Effect of Edge Geometry on Coated Carbide Tools when Face Milling Titanium Alloy

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Abstract

This paper presents the experimental investigation on the effect of edge geometry of coated carbide inserts on cutting performance during face milling of titanium alloy, Ti-6Al4V. Two similar PVD-TiN coated inserts with different edge geometry were used in the face milling experiment at various cutting speeds of 55, 65 80 and 100 m/min with a feed rate of 0.1mm/tooth. Tool life and tool failure characteristics were examined at the above cutting conditions. Results showed that edge geometry had a significant effect on the tool performance. Insert with sharp cutting edge was observed to perform better than chamfered edge insert at all conditions investigated. Excessive chipping at the cutting edge and chipping and/or flaking on the rake face were the dominant failure modes on both tools under most cutting conditions.

Keywords: tool wear, carbide tools, face milling, titanium alloys

1 Introduction

The extensive used of titanium and its alloys in aerospace, chemical and petroleum industries are mainly due to their attractive properties such as strength to weight ratio, superior corrosion resistance and compatibility with composite materials [1].

However machining of titanium alloys is extremely difficult and has been hindered by their high temperature strength, very low thermal conductivity, relatively low modulus of elasticity and chemical reactivity [2]. Great advancement in the development of cutting tools for the past few decades has not improved the machinability of titanium alloys. Almost every cutting tool developed so far, including diamond, ceramics and cubic boron nitride, is highly reactive with titanium alloys, causing rapid wear at high cutting speeds [3-6].

Most of the machining studies for titanium and its alloys have been focused on the turning process that involves continuous cutting. These results are not applicable to milling process where interrupted cutting takes place, subjecting the tools to a variety of hostile conditions. Severe chipping and flaking of the cutting edge were reported to be the main failure modes when milling titanium alloys with carbide tools. These types of failure modes are a result of a combination of various factors such as high thermo-mechanical and cyclic stresses, as well as the adhesion to and breaking of workpiece material from the tool faces. Despite some investigations on face milling of titanium alloys [7- 9], there is lack of study on the effect of edge geometry of the tools on cutting performance. Previous studies on face milling of steel have shown that edge bevelling strengthened the cutting edge and significantly improved the tool life.

This work is aim to investigate the influence of edge chamfering of PVD-TiN coated carbide tools on cutting performance with respect to tool life and failure modes during face milling of titanium alloy, Ti-6Al4V at various cutting conditions.

2 Experimental Procedure

2.1 Machining test

All face milling tests were carried out on a Sabre 750 Cincinnati CNC vertical machining centre with a 9 kW motor drive under the conditions shown in Table 1. The milling cutter was positioned at the centre of the workpiece to perform neutral machining mode. This position was recommended by ISO [10] to avoid the occurrence of “foot formation” as a result of the unfavourable exit angles [11]. The presence of “foot formation” could lead to premature tool failure through excessive chipping and fracture of the cutting edge. Coolant was used throughout the milling tests.

2.2 Workpiece material

Face milling trials were carried out on a rectangular bar of 125 mm x 58 mm x 400 mm, which was machined from 140 x 140 x 400 mm billet of alpha-beta Ti-6Al-4V titanium alloy. The billet was hot rolled at 925^{o}C and air cooled without further treatment. In order to maintain a constant entry and exit angles during cutting, one end of the bar where the cutter starts cutting was premachined whilst the other end was left uncut. The composition and properties of the workpiece material are shown in Tables 2 and 3 respectively.

2.3 Inserts

Two PVD-TiN coated inserts of similar substrate and properties but with different edge geometry were used and were labelled as Tool A and Tool B. Tool A consists of negative chamfer (γ) of - 20^{o} and a land width (b) of 0.213 mm while Tool B is a sharp edge insert. The cutting edge radius of both inserts, r is < 0.2 mm.. They were square in shape with wiper edges at the corner edge. The edge geometry of both inserts are shown in Figure 1. The inserts were clamped to a standard cutter to provide the cutting geometry as given in Table 1.

2.4 Tool wear measurement and analysis

The tools were examined and wear land measured at various stages of each test using a toolmaker microscope without dismounting the inserts from the milling cutter. A SEM was used to examined the tool wear and tool failure mode. Tool rejection or failure was determined based on the following criteria:

(a) Average flank wear = 0.35mm (average of all six inserts)
(b) Maximum flank wear = 0.7 mm (on any of the inserts)
(c) Excessive chipping/flaking or fracture of the cutting edge.

