DOI: 10.3901/CJME.2016.0405.045, available online at www.springerlink.com; www.cjmenet.com

Effects of Cutting Parameters on Tool Insert Wear in End Milling of Titanium Alloy Ti6Al4V

LUO Ming*, WANG Jing, WU Baohai, and ZHANG Dinghua

Key Laboratory of Contemporary Design and Integrated Manufacturing Technology of Ministry of Education, Northwestern Polytechnical University, Xi'an 710072, China

Received September 29, 2015; revised December 7, 2015; accepted April 5, 2016

Abstract: Titanium alloy is a kind of typical hard-to-cut material due to its low thermal conductivity and high strength at elevated temperatures, this contributes to the fast tool wear in the milling of titanium alloys. The influence of cutting conditions on tool wear has been focused on the turning process, and their influence on tool wear in milling process as well as the influence of tool wear on cutting force coefficients has not been investigated comprehensively. To fully understand the tool wear behavior in milling process with inserts, the influence of cutting parameters on tool wear in the milling of titanium alloys Ti6Al4V by using indexable cutters is investigated. The tool wear rate and trends under different feed per tooth, cutting speed, axial depth of cut and radial depth of cut are analyzed. The results show that the feed rate per tooth and the radial depth of cut have a large influence on tool wear in milling Ti6Al4V with coated insert. To reduce tool wear, cutting parameters for coated inserts under experimental cutting conditions are set as: feed rate per tooth less than 0.07 mm, radial depth of cut less than 1.0 mm, and cutting speed sets between 60 and 150 m/min. Investigation on the relationship between tool wear and cutting force coefficients shows that tangential edge constant increases with tool wear and cutter edge chipping can lead to a great variety of tangential cutting force coefficient. The proposed research provides the basic data for evaluating the machinability of milling Ti6Al4V alloy with coated inserts, and the recommend cutting parameters can be immediately applied in practical production.

Keywords: tool wear, Ti6Al4V, cutting parameter, hard-to-cut material

1 Introduction

Titanium alloys are widely applied in aerospace, power and energy industries due to its good mechanical properties, corrosion resistance property and high strength-to-weight ratios[1–2]. Titanium alloy is difficult-to-cut materials and is expensive to machine. Due to its low thermal conductivity, cutting temperatures up to 1100 ℃ will be achieved in a narrow region near the cutting edge at the tool-chip interface during titanium alloy machining[3]. This will lead to high reaction and diffusion rates, resulting in high cutting tool wear rates. Tool wear has a great impact on the surface integrity of the finished part as well as the part surface quality. Therefore, knowing about wear mechanisms and their trends along the cutting length in the machining process is needed for cutting tool life control.

As for the machinability of titanium alloy, PERVAIZ, et al[4], reviewed the machinability of titanium alloys concerning cutting tool materials, associated wear mechanism and so on, they pointed out that heat generation is the main reason for tool failure in carbide material. ARRAZOLA, et al[5], presented the machinability results carried out for Ti555.3 compared with the commonly used Ti6Al4V, they found that it's more difficult to machine Ti555.3. ODELROS[6] studied tool wear during the orthogonal turning of titanium alloy. In the study, the cutting tool inserts were analyzed by SEM, EDS and optical imaging in Alicona InfiniteFocus. Their results show that crater wear was the dominating wear mechanism during the cutting speeds of 90-115 m/min. DA SILVA, et al[7], investigated the behavior of Polycrystalline Diamond (PCD) tools when machining Ti6Al4V alloy at high speed conditions using high pressure coolant supplies. They found that increase in coolant pressure tends to improve tool life and reduce the adhesion. RAZA, et al[8], investigated the effect of different strategies on the flank tool wear during turning of titanium Ti6Al4V using uncoated carbide tools, they found that the adhesive and abrasive wear mechanisms were dominant at the flank face. WEI, et al[9], investigated the influence of hydrogen contents on tool wear, they founded that the tool wear is closely related to cutting speed in machining hydrogenated Ti6Al4V alloy. SUN, et al[10], investigated the evolution of tool wear and its effect on cutting forces during dry machining of Ti6Al4V alloy and found that both the

* Corresponding author. E-mail: luoming@nwpu.edu.cn
Supported by National Basic Research Program of China (973 Program, Grant No. 2013CB035802), National Natural Science Foundation of China (Grant No. 51575453), Fundamental Research Funds for the Central Universities(Grant No. 3102015JCS05002), and the 111 Project, China (Grant No. B13044)
© Chinese Mechanical Engineering Society and Springer-Verlag Berlin Heidelberg 2017

average and maximum flank wear increased more significantly with volume of material removed at higher cutting speed.

