Monitoring of Tool Wear by Ratio of Cutting Force Components in End Milling Process for Titanium Alloy Ti6Al4V

Eiji Kondo[1, a *], Daisuke Tabuchi[1, b] and Noriyoshi Kumazawa[1, c]

[1] Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan

[a] kondo@mech.kagoshima-u.ac.jp, [b] tabuchi@mech.kagoshima-u.ac.jp,
[c] kumazawa@mech.kagoshima-u.ac.jp

Keywords: end milling, titanium alloy, cutting force, monitoring, tool wear

Abstract. As titanium alloys have a high strength-to-weight ratio and superior corrosion resistance, they are widely used in industries. However, these alloys exhibit very poor machinability, which results in problems such as short tool life and high-cost manufacturing. The purpose of this study is here to examine cutting forces for relationship to tool wear during end milling of the titanium alloy, and reveal possibility of monitoring of tool wear by the cutting forces. Up-cut milling was performed with single edge end mill in order to measure the widths of flank wear and rake wear and the cutting forces as the cutting length was increased at cutting speeds of 10 m/min and 50 m/min, respectively. Obtained ratio of radial cutting force to tangential cutting force suddenly increase in early stage of up-cut where uncut chip thickness was smaller than width of rake wear land, and then decreased with progress of cutting as uncut chip thickness increased. And the cutting time during one cutting process when the ratio was larger than the threshold in advance was getting longer at cutting speeds of 10 m/min as the tool wear increased. However, ratio of radial force to tangential force obtained at cutting speed of 50 m/min did not increase with increase of tool wear because of occurrence of vibrations in cutting process. Consequently, it was concluded that the tool wear could be monitored by the ratio of radial force to tangential force during up-cut milling at cutting speed of 10 m/min but it could not be monitored at cutting speed of 50 m/min.

Introduction

Titanium alloys have been widely used in the aerospace, biomedical and automotive industries because of their good strength-to-weight ratio and superior corrosion resistance. However, it is very difficult to machine Titanium alloy materials due to their poor machinability like its short tool life [1] [2]. Consequently mechanisms of tool wear and tool lives have been serious problems in end-milling of Titanium alloy. However, prediction technique of tool life in end-milling has not been established, and the tool life fairly depends on an individual end-mill [3]-[8]. Thus, in-process monitoring of tool wear is required due to achieve high productivity. On the other hand, previous studies revealed that tool wear causes increase of cutting forces in metal cutting process [9] [10], especially dynamic component of cutting forces [11]. However, it is required to prepare the relationship between tool wear and cutting forces in advance at each cutting condition in previous detection method when tool wear would be monitored by the cutting forces.

The aim of this study is to get useful criteria without preparation in advance for detection of tool wear by using cutting forces. Cutting tests, in which cutting speed and cutting length are adopted as experimental parameters, were carried out to measure cutting forces during cutting process and measure width of wear land of cutting edge at intervals of constant cutting length to examine relationship between the ratio of radial cutting force to tangential cutting force cutting and the width of wear land of cutting edge.

End Milling Process and Experimental Conditions

Cutting tests were carried out on a vertical machining center. End milling process used in this study is shown in Fig.1 and cutting conditions are shown in Table 1. Workpiece material is typical Titanium alloy Ti6Al4V. Upper square end face of workpiece with edge length of 25 mm was milled with single cutting edge of end-mill. Consequently, cutting length in one stroke of tool feed is 25 mm. Cutting tests, in which cutting speed and cutting length are adopted as experimental parameters, were carried out. Cutting force components were measured with a high-rigid dynamometer. Measured cutting force components will be respectively defined as follows: cutting force component F_x in feed direction shown in Fig. 1 is defined as feed force, cutting force component F_y in the direction normal to machined surface is defined as normal force. Furthermore, width of wear land of cutting edge was measured off machine at intervals of constant cutting length with a reading microscope.