Table 1. Face milling test conditions.

Cutter Geometry	Diameter = 80 mm No of inserts = 6 (fully loaded) Approach angle = 45^{o}	Radial rake angle = - 11^{o} Axial rake angle = +20^{o} Effective rake angle = +6^{o}
Cutting conditions	Axial depth of cut (DOC) = 2 mm Radial depth of cut (DOC) = 58 mm Cutting speed = 55, 65, 80 and 100 m/min Feed = 0.1 mm/tooth	
Inserts	ISO Grade: (P25 - P40, M30 - M40, K20 - K30) coated with TiN using PVD technique Edge radius, r < 0.02 mm	
Cutting fluid	Hocut 808 - 6 - 7% concentration	

Table 2. Nominal composition of Ti-6Al-4V.

CHEMICAL COMPOSITION OF Ti-6Al-4V, wt. %					
Al	V	Fe	H_2	$O_2 + N_2$	Titanium
5.5 - 6.75	3.5 - 4.5	0.03 (max)	0.0125 (max)	0.25 (max)	Bal.

Table 3. Physical properties of Ti-6Al4V.

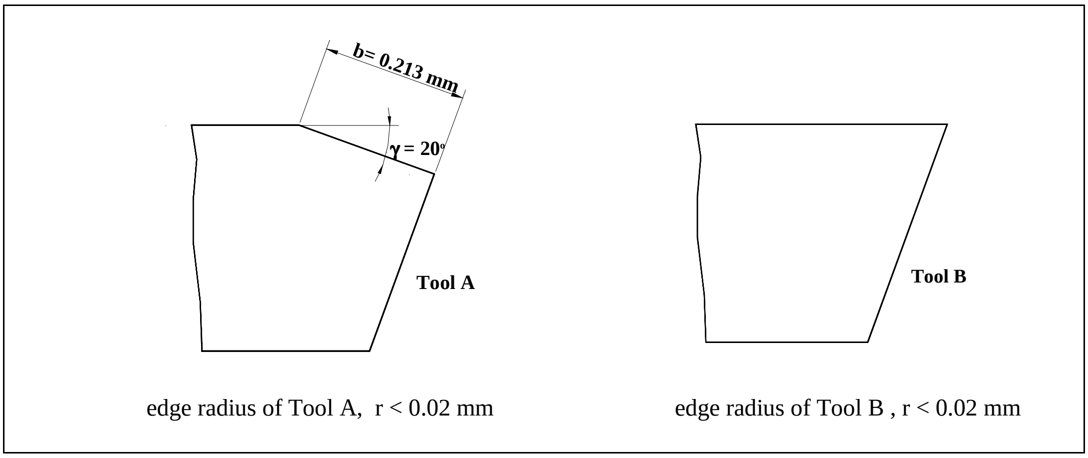
PHYSICAL PROPERTIES OF Ti-6Al-4V (at room temperature)						
Tensile strength (MPa)	0.2% proof stress (MPa)	Density (g/cm^3)	Elongation 5D (%)	Modulus of elasticity tension (Gpa)	Hardness (Hv)	Thermal conductivity (W/mK)
960 - 1270	885	4.42	≥ 8	100 – 130	330 - 370	7

Table 4. Properties of substrate of Tool A and Tool B.

SUBSTRATE	
Nominal Composition (wt %)	WC = 86 Co = 11.5 Ta(Nb)C = 2.5
Grain Size (µm)	1 ~ 6
Hardness (kg/mm^2)	1460
Transverse Rupture Strength (GPa)	2.61
Density (gm/cc)	14.2
Thermal Conductivity (cal/cm-sec-^{o}C)	0.161

Table 5. Properties of PVD coating.

COATING ON TOOL A AND TOOL B	
Coating Technique	PVD-Ion Plating
Coating	TiN
Coating Thickness (µm)	2 ~3.5 µm
Hardness (kg/mm^2)	2200
Adhesion Strength	~ 45 kg (indent adhesion)
Thermal Conductivity (W/mk)	25



edge radius of Tool A, r < 0.02 mm

edge radius of Tool B , r < 0.02 mm

Figure 1. Edge geometry of Tool A and Tool B.