In order to reduce tool wear in cutting titanium alloys, RIBEIRO, et al[11], performed turning tests and their results showed that better surface roughness can be obtained under the speed of 90 m/min than 70 m/min. YANG, et al[12], presented a tool wear prediction model, including abrasive, adhesion and diffusion wear and they found a reasonable range of cutting parameters: the cutting speed is in the range of 50–100 m/min, and the feed is in 0.15–0.25 mm/r. ZHANG, et al[13], studied tool wear in precision turning of titanium alloy, the ultrasonic vibration turning method was adopted to reduce the wear of diamond tool in the turning of TC4 titanium alloy. DENG, et al[14], examined the element diffusion from the Ti6Al4V titanium alloy to WC/Co carbide tools at temperature up to 800 ℃. They found that the element diffusion from the Ti6Al4V to the WC/Co carbide tools through the tool-chip interface in machining processes leads to a composition change of the tool substrate, which may accelerate the tool wear. SUI, et al[15], proposed a tool path generation and optimization method for pocket flank milling of aircraft structural parts. A combination strategy of corner-looping milling and clothoid curve transition is proposed to reduce cutting force and machining vibration, thus to further reduce tool wear.

Despite lots of researches have been performed on the machinability of titanium alloy Ti6Al4V, most of them focused on the turning process. These research results provide basic cutting parameters for industrial application. But for practical application, particularly for milling process, these results are not enough for selecting appropriate cutting parameters since the cutting conditions are not actually the same as those employed in experiments. To study the tool wear behavior in milling process with inserts and reduce tool wear, the effects of cutting parameters on tool wear in the end milling of titanium alloy Ti6Al4V with indexable milling cutters is studied. The cutting conditions are the same as industrial application and the parameters can be immediately employed in the workshop. Materials and methods are described in section 2. Results and discussion are discussed in section 3. Finally, some conclusions are given in section 4.

2 Materials and Methods

The material used in this research is titanium alloy Ti6Al4V. The chemical components are Ti-90%, Al-6%, V-4%, Fe-max 0.25%, O-max 0.2% and the physical properties of Ti6Al4V are as follows: 4430 kg/m^3 (Density), 880MPa (Tensile strength, yield), 113.8 MPa(Modulus of Elasticity), 6.7W/m-K (Thermal Conductivity), 36HRC (Hardness), 1604–1660 ℃(Melting Point).

In order to study tool wear in the milling of Ti6Al4V under different cutting parameters with indexable milling cutters, a series of milling experiments of Ti6Al4V were performed. The setup for milling experiment is shown in Fig. 1. The inserts used in the experiments are MITSUBISHI APMT1135PDER-M2 VP15TF and the cutter diameter is 16mm. The machining center used is YHVT850Z.

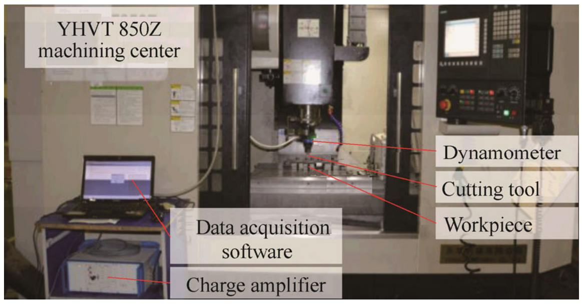

Fig. 1. Test setup

Listed in Table 1 are the used cutting parameters, water soluble coolant was used in the milling tests. In the table, v is the cutting speed, a_e is the radial depth of cut, a_p is the axial depth of cut, f_t is the feed per tooth. Four components dynamometer(Kistler 9123C) was used for measuring cutting forces in three coordinate directions(X, Y and Z) and the spindle torque in the milling process. In order to measure the tool wear, Alicona Infinitefocus G4 was used to get the tool wear width.

