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SLOT MACHINING OF TI6AL4V WITH TROCHOIDAL MILLING TECHNIQUE

Titanium usage for aerospace growing day by day as application of titanium and its alloys covers wide range. Most of the aerospace components made up of wall structure involves lot of pocket slot milling since those components are monolithic components, eliminating need to manufacture multiple pieces for assembly into one final part. The increasing complexity of titanium parts used in aviation industry, increasing demand for productive manufacturing methods like trochoidal milling. This paper aims at evaluating its potential in slot milling for Ti6Al4V component by conducting experiments on 5-axis CNC machine. This study focuses on Productivity, Quality and Machine tool Dynamics.

1. INTRODUCTION

The increasing use of titanium & its alloy for aerospace applications results from the advantageous properties associated with the metal. Applications covers a wide range of airframe structural and engine parts [1]. Titanium and its alloys retain their position as a key metal for air vehicles mainly due to excellent corrosion resistance, excellent strength to weight ratio that can be maintained at elevated temperatures, good compatibility with graphite reinforced composites and very good damage tolerance characteristics [2].

Although, Titanium is an attractive material to aerospace designers due to its unique combination of strength and lightness however, it poses considerable problems in manufacturing because of its poor machinability [3]. Among the different alloys of titanium, Ti–6Al–4V is by far the most popular one with its widespread use in the chemical, surgical, ship building and aerospace industry [4].

Due to rising demand in aerospace sector, lot of developments are taking places in related industries forces to improve machining process to make it more productive to cope up with demand. Experts forecasted continuous demand for next 20 years. These gave rise to lot of effective and efficient Modern manufacturing Techniques like High Speed Machining (HSM). HSM is employed to increase productivity while simultaneously

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improving product quality and reducing manufacturing costs. Due to its high material removal rate and short product cycle time, HSM has received steadily growing applications in recent years in many industrial sectors such as Aerospace, Automotive and Die & Mould [5].

Now certain parts can be machined from one piece of metal, eliminating the need to manufacture multiple pieces for assembly into one final part. In fact, thin walled parts can be machined as one piece. Few cases, a structural part made up of lot of pieces is now machined as one piece using thin wall techniques. These kind of advanced processes, reduced expensive and time-intensive multiple-part manufacturing to a certain extent as well reduced bottle-necks in manufacturing and assembly.

These days, monolithic components are commonly used as structural parts in the aeronautical industry due to their homogeneity and excellent strength to weight ratio. Monolithic parts are made of thin walls and webs, which confer enough stiffness to the whole part [6]. Due to its low rigidity, the thin-walled parts easily deform during the cutting process. This makes the precision difficult to master. The resulting errors are usually compensated through repetitive feeding, numerical control compensation and manual calibration. However, these methods create low efficiency and difficulty in ensuring the quality of parts [7]. This problem can be solved through HSM technique since application of HSM technique involved low depth of cut, high speed, low cutting forces.

1.1. HIGH SPEED MACHINING

'High Speed Machining' is not just high spindle speed. In milling, it is product of reduced radial width of cut (WoC) combined with increased chip load per tooth, higher cutting speed and higher feed which leading to substantial productivity increase [8].

For example, ø12mm solid carbide end mill is used for shoulder milling. If cutter taking a 6mm WoC, the cutter engagement is 50% and the arc of cut is 90°, shown in Fig. 1. If the radial WoC is reduced to 0.3mm, the arc of cutter engagement becomes 2.5% (0.3/12·100=2.5%) of total cutter diameter. It means while cutting, only less portion of cutter actually engaged and balanced portion of cutter is in the air which helps to cooling-off the cutter. Cutter engagement is greatly reduced, and the thickness of the chip produced shrinks as well. Inadequate chip thickness can hasten heat build-up in the tool, accelerating tool wear. An adequately thick chip carries away heat, and producing a thick chip also assures a clean cutting action that minimizes rubbing and the heat it generates.