3 Results and Discussion

3.1 Tool life

Data on tool life when face milling Ti-6Al4V using Tool A and Tool B are shown in Table 6 and Figure 2. As shown in Figure 2, Tool B with chamfered edge recorded the best tool life performance of 30 minutes at the lowest cutting speed of 55 m/min. An increment of 200 % in tool life was achieved by Tool B when compared to Tool A under the same cutting speed. Tool A only achieved a highest tool life of 10 minutes of tool life at this cutting speed. Face milling above cutting speed of 65 m/min showed a significant decrease in tool life for both tools. Results showed that Tool A or chamfered tool failed prematurely when short tool lives were recorded at all cutting speed. Shortest tool lives of 5 and 7 minutes were recorded for Tool A and Tool B respectively at the highest cutting speed of 100 m/min as displayed in Table 6. Best overall performance was achieved with Tool B or sharp cutting edge tool with reasonable tool lives at all cutting speed as compared to Tool A.

3.2 Tool wear and failure mode

As shown in Figure 3 both tools exhibit a similar flank wear pattern at all cutting speeds except at 55 and 65 m/min, where the wear rate of the sharp edge tool (Tool B) was more gradual. The growth of flank wear was significantly reduced by employing the lowest cutting speed of 55 m/min. In general, an increase in cutting speed, increases the tool wear. Non-uniform flank wear was dominant at all cutting conditions for both tools. Uniform flank and nose wear which were observed at the initial cut were suppressed as cutting progressed. Wear on the minor cutting edge of the tool was too small to cause any significant effect to the tool during machining.

Shorter tool lives were recorded for both tools at high cutting speeds due to rapid tool wear as a result of severe chipping and flaking on the cutting edge

Table 6. Data on tool life data and tool failure modes when face milling Ti-6Al4V with chamfered (Tool A) and sharp (Tool B) tools at various cutting speeds and feed rate of 0.1 mm/tooth.

Data obtained when face milling Ti-6Al-4V at various cutting speed				
Cutting Speed (m/min)	Feed : 0.1 mm/tooth, Axial DOC: 2mm, Radial DOC : 58 mm			
	Tool A (chamfered edge)		Tool B (sharp edge)	
	Tool life (min)	Tool failure mode	Tool life (min)	Tool failure mode
100	5	CH/FL	7	CH/FL
80	7	CH/FL	11	CH/FL
65	8.5	AFW/CH/FL	17	FL
55	10	CH/FL	30	FL
Note: CH - chipping		FL - Flaking	AFW - Average Flank Wear	

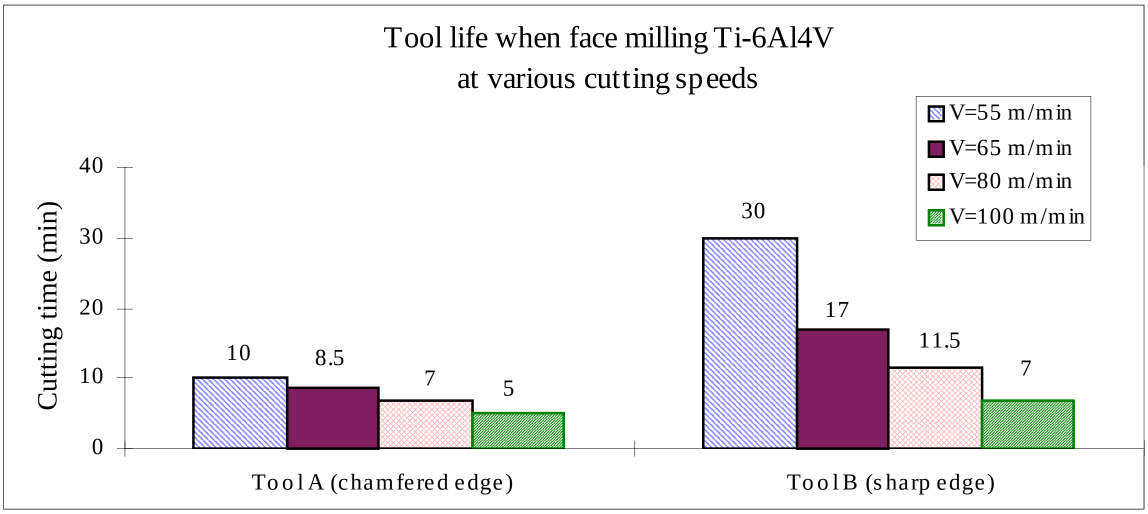
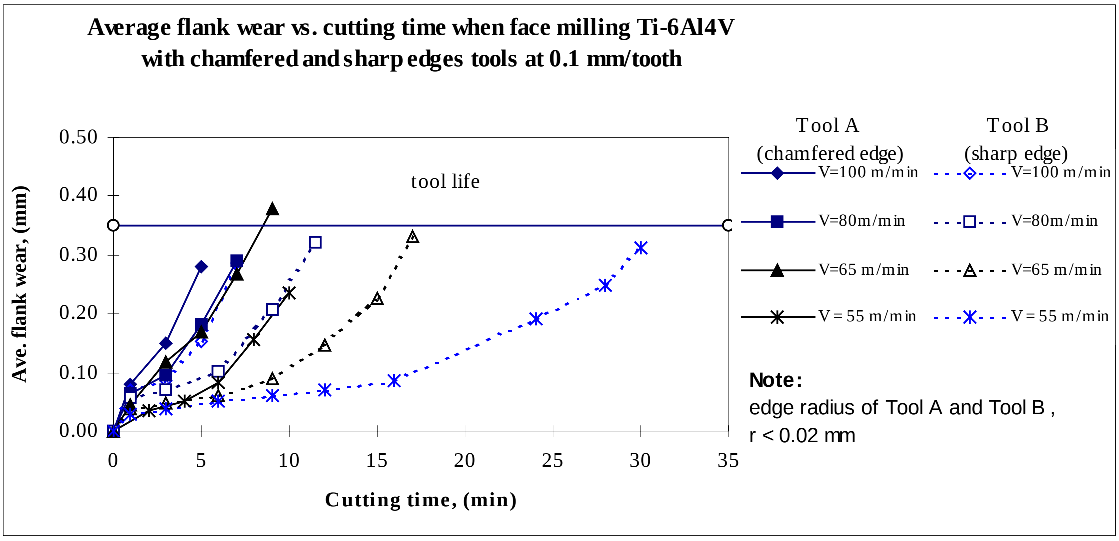


