

## Machinability Investigation when Drilling Titanium Alloys

E. A. RAHIM<sup>1</sup>, S. SHARIF<sup>2</sup>, Z.A. AHMAD<sup>2</sup>, A.S. MOHRUNI<sup>2</sup> and I.A. SYED<sup>2</sup>

<sup>1</sup>Faculty of Mechanical and Manufacturing Engineering, University of College Technology Tun Hussein Onn, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

Tel: +607-4536000, Fax: +607-4536080, email:erween@kuittho.edu.my

<sup>2</sup>Faculty of Mechanical Engineering, University of Technology Malaysia, 81310 Skudai, Johor, Malaysia  
Tel: +607-5534850, Fax: +607-5566159, email:safian@fkm.utm.my

### Summary

Investigation on the drilling of two alpha beta titanium alloy series, Ti-6Al-4V and Ti-5Al-4V-0.6Mo-0.4Fe was conducted using uncoated WC/Co carbide drill. Tool life, tool failure mode and surface integrity were examined when drilling both alloys at various cutting speeds. Results showed that Ti-6Al-4V exhibited a more superior machinability property in the drilling tests when compared to the Ti-5Al-4V-Mo/Fe alloy system. The tool wear progression when drilling Ti-6Al-4V was significantly lower than that of Ti-5Al-4V-Mo/Fe. Non uniform wear and chipping on the drill were the main tool failure modes when drilling both alloys. Examination on the microstructure of the sub-surface of the drilled surface, indicated that both materials suffered significant plastic deformation at all cutting speeds.

Keywords: Titanium alloys, Drilling, Tool wear, Carbide drills

### 1. Introduction

Titanium alloys are now being constituted in modern aerospace structure, marine, automotive and chemical industry due to their strength-to-weight ratio that can be maintained at elevated temperatures, excellent corrosion and fracture resistance and low modulus of elasticity<sup>(1)-(3)</sup>. However, machining of titanium and its alloys can be considered very difficult due to its highly chemical reactivity and tendency to weld to the cutting tool, which resulted in edge chipping and rapid tool failure<sup>(3)</sup>. The advancement in the development of cutting tools for the past few decades showed little improvement in the machinability of titanium alloys. Most of the cutting tool developed so far, including diamond, ceramics and cubic boron nitride, is highly reactive with titanium alloys, causing rapid wear at especially at high cutting speeds<sup>(4)-(5)</sup>.

Titanium alloy, Ti-6Al-4V is known to be the workhorse for aerospace and non-aerospace applications. Unlike Ti-6Al-4V, the Ti-5Al-4V-0.6Mo-0.4Fe (Ti-5Al-4V-Mo/Fe) alloy system or so-called a low-cost titanium alloy has been developed to minimize the production cost through utilization of existing titanium alloy scrap and low cost alloying additions, and which was also designed to be suitable for low cost melting and processing methods<sup>(6)</sup>. Despite the extensive research on drilling of Ti-6Al-4V over the past 10 years<sup>(7)-(12)</sup>, reports on the drilling of Ti-5Al-4V-Mo/Fe are still limited<sup>(6)</sup>, perhaps due to the limited availability of the material commercially. Previous study by Kosaka et al.<sup>(6)</sup> indicated that Ti-5Al-4V-Mo/Fe alloy possessed superior machinability in both drilling and turning tests when compared to Ti-6Al-4V.

The aim of this work is to investigate the machinability of Ti-6Al-4V and Ti-5Al-4V-Mo/Fe titanium alloys during the drilling operation using a K-grade WC/Co carbide drill. The effect of cutting conditions on tool life, tool wear and surface integrity are also evaluated on both alloys.

### 2. Materials and Methods

The drilling trials were carried out on a 104 mm x 103 mm rectangular blocks with different thickness of 20 mm and 15.6 mm for alloys Ti-6Al-4V and Ti-5Al-4V-Mo/Fe respectively. The nominal chemical composition and the microstructure for both workpiece materials are given in Table 1 and Figure 1 respectively.

Table 1 Chemical composition (wt. %)

Alloy	Al	V	Fe	C	Mo	Si	Ti
Ti-6Al-4V	6.37	3.89	0.16	0.002	~0.01	0.01	Bal.
Ti-5Al-4V-Mo/Fe	4.9	3.7	0.34	0.01	0.53	0.03	Bal.