The combination of cutting parameters employed in high-performance milling provides many benefits. The small radial WoC results in a lighter cut that is smoother and produces less wear and tear on the machine tool's spindle bearings and ways. The radial cutting forces causes the tool to deflect and chatter , whereas the axial force goes in the direction of the spindle [9].

Heat, the enemy of cutting tool life, is reduced because the engagement time for the cutting edge is short; it spends a longer time in cooling air than it would when milling conventionally. In effect, the edge feeds into and out of the cut too quickly for heat to be absorbed.

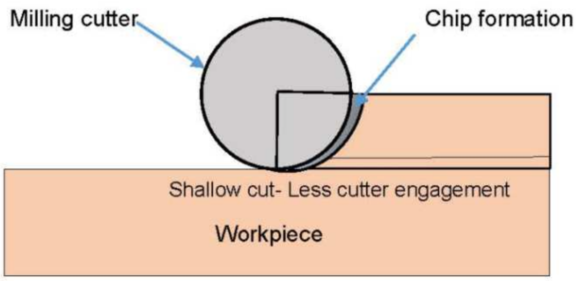

Fig. 1. Cutter engagement

High speed milling also greatly reduces side loads on the cutter, permitting use of an end mill's entire cutting edge (its axial DoC). This is key to full utilization of the tool's cutting edges. The increased axial depth of cut (DoC) directly boosts the volume of metal removed because the metal-removal rate is determined by the product of the radial WoC, axial DoC and feed rate (MRR = radial WoC × axial DoC × feed rate) [6].

1.2. TROCHOIDAL MILLING

This is another HSM technique securing its position in metal cutting is 'Trochoidal' milling. This method was developed for the production of slots in order to use HSM. Trochoidal milling is defined as the combination of uniform circular motion that includes simultaneous forward movements [10]. This method makes use of the advantage of circular milling and slicing so that the forces on the tool are kept constant [11].The cutter removes repeated 'slices' of material in a sequence of continuous spiral tool paths in its radial direction. A constant circular interpolation movement is used in order to produce the required slot width. An excellent method for slotting when vibration is a problem. Fig. 2, illustrate more about trochoidal milling by comparing with conventional milling.

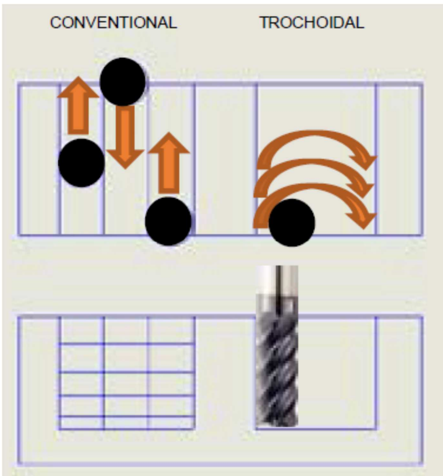

Fig. 2. Comparison between conventional and trochoidal

In conventional milling, slot width bigger than end mill/ cutter diameter can be generated by addition of extra cutting passes whereas have to take multiple passes for deep slots to achieve desired depth of slot. Conventional slot milling has limitation when cutter diameter is fully engaged i.e.180° engagement while cutting slot and no room for chip evacuation.

As shown in Fig. 2, multiple passes are required to machine a slot from solid block by conventional milling. This operation requires a total of 3 passes x 5 depth of cuts to achieve desired size. Whereas same slot can be machined in just single cut by trochoidal technique, provided depth of slot is smaller than cutting edge/flute length.

Fig. 3 shows tool path for trochoidal milling where cutter rotates and feed forward in constant circular interpolation. Upon completion of one cycle tool moves forward with small radial cut i.e. step over. Due to circular interpolation, wider slot than cutter diameter easily machined by smaller cutter.