Figure 2. Comparison of tool life when face milling Ti-6Al4V with chamfered (Tool A) and sharp (Tool B) tools at various cuting speeds and feed rate of 0.1 mm/tooth.

before any form of gradual wear can take place. In general, the wear rate on the flank of sharp edge tool (Tool B) was slightly lower than the chamfered tool (Tool A), hence better tool lives were recorded.

Results on the tool failure modes as shown in Table 6 indicate that in all cases, excessive chipping and/or flaking on the rake face were the main modes of failure in rejecting both tools before the flank wear criteria are met. At lower cutting speeds, attrition wear was the major contributor to the occurrence of chipping and flaking on the rake face of the tool. At higher speeds, significant increase in cutting temperature and thermal stresses occurred thus encouraging thermally related wear mechanisms to operate such as diffusion, plastic deformation and thermal cracks on the cutting tools. These may eventually promote chipping and flaking of the tool. Figures 4 and 5 show excessive chipping, flaking and cracks on the rake face of Tool A and Tool B respectively. Previous researchers [12] have shown that the temperature at the interface between the flank and the workpiece can reach up to 800 °C when face milling Ti-6Al4V at cutting speed of 47 m/min and feed rate of 0.1 mm/tooth. In this study, machining trials were carried out at higher speeds and hence higher temperature generation would enhance the thermally related wear mechanisms. Notching at the DOC, a common phenomena in turning of titanium alloy [9,13], was not observed on any of the worn tools throughout the face milling trials.


Average flank wear vs. cutting time when face milling Ti-6Al4V with chamfered and sharp edges tools at 0.1 mm/tooth

Note: edge radius of Tool A and Tool B, r < 0.02 mm

Figure 3. Average flank wear vs. cutting time when face milling Ti-6Al4V with chamfered (Tool A) and sharp (Tool B) tools at feed rate of 0.1 mm/tooth.

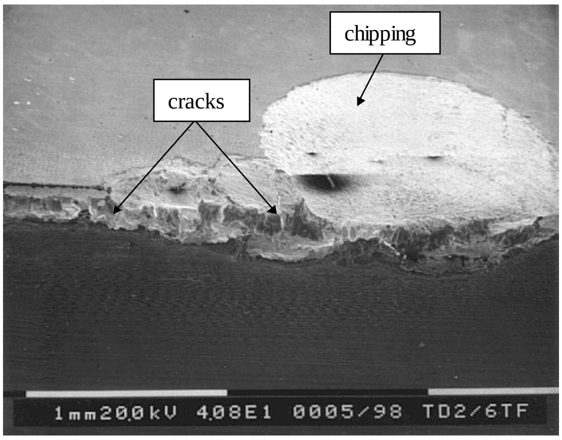


Figure 4. Catastrophic failure, showing severe flaking on the rake face of Tool A (chamfered edge) after face milling Ti-6Al4V for 7 minutes at 80 m/min and 0.1 mm/tooth.