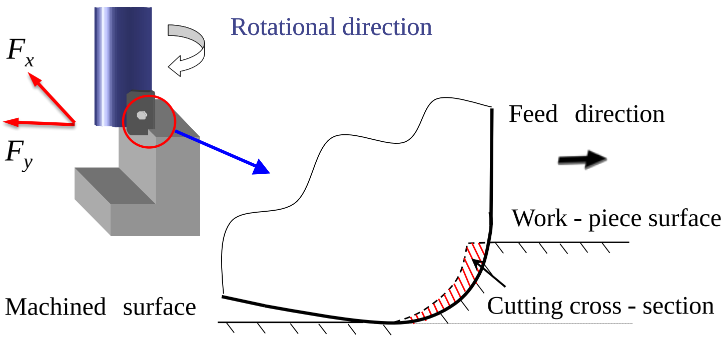


Fig. 1 Schematic diagram of end milling process

Table 1 Cutting conditions

Work-piece	Material	Ti-6Al-4V	
	Dimension	□25 mm	
	Height	25 mm	
Tool	Insert Material	Cemented carbide	
	Diameter	20 mm	
	Rake angle	11 °	
	Clearance angle	16 °	
	Number of flutes	1	
Cutting speed		10 m/min	50 m/min
Feed rate		0.08 mm/rev	
Radial depth of cut		0.5 mm	
Axial depth of cut		0.5 mm	
Cutting length / feed		25 mm	
Type of cut		Up cut	
Cutting fluid		Non (Dry)	

Tool Wear

Cutting Speed of 50 m/min. As shown in Fig. 1, end face of workpiece was milled with the round corner of a cutter since depth of cut was smaller than the radius of corner of the cutter. Consequently, shape of cutting cross section is similar to the character comma. Figure 2 shows schematic diagram of tool wear in end milling process obtained from the photographs shown in Fig. 3. It can be seen from Fig. 2 that the rake face at the top of cutting edge generated by the tool wear could have negative angle. Consequently, it can be predicted that the radial cutting force F_r will be larger than the tangential cutting force F_t in early stage of end milling process in up-cut where the uncut chip thickness land is smaller than width of rake wear and then it will be smaller than the tangential cutting force F_t as the uncut chip thickness linearly increases with progress in up-cut shown in Fig. 2.

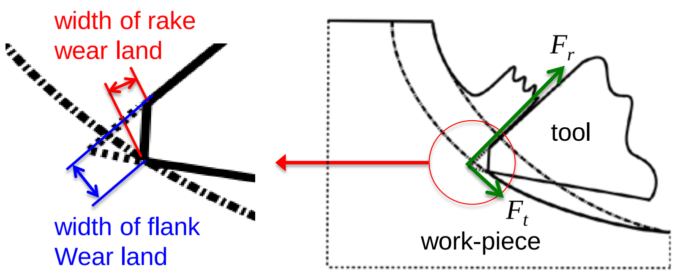


Fig. 2 Schematic diagram of tool wear in end-milling process

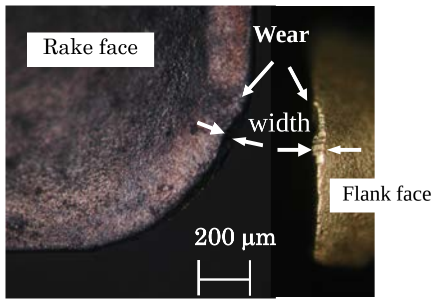
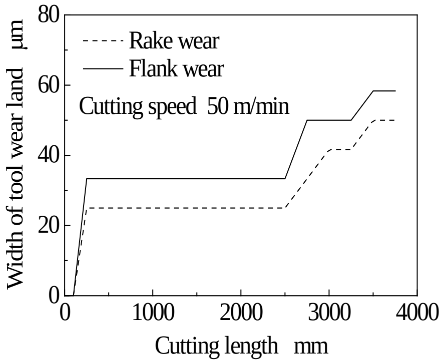
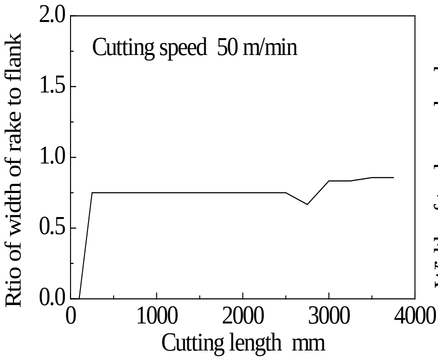


