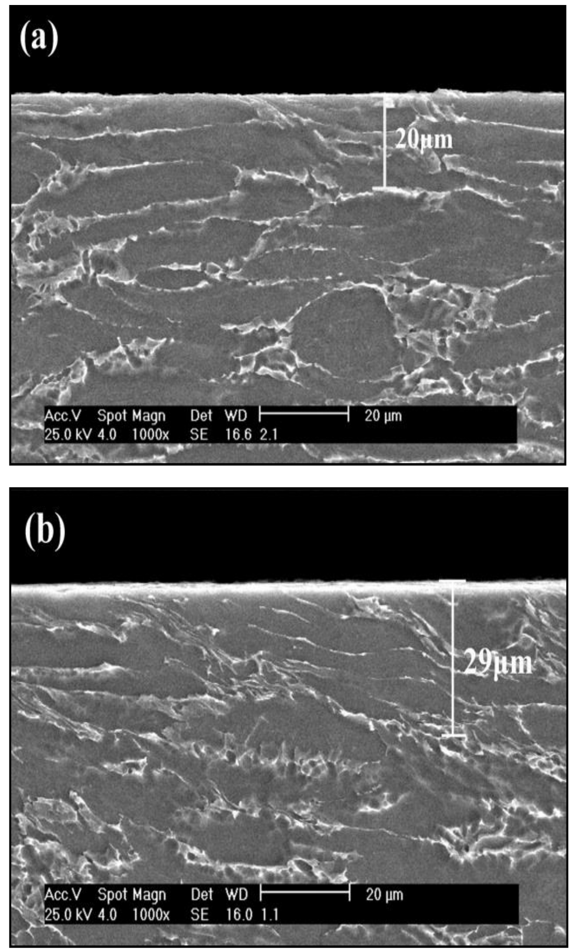


Figure 5 SEM micrographs of the cross-sectional sub-surface of the milled alloy at feed rate of 0.03 m/min and cutting speed of 200 m/min using and using (a) new tool and (b) worn tool

The cross-sectional microstructure of sub-surface of the work-piece did not show any recast or white layers as well. This is due to the fact that the temperature in the cutting zone during HSDEM process was definitely lower than the melting temperature of the alloy. This is in line with the observations reported by other researchers when machining Ti-6Al-4V alloy [15-17]. The combination of mechanical and thermal loads was the main reason for the alterations in the microstructure of the alloy just beneath the milled surface. It is suggested that the alterations in microstructure underneath the milled surface can be influenced by tool wear which is resulting in more plastic deformation and relatively deeper alterations of the microstructure.

3.4 Entry and Exit Edges Micrograph

Figure 6 shows SEM micrographs of the burrs forming on entry and exit edges of the milled Ti-6Al-4V work-piece at cutting speed 300 m/min and feed rate 0.06 mm/tooth using new and worn tool during HSDEM. As can be seen from Figure 6 (a), an irregular burr is formed on the entry edge using the new tool. This is due to machining cutting condition which is affected the burr formation at entry edge.

