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PREFACE

This book present selected advance related to manufacturing and industrial engineering. It presents 12 technical papers written by professors, lecturers, students and associate partners of the Department of Manufacturing and Industrial Engineering, Universiti Teknologi Malaysia.

The issues covered in this book include application of industrial engineering in construction industry, quality engineering, total quality management and ISO/TS16949 certification, statistical process control, control chart patterns classification, end-of-life vehicle design and development process, product disassembly analysis and disposal. Updates related to manufacturing technology covers turning, face milling, tool life, surface roughness, and evaluation of ground optical glass. The book concludes with a chapter on computer integrated manufacturing system.

Many individuals have helped make this book a reality. We are most grateful to the chapter contributors, and all the staff and management of the Faculty of Mechanical Engineering, Universiti Teknologi Malaysia. Without their cooperation, this book would have not come to this completion.

Above all, we thank Allah for granting us perseverance and strength we needed to complete this book.

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10

FACE MILLING OF TITANIUM ALLOY Ti-6246 USING PVD-TiN COATED CARBIDE TOOLS

Safian Sharif
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10.1 INTRODUCTION

The increasing trend of using titanium alloys in aerospace, chemical, biomedical and petroleum industries are mainly due to their attractive properties such as strength to weight ratio, low density, superior corrosion resistance and compatibility with composite materials (Boyer, 1998 and Brewer et. al., 1998). On the other hand, many researchers have classified titanium and its alloys as "difficult to cut materials" with respect to machinability due to their high temperature strength, low thermal conductivity, low modulus of elasticity and chemical reactivity (Hong et. al., 1993). The inhomogeneous deformation by catastrophic shear during machining tends to fluctuate the cutting force and with its low modulus of elasticity, thereby aggravating tool wear and chatter (Machado and Wallbank, 1990).

Great advancement in the development of cutting tools for the past few decades showed little improvement on the machinability of titanium alloys. Previous studies have shown that almost every cutting tool developed so far, including diamond, ceramics and cubic boron nitride, are highly chemical reactive with titanium alloys, causing rapid tool wear and premature tool failure

(Souza et. al., 2006, Kramer, 1987, Komanduri and von Turkovich, 1981). Most of the studies have concluded that uncoated WC/Co or straight carbide tool still remains the first choice when turning (Narutaki and Murakoshi, 1983 and Hartung and Kramer, 1982) and face milling (Jawaid et. al., 2000 and Ezugwu and Machado, 1988) of titanium alloys.

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 due to the combination of high thermo-mechanical and cyclic stresses, as well as the strong adhesion to and breaking of workpiece material from the tool faces. Despite numerous investigations on milling of titanium alloys (Su et. al., 2006, Usuki et. al., 1996, and Min and Youzhen, 1988), study on the effect of tool edge geometry on cutting performance is still lacking. Previous studies (Paul et. al., 1994, Sidkar et. al., 1992, and Sabberwal and Fleischer, 1964) on face milling of steels have shown that edge bevelling, strengthened the cutting edge and significantly improved the tool life.

This chapter discusses the investigation on the influence of edge chamfering of PVD-TiN coated carbide tools on the tool life performance, tool wear characteristics and failure modes during face milling titanium alloy, Ti-6246 at various cutting conditions.

10.2 EXPERIMENTAL DETAILS

The experimental details of the investigation on face milling of Ti-6246 using PVD-coated carbide tools are discussed in the following sections.

10.2.1 Workpiece Material

Machining trials were conducted on a rectangular bar of alpha-beta Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) or IMI 646 with dimension of 125 mm x 52 mm x 400 mm, which was machined from a diameter 203 mm round bar. The received material was open forged at 920^0C in alpha beta condition and air cooled with no further heat treatment. In order to maintain a constant entry and exit angles during face milling trials, one end of the bar where the cutter enters was pre-machined using a spare cutter, whilst the other end was left uncut.

The chemical composition and properties of the workpiece material are shown in Table 10.1.