Fig. 3 Tool wear and its measurement (50 m/min, cutting length: 3750 mm)

Figure 4 shows width of wear land with increase of cutting length and the ratio of width of rake wear land to width of flank wear land at cutting speed of 50 m/min. Obtained width of flank wear land and width of rake wear land shown in Fig. 4 (a) rapidly increased at short cutting length and then it rapidly increased again behind cutting length of about 2500 mm. The ratio of the width of rake wear land to the width of flank wear land shown in Fig. 4(b) rapidly increased at short cutting length and it approximately kept constant. Consequently, it can be found that the rake angle at the top of cutting edge generated by the tool wear approximately kept constant with increase of cutting length and the rake face at the cutting edge formed by the tool wear had the rake angle of about –50 ° .

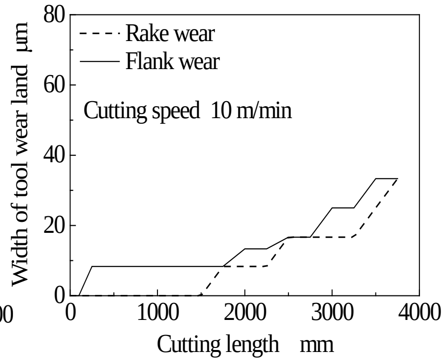


(a) Width of tool wear land

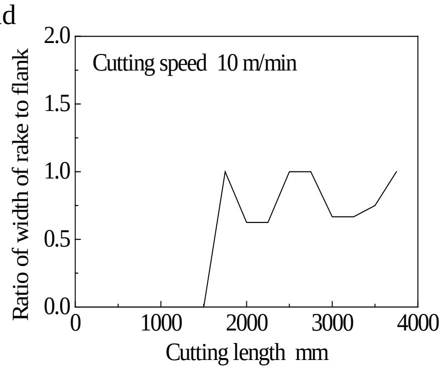


(b) Ratio of width of rake wear land to width of flank wear land

Fig. 4 Tool wear with progress of end milling (50 m/min)



(a) Width of tool wear land



(b) Ratio of width of rake wear land to width of flank wear land

Fig. 5 Tool wear with progress of end milling (10 m/min)

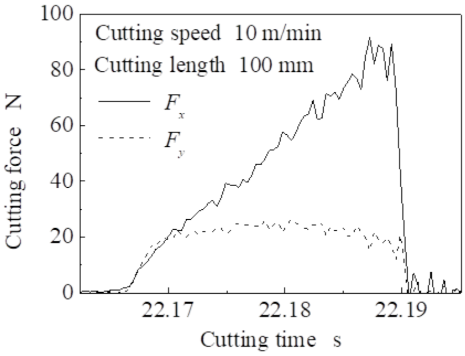
Cutting Speed of 10 m/min. Figure 5 shows width of wear land and ratio of width of rake wear land to width of flank wear land at cutting speed of 10 m/min. Obtained width of flank wear land in Fig. 5 (a) increased a little at short cutting length and then flank wear and rake wear rapidly increased behind cutting length of about 1500 mm. The ratio of the width of rake wear land to the width of flank wear land shown in Fig. 5(b) rapidly increased at cutting length of about 1500 mm and it approximately kept same constant as the ratio of width of rake wear land to flank wear obtained at cutting speed of 50 m/min.

