

Step Over (ae) Effect on Cutting Parameters when Trochoidal Pocket Milling of Titanium Alloy Ti-6Al-4V



A.S.Ramli, S.Sharif, A.Y.M.Said, Z.Karim

Abstract: Titanium alloy is highly demanding in the aerospace industry due to its unique properties such as high strength-to-weight ratio and high thermal conductivity thus, made the material widely used in aerospace industries and excellent in its applications. However, those criteria's become a crucial issue for machinists as titanium is categorized as difficult-to-machined material. High thermal conductivity caused shorten tool life because of the heat generated during machining was transferred directly to the cutting tool and leads to rapid tool wear. This experiment was conducted using 3 axis CNC Milling machine under wet cutting conditions. In order to identify the effect of step over, cutting speed and feed rate were fixed at constant values while step over (ae) values were varieties. The effect investigated were tool wear, wear mechanisms and tool failure modes. Tools experienced a longer tool life at low cutting speed of 60m/min, while chipping and notch wear appeared at high cutting speed 90m/min. The increasing of the step over value give less than 10% of the wear and reduced only 15% of machining time. With this, trochoidal milling proved that the step over give a minor contribution to wear while the dominant contribution was cutting speed followed by feed rate where the wear rate increased as the cutting speed increased.

Index Terms: Trochoidal, Tool wear, Step Over (ae), Titanium Alloy and Coated Carbide Insert

I. INTRODUCTION

In machining of advanced material such as super alloys, tool wear is a critical and unavoidable aspect which influenced the tool performance and affected the machined surface. This phenomena become a crucial issue as it involved high machining cost due to the short tool life. Nowadays, a lot of researches works on this matter and proposed new machining methods and a new tool has been designed to solve these issues.

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Furthermore, the root cause of this problems are high friction, load and temperature at cutting zone between workpiece and cutting tool induced a fatigue life of the tools and affected the surface integrity [1-5]. However, titanium alloy widely used in aerospace industries due to its unique characteristic which made it highly demanded. Titanium is excellent in it applications where high strength at elevated temperature and high strength-to-weight ratio meets the main criteria of aerospace materials. Besides that, low thermal conductivity and relatively low modulus of elasticity make it become a great interest in aerospace, automotive, petrochemical plant and biomedical sectors [6-8]. Meanwhile, those criteria's become a crucial issue for machinist. Low thermal conductivity caused the heat generated at the cutting zone being transfer directly to the cutting tool and caused rapid tool wear hence, affected the surface integrity of machined surface [2].

In order to overcome the problems, new methods being introduced such as trochoidal milling. A trochoidal strategy is claimed to be better than conventional milling while double trochoidal is claimed to be more efficient on cutting force as compared to single trochoidal milling [9].

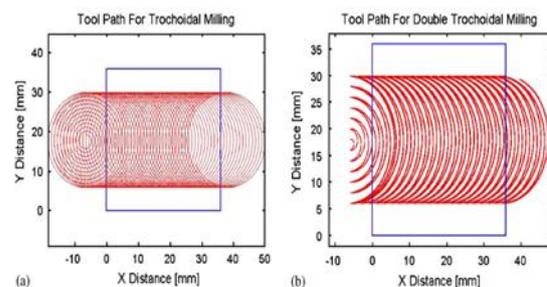


Fig. 1 Tool path for (a) trochoidal milling (b) double trochoidal milling [9]

A. Pleta, D. Ulutan and L. Mears [10], claimed the trochoidal milling was superior as compared to conventional milling where the material removal rates of trochoidal was 7 times better than conventional milling. However, trochoidal milling suffered from notch wear and chipping. With this, Variable Depth Milling (VDM) has been introduced and claimed able to reduce the notch wear but slightly decreased the productivity. Furthermore, cutting fluid plays an important role in reducing the tool wear.

Cutting fluid should appropriate with the titanium to avoid the rapid tool wear [11]. The flow rate of the cutting fluid is also important to ensure the chip completely flown out from the cutting zone especially for pocket milling where the possibility to chip trapped inside the pocket was high. The trapped chip caused a re-cut chip where generated uneven tool impact and suddenly increased the cutting force. Herewith, the high pressure coolant is highly recommended in pocket milling where the coolant able to fly out the chip from the cutting zone.

II. METHODOLOGY

A. Workpiece Material

Titanium alloy Ti-6Al-4V of alpha-beta was used as a workpiece material in this research in rectangle block with a size of 170mm x 100mm x 15mm. The workpiece was rigidly mounted onto dynamometer sensor (Kistler 9257B) and the workpiece size is similar to dynamometer size due to avoid from overhang area which causes a misreading issue as shown in figure 3.