Table 10.1 Material properties of Ti-6246

Properties	Value
Chemical composition	5.5 - 6.5 (Al), 1.75 - 2.25 (Sn), 3.5 - 4.5 (Zr), 5.5 - 6.5 (Mo), 0.15 (Fe), 0.01), 0.0125 (H_2), 0.15 (O_2), 0.04(N_2), balance (Ti)
Tensile strength (MPa)	1214
Yield strength (MPa)	1118
Density (g/cm^3)	4.65
Elongation in area (%)	13
Reduction of area (%)	37
Modulus of elasticity (GPa)	130
Hardness (Hv)	370 – 390
Thermal conductivity (W/mK)	7.7

10.2.2 Inserts

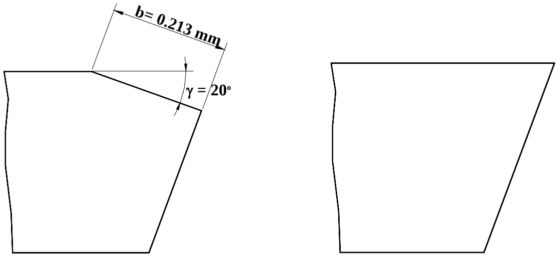
Investigation was conducted on two PVD-TiN coated carbide inserts of similar substrate and properties but with different edge geometry and labelled as Tool A and Tool B which represent chamfered and sharp edge tools respectively. Properties of the tool substrate and coatings for both tools are listed in Tables 10.2 and 10.3 respectively.

Table 10.2 Properties of tool 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 10.3 Properties of PVD coating

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



Tool A Tool B

Figure 10.1 Edge geometry of chamfered tool (Tool A) and sharp edge tool (Tool B)

Tool A consists of a negative chamfer (γ) of 20^o and a T-land width (b) of 0.213 mm whilst Tool B is a sharp edge insert as shown in Figure 10.1. Both inserts were square in shape with wiper edges at the corner. The inserts were clamped to a standard cutter to provide the cutting geometry listed in Table 10.4.

10.2.3 Machining Test

Face milling tests were carried out on a Sabre 750, 9KW Cincinnati CNC machining centre using the parameters shown in Table 10.4.

Table 10.4 Face milling test conditions

Cutter Geometry	Diameter = 80 mm No of inserts = 6 (fully loaded) Approach angle = 45°	Radial rake angle = - 11° Axial rake angle = +20° Effective rake angle = +6°
Cutting conditions	Axial depth of cut (DOC) = 2 mm Radial depth of cut (DOC) = 52 mm Cutting speed = 55, 65, 80 and 100 m/min Feed = 0.1 mm/tooth	
Inserts	PVD coated with TiN of thickness 2 ~3.5 μm Edge radius, r < 0.02 mm	
Cutting fluid	6 % concentration	

As recommended by ISO 8688-1 (E), (1989) for milling operation, neutral milling mode was performed to avoid the occurrence of “foot formation” as a result of the unfavourable exit angles. As pointed out by Pekelharing (1984), the presence of “foot formation” could lead to premature tool failure through excessive chipping and fracture of the cutting edge. Concentration of 6 % coolant under flood condition was used throughout the milling tests.

10.2.4 Tool Wear Measurement and Analysis

The tools wear land were examined and measured using a Nikon tool-maker’s microscope at 30X magnification without dismounting the inserts from the milling cutter. A Scanning Electron Microscope (SEM) was used to examined the tool wear and tool failure modes after face milling at various cutting speeds. Tool rejection or failure was established when any of the following criteria has reached; average flank wear ≥ 0.35mm (average of all six inserts), maximum flank wear ≥ 0.7 mm (on any of the inserts) or excessive chipping/flaking or catastrophic failure of the cutting edge.

10.3 RESULTS AND DISCUSSION

Results of the experimental trials when face milling of Ti-6246 using PVD-coated carbide tools are discussed in the following sections.

10.3.1 Tool Life

Experimental results on tool life when face milling Ti-6246 using chamfered tool (Tool A) and sharp tool (Tool B) are shown graphically in Figure 10.2. Tool B recorded the best tool life performance of 16 minutes at the lowest cutting speed of 55 m/min. when compared to bevelled Tool A which only managed to obtain 6.5 minutes tool life. This implies that an increment of 146% tool life was recorded with Tool B as compared to Tool A. Face milling above cutting speed of 65 m/min showed a significant decrease in tool life for both tools. Shortest tool lives of 3.4 and 3.7 minutes were recorded for Tool A and Tool B respectively at the highest cutting speed of 100 m/min as displayed in Figure 10.2.

Tool A or chamfered tool failed prematurely when short tool lives were recorded at all cutting speeds, probably due to the effect of the negative T-land which may cause unstable cutting hence accelerating chipping and flaking of the cutting edge. As shown in Figure 10.2, the effect of cutting speed on the performance of Tool A was less significant as compared to Tool B. The influence of cutting speed on tool life of Tool B was very significant especially when cutting speed was reduced from 65 to 55 m/min.

An increment of 100% tool life was achieved with only

15% reduction in cutting speed. Similar results were also reported by Sharif et. al. (2000) in their earlier study on face milling Ti-6Al4V whereby sharp edge tool outperformed bevel under all cutting conditions.