Cutting Forces for Relationship to Tool Wear

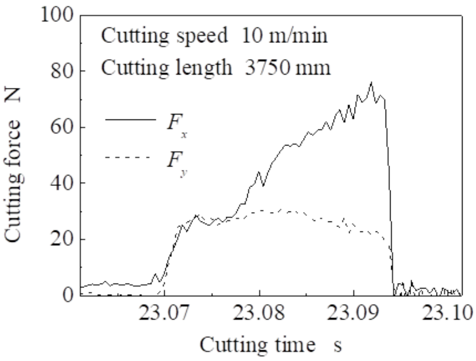
Cutting Speed of 10 m/min. Figure 6 shows the feed force F_x and the normal force F_y during one cutting process at cutting speed of 10 m/min. Magnitude of obtained feed force F_x almost the same as magnitude of obtained normal force F_y at beginning of the cutting process and then the feed force F_x kept almost constant with progress of cutting process although the normal force F_y linearly increased at cutting length of 100 mm shown in Fig. 6 (a). Obtained feed force F_x and obtained normal force F_y at cutting length of 3750 mm were larger than the cutting forces at cutting length of 100 mm shown in Fig. 6 (a) but the characteristics of increase of the cutting forces at cutting length of 3750 mm were different little from the characteristics of the cutting forces at cutting length of 100 mm.

Figure 7 shows coordinate system of cutting force components in end milling process. The cutting forces F_x and F_y shown in Fig. 6 were transformed to radial cutting force F_r and tangential cutting force F_t by using Eq. (1). The radial cutting force F_r will be referred to as the radial force and the tangential cutting force F_t will be referred to as the tangential force after this.

$$\left.\begin{aligned} F_t &= F_x \cos\theta - F_y \sin\theta \\ F_r &= F_x \sin\theta + F_y \cos\theta \end{aligned}\right\} \quad (1)$$



(a) Cutting length: 100 mm



(b) Cutting length: 3750 mm

Fig. 6 Cutting forces in feed direction and normal to feed direction

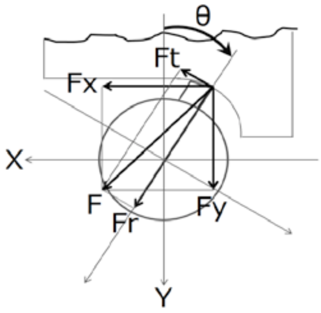
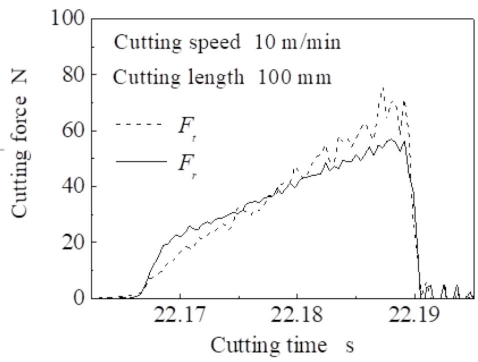
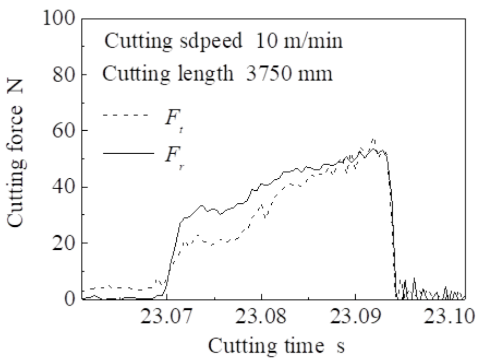


Fig. 7 Coordinate system of cutting force components in end milling process



(a) Length of cut: 100 mm



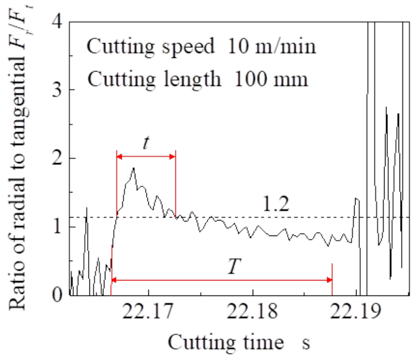
(b) Length of cut: 3750 mm

Fig. 8 Cutting forces in radial and tangential directions (10 m/min)