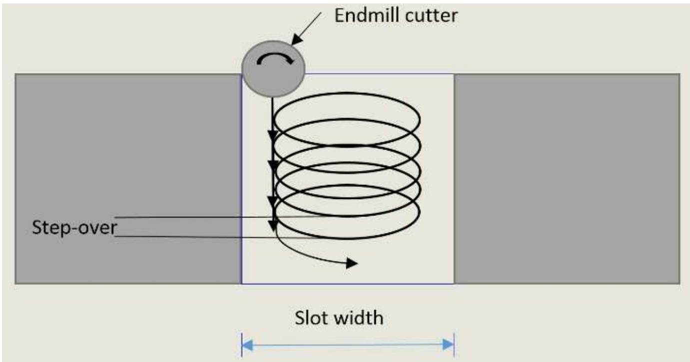

Fig. 3. Trochoidal milling tool path

1.3. TITANIUM AND NECESSITY OF COOLANT

Cutting fluid has a significant impact on the performance of a tool. If coolant is not appropriately applied in titanium, tools tend to wear quickly or fail. There are many reasons for this, including chip issues, poor lubrication, and the phenomenon of super-heated steam [12]. When machining at high speeds, proper chip evacuation is always a potential point of failure. If chips fall back into the chip/tool interface or don‘t clear the cutting area, the result will inevitability cause damage to the tool or work piece, often re-cutting the chips. Beyond evacuation, super-heated chips tend to not break into smaller pieces, compounding the problem of poor evacuation by clogging the tool flute. So not only do the chips have to be flushed out of the machining zone, they also have to be cooled so they are easily broken into smaller, more manageable pieces. Because many standard coolant delivery systems spray coolant over a large area in an attempt to cover the entire machining area, the coolant often does not properly flush or cool the chips, especially of a hardened material being machined at high speeds [13].

According to Sandvik Coromant, another common coolant issue in titanium is poor lubrication. This is often caused by coolant pressure not being great enough to push through the tool tip while machining at high speeds or being vaporized by the high heat of the cut. Poor lubricity is one of the most common reasons for tool failure and accelerated tool wear in titanium, raising the cost of metal removal and extending cycle times. Water based fluids are the best choice to provide heat-dissipation and good cleanliness for machining titanium. Soluble oils offer excellent lubricity.

Finally, during the machining of titanium, the tool tip can reach temperatures of 1100°C or more. This tremendous heat often causes super-heated steam to form in water-based coolants, making the coolant vaporize before it even touches the work piece. This leads to all the problems listed above, plus additional heating of the work piece instead of cooling, making accuracy even more challenging. In order to control heat levels, water-based coolant must be injected directly between the cutter edge and material at high pressures and high volumes. This approach provides sufficient lubrication to reduce the coefficient of friction and overall production of heat, providing for extended tool life in titanium machining operations. High pressure coolant supply is highly recommended for high speed machining and especially when it comes to titanium alloys (by Makino).

1.4. TOOL HOLDING AND CLAMPING

The axial forces created when machining in Heat resistance super alloys like titanium and nickel with a solid carbide end mill puts very high demands on the clamping mechanism. In some situations the tool can pull out from the chuck despite the chuck's high clamping force. Components that are produced in these materials are expensive with a large number of machining hours invested and the consequence of tool pull out is catastrophic.

For high speed, or high torque machining major benefit of shrink fit tool holders is reduction in vibration and cutting is noticeably faster and smoother. Manufacturing times can be reduced while maintaining the quality and accuracy demanded by today's competitive markets.

Considering all above factors, an experimental plan designed. Experiment design based on a series of experiments, carried out with different combination of parameters includes Depth of cut (DoC) ranging from 1mm-24mm, Cutting speed (Vc) ranging from 50-125m/min and Feed per tooth (Fz) from 0.1-0.4mm/tooth and it was concluded not to go beyond the cutting speed 120m/min and feed-rate 0.35mm/tooth.

The present work aims at find out suitability of trochoidal milling technique for Ti6Al4V slot machining with an objective to investigate influence of step-over on surface finish, cutting forces, tool life and chip morphology.

