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Effect of Cutting Parameters on Tool Wear when Trochoidal Pocket Milling Ti6Al4V

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Abstract: Despite being an attractive material for aerospace components such as engine parts and airframes, titanium alloy is categorized as a difficult-to-machine material which results in rapid tool wear and tool failure. It was reported that trochoidal machining method is preferred as compared to conventional machining due to its ability to prolong the tool life. This machining technique has the ability to reduce the load and provide enough space for the chips to evacuate and allowing sufficient time for the tool to be cooled. This study was conducted to investigate the effect of cutting parameters on the tool wear of TiAlN/TiN coated carbide tool when trochoidal milling Ti6Al4V under wet condition. Design of experiment based on response surface method (RSM) was adopted with three factors (cutting speed, feed rate and step over), two levels and five centre points with a total of 17 experimental runs. The cutting speed (Vc) was set at 60 to 90 m/min, feed rate (fz) at 0.06 to 0.1 mm/tooth and step over (ae) at 1.5 to 2.5 mm. The experimental results indicated that cutting speed was the dominant factor affecting the tool wear, followed by feed rate and lastly the step over. ANOVA results showed that all three cutting parameters exhibit positive interaction towards wear condition thus implying that higher value of cutting speed, feed rate and step over resulted in rapid tool wear and shorten the tool life.

Keywords: Titanium Alloy, trochoidal milling, pocket milling, tool wear, carbide tool

1. Introduction

Titanium alloy is widely used in aerospace components such as engine parts and airframes due to its excellent mechanical and thermal properties. Its high strength-to-weight ratio contributes significantly to the lightweight properties, giving an advantage to low fuel consumption of an aircraft (Inagaki, Takechi, Shirai, & Ariyasu, 2014). One of the attractive characteristics of this alloy is low thermal conductivity and its ability to withstand high operating temperature of 500 to 600 °C. However, titanium alloy is categorized as a difficult-to-machine material as a result of

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rapid tool wear and shorter tool life (Krishnaraj, Samsudeensadham, Sindhumathi, & Kuppan, 2014) and (Wu, Zheng, Luo, & He, 2012). This is due to the heat generated during machining remains in the material and exposing the cutting tool to high temperature hence deteriorates the cutting edge rapidly. As reported, trochoidal machining is preferred as compared to conventional machining when pocket milling of parts with cavity and ribs, due to its ability to prolong the tool life (Pleta, Ulutan, & Mears, 2015) and (Wu Shixiong, 2016). The small immersion angle and intermittent tool engagement are able to reduce the machining load and provide enough space for chip evacuation, at the same time allowing sufficient time for the tool to be cooled (Pleta, Ulutan, & Mears, 2014).

P. Bach et al. (Bach, Trmal, Zeman, Vana, & Maly, 2012) reported that machining of titanium is more stable at low cutting speeds of 20 to 35 m/min and permits an increase of axial depth of cut without increasing the wear. However, rigidity of the machine is essential to absorb the torque at low cutting speed. Most researchers that involved in machining of advanced materials (Patil, Polishetty, Goldberg, Littlefair, & Nomani, 2014),(Safari, Sharif, Izman, & Jafari, 2012) and (Li, Zhao, Luo, Pei, & Wang, 2011) were focusing on high speed machining (HSM) to prolong the tool life and obtain better surface finish. HSM is applied to various machining strategies such as traditional and trochoidal milling. It was reported that trochoidal milling has the tendency to prolong the tool life when dealing with materials such as aluminium, steel, titanium and nickel base alloy (Pleta et al., 2015) and (Wu Shixiong, 2016).

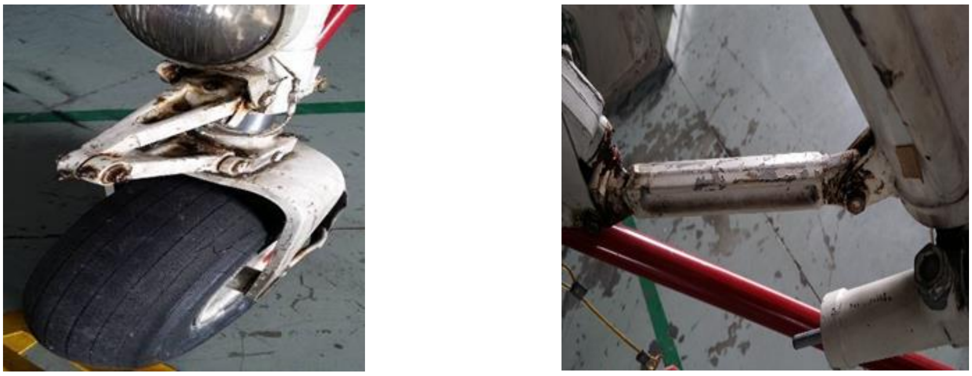


Fig. 1- The application of pocket milling at lever beam of a plane.