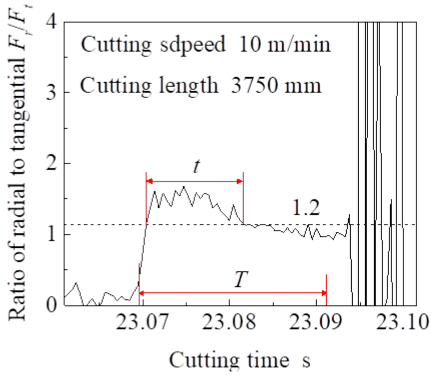
Figure 8 shows the radial force F_r and the tangential force F_t calculated by using Eq. (1). Calculated radial force F_r at cutting length of 100 mm shown in Fig. 8 (a) rapidly increased at beginning of cutting process which was larger than calculated tangential force F_t and then it gradually increased to become smaller than the tangential force F_t while the force F_t linearly increased with progress of cutting process. Calculated radial force F_r at cutting length of 3750 mm shown in Fig. 8 (b) rapidly and fairly increased at beginning of cutting process which was larger than calculated tangential force F_t and then it gradually increased to keep larger than the tangential force F_t although the tangential force F_t also rapidly increased with progress of cutting process.

Figure 9 shows the ratio of the radial force F_r to the tangential force F_t shown in Fig. 8 where symbol T is theoretical time during cutting workpiece in one rotation of end mill. Obtained ratio F_r/F_t at cutting length of 100 mm shown in Fig. 9 (a) rapidly increased at beginning of cutting where uncut chip thickness was smaller than radius at cutting edge roundness, and then it gradually decreased with increase of uncut chip thickness. On the assumption that the ratio F_r/F_t was over the threshold of 1.2 while uncut chip thickness was smaller the width of rake wear land, the cutting time while uncut chip thickness was smaller than the width of rake wear land could be expressed by the time t shown in Fig. 9 (a). Obtained ratio F_r/F_t at cutting length of 3750 mm shown in Fig. 9 (b) rapidly also increased at beginning of cutting process, and then it kept constant over the threshold of 1.2 for a while. Consequently, the time t was longer than the time t at cutting length of 100 mm because the width of rake wear land was larger than the width at cutting length of 100 mm. Consequently, the time t could be expected to increase with increase of width of tool wear land.

Figure 10 shows the time t normalized the time T shown in Fig. 9 which are plotted for each threshold with increase of cutting length. The magnitude of the ratio t/T shown in Fig. 10 for each threshold is the average of t/T during ten



(a) Cutting length: 100 mm



(b) Cutting length: 3750 mm

Fig. 9 Ratio of cutting force in radial direction F_r to cutting force in tangential direction F_t (10 m/min)

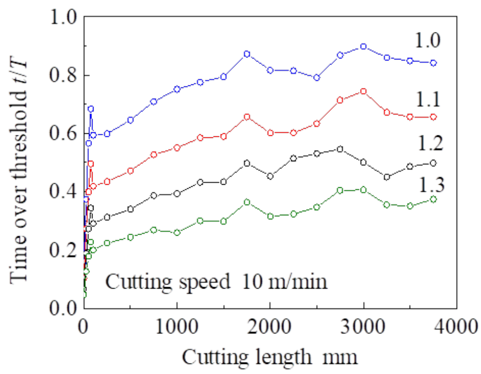


Fig. 10 Time during width of rake wear land larger than uncut chip thickness in one revolution of spindle (average)

revolutions of end mill, respectively: that is, the average is mean value in a set of ten values of obtained ratio t/T. Obtained ratio t/T for the threshold of 1.2 increased with increase of cutting length although it temporarily decreased at some cutting lengths. The magnitude and the increasing rate of the ratio t/T increased until about 1500 with decrease of the value of the threshold but the increasing rate of the ratio t/T behind cutting length about 1500 mm were almost same among all values of threshold. Consequently, it was found that the ratio t/T for threshold of 1.3 exceedingly corresponded with the tool wear shown in Fig. 5 (a) because the tool wear gradually increased until about 1500 mm and then it rapidly increased behind about 1500 mm.

Figure 11 shows also the ratio of F_r to F_t at cutting length of 100 mm but the value of F_r/F_t is average of F_r/F_t trued up each the start point of each cutting process during ten revolutions of end mill. The ratio t/T for threshold of 1.2 with increase of cutting length shown in Fig. 12 had similar feature to the ratio t/T for the threshold of 1.3 shown in Fig. 10 but the increasing and decreasing rate of the ratio t/T were larger than the rate t/T for threshold of 1.2 shown in Fig. 10. Features of the ratio t/T for the other threshold were fairly different from the feature of tool wear shown in Fig. 5 (a).