2. EXPERIMENTAL DESIGN

All machining trials were conducted on a 'Spinner – U620' 5 Axis-CNC machine with high pressure coolant. Castrol Hysol-X, water soluble lubricant with 8% concentration used as coolant.

The workpiece consisted of a Titanium alloy (Ti6Al4V) rectangular block, with length (L) 150mm, height (H) 70mm and width (W) 50mm. The cutting tool used was Iscar make Ø 12mm, 4 flute, Solid carbide endmill with 30° helix angle (EC-A4 12-22C12E73 IC900) was clamped in HSK Shrink-fit holder, used to generate 8 slots of L50mm × W15mm × H20mm.

Table 1. Trial parameters

Trial	Cutting Speed (VC)	Spindle speed (n)	Feed Per tooth (Fz)	Table feed (Vf)	Depth of cut (ap)	step over (ae)	Material removal rate (MRR)
	m/min	rpm	mm/tooth	mm/min	mm	mm	cm3/min
1	90	2389	0.25	2389	20	0.20	9.55
2	90	2389	0.25	2389	20	0.30	14.33
3	90	2389	0.35	3344	20	0.20	13.38
4	90	2389	0.35	3344	20	0.30	20.06
5	120	3185	0.25	3185	20	0.20	12.74
6	120	3185	0.25	3185	20	0.30	19.11
7	120	3185	0.35	4459	20	0.20	17.83
8	120	3185	0.35	4459	20	0.30	26.75

The experimental design focused on observing the influence of varying three parameters, cutting speed, feed and step over. Two variables were selected for each parameter, as shown in Table 1, i.e. for cutting speed V_1=90m/min and V_2=120m/min.

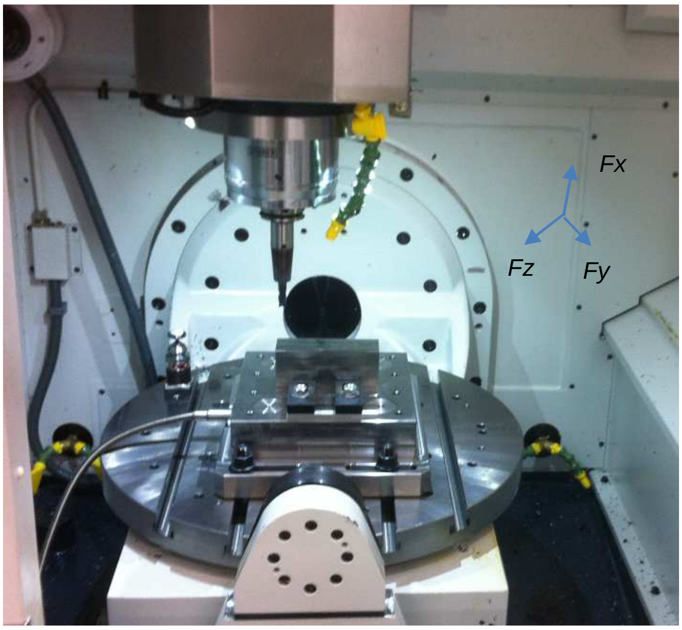

Fig. 4. Actual Machine set-up

These set of variables gave 8 different combinations by changing 1 variable at a time. A total 8 slots of width 15mm and depth 20mm were generated with different set of parameters by a single ø12mm endmill cutter. As stated before, machining parameters was based on various preliminary trials and recommended guidelines from cutting tools manufactures.

Figure 4 displays the experimental setup consisting of the workpiece, 5 Axis-CNC machining centre, cutting tool and force dynamometer. Mechanical removal of material gives rise to cutting forces, whose magnitude depends on numerous factors. They are extremely important in enabling analysis and optimizations of cutting processes. To measure these forces “Kistler-9255” stationary dynamometer was used, mounted directly on the table of the machine and workpiece to be machined was clamped on the dynamometer. The coordinate system of the dynamometer was fixed relative to that of the machine tool, highlighted in Fig. 4. Three orthogonal components, feed force *Fx*, normal feed force *Fy*, and axial cutting force *Fz* were measured with the dynamometer. Surface roughness and tool wear observations were taken using an Alicona ‘InfiniteFocus’ optical 3D profilometer.