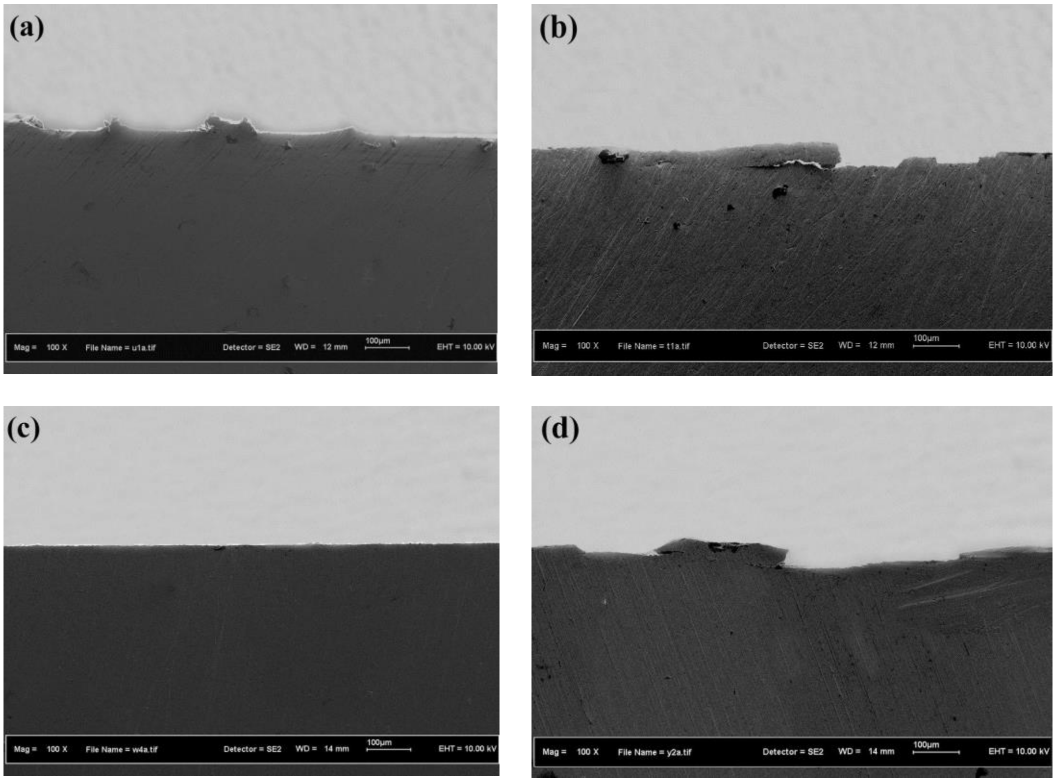


Figure 6 SEM micrographs showing the burrs forming on entry and exit edges of the milled Ti-6Al-4V work-pieces at cutting speed 300 m/min and feed rate 0.06 mm/tooth using (a) new tool and entry edge (b) worn tool and entry edge (c) new tool and exit edge (d) worn tool and exit edge

Since work-piece material properties and cutting condition parameters are critical to burr formation [18-21]. Figure 6 (b) represents the damage on the entry edge using the worn tool. These damages are including deformation, crack and scission. Whereas certain work-piece material and fixed cutting parameters were employed, tool wear condition is the only reason for these alterations. Figure 6 (c, d) shows the exit edge SEM micrographs of the milled alloy using new and worn tools, respectively. It can be seen that besides work-piece material properties and cutting condition parameters which are reported by other researchers, the alterations in the exit edge can be controlled by tool wear as well. Tool wear can be considered as the other contributing factor in developing more entry and exit edge damage. The same damages on the entry and exit edges represented the fact that edges failure was not affected by entrance or exit the tool in this experiment.

■4.0 CONCLUSION

Based on the investigation conducted on HSDEM of Ti-6Al-4V alloy, the following conclusions can be drawn:

1. Tool rejection criteria affected the surface roughness value. Gradually tool wear rejection gave the better surface quality compare to chipping tool rejection.
2. The lamellae distance on the milled surface represented a single feed band. This stand for that the lamellae were replaced to the feed marks in the other machining operations such as turning.
3. Besides work-piece material properties and cutting condition parameters which are reported by other researchers, the alterations on entry and exit edges can be controlled by tool wear as well.
4. Considerable sub-surface alterations were observed when HSDEM of Ti-6Al-4V alloy. Using worn tools resulting in deeper alterations of the microstructure beneath the milled surface.

Acknowledgement

The authors wish to thank the Ministry of Higher Education Malaysia (MOHE) and Research Management Center, UTM for the financial support to this work through the FRGS funding RUG 02H43.

References

[1] Devillez, A., Le Coz, G., Dominiak, S. and Dudzinski, D. 2011. Dry Machining of Inconel 718, Workpiece Surface Integrity. *Journal of Materials Processing Technology*. 211: 1590–1598.

[2] Aurich, J.C., Sudermann, H. and Bil, H. 2005. Characterization of Burr Formation in Grinding and Prospects For Modeling. *CIRP Annals–Manufacturing Technology*. 54(1): 313–316.

[3] Pekelharing, A.J. 1978. Exit Failure in Interrupted Cutting. *Gen Assem of CIRP, 28th, Manuf Technol*. 27(1): 5–10.