Cutting speed of 50 m/min. Figure 13 shows the radial force F_r and the tangential force F_t. The radial force F_r at cutting length of 100 mm shown in Fig. 13 (a) rapidly increased at beginning of cutting process which was fairly larger than the tangential force F_t and then it increased with some undulations. The tangential force F_t also increased with some undulations. The radial force F_r at cutting length of 3750 mm shown in Fig. 13 (b) increased at beginning of cutting process more rapidly than that at cutting length of 100 mm and then it repeatedly increased and decreased with progress of cutting process. Figure 14 shows the ratio the forces F_r/F_t shown in Fig. 13. The ratio F_r/F_t at cutting length of 100 mm shown in Fig. 14 (a) rapidly increased at beginning of cutting, and then it gradually decreased with undulations. The ratio F_r/F_t at cutting length of 3750 mm

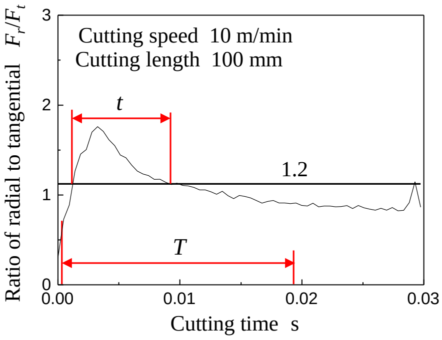


Fig. 11 Ratio of cutting force in radial direction to cutting force in tangential direction (trued up)

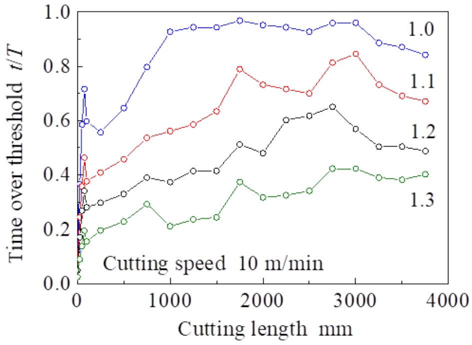
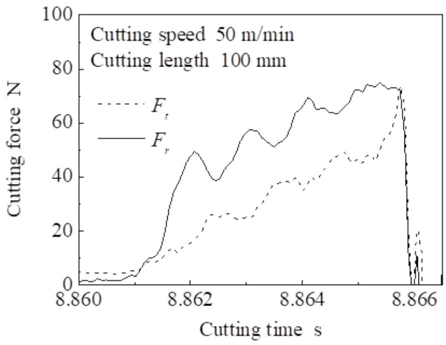
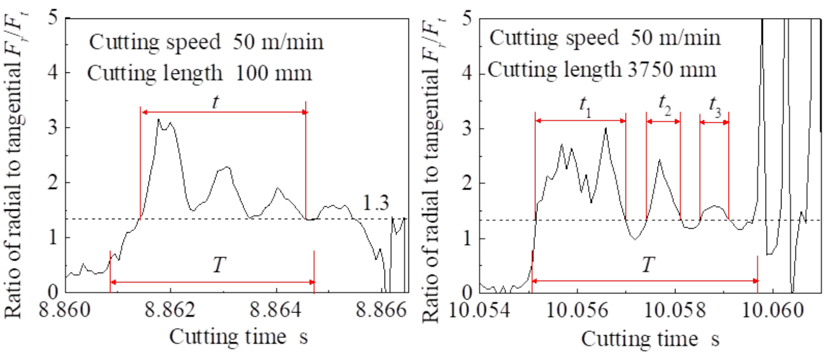


Fig. 12 Time during width of rake wear land larger than uncut chip thickness in one revolution of spindle (trued up)