3. RESULT AND DISCUSSION

The results of this experiment was a titanium removal rate of 26.75cm^3/min and tool life about 26-30 minutes. As the entire flute length/cutting edge was utilized, the heat and wear were uniformly spread out, leading to effective utilization than traditional slot milling.
Rapid increase in cutting forces i.e. more than double, was observed when cutter engagement increased from 0.2mm step over to 0.3mm step-over for cutting speed 120m/min. Fig. 5 shows comparison between Trial 5 and Trial 6 in which step-over was the only variable whereas other parameters remained constant.

On the other hand, cutting forces increased proportionally for lower cutting speed i.e.90m/min. It means, there were no rapid increase.

It is observed that at V_1=90m/min, the max feed force *Fx*, was always lower than the max normal feed force *Fy*, irrespective of the step over value. Whereas at V_2=120m/min, the max *Fx* was found to be significantly higher than the max *Fy*, this would be caused by increased chip load at higher speed, refer to Fig. 15 in the appendix.

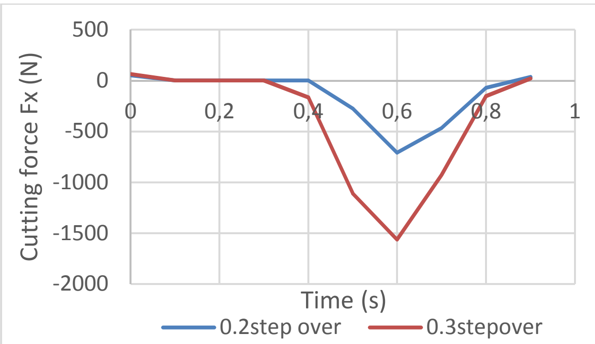

Fig. 5. Effect of step-over on cutting force

Surface roughness (Ra) was measured at various locations at each slot. The average roughness is displayed in Fig. 6. As expected, the surface roughness (Ra) was found to be higher in slots produced by larger step-over irrespective of cutting speed. In fact, there was minimum change in Ra between the two measured feed-rates, provided step-over remaining constant.

It was found the feed rate would need to be reduced to achieve a better Ra at higher cutting speed with high step-over.

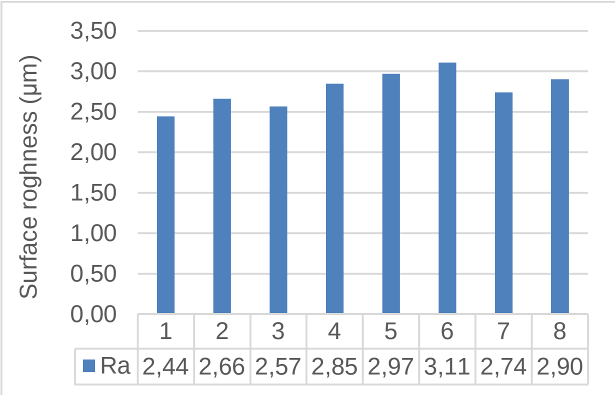

Fig. 6. Surface roughness

It is observed that it was safe to perform trochoidal milling with 0.2−0.25mm step-over i.e. up to 2% engagement of cutter. Further increase in step over leads to chipping. This is due to large portion of cutter engagement which generate higher cutting forces and excessive load on cutter.

			
Vc=90 m/min, ae=0.2mm Fz=0.25mm/rev	Vc=90 m/min, ae=0.3mm Fz=0.25mm/rev	Vc=90 m/min, ae=0.2mm Fz=0.35mm/rev	Vc=90 m/min, ae=0.3mm Fz=0.35mm/rev
			
Vc=120m/min, ae=0.2mm Fz=0.25mm/rev	Vc=120 m/min, ae=0.3mm Fz=0.25mm/rev	Vc=120 m/min, ae=0.2mm, Fz=0.35mm/rev	Vc=120 m/min, ae=0.3mm, Fz=0.35mm/rev

Fig. 7. Chip morphology

It was noted that titanium slot machining, using trochoidal milling technique was safe till 1560N cutting force. It was noticed, the chip generation was perfectly smooth irrespective of step-over but noise level kept on increasing with higher feed rate and cutting speed.