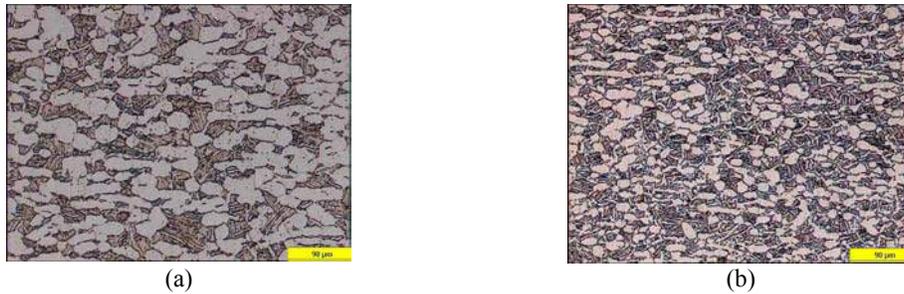


Figure 1 Microstructure of (a) Ti-6Al-4V and (b) Ti-5Al-4V-Mo/Fe

All the cutting tools used were manufactured from K30 grade, WC/Co carbide with 6 mm diameter. Details on the drill geometry is listed in Table 2. The drilling tests were conducted on a MAHO 700S CNC machining centre and the workpiece was clamped on to the machine table as shown in Figure 2. Cutting speed was varied at 25, 35 and 45 m/min while a constant feed of 0.06 mm/rev was selected during the drilling experiments. Water soluble coolant with 6 % concentration was employed throughout the drilling trials. In order to maintain rigidity and stability during the drilling operation, a tool overhang of 35 mm was employed.

Table 2 Cutting tool geometry

	Diameter (mm)	6
	Helix angle	25°
	Point angle	120°
	Web thickness (mm)	0.63

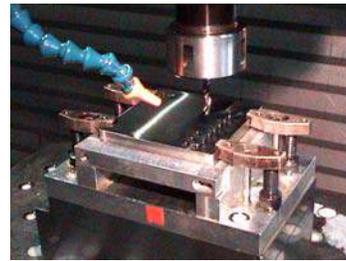


Figure 2 Experimental set-up

Tool wear measurement at 30X magnification was carried out using a Nikon tool-maker's microscope which was connected to a digital read-out. The experiment was stopped after drilling a cutting distance of 500 mm or when any of the following criteria had reached:

- i. Average non-uniform flank wear  $\geq 0.15$  mm.
- ii. Maximum flank wear  $\geq 0.2$  mm.
- iii. Chipping  $\geq 0.2$  mm.
- iv. Fracture or catastrophic failure.

Due to the difference in thickness of the two alloys, there is a discrepancy in the number of hole drilled in determining the tool life criteria. Experiment was stopped after drilling the 25<sup>th</sup> hole and 32<sup>nd</sup> hole for Ti-6Al-4V and Ti-5Al-4V-Mo/Fe respectively which is equivalent to 500 mm cutting length for both materials.

### 3. Results and Discussion

#### 3.1 Tool wear and tool life

Figure 3 shows the tool wear progression when drilling Ti-6Al-4V and Ti-5Al-4V-Mo/Fe at various cutting speeds. It was found that the flank wear of the WC-Co drill followed the usual trend whereby it increases with increase in cutting time or cutting distance. In general the flank wear rate of the drill was higher when drilling the low-cost titanium alloy as compared to that of Ti-6Al-4V. This phenomenon was observed at all cutting speeds tested. As depicted in Figure 3, the WC-Co drill experienced rapid flank wear the highest cutting speed of 45 m/min when drilling both titanium alloys. At the lowest cutting speed of 25 m/min, it exhibited a lower tool wear rate whereby the Ti-6Al-4V demonstrated the lowest rate when compared to Ti-5Al-4V-Mo/Fe alloy. In fact, at this speed, the drill experienced a very low flank wear of under 0.1 mm which is far below the limiting value.

Result on tool life (Figure 4) shows that the longest tool life was recorded when machining both Ti-6Al-4V and Ti-5Al-4V-Mo/Fe at cutting speed of 25 m/min. Experiment trials were stopped after drilling a distance of 500 mm for both titanium alloys due to the limited source of materials although the tool wear was still far below the criteria limit. Although both materials resulted in the same tool life of the drill, Ti-6Al-4V