Table 1. Cutting parameters used in the experiments

No.	Cutting speed v/(m • min^{-1})	Axial depth of cut a_p/mm	Radial depth of cut a_e/mm	Feed per tooth f_t/(mm • tooth^{-1})
01	60.29	2	1	0.05
02	60.29	2	2	0.05
03	60.29	2	3	0.05
04	60.29	2	4	0.05
05	90.43	2	1	0.05
06	90.43	2	1	0.07
07	90.43	2	1	0.09
08	90.43	2	1	0.11
09	120.58	2	1	0.05
10	150.72	2	1	0.05
11	90.43	1	1	0.07
12	90.43	3	1	0.07
13	90.43	4	1	0.07

3 Results and Discussion

Optical 3D topography measurements were performed for inserts using Alicona InfiniteFocus, both before and after wear tests in the milling. Images measured before and after machining were analyzed and the wear length was estimated. Cutting forces and the spindle torque were measured in the milling process.

From the optical measurement results, flank wear is observed as the main wear mechanism in the milling test with inserts. Flank wear is caused by friction between the flank surface of the cutter and the machined workpiece surface[16].

3.1 Influence of cutting parameters

3.1.1 Influence of feed per tooth

Tool wear under different feed per tooth is investigated: 0.05, 0.07, 0.09, and 0.11 mm/tooth. Other cutting parameters are v=90.43 m/min, a_p=2.0 mm, a_e=1.0 mm. Tool wear(VB) results are shown in Fig. 2. The results show that tool wear increases greatly with the increase of feed per tooth. When the length of cut exceeds 2760 mm under feed per tooth of 0.07 mm/tooth, insert edge breakage was observed. For larger feed per tooth, the breakage did not happen, it may due to the hard point in the workpiece for feed per tooth 0.07 mm/tooth. When f_t=0.05 mm/tooth, tool wear increases gradually with the increase of cutting length. For different f_t, results show that tool wear is slow for a certain length of cut. After that, tool wear grows fast. As feed per tooth increases, the material removal rate increases and so does the cutting heat. The same happens to the unit cutting force. Increase of cutting heat will lead to higher cutting temperature, which will aggravate the failure of insert coating. Hence, tool wear will increase under high cutting temperature and large cutting force.

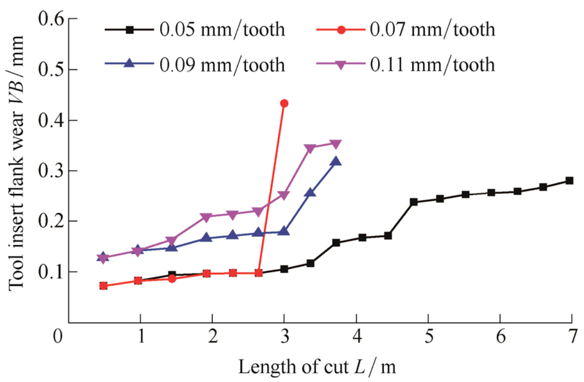

Fig. 2. Effects of feed per tooth on tool flank wear

3.1.2 Influence of cutting speed

Under four different cutting speeds: 60.29, 90.43, 120.58, 150.72 m/min, the tool wear increases gradually with the increase of cutting length, as shown in Fig. 3. For different cutting speeds, it is observed that there is no big difference of tool wear trend. As for the tool wear in the experiments, none of the four inserts reaches 0.3 mm. An approximately linear dependence between tool wear and increasing cutting length is found for cutting speeds 120.58 m/min and 150.72 m/min. For lower cutting speeds, 60.29 m/min and 90.43 m/min, the tool wear is not showing an obvious dependence on the cutting length or the cutting time. For high cutting speeds, 120.58 m/min and 150.72 m/min, it seems that the steady-state wear region is reached.