On the other hand, chip evacuation improved as step-over and cutting speed increased since thick chip carries away heat, and producing a thick chip also assures a clean cutting action that minimizes rubbing and the heat it generates. Higher spindle rotation along-with extra room due to wider slot provided better chip evacuation. Chip produced were needle type, twisted and serrated as shown in Fig. 7. Endmill chipped off after trial 6, broke chips into small pieces where material rubbed against cutting edge than proper shearing.It is assumed the low radial width of cut (WoC) generated less cutting force/deflection and reduced temperature at cutting zone. This would greatly benefit towards achieving deeper axial cuts and cutting at higher speeds.

It is recommended the following parameters are suitable to perform safe trochoidal milling:

Cutting speed = 90 − 120m/min,
Feed per tooth = 0.3 − 0.35mm,
Step over = 0.2 − 0.25mm,
Axial depth = up to 2·dia. of tool.

With these recommended set of parameters along with experimental results, it is practically possible to achieve material removal rate of > 25cm^3/min and up-to 30 minutes of tool life. Fig. 8 shows the final product, 8 slots produced by trochoidal milling technique.

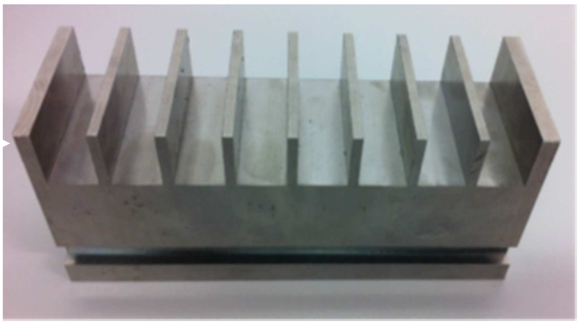

Fig. 8. Component produced

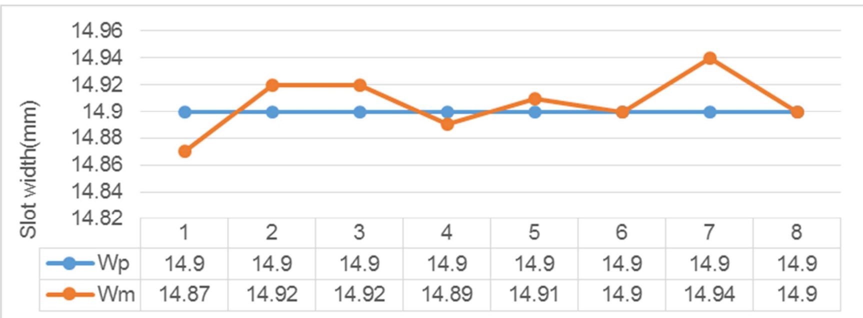

Fig. 9. Slot width at start of slot

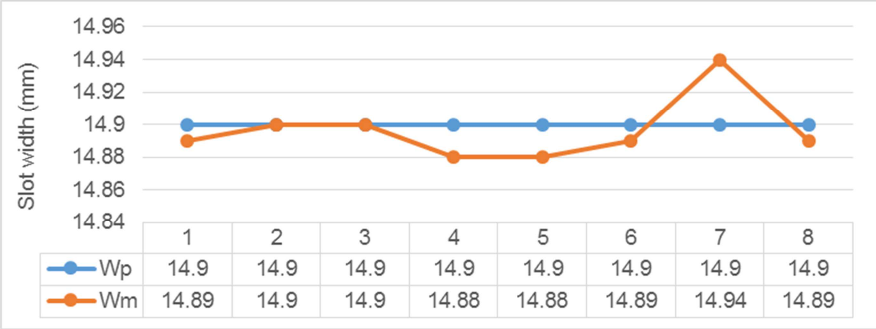