Ezugwu et al. (Ezugwu & Wang, 1997) and Leigh et al. (Leigh & Schueller, 2000) have studied HSM of advanced materials with the aim to increase the material removal rate. On the other hand, Pavel Bach et al. (Bach et al., 2012) focused on low cutting speed when machining titanium alloy and they claimed that cutting speed 20 to 35 m/min displayed a high stability region and able to eliminate chatter. In an effort to improve the tool life, new tool path strategy has been proposed commonly known as trochoidal strategy. This strategy has been recognized to improve the tool life performance and reduce the machining time when machining aluminium (Pleta & Mears, 2016). Moreover, the trochoidal milling for aluminium seems to be more advance where M. Otkur and I.Lazoglu (Otkur & Lazoglu, 2007) proposed a double trochoidal strategy which has the ability to shorten the machining time by halved the tool path.

Despite the positive outcomes of trochoidal machining of aluminium, reports on this strategy when dealing with titanium alloys was limited. Currently, no study was reported on the dominant effect of trochoidal milling and correlation between vc, fz and ae. Figure 1 shows the application of pocket milling in landing gear system for an aircraft. The main purpose of applying pocket milling is to reduce the weight of the parts without reducing the strength of the material. Most of the parts is produced using rough milling operation and as expected trochoidal milling is suitable for this application especially for rough milling where surface finishing is not the main requirement of the part. This study is undertaken to evaluate the effect of machining parameters on tool wear and tool life when trochoidal milling of Ti6Al4V using coated carbide insert.

2. Methodology

Trochoidal pocket milling experiments on Ti6Al4V were performed on a three-axis HAAS CNC milling machine as shown in Figure 2. TiAlN/TiN coated carbide inserts from SECO TOOLS were used in this study. The inserts were mounted onto a two flutes tool holder of diameter 12 mm (Figure 3) through a collet with 30 mm overhang to ensure rigidity of the setup and reduce the possibility of tool deflection during machining.. Titanium alloy, Ti6Al4V block was used as the workpiece material. The final pocket size of 90 mm x 50 mm x 10 mm (Figure 4) was machined under wet condition using water-based cutting fluid of 6% concentration. The coolant concentration was measured each time before each trial in order to control the consistency of machining condition for all experiments.

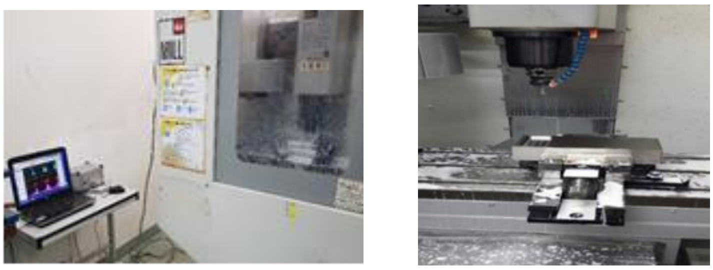


Fig. 2 – Machining and cutting force measurement on HAAS CNC milling machine

Fig. 3 – Two flutes tool holder

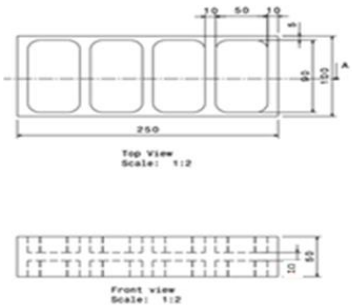


Fig. 4 - Orthographic view of the milled pocket

The round out of the cutting inserts was measured using a dial indicator and maintained at ± 30 micron after each time of inserts change. Setting up of the machining parameters were carried using MasterCamX7 where the option for trochoidal strategy is under high speed machining using climb milling mode. Climb milling has a potential to reduce the rubbing condition between the inserts and the work material. Trochoidal strategy with circular ramping as a tool entry was used throughout the experiments. Design of Experiment (DOE) approach was adopted involving three factors (cutting speed (Vc) feed per tooth (fz) and step over (ae)), two levels and five centre points with a total of 17 runs as shown in Table 1. The DOE was generated using the response surface method (RSM) under Box Behnken design.

Table 1 - Experimental runs based on Box Behnken DOE

RUN	Vc	Fz	ae
1	60	0.06	2
2	75	0.08	2
3	90	0.08	1.5
4	75	0.10	1.5
5	60	0.08	1.5
6	90	0.06	2
7	90	0.08	2.5
8	75	0.08	2
9	75	0.08	2
10	90	0.1	2
11	60	0.08	2.5
12	75	0.06	1.5
13	75	0.06	2.5
14	75	0.08	2
15	60	0.1	2
16	75	0.08	2
17	75	0.1	2.5

The flank wear was measured and observed using a tool maker's microscope with magnification 70X to 80X as shown in Figure 5. New inserts were used for each parameter and tool wears were measured for every 5th paths with 2 mm axial depth of cut which equal to 10 mm depth for each run. Cutting forces were measured using a three components Kistler 9257B tool dynamometer (Figure 2) to measure the feed force (fx), normal force (fy) and axial cutting force (fz). DEWEsoft software was used to record and analyse the cutting forces obtained.