Based on the above findings it is appropriate to suggest that sharp cutting edge insert (Tool B) should be used when face milling titanium alloys.

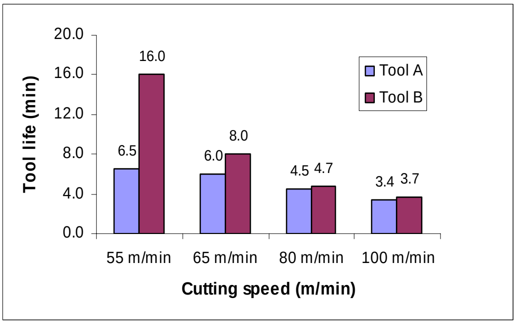


Figure 10.2 Tool life performance between chamfered tool (Tool A) and sharp edge tool (Tool B) at various cutting speeds and feed of 0.1 mm/tooth

It is also recommended that cutting speed should remain low for maximum tool life performance of TiN coated carbide tools whenever face milling Ti-6246 is to be carried out.

10.3.2 Tool Wear and Failure Mode

Results showed that both tools exhibit a similar flank wear pattern at all cutting speeds except at 55 m/min, where the wear rate of Tool B was more gradual than Tool A. The growth of flank wear was significantly reduced when 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 dominant during the initial cutting were suppressed with prolong machining. Wear on the minor cutting edge of the tool was too small to cause any significant effect to the tool during machining. In general, the flank wear rate of sharp Tool B was slightly lower than the chamfered Tool A resulting in better tool lives.

Results on the tool failure modes indicated that in most cases, average flank wear with combination of excessive chipping and/or flaking on the rake face were the dominant modes of failure in rejecting both tools especially at higher cutting speeds as shown in Figures 10.3 and 10.4. Thermal cracks were also observed on Tool A (Figure 10.3) and Tool B (Figure 10.4) after reaching their tool life criteria when face milling at 100 and 80 m/min respectively.

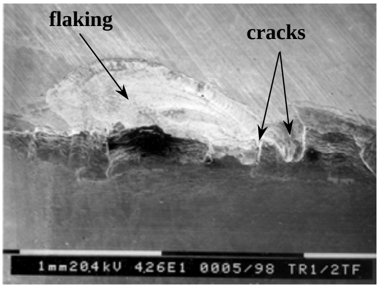


Figure 10.3 Severe flaking and thermal cracks on Tool A after 3.5 minutes of face milling at 100 m/min

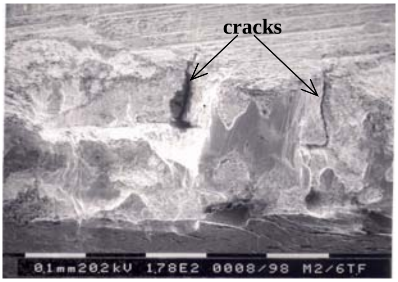


Figure 10.4 Severe chipping and thermal cracks on Tool B after 5 minutes of face milling at 80 m/min

Wang and Zhang (1981) reported that the temperature at the tool-chip interface can reach up to 800 °C when face milling Ti-6Al4V at cutting speed of 47 m/min with feed of 0.1 mm/tooth. The high cutting temperature and cyclic mechanical stresses encourage 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. In this study, machining trials were carried out at higher speeds hence higher temperature generation was anticipated which would further facilitate the thermally related wear mechanisms to operate. It was also observed that at lowest cutting speed of 55 m/min, attrition wear was the major contributor to the occurrence of chipping and flaking on the rake for both tools.

Both tools experienced coating delamination almost instantly (after 5 seconds) as the cutter enters the workpiece. Such evidence is shown in Figures 10.5 and 10.6 for Tool A and Tool B when face milling Ti-6246 at 80 m/min and 55 m/min respectively.

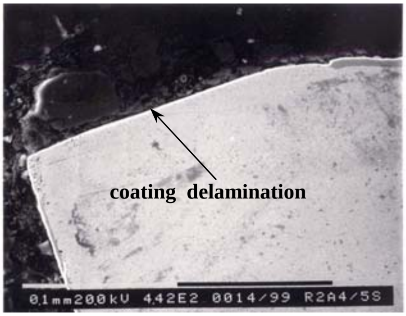


Figure 10.5 Sectioned of Tool A showing delamination of coating on the bevelled face after face milling for 5 seconds at 80 m/min

Figure 10.6 Delamination of coating and adherent of work material on Tool B after face milling for 5 seconds at 55 m/min

Based on the above findings, it is appropriate to suggest that TiN coatings is not recommended to be used as coating material in protecting the carbide substrate from wear and plastic deformation when dealing with titanium alloys, probably due the high reactivity of titanium material.