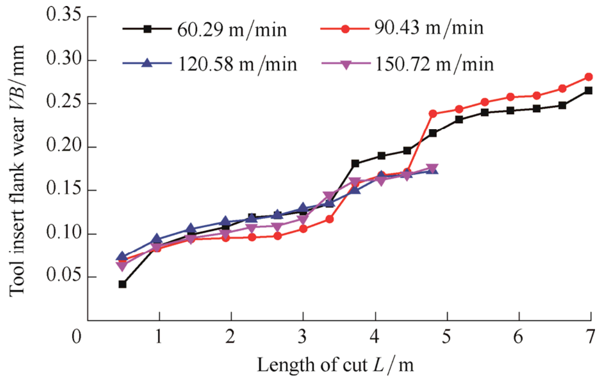

Fig. 3. Effects of cutting speed on tool flank wear

3.1.3 Influence of axial depth of cut

Fig. 4 shows the effects of axial depth of cut on the tool wear. Under different axial depth of cut, tool wear increase slowly with the increase of cutting length, it seems the steady state region is reached. When cutting length reaches 2760 mm under an axial depth of cut 3.0 mm and 4.0 mm, cutter insert edge breakages were observed at the upper edge of the insert. It is mainly caused by large stress due to large cutting load. As for the tool wear behavior, a gradual, approximately linear tool wear development with increasing cutting length is observed at the axial depth of cut a_p=1.0 mm and a_p=2.0 mm. As the axial depth of cut increased, the heat generated and cutting force might increase, but the working length of the cutting tool insert edge increased as well. The cutter insert edge breakage is mainly caused by the large tool load.

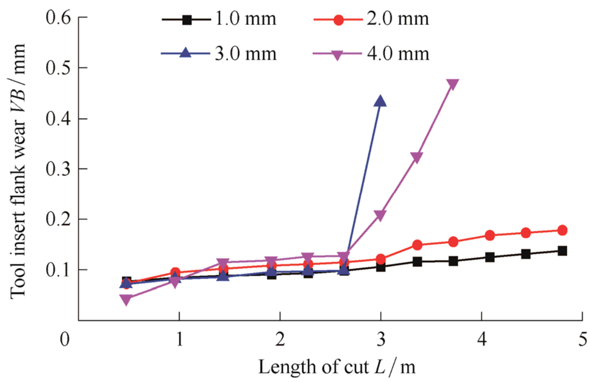

Fig. 4. Effects of axial depth of cut on tool flank wear

3.1.4 Influence of radial depth of cut

When the radial depth of cut increases, insert edge breakage is prone to occur, as shown in Fig. 5. For small radial depth of cut (a_e=1.0 mm), tool wear increases slowly, it seems the steady state region is reached. For large radial depth of cut ($a_e\geqslant$2.0 mm), the tool wear rate is much larger and the edge breakage is prone to happen. Tool wear rate grows with the increase of radial depth of cut and it seems accelerated wear zone is reached rapidly. Besides, the tool wear behavior is approximately exponential for radial depth of cut larger than 1.0 mm, and approximately linear tool wear trend is observed for the radial depth of cut a_e=1.0

mm.

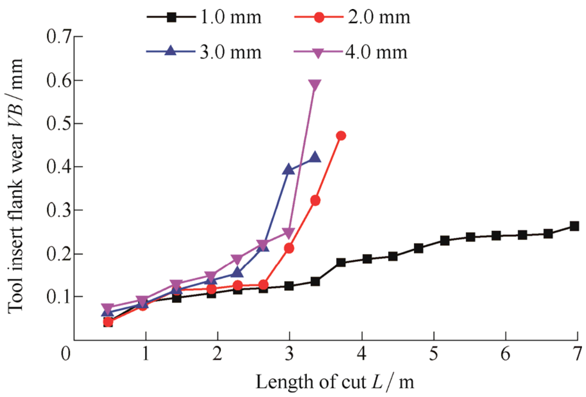

Fig. 5. Effects of axial depth of cut on tool flank wear

3.1.5 Discussion

With the increase of radial depth of cut, cutting time during one cutter revolution of the insert increase as well, which means the tool insert withstands high temperature and high tool load for much longer time. Hence, the heat generated during cutting accumulated and tool wear increases. Besides, the peak temperature grows with the increase of radial depth of cut and accumulation of heat. Higher contact temperatures give higher reaction rates and probably higher tool wear rates. Therefore, higher tool wear rate was observed with the increase of radial depth of cut.