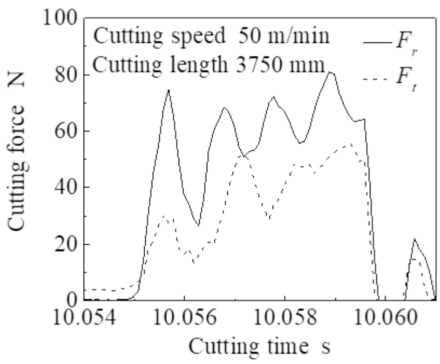
(a) Length of cut: 100 mm



(a) Length of cut: 100 mm

(b) Length of cut: 3750 mm

Fig. 14 Ratio of cutting force in radial direction to cutting force in tangential direction (50 m/min)



(b) Length of cut: 3750 mm

Fig. 13 Cutting forces in radial and tangential directions (50 m/min) shown in Fig. 14 (b) also rapidly increased at beginning of cutting process, and then it repeatedly increased and decreased with larger amplitude than the amplitude of the ratio F_r/F_t at cutting length of 100 mm shown in Fig. 14 (a). As a result of the large undulations of the ratio F_r/F_t, the time t was smaller than the time obtained at cutting length of 100 mm because the ratio F_r/F_t crossed the threshold at some cutting times. Consequently, the time t could not be expected to increase with increase of width of tool wear at cutting speed of 50 m/min.

Conclusions

The following conclusions were obtained from this study:

1) At cutting edge of tool, fine rake face with angle of about －50 ° was formed by tool wear.
2) The ratio of radial force to tangential force rapidly increased at beginning of cutting process and it degreased with progress of cutting process. The time during the ratio of radial force to tangential force larger than threshold of over 1.0 increased with progress of cutting process.
3) When the time during the ratio of radial force to tangential force over the threshold was defined as average value during ten revolutions of end mill, the time during the ratio for threshold of 1.3 exceedingly corresponded with the tool wear.
4) When the ratio of radial force to tangential force trued up each the start point of each cutting process during ten revolutions of end mill, the time during the ratio for threshold of 1.2 exceedingly corresponded with the tool wear.

References

[1] E. O. Ezugwu, Z. M. Wang, Titanium alloy and their machinability – a review, Materials Processing Technology, 68 (1995), 262-274.

[2] M. Rahman, Z. G. Wang, Y.S. Wong, A review on high-speed machining of titanium alloys, JSME International Journal, Vol. 49, No. 2 (2006), 11-20.

[3] Y. Su, N. He, L. Li, X.L. Li, An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V, Wear, 261 (2006) 760-766.

[4] H. Usuki, K. Sato, S. Furuya, High speed dry end milling of Titanium alloys with coated carbide tool, Journal of JSPE, Vol. 71, No. 4 (2005), 491-495 (in Japanese).

[5] X. Qin, et al., Feasibility study on the minimum quantity lubrication in high speed helical milling of Ti-6Al-4V, Journal of Advanced, Mechanical Design, Systems, and Manufacturing, Vol. 7, No. 6 (2012), 1222-1233.

[6] R. Tanaka, et al., Influence of cutting fluid on tool edge temperature in end milling titanium alloy, Journal of Advanced, Mechanical Design, Systems, and Manufacturing, Vol. 9, No. 5 (2015), DOI: 10.1299/ jamdsm.2015jamdsm0074.

[7] E. Kondo, et al., Effects of oil mist and air jet flushing on tool wear in milling of Ti6Al4V at high speed, Procedia CIRP, (2016), 95-98 DOI information: 10.1016/ j.procir.2016.03.125.

[8] E. Kondo, et al., Effects of cutting atmosphere on high-speed end milling process for titanium alloy Ti6Al4V, Material Science Forum, Vol. 874, Trans. Tech. Publications, (2016), 46-51.

[9] G. F. Micheletti, W. Koenig, H. R. Victor, In process tool wear sensors for cutting operations, Annals of the CIRP, Vol. 25, No. 2(1976), 483-496.

[10] G. Byne, et al, Tool condition monitoring (TCM) – The status of research and industrial application, Annals of the CIRP, Vol. 44, No. 2 (1995) 541-567.

[11] E. Kondo, M. Yamasaki, N. Kawagoishi, Tool Wear Monitoring in End-Milling of Titanium Alloy, Proc. the 5th International Conference on Leading Edge Manufacturing in 21st Century, (2009), 471-476.