Examination of the sectioned worn inserts under the SEM, demonstrates that both Tool A and Tool B suffered severe plastic deformation and adherent of work material when face milling Ti-6246 at high cutting speed. Sample of such deformation on sharp edge (Tool B) is illustrated in Figure 10.7 after 4 minutes of machining at 100 m/min. Trent (1970) pointed out that one of the main contributor for plastic deformation to occur when machining with cemented carbide tools was the extrusion of cobalt content after the softening effect. This softening effect intensifies with higher cobalt content and high cutting temperature as what happened in this investigation. In addition, the high reactivity of titanium towards cobalt elements accelerated the diffusion process hence weakening the structure of the tool substrate.

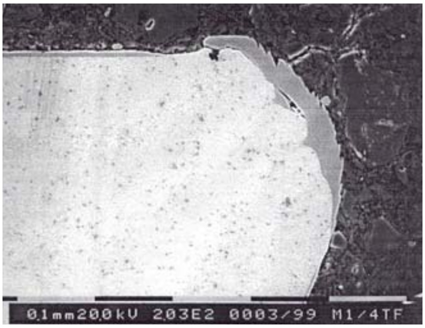


Figure 10.7 Sectioned of Tool B, showing severe plastic deformation after face milling Ti-6246 for 4 minutes at 100 m/min

Notching at the depth of cut (DOC), a common phenomenon in turning of titanium alloys (Hartung and Kramer (1982), Komanduri and von Turkovich (1981)), was not observed on any of the worn inserts of both Tool A and Tool B throughout the face milling trials.

10.3.3 Effect of Edge Geometry

Many researchers (Sharif et. al., 2000, Paul et. al., 1994, Sidkar et. al., 1992, Sabberwal and Fleischer, 1964 and Colwell, 1961) found that bevelling or chamfering of the main cutting edge can influence the tool life quite significantly. Results showed that chamfered Tool A which was originally designed to cater the problem of edge fracture did not exhibit promising results when face milling Ti-6246 as a result of shorter tool lives recorded. Tool life results in Figure 10.2 illustrate that the performance of Tool A was never higher than Tool B at all cutting speeds investigated. The tool life variations of both tools were quite substantial when machining at lower cutting speed between 55 and 65 m/min.

Introducing a negative T-land that is greater than the feed on Tool A restricts the chip flow within the chamfer face which results in a negative rake cutting. 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 and the poor ejection of the serrated chips with the negative-positive cutter can cause severe damage to the tool and the workpiece (Stephenson and Agapion (1997), Fowler (1960)). All these factors, coupled with the high cutting temperature at the chamfer face of Tool A may 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 was relatively short (6.5 minutes).

Despite experiencing similar failure modes and wear mechanisms as chamfered tool, (Tool A), sharp edge (Tool B) offered much better tool life when machining Ti-6246 at all cutting conditions investigated. The outstanding performance of Tool B was probably due to the favourable geometry of negative-positive cutter which offered many advantages when machining titanium alloys. The negative radial rake angle of the tool provides a strong cutting edge, while positive axial rake angle allows smooth ejection of the chips and reduces cutting force during machining (Stephenson and Agapion, 1997 and Fowler, 1960).

Although many researchers have outlined the advantages of using chamfered tool, this study suggests that chamfered tool (Tool A) is not recommended to be used in face milling titanium alloy, Ti-6246 when compared to sharp tool (Tool B). In order to realize the greatest potential of chamfered tools when machining titanium, optimization of the edge parameters such as rake angles and edge geometry are essential.

10.4 CONCLUSION

Conclusions drawn from face milling titanium alloy Ti-6246 with two different edge geometry of PVD-TiN coated carbide inserts are as follows:

1. In general, sharp cutting edge inserts (Tool B) produced better tool life performance at all cutting conditions when compared to chamfered/bevelled edge inserts (Tool A) when face milling titanium alloy Ti-6246. The best cutting condition with respect to highest tool life (16 minutes) was achieved with sharp edge inserts (Tool B) at cutting speed of 55 m/min and feed 0.1 mm/tooth.
2. Edge bevelling or chamfering of the cutting edge had not improve the cutting performance of the tools when face milling Ti-6246 as what have been claimed when face milling of steel.
3. A combination of non-uniform flank wear, excessive and flaking and/or chipping of the cutting edge was the dominant failure mode on both tools at most cutting conditions.

TiN coatings were not able to prevent the occurrence of plastic deformation and thermal cracks at the cutting edge due to its early delamination effect during face milling Ti-6246.

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