Fig. 3 The workpiece was rigidly mounted onto the dynamometer

B. Machining Setup

A 3-axis HAAS CNC Milling Machine with a 7.5kW motor drive with spindle speed 6-7000 RPM which provided with FANUC controller used to performed all of the machining parameters. The program were generated using MasterCam X7 where trochoidal was placed under high speed machining. Climb milling was choose since it is the most suitable path for high strength material and able to reduce a rubbing condition in machining [12]. The tool rotates opposite the feed direction and produced a thick to thin chip where thin chip on exit able to reduce a shock load and built up edge breakage [13]. Apart of that, trochoidal promises an intermittent tool engagement that gives an irregular impact between tool and workpiece.

The machining was performed under wet condition using water-based cutting fluid and the consistency of the coolant concentration maintained at 6% for all parameters. The refractometer was used to check the coolant concentration regularly. Indeed, tool entry was an initial step in performing a pocket milling where the tool entered into the workpiece hence, the selection of the tool entry is important to avoid initial wear. Based on preliminary data, circular ramping was choose as a tool entry for the experiments.

Dial Test Indicator (DTI) was used to check the tool runout in order to control the tool balancing where the range was set up to $\pm 15\mu\text{m}$ as shown in figure 4 (a). Tool balancing was important due to shape of the inaccurate inserts and to ensure the balancing of tool engagement contact surface thus, reduce the possibility of having a varying load on both cutting edges [14]. All procedure was repeated for all 45 runs.

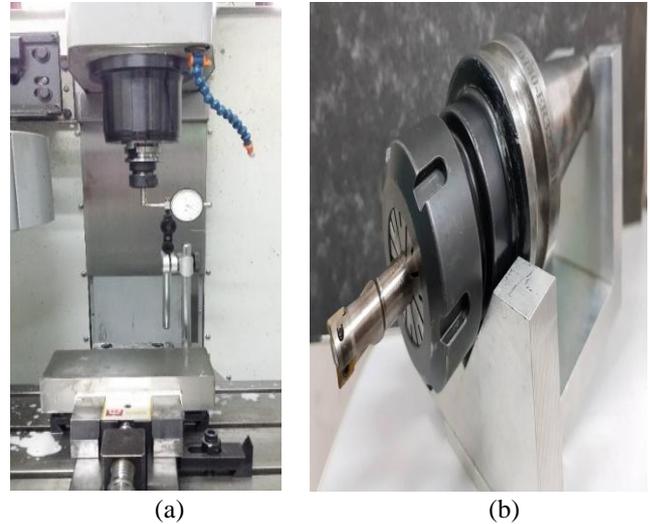


Fig. 4 Tool setup (a) tool runout measurement, (b) cutting tool attached to the collet

The parameters involved was based on three factors (cutting speed (Vc), feed rate (fz) and step over (ae)) and three levels. In order to investigate the step over effect on tool wear, feed rate (fz) was fixed at 0.08mm, and the variable values were cutting speed (Vc) and step over (ae). The cutting parameter are as show in table I below:

Table. 1 Cutting Parameters

Parameter	Levels		
	1	2	3
Cutting Speed (m/min)	60	60	60
Feed Rate (mm/tooth)	0.08	0.08	0.08
Step Over (ae) (mm)	1.5	2	2.5
Parameter	Levels		
	1	2	3
Cutting Speed (m/min)	75	75	75
Feed Rate (mm/tooth)	0.08	0.08	0.08
Step Over (ae) (mm)	1.5	2	2.5
Parameter	Levels		
	1	2	3
Cutting Speed (m/min)	90	90	90
Feed Rate (mm/tooth)	0.08	0.08	0.08
Step Over (ae) (mm)	1.5	2	2.5

C. Cutting Tools

SECO TOOLS inserts types were selected to be used in the experiments. The parallelogram types of tungsten cemented carbide insert (SECO XOMX060208R- M05) known as PVD coated carbide (F40M, TiAlN + TiN) was used as a cutting tool (table II and figure 5).



Inserts were placed on 2 flutes tool holder with diameter 12mm. Tool holder then attached to collet with 30mm of shank length as shown in figure 4 (b) in order to ensure the tool rigidity and avoid from tool deflection as titanium is categorized as hard-to-machined material (figure 5).



Fig. 5 Insert F40M

Table. 2 Cutting Tools Specification

Tool holder	Ø 12mm
No. of inserts	2
Material	Carbide
Coating	TiAlN/TiN
Width	0.1610
Length	0.2730
Thickness	0.0960
Corner Radius	0.0310
Relief Angle	7°
Rake Angle	21°
Coating process	PVD
Shape	Parallelogram
Chip Breaker	M05

D. Tool Wear Measurement

Tool Maker’s Microscope was used to measure wear occur at the inserts with magnification fixed constantly at 90x.