Fig. 5 - Tool maker's microscope

3. Results and Discussion

The data obtained was analyzed using ANOVA and results indicated that the dominant factors contributing to tool wear are cutting speed (Vc), followed by feed (fz), and lastly, step over (ae). According to the graph in Figure 6, it was observed that the wear progressed gradually when employing lower conditions of cutting speed 60 m/min, feed 0.06 mm/tooth and ae 2 mm. The recorded flank wear was 0.045mm.

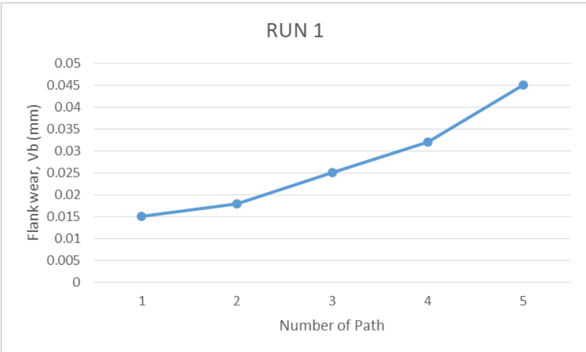


Fig. 6 - The progression wear for run 1

In addition, the dominant effect varied significantly between traditional milling and trochoidal milling due to the tool path pattern. According to Luo.M, (Luo, Wang, Wu, & Zhang, 2017) feed rate and radial depth of cut have a significant influence on the tool wear in traditional milling. However, in trochoidal strategy, cutting speed is more dominant which contributes to rapid tool wear as the tool path moves in cycloid pattern. The machining time depends on the value of cutting speed whereby higher cutting speed results in shorter tool or machining time. However, lower feed rate resulted in a better surface finish even at higher cutting speed and step over (Patil et al., 2014). Meanwhile, increasing the step over value promotes chipping at the cutting tool due to the large tool engagement area and higher cutting force which leads to rapid tool wear. Besides, the noise level increased at higher cutting speed and feed due to the effect of low modulus of elasticity of titanium alloy.

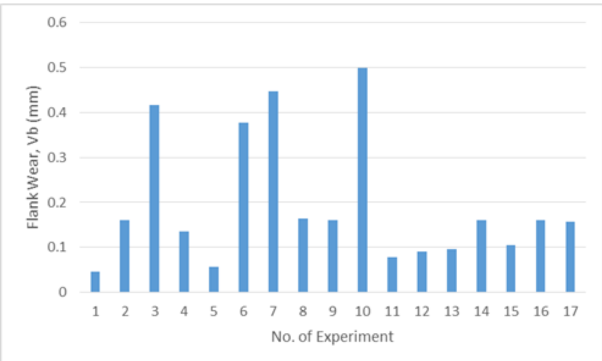


Fig. 7 - Flank wear versus experimental runs at various cutting conditions

Overall results on the flank wear for all 17 experimental runs are shown graphically in Figure 7. The wear progression for every run is displayed with total of 5 paths for each run. By increasing the cutting speed, the flank wear also increased thus exposing the substrate to high temperature generated from the high friction. The graph shows that the effect of cutting speed was significant whereby highest cutting speed of 90 m/min recorded higher flank wear values regardless of the feed used. At highest cutting speed of 90 m/min, experiments number 3, 6, 7 and 10 recorded higher values of flank wear as compared to those obtained under lower cutting speeds of 60 and 75 m/min. This is due to the fact that machining at higher cutting speed results in high temperature generation which facilitates thermal-mechanical wear mechanism of diffusion and chemical wear phenomena. The highest flank wear was recorded under experimental run number 10 with 0.498 mm of flank wear under cutting speed 90 m/min, feed 0.1 mm/tooth and 2 mm ae as the highest cutting parameter as displayed in Figure 8. Meanwhile, run number 1 which was the lowest condition employed, recorded the lowest flank wear of 0.045 mm.