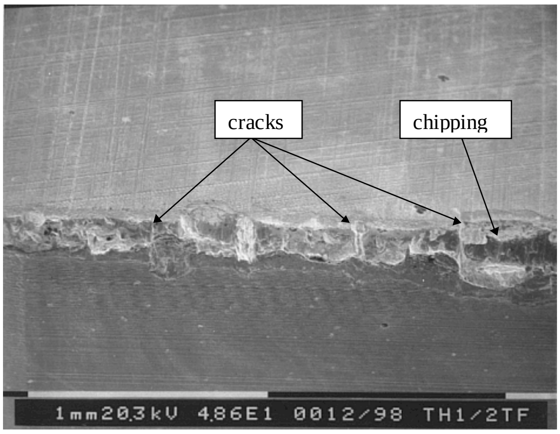


Figure 5. Combed cracks and excessive chipping on the rake face of Tool B (sharp edge) after face milling Ti-6Al4V for 11.5 minutes at 100 m/min and 0.1 mm/tooth.

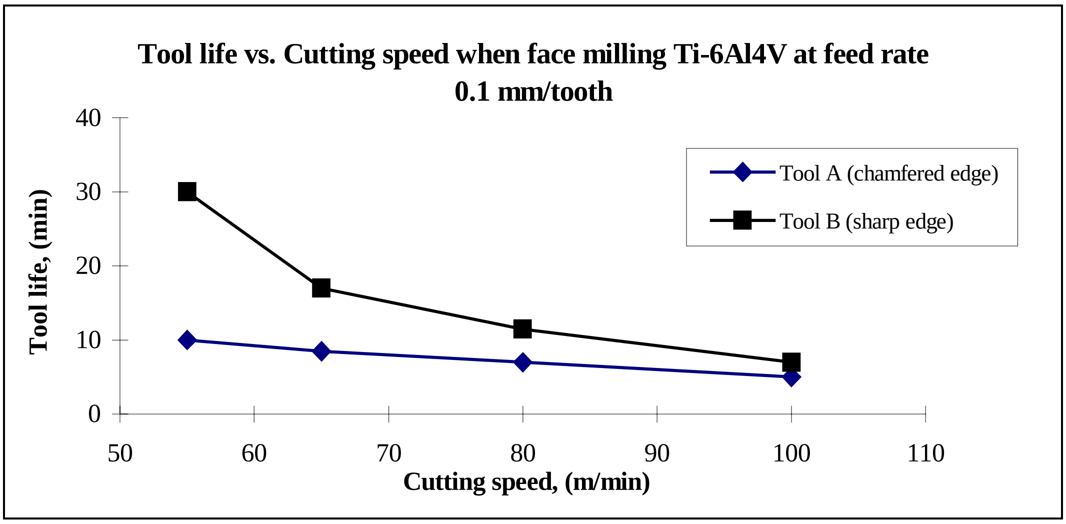

Tool life vs. Cutting speed when face milling Ti-6Al4V at feed rate 0.1 mm/tooth

Figure 6. Tool life curve when face milling Ti-6Al-4V with chamfered (Tool A) and sharp (Tool B) tools at feed rate of 0.1 mm/tooth

3.3 Effect of cutting speed on tool life

The effect of an increase in cutting speed on the tool life for both tools are presented graphically in Figure 6. Experimental results showed that cutting speed played a significant role in controlling tool life performance and hence wear mechanisms when face milling titanium alloy Ti-6Al4V. As shown in Figure 6, the tool life of Tool A increased linearly with increase in cutting speeds. The effect of cutting speed on tool life was less significant when face milling with chamfered tool (Tool A) as shorter tool lives were recorded at all cutting speeds. This was due to premature failure of the tool, probably as a result of edge bevelling of the cutting edge which may cause unstable cutting hence accelerating chipping and flaking process of the cutting edge.