The above results show that feed rate per tooth and radial depth of cut have great influence on tool wear, axial depth of cut and cutting speed have a small influence on tool wear. Therefore, selecting proper feed rate per tooth and radial depth of cut are the key factors in extending tool life. For the given tool-workpiece material pair, suggested cutting parameters are $f_t \leqslant 0.07$ mm/tooth, $a_e \leqslant 1$ mm, $a_p \leqslant 2$ mm, the cutting speed can be set between 60 m/min and 150 m/min. In order to reduce tool wear in milling titanium alloy by using cutters with inserts, the ratio between working time and cooling time of the insert should be set properly according to the cutting conditions. Radial depth of cut can be optimized according to the working-cooling time ratio to reduce tool wear rate. Since axial depth of cut does not increase tool wear rate noticeably, it can be increased according to the tool load to get higher machining efficiency. Therefore, the trochoidal milling strategy can be an alternative method for high efficiency milling of hard-to-cut material with longer tool life[17–19]. In the subsequent study, selection of proper cutting parameters for trochoidal milling of titanium alloy to get higher machining efficiency and longer tool life will be carried out.

3.2 Tool life prediction

Tool life can be expressed as a function of cutting conditions as follows[16]:

$$T_t = \frac{C_t}{v^p f_t^q}, \tag{1}$$

where T_t is tool life, C, p and q are constants for a given tool-workpiece material pair. Based on the test above, the machinability test results are shown in Table 2.

Table 2. Machinability tests

No.	Cutting speed v/(m • min^{-1})	Feed rate f_t/(mm • tooth^{-1})	Measured tool life T_t/min
1	60.29	0.05	125
2	90.43	0.05	79
3	90.43	0.11	16

From tests 1 and 2,

$$p = \frac{\ln\left(T_{t1}/T_{t2}\right)}{\ln\left(v_2/v_1\right)} = 1.135. \tag{2}$$

From tests 2 and 3,

$$q = \frac{\ln\left(T_{t3}/T_{t2}\right)}{\ln\left(f_{t2}/f_{t3}\right)} = 2.011. \tag{3}$$

Substituting p and q into Eq. (1) gives the third parameter as

$$C_t = 31.7. \tag{4}$$

Then the resulting empirical Taylor tool life equation for tested tool-Ti6Al4V pair becomes

$$T_t = \frac{31.7}{v^{1.135} f_t^{2.011}}. \tag{5}$$

It can be observed that feed rate per tooth has more influence than cutting speed on tool life within the tested parameter range.

3.3 Influence of the tool wear on cutting force coefficients

To further analyze tool wear's influence on cutting process, cutting force coefficients were tracked and analyzed. In the milling process, cutting forces in tangential ($F_{t,j}(\phi)$), radial ($F_{r,j}(\phi)$) and axial ($F_{a,j}(\phi)$) directions for cutter tooth j can be expressed as[16]

$$\begin{cases} F_{t,j}(\phi) = K_{tc} \cdot h_j(\phi) \cdot a_p + K_{te} \cdot a_p, \\ F_{r,j}(\phi) = K_{rc} \cdot h_j(\phi) \cdot a_p + K_{re} \cdot a_p, \\ F_{a,j}(\phi) = K_{ac} \cdot h_j(\phi) \cdot a_p + K_{ae} \cdot a_p, \end{cases} \tag{6}$$

where K_{tc}, K_{rc}, and K_{ac} are the cutting force coefficients contributed by the shearing action in tangential, radial, and axial directions, respectively, and K_{te}, K_{re} and K_{ae} are the edge constants, $h_j(\phi)$ is the chip thickness at instantaneous tool immersion angle ϕ, a_p is the cutting depth.

In the milling process, the cutting torque acting on the cutting tool is

$$T_c = r \cdot \sum_{j=1}^{n} F_{tj}\left(\phi_j\right), \quad \phi_{st} \leqslant \phi_j \leqslant \phi_{ex}. \tag{7}$$

Since the power consumed by the spindle can be expressed as

$$P_c = v\sum_{j=1}^{N} F_{tj}\left(\phi_j\right),, \quad \phi_{st} \leqslant \phi_j \leqslant \phi_{ex}. \tag{8}$$

Then, the relationship between the torque and power is

$$T_c = \frac{P_c}{2\pi\omega}. \tag{9}$$

The work (dE) done by unit cutting length material can be expressed as

$$\mathrm{d}E = K_{tc} h(\phi_j(z)) r\mathrm{d}\phi\mathrm{d}z + K_{te} r\mathrm{d}\phi\mathrm{d}z, \tag{10}$$

where r is the cutter radius. Then, the work done by the ith element on the jth tooth of the cutter is

$$E_{ij} = K_{tc}\int_0^z \int_{\phi_{st}}^{\phi_{ex}} h\left(\phi_j\left(z\right)\right) r\mathrm{d}\phi\mathrm{d}z + K_{te}\int_0^z \int_{\phi_{st}}^{\phi_{ex}} r\mathrm{d}\phi\mathrm{d}z. \tag{11}$$