Fig. 10. Slot width at middle of slot

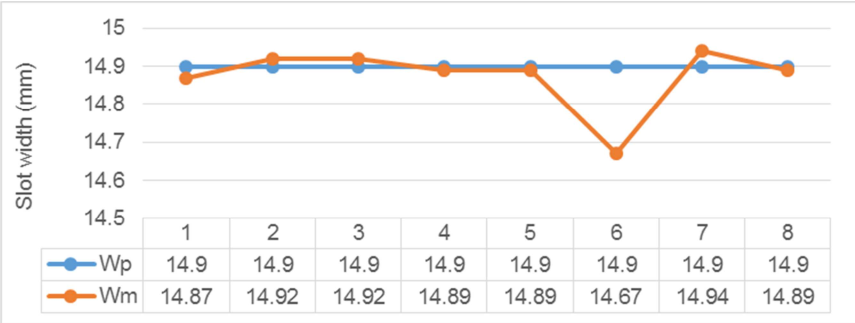

Fig. 11. Slot width at end of slot

The width of the slots were measured to check dimensional accuracy, as shown in Fig. 8, at 3 different locations i.e. at start of slot, middle of slot and end of slot. It was observed that dimensions are within limit of -0.04 to +0.03mm, except for slot 6 which was result of endmill chip-off. Dimensional accuracy could be maintained by minor adjustment in program. Following graphs in Fig. 9, 10, 11, shows variations in slot dimensions.

Where: Wp = Programmed width of slot,

Wm = Measured width of slot.

After 26min of tool usage, tool wear observed was normal flank wear as shown in Fig. 12 for land and Fig. 13 shows magnified view of land width.

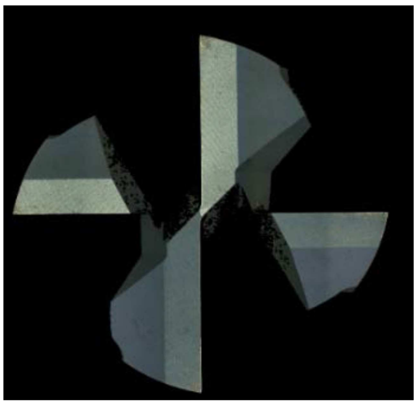

Fig. 12. Endmill face

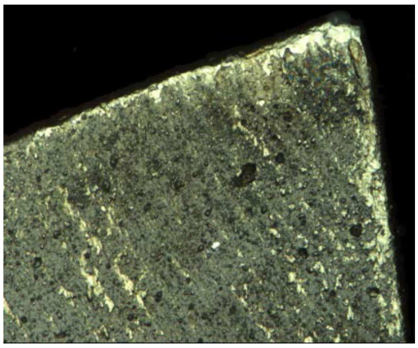

Fig. 13. Endmill- Magnified view

Further usage of the tool caused sudden chip-off which was experienced while conducting trial 6. It’s always advisable to change cutting tool at first sign of wear to avoid damage to part or tool. Find endmill after chip-off as shown in Fig. 14.

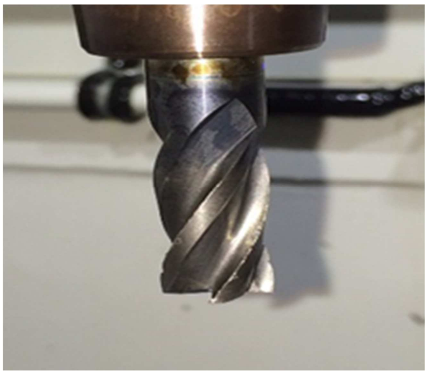

Fig. 14. Endmill – Chipped off

4. CONCLUSION

This article presented the outcome gained by performing trochoidal milling trials on Ti6Al4V which is most popular titanium alloy. The experiments that were carried out have provided the general conclusions listed below:

- step-over causes rapid increase in cutting forces if applied at higher cutting speed i.e.> 120m/min,
- for slot milling, trochoidal milling would be a preferred technique since it generates better surface finish i.e. Ra less than 5μm,
- endmill tool life > 25min and material removal rate > 25cm^3/min easily achievable with trochoidal milling,
- trochoidal milling is favourable milling technique when it comes to chip generation and chip evacuation. Needle shaped, twisted chips generated and machining of wider slots than diameter of endmill helps by providing room for chip evacuation,

- for effective utilisation of tool, recommended to use endmill cutter engagement up to 2.5% of diameter of cutter.

In short, efficient trochoidal milling of titanium alloys is certainly possible. Undoubtedly, it is economical, productive and safe method as compared with traditional slot milling method.

Economical, since entire flute length i.e. up to 2 times of diameter can be easily utilized which leads to maximum utilization of cutting tool and slot width, bigger than diameter of cutter can be produced with smaller diameter endmill which help to reduce contribution of cutting tool’s cost in overall cost of production.

Whereas due to higher axial depth of cut ultimately material removal rate (MRR) increases which proves Trochoidal milling as productive too.

Trochoidal milling is safe as compared to conventional slot milling since this method uses small radial depth of cut which generates low cutting forces makes it is more stable process. Also, huge reduction in heat generation due to small contact time and engagement.

5. FUTURE WORK

Future work may include machining of slot by using separate tool for each trial to measure surface roughness value, dimensional accuracy. Extensive trial with separate endmill for each set of parameters will help for comparative assessment in terms of life of endmill, material removal cost per cubic centimetre, surface texture analysis and to monitor changes in surface finish through-out life of endmill. This would further aid in determining the effects of step-over, feed rate and cutting speed in trochoidal milling.

6. APPENDIX

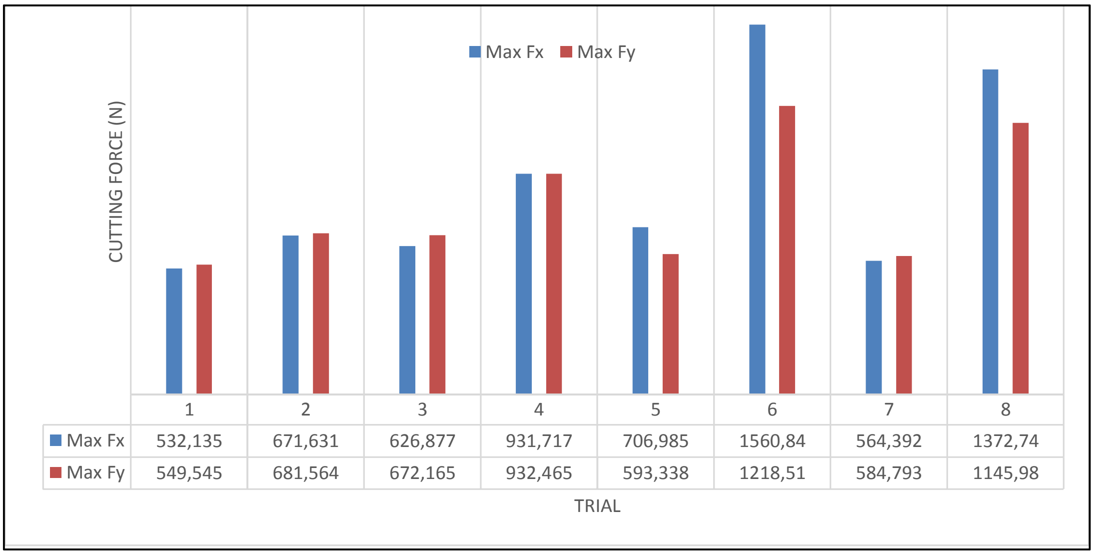

Fig. 15. Maximum cutting forces

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