Similarly, Tool B achieved very slight improvement in tool life when cutting speed was reduced from 100 to 65 m/min However, the influence of cutting speed on the performance of Tool B was very significant when cutting speed was reduced from 65 to 55 m/min. A reduction of 15 % in cutting speed generated an increase in tool life of 76 %. Machining Ti-6Al4V at high speeds produced thinner chips which resulted in shorter tool-chip contact length/area, hence more heat and high stresses will be localised in a relatively small area of the tool. The cumulative effects of higher temperature and stresses developed at high cutting speeds increased the response of temperature related wear mechanisms which were disadvantageous. These wear mechanisms which include diffusion/dissolution, attrition and cracks were prominent at high cutting speeds and thus accounted for the rapid wear and failure of both the tools hence shorter tool life. Based on the results obtained, it is suggested that cutting speed should remain low when machining titanium alloys in order to achieve maximum cutting performance of the carbide tools investigated

3.4 Effect of edge geometry

The effect of edge geometry on wear and tool life in face milling have been investigated by many researchers [13-15]. The main consensus is that bevelling or chamfering of the main cutting edge was found to influence the tool life quite significantly.

Chamfered tool (Tool A) which was originally designed to overcome the problem of edge fracture did not exhibit promising results when face milling titanium alloy, Ti-6Al4V as compared to sharp edge tool (Tool B) due to shorter tool lives recorded. V-T curves in Figure 6 demonstrate that the tool lives obtained with Tool A were never higher than Tool B at all cutting conditions tested. The tool life variations of both tools were significantly greater when machining at lower cutting speed between 55 and 65 m/min. Introducing a negative land that is longer than the feed rate on Tool A will restrict the chip flow within the chamfer face which now acts as an effective rake face. Hence the geometry of the cutter with Tool A inserts changed to a negative-negative cutter from a negative-positive cutter which was the case for Tool B inserts. The disadvantages of double negative cutter when machining titanium alloys were probably the reasons underlying the poor performance of chamfered tool (Tool A). The generation of high cutting forces [16-18] and the poor ejection of the serrated chips [16,17] by this type of cutter can cause severe damage to the tool and the workpiece. All these factors coupled with the high cutting temperature at the chamfer face of Tool A can escalate the wear mechanisms of diffusion and attrition thus promoting the occurrence of various failure modes. As a result, rapid flank wear and premature failure of Tool A occurred at all cutting conditions and no improvement in tool life was achieved. Even at the lowest cutting speed of 55 m/min, the tool life obtained were relatively short (10 minutes) when face milling Ti-6Al4V.

Despite experiencing similar failure modes as Tool A or chamfered tools, Tool B or sharp edge tools offered much better tool lives when machining both alloys at all cutting conditions investigated. Best tool life performance was obtained at cutting speed of 55 m/min and feed rate of 0.1 mm/tooth with recorded tool lives of 30 when face milling Ti-6Al4V. The outstanding performance of sharp edge tool (Tool B) was probably due to the favourable negative-positive geometry of the cutter which offered many advantages when machining titanium alloys. The negative radial rake angle provides a strong cutting edge, while positive axial rake angle allows smooth ejection of the chips and reduces cutting force during machining [16,17].

Despite the advantages outlined by many researches on chamfered tool, it was found that chamfered tool (Tool A) was unsuitable for face milling titanium alloy Ti-6Al4V when compared to sharp tool (Tool B). The poor performance of Tool A, was probably due to unsuitable edge preparation given to these tools in face milling Ti-6Al4V. In order to realise the greatest potential of chamfered tools when machining titanium, optimisation of the edge parameters such rake angles and edge geometry are essential.

4 Conclusion

Conclusions drawn from face milling titanium alloy Ti-6Al4V with two different geometry inserts are as follows:

1. In general, sharp cutting edge inserts (Tool B) produced better cutting performance at all cutting conditions when compared to chamfered/bevelled

edge inserts (Tool A) when face milling titanium alloy Ti-6Al4V.

2. The best cutting condition with respect to highest tool life (30 minutes) was achieved by sharp edge inserts (Tool B) at cutting speed of 55 m/min and feed of 0.1 mm/tooth.
3. Edge bevelling or chamfering of the cutting edge had not improve the cutting performance of the tools when face milling titanium alloy Ti-6Al4V as what have been claimed when face milling of steel.
4. Non-uniform flank wear was the dominant wear pattern exhibited by both chamfered and sharp edge tools.
5. Excessive chipping at the cutting edge and flaking and/or chipping on the rake face of both tools were the dominant failure modes at most cutting conditions.

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