Special jigs were made to ensure the consistency of flank and rake wear measurement thus, able to eliminate human error. Wear progressions were measured for each path or every 2mm of the depth of cut in a total of 5th paths which equal to 10mm pocket of depth. Inserts were changed after 5th paths. New inserts were used for every parameter. The collet needs to be taken out from machine chuck without taking out the insert or tool holder. Chuck then placed on the jig to ensure the consistent gap between tool and microscope lens (figure 6). This procedure was repeated for every runs and parameter.

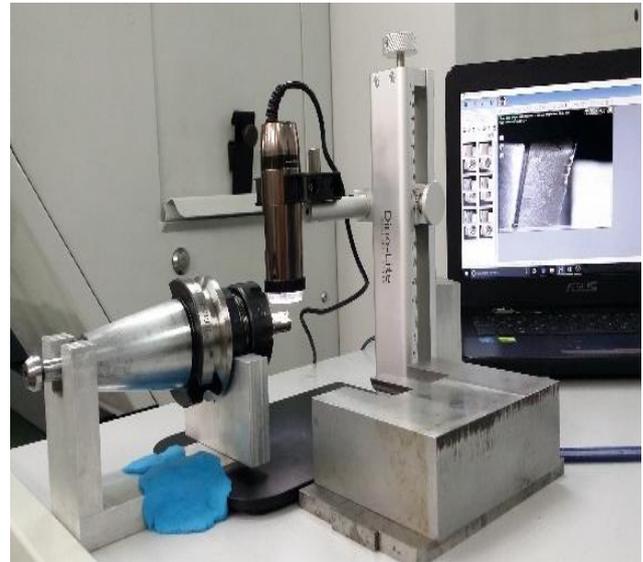


Fig. 6 Tool wear measurement setup

III. RESULTS AND DISCUSSIONS

The tool wear data recorded at various cutting conditions when pocket milling of titanium alloy Ti-6Al-4V are given in table III where the result shows the average $V_{b_{max}}$ for insert 1 and insert 2 measured. The feed rate was fixed at 0.08mm and step over (ae) and cutting speed (Vc) were varied in order to evaluate the effect of step over (ae).

Table. 3 Data obtained for average tool wear

PARAMETER			Avg.
Vc	Fz	ae	$V_{b_{max}}$
60	0.08	1.5	0.084
		2	0.098
		2.5	0.099
75	0.08	1.5	0.185
		2	0.289
		2.5	0.299
90	0.08	1.5	0.259
		2	0.395
		2.5	0.463

A. Tool wear and failure mode

Tool wear measurement was focused on the flank face for all parameters. Figure 7 shows the images of tool wear at 5th paths for all cutting speed and step over. According to that, it clearly shows only uniform wear appeared for all parameters under Vc 60m/min, feed rate 0.08mm and ae 1.5mm as this cutting speed was the lowest in this experiment. There was no chipping occur at this parameter. This is due to the low machining impact as the cutting speed and ae is low. However, tool coating erodes as early at 1st path but the size is too small and acceptable. Tool wear recorded for all step over under cutting speed Vc 60m/min was less than 0.1mm. This shows the machining effect only exceed less than 3/4 of tool strength. Nevertheless, the tool wear is small, but this parameters recorded as the longer machining times especially for the lower value of step over.

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According to Vc 75m/min images, tool wear recorded were less than 0.3mm however for ae 2.5mm the wear value recorded is 2.99mm. The wear value slightly increased as the step over values increased. Chipping seemed to be dominant at this cutting speed even for a small value of step over (1.5 mm). At this stage, the heat generated at the cutting zone caused the reaction between workpiece material (titanium) and the tool then initiated the workpiece material to weld at the cutting tool the been pulled out during the tool rotations and leads to the formation of chipping at the cutting edge [15].

Huge chipping clearly appeared at cutting speed Vc 90m/min. The tool experienced chipping for a low, medium and high value of step over. This proved that high force applied to the tool during machining and generated the high temperature and cause the adhered workpiece material at the tool edge being hit and squashed during the tool rotation and generated huge chipping. Yet, there was no thermal crack happened at this stage. The chipping was increased as the step over values increased.