Since $r\mathrm{d}\phi$ is the differential arc length, $h(\phi_j(z))r\mathrm{d}\phi\mathrm{d}z$ is the volume of removed material, $r\mathrm{d}\phi\mathrm{d}z$ is the contact area between the cutter and the workpiece. Therefore, Eq. (11) can be expressed as

$$E_{ij} = K_{tc}V_{ij} + K_{te}A_{ij}, \tag{12}$$

where

$$\begin{cases} V_{ij} = \int_0^z \int_{\phi_{st}}^{\phi_{ex}} h\left(\phi_j\left(z\right)\right) r\mathrm{d}\phi\mathrm{d}z, \\ A_{ij} = \int_0^z \int_{\phi_{st}}^{\phi_{ex}} r\mathrm{d}\phi\mathrm{d}z. \end{cases} \tag{13}$$

Then the total work in one cutter revolution is

$$E_T = \sum_j \sum_i E_{ij}, \tag{14}$$

and the power consumed in one cutter revolution is

$$P_c = \frac{E_T}{\tau} = \sum_j \sum_i \frac{E_{ij}}{\tau} = K_{tc}\dot{V} + K_{te}\dot{A}, \tag{15}$$

where τ is the cutting period. Substituting Eq. (15) into Eq. (9), gives

$$T_c = \frac{E_T}{2\pi\omega\tau} = \frac{1}{120\pi}\sum_j \sum_i \left(K_{tc}V_{ij} + K_{te}A_{ij}\right) = \frac{1}{120\pi}\left(K_{tc}V + K_{te}A\right) = \begin{pmatrix} \frac{V}{120\pi} & \frac{A}{120\pi} \end{pmatrix}\begin{pmatrix} K_{tc} \\ K_{te} \end{pmatrix}. \tag{16}$$

During the milling process, the total torque can be measured by Kistler 9123C dynamometer and it contains two parts: one is the idle running torque T_f and the other one is cutting torque T_c, that is

$$T_m = T_f + T_c. \tag{17}$$

Substituting Eq. (16) into Eq. (17) gives

$$T_m = \begin{pmatrix} 1 & \frac{V}{120\pi} & \frac{A}{120\pi} \end{pmatrix}\begin{pmatrix} T_f \\ K_{tc} \\ K_{te} \end{pmatrix} = \boldsymbol{SK}, \tag{18}$$

where

$$\begin{cases} \boldsymbol{S} = \begin{pmatrix} 1 & \frac{V}{120\pi} & \frac{A}{120\pi} \end{pmatrix}, \\ \boldsymbol{K} = \begin{pmatrix} T_f \\ K_{tc} \\ K_{te} \end{pmatrix}. \end{cases} \tag{19}$$

Then

$$\boldsymbol{K} = T_m\left(\boldsymbol{S}^T\boldsymbol{S}\right)^{-1}\boldsymbol{S}^T. \tag{20}$$

The material removal volume V and the cutter-workpiece contact area A can be calculated by CAM software, T_m and T_f are measured by Kistler 9123C.

XU, et al[20], stated that the tangential cutting coefficients behave differently with tool wear. In this paper, tangential cutting coefficient and tangential edge constant are also used in this paper. Cutting force coefficients variation with tool flank wear under different feed per tooth are shown in Fig. 6. Results show that tool wear does not have great influence on cutting force coefficients. But when cutter edge chipping happens, cutting force coefficient will change dramatically, as the data shown in Fig. 6 for feed per tooth 0.09 mm/tooth.

Edge constant variation with tool wear in all tests is shown in Fig. 7. Results shown that approximately linear relationship between edge constant and tool flank wear can be found based on the tested data. By applying a linear least squares fit, the following equation can be get:

$$K_{te} = 252.12 \cdot VB + 15.8. \tag{21}$$

Based on Eq. (20) and Eq. (21), tool flank wear can be estimated based on the online measured torque. Once estimated tool wear is observed too large in the milling process, the milling process can be stopped for detail tool wear measurement.