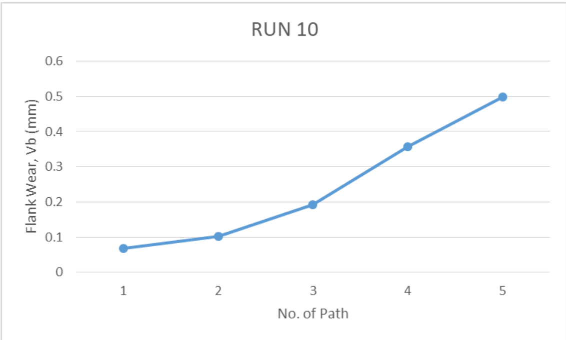
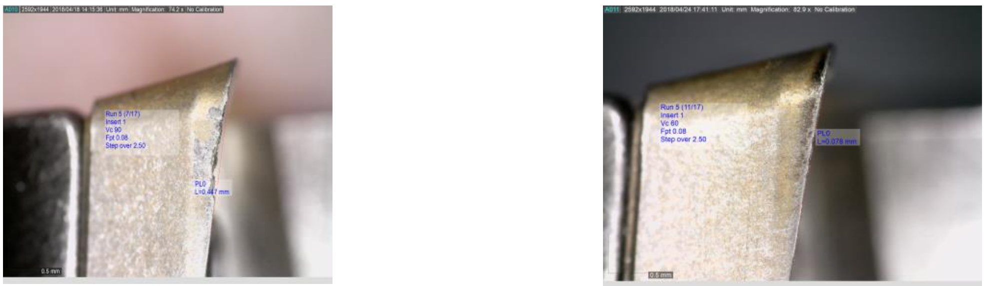


Fig. 8 - The progression wear of experiment number 10 under 90 m/min

High friction at the tool workpiece interface generated high temperature and the heat was directly transferred to the cutting tool due to the low thermal conductivity of titanium alloy. Figure 9 shows images of flank wear at the cutting tool under high cutting condition. Chipping was clearly observed at the cutting edge due to the high impact between the tool and workpiece during the tool offset (ae) in the trochoidal milling. High cutting speed caused high impact and affected the cutting inserts significantly.



(a) (b)

Fig. 9 - Effect of highest cutting speed on the tool wear a) run number 7 and b) run number 11

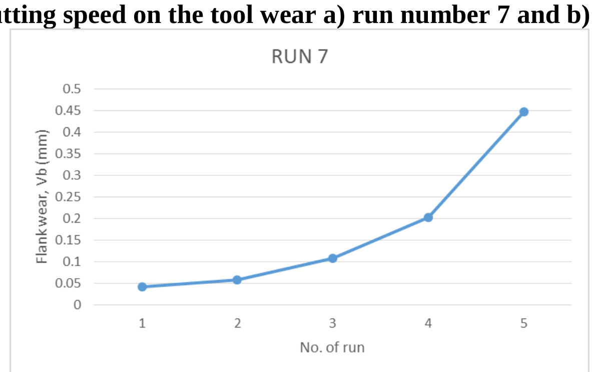


Fig. 10 - The progression wear for run number 7

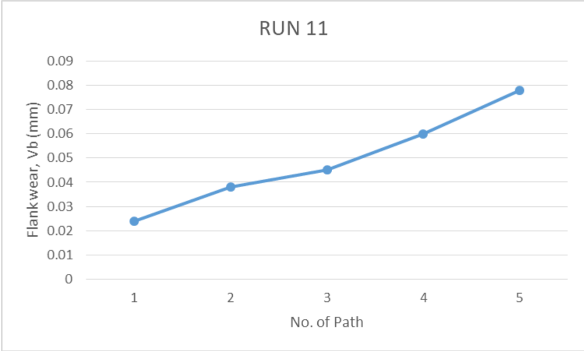


Fig. 11 - The progression wear for run number 11

In general, the wear trend seems to be similar for most cutting parameters where it clearly shown that the wear increased drastically after path 3 as shown in Figures 10 and 11 for run number 7 and number 11 respectively. This situation occurred due the worn out of the coating layer of the carbide insert thus exposing the substrate to high cutting temperature hence causing rapid flank wear.

4. Conclusion

The paper presents the results of performing trochoidal milling on titanium alloy Ti6Al4V using TiAlN/TiN coated carbide insert. The general conclusions drawn from the above study are as follows:

- Cutting speed (Vc) is observed to have a significant effect on the tool wear under all cutting parameters. The effect is proportional with the value of cutting speed selected where higher cutting speed resulted in higher flank wear and shorten the tool life. Highest wear value of 0.498 mm flank wear was recorded under highest cutting condition with cutting speed of 90 m/min and feed 0.1 mm/tooth. Step over (ae) gives the lower impact on tool wear.
- According to the results, it could be concluded that the dominant effect is not similar to conventional milling where cutting speed is observed to have less effect as compared to feed rate.
- It would be fruitful to pursue further research on the dominant effect when trochoidal milling a hard-to-machined material such as titanium and nickel based alloy under various cutting parameters. It is also worth to study the step over effect during trochoidal strategy.

Acknowledgement

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