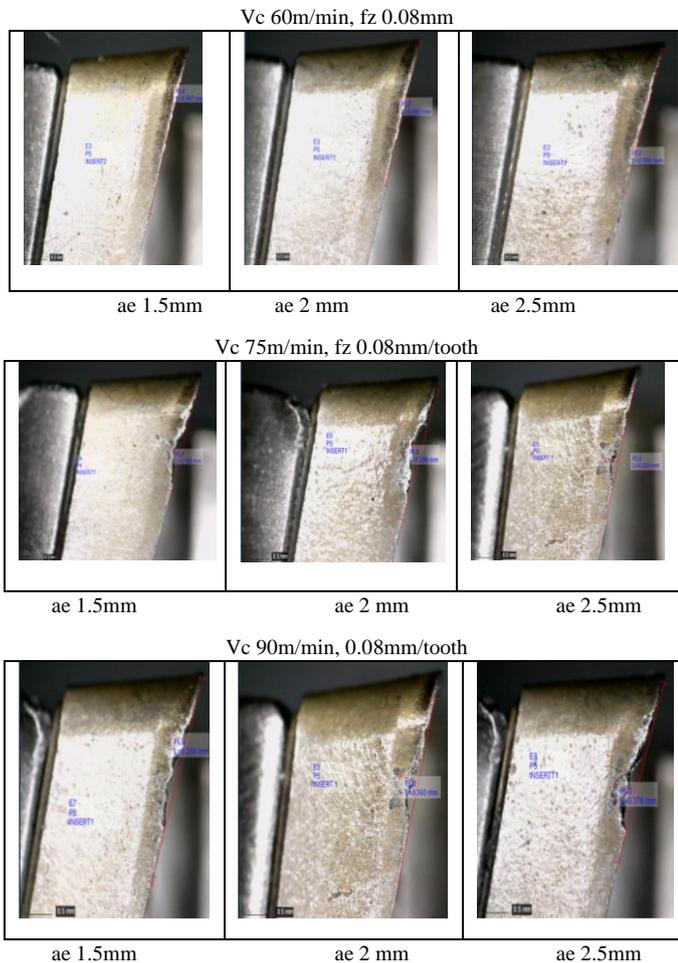


Fig. 7 Tool wear measurements

B. Effect of step over (ae) on the tool wear

Step over is a tool offset value for trochoidal milling where the small value of step over equal to a small cutting radius in trochoidal tool path as tool moved in cycloid movement as shown in figure 8 where the lace of the tool path can clearly be seen on the machine surface. According to the result gained during machining, it clearly shows the step over give a minor impact toward the tool wear issues as compared to cutting

speed and feed rate. By referring to the graph in figure 9, Vc 60m/min results the lowest tool wear followed by Vc 75m/min and Vc 90m/min where the highest tool wear recorded. Tool wear for Vc 60m/min more stable where it is slightly increased as the step over increased while for Vc 75m/min and Vc 90m/min, the 2mm of step over recorded significant wear increased. This is due to the combination of the cutting speed, feed rate and step over which give a huge impact and generated high temperature at cutting zone. The unique characteristic of the workpiece material (titanium) which is low thermal conductivity transferred the heat directly to the cutting tools and leads to rapid tool wear.

General observations under the same cutting speed show the wear value recorded was slightly increased with the value was less than 10% for all parameters. This values proved the step over contributed only a minor effect of total flank wear and by increasing the step over values will only increase 15% of the machining time.



Fig. 8 Step over laces appeared at the machine surface

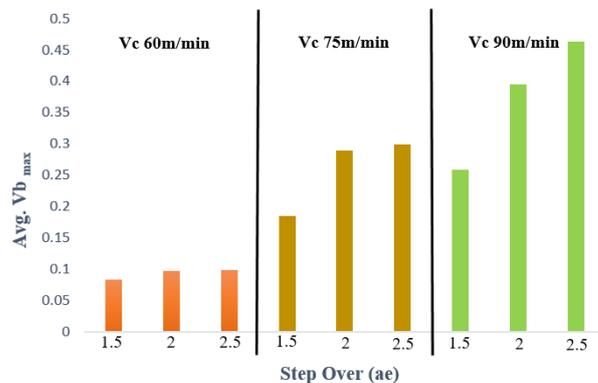


Fig. 9 The compilation data of Average Vb_{max} vs step over (ae)

IV. CONCLUSION

According to the results recorded for trochoidal pocket milling of titanium alloy Ti-6Al-4V with PVD coated carbide (F40M, TiAlN + TiN) where the value of feed rate was fixed at 0.08mm, clearly shows the alteration of wear rate as the cutting speed and feed rate increased. Thus, it can be concluded that the step over contributed very minor effect to the flank wear and machining time.

The most dominant factors which contributed to tool wear is cutting speed followed by feed rate. The wear increased significantly as cutting speed increased. Those factors give a high impact on the cutting tools and caused flank wear and chipping for medium and high cutting speed. As the step over value is not critical in affecting the machining condition thus, there is no limit for step over values selection as long as not exceed the tool diameter in order to avoid the formation of an island at the machined surface.

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