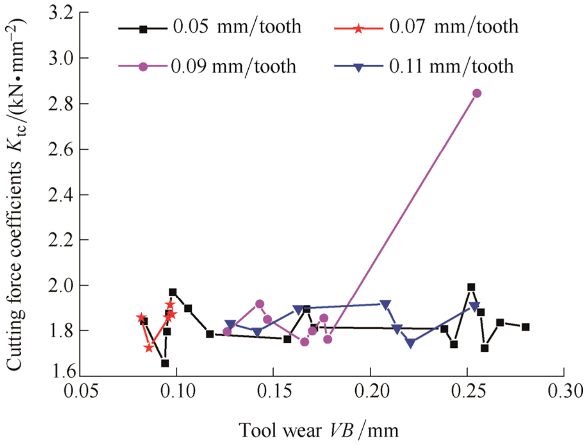

Fig. 6.　Cutting force coefficients variation with tool wear (v=90.43 m/min, a_e=1.0 mm, a_p=2.0 mm)

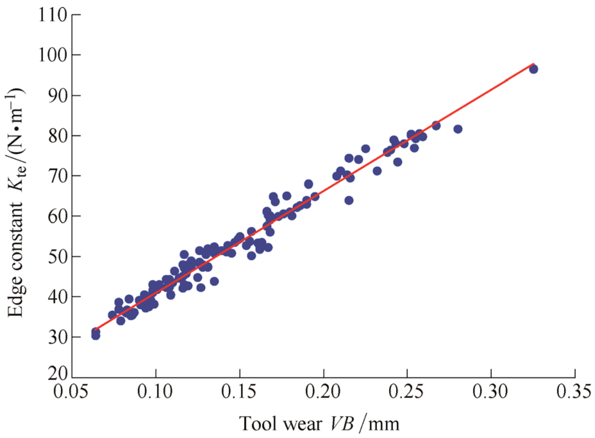

Fig. 7.　Edge constant variation with tool wear

4　Conclusions

(1) Cutting speed is observed to have less effect on tool wear under low feed rate per tooth(0.05 mm/tooth). Besides, tool wear behavior is approximately linear for higher cutting speeds(120.58 m/min and 150.72 m/min).

(2) Feed rate per tooth and radial depth of cut have great influence on tool wear, and the tool wear behavior is approximately exponential under large value.

(3) To reduce tool wear in milling titanium alloy with inserts, the recommended cutting parameters are $f_t \leqslant 0.07$ mm/tooth, $a_e \leqslant 1.0$ mm, $a_p \leqslant 2.0$ mm, the cutting speed can be set between 60 m/min and 150 m/min.

(4) Tangential edge constant increases almost linearly with the increase of tool wear.

(5) Cutting parameters and strategies can be further studied based on the results of this research to get higher machining efficiency and longer tool life in the milling of titanium alloys.

References

[1] BERMINGHAM M J, PALANISAMY S, DARGUSCH M S. Understanding the tool wear mechanism during thermally assisted machining Ti-6Al-4V[J]. *International Journal of Machine Tools and Manufacture*, 2012, 62: 76–87.

[2] ZAREENA A R, VELDHUIS S C. Tool wear mechanisms and tool life enhancement in ultra-precision machining of titanium[J]. *Journal of Materials Processing Technology*, 2012, 212(3): 560–570.

[3] EZUGWU E O, WANG Z M. Titanium alloys and their machinability—a review[J]. *Journal of Materials Processing Technology*, 1997, 68(3): 262–274.

[4] PERVAIZ S, RASHID A, DEIAB I, et al. Influence of tool materials on machinability of titanium- and nickel-based alloys: a review[J]. *Materials and Manufacturing Processes*, 2014, 29(3): 219–252.

[5] ARRAZOLA P J, GARAY A, IRIARTE L M, et al. Machinability of titanium alloys(Ti6Al4V and Ti555.3)[J]. *Journal of Materials Processing Technology*, 2009, 209(5): 2223–2230.

[6] ODELROS S. *Tool wear in titanium machining*[D]. Uppsala Universitet, 2012.

[7] DA SILVA R B, MACHADO Á R, EZUGWU E O, et al. Tool life and wear mechanisms in high speed machining of Ti–6Al–4V alloy with PCD tools under various coolant pressures[J]. *Journal of Materials Processing Technology*, 2013, 213(8): 1459–1564.