[4] Chern, G. L. 2006. Experimental Observation and Analysis of Burr Formation Mechanism in Face Milling of Aluminum Alloys. *International Journal of Machine Tools & Manufacture*. 46: 1517–1525.

[5] Shaw, M.C. 1979. Fracture of Metal Cutting Tools. *Annals of the CIRP*. 28(1): 19–21.

[6] Li, A., Zhao, J., Luo, H., Pei, Z. and Wang, Z. 2012. Progressive Tool Failure in High-Speed Dry Milling of Ti-6Al-4V Alloy with Coated Carbide Tools. *International Journal of Advanced Manufacturing Technology*. 58: 465–478.

[7] Li, A., Zhao, J., Luo, H. and Zheng, W.2011. Machined Surface Analysis in High-Speed Dry Milling of Ti-6Al-4V Alloy with Coated Carbide Inserts. *Advanced Materials Research*. 325: 412–417.

[8] Boyer, R.R. 1996. An Overview on the use of Titanium in the Aerospace Industry. *Materials Science and Engineering*. A213: 103–114.

[9] Zoya Z.A. and Krishnamurthy, R. 2000. The Performance of CBN Tools in the Machining of Titanium Alloys. *Journal of Materials Processing Technology*. 100: 80–86.

[10] Che-Haron, C.H. and Jawaid, A. 2005. The Effect of Machining on Surface Integrity of Titanium Alloy Ti–6% Al–4% V. *Journal of Materials Processing Technology*. 166: 188–192.

[11] Zhang, S. and Li, J.F. 2010. Tool Wear Criterion, Tool Life, and Surface Roughness During High-speed End Milling Ti-6Al-4V alloy. *Journal of Zhejiang University Science A (Applied Physics & Engineering*). 11(8): 587–595.

[12] Su, H., Liu, P., Fu, Y., Xu, J. 2012. Tool Life and Surface Integrity in High-speed Milling of Titanium Alloy TA15 with PCD/PCBN Tools. *Chinese Journal of Aeronautics*. 25: 784–790.

[13] Ezugwu, E. O. and Wan, Z. M. 1997. Titanium Alloys and Their Machinability A Review. *Journal of Materials Processing Technology*. 68: 262–274.

[14] Kitagawa, T., Kubo, A. and Maekawa, K. 1997. Temperature and Wear of Cutting Tools in High-speed Machining of Incone1718 and Ti-6A1-6V-2Sn. *Wear*. 202: 142–148.

[15] Sun, J. and Guo, Y.B. 2009. A comprehensive Experimental Study on Surface Integrity by End Milling of Ti-6Al-4V. *Journal of Materials Processing Technology*. 209: 4036–4042.

[16] Rahim, E. A. and Sharif, S. 2006. Investigation on Tool Life and Surface Integrity when Drilling Ti-6Al-4V and Ti-5Al-4V-Mo/Fe. *JSME International Journal, Series C: Mechanical Systems, Machine Elements and Manufacturing*. 49(2): 340–345.

[17] Klocke, F., Lung, D., Arft, M., Priarone, P.C. and Settineri, L. 2013. On High-Speed Turning of a Third-generation Gamma Titanium Aluminide. *International Journal of Advanced Manufacturing Technology*. 65(1–4): 155–163.

[18] Nakayama, K. and Arai, M. 1987. Burr Formation in Metal Cutting. *CIRP Annals-Manufacturing Technology*. 36(1): 33–36.

[19] Hashimura, M., Chang, Y.P. and Dornfeld, D. 1999. Analysis of Burr Formation Mechanism in Orthogonal Cutting. *Journal of Manufacturing Science and Engineering*. 121(1): 1–7.

[20] Komanduri, R., Chandrasekaran, N. and Raff, L.M. 2001. MD Simulation of Exit Failure in Nanometric Cutting. *Materials Science and Engineering*. A311: 1–12.

[21] Long, Y. and Guo, C. 2012. Finite Element Modeling of Burr Formation in Orthogonal Cutting. *Machining Science and Technology*. 16 (3): 321–336.