[8] RAZA S, PERVAIZ S, DEIAB I. Tool wear patterns when turning of titanium alloy using sustainable lubrication strategies[J]. *International Journal of Precision Engineering and Manufacturing*, 2014, 15(9): 1979–1985.

[9] WEI Weihua, XU Jiuhua, FU Yucan, et al. Tool wear in turning of titanium alloy after thermohydrogen treatment[J]. *Chinese Journal of Mechanical Engineering*, 2012, 25(4): 776–780.

[10] SUN S, BRANDT M, MO J PT. Evolution of tool wear and its effect on cutting forces during dry machining of Ti-6Al-4V alloy[J]. *Proc IMechE Part B: Journal of Engineering Manufacture*, 2012, 228(2): 191–202.

[11] RIBEIRO M V, MOREIRA M R V, FERREIRA J R. Optimization of titanium alloy(6Al–4V) machining[J]. *Journal of Materials Processing Technology*, 2003, 143–144: 458–463.

[12] YANG S, ZHU G, XU J, et al. Tool wear prediction of machining hydrogenated titanium alloy Ti6Al4V with uncoated carbide tools[J]. *The International Journal of Advanced Manufacturing Technology*, 2013, 68(1): 673–682.

[13] ZHANG Y, ZHOU Z, WANG J, et al. Diamond tool wear in precision turning of titanium alloy[J]. *Materials and Manufacturing Processes*, 2013, 28(10): 1061–1064.

[14] DENG J X, LI Y S, SONG W L. Diffusion wear in dry cutting of Ti–6Al–4V with WC/Co carbide tools[J]. *Wear*, 2008, 265(11–12): 1776–1783.

[15] SUI Shaochun, LI Yingguang, SHAO Wenyao, et al. Tool path generation and optimization method for pocket flank milling of aircraft structural parts based on the constraints of cutting force and dynamic characteristics of machine tools[J]. *International Journal of Advanced Manufacturing Technology*, DOI 10.1007/s00170-015-8050-x.

[16] ALTINTAS Y. *Manufacturing automation: metal cutting mechanics, machine tool vibration, and CNC design*[M]. 2nd ed. Cambridge: Cambridge University Press, 2012.

[17] FERREIRA J C E, OCHOA D M. A method for generating trochoidal tool paths for 2½D pocket milling process planning with multiple tools[J]. *Journal of Engineering Manufacture*, 2013, 227(9): 1287–1298.

[18] WU B H, ZHENG C Y, LUO M, et al. Investigation of trochoidal milling Nickel-based superalloy[J]. *Materials Science Forum*, 2013, 723: 332–336.

[19] OTKUR M, LAZOGLU I. Trochoidal milling[J]. *International Journal of Machine Tools and Manufacture*, 2007, 47(9): 1324–1332.

[20] XU M, JERARD R B, FUSSELL B K. Energy based cutting force model calibration for milling[J]. *Computer-Aided Design & Applications*, 2007, 4(1–4): 341–351.

Biographical notes

LUO Ming, born in 1983, is currently a junior research scientist at *Key Laboratory of Contemporary Design and Integrated Manufacturing Technology of Ministry of Education, Northwestern Polytechnical University, China*. He received his PhD degree from *Northwestern Polytechnical University, China*, in 2012. His research interests include CAD/CAM, smart machining, machining dynamics and high performance cutting.
Tel: +86-29-88493232-409; E-mail: luoming@nwpu.edu.cn

WANG Jing, born in 1986, is currently a PhD candidate at *Key Laboratory of Contemporary Design and Integrated Manufacturing Technology of Ministry of Education, Northwestern Polytechnical University, China*. He received his master degree on advanced manufacturing engineering in *Northwestern Polytechnical University, China*, in 2014.

WU Baohai, born in 1975, is currently an professor at *Key Laboratory of Contemporary Design and Integrated Manufacturing Technology of Ministry of Education, Northwestern Polytechnical University, China*. His research interests include CAD/CAM, smart machining, tool wear.

ZHANG Dinghua, born in 1958, is currently a professor at *Key Laboratory of Contemporary Design and Integrated Manufacturing Technology of Ministry of Education, Northwestern Polytechnical University, China*. His research interests include CAD/CAM, smart machining, mold design and manufacturing, nondestructive testing and cone beam CT technology.