showed a more superior machinability over Ti-5Al-4V-Mo/Fe, perhaps due to the lower wear rate of the tool as shown in Figure 3. Short tool life was recorded at higher cutting speed of 45 m/min when drilling both alloys. At higher cutting speed, high cutting temperature was generated due to the low thermal conductivity of titanium alloys, and coupled with higher stresses acting at the cutting edges tends to accelerate the tool wear<sup>(13)-(15)</sup> thus resulting in shorter tool life. In addition, drilling trial at cutting speed of 35 m/min for Ti-6Al-4V was also stopped at the same distance (500 mm). Similarly at cutting speed of 45 m/min, the Ti-6Al-4V recorded a better drill life of 35 % higher when compared to that of Ti-5Al-4V-Mo/Fe. Overall results showed that Ti-6Al-4V exhibited superior machinability property over Ti-5Al-4V-Mo/Fe alloy at all cutting conditions tested, probably due to the lower tool wear rate and excellent tool life. However this result contradicts the work reported by Kosaka et al.<sup>(6)</sup>, when they found that the low-cost titanium alloy have a better machinability property when compared to Ti-6Al-4V.

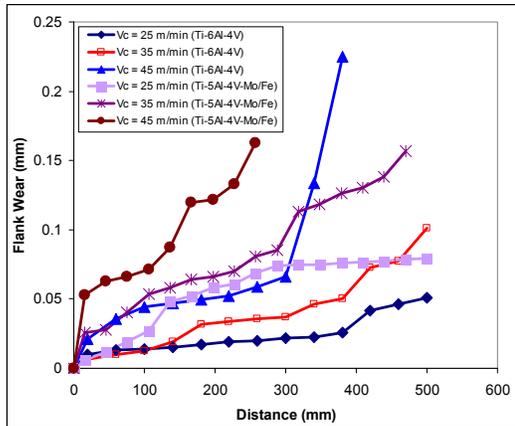


Figure 3 Tool wear progression

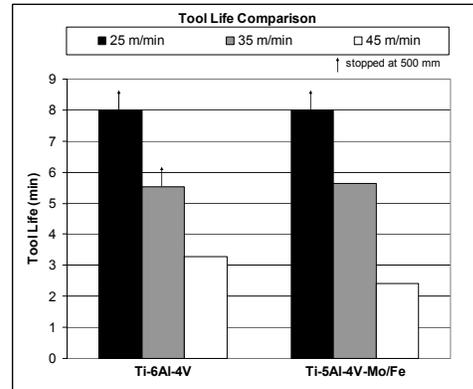
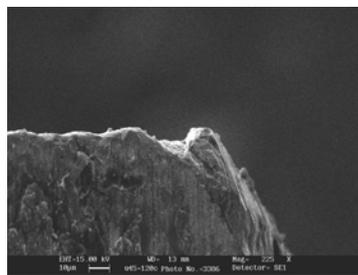
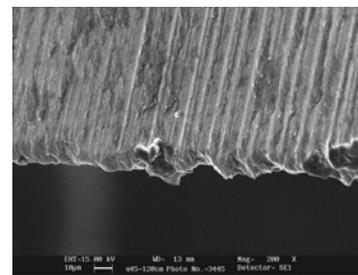


Figure 4 Tool life when drilling titanium alloys

Non-uniform flank wear and micro-chipping (Figure 5) were the dominant wear pattern in most of the drilling trials. These are probably due to the combination of various wear mechanisms such as adhesion, diffusion and plastic deformation which are common in machining titanium alloys<sup>(15)</sup>. The formation of adhered layer was observed on the chisel edge and the cutting edges which may be caused by pressure welding between the tool and the chips. With increasing cutting temperature, the adhered layer becomes weaker and can no longer withstand the high compressive stresses, eventually plucking of the tool particles occurred along with the moving chips. This attrition wear mechanism resulted in severe tool wear and chipping of the cutting edges.



(a) Ti-6Al-4V, Vc 45 m/min



(b) Ti-5Al-4V-Mo/Fe, Vc 45 m/min

Figure 5 Magnified view showing the evidence of micro-chipping on the cutting edge at the end of tool life

### 3.2 Surface Roughness

Figure 6 shows the influence of cutting speed on the drilled surface obtained when drilling Ti-6Al-4V and Ti-5Al-4V-Mo/Fe. In general the surface roughness of drilled surface for both titanium alloys improved with increase in cutting speed. One of the reasons why the surface roughness decreases with increase in cutting speed may be the disappearance or the reduction of built-up edge. It can be suggested that adherence of the workpiece material at high cutting speed are less pronounced, perhaps due to the high temperature generated. At cutting speed of 25 m/min, the surface roughness of the Ti-6Al-4V alloy was slightly higher (1.76  $\mu\text{m}$ ) than the Ti-5Al-4V-Mo/Fe alloy (1.52  $\mu\text{m}$ ). However, the difference in surface roughness values was less significant when cutting speed was increased to 35 m/min and 45 m/min as shown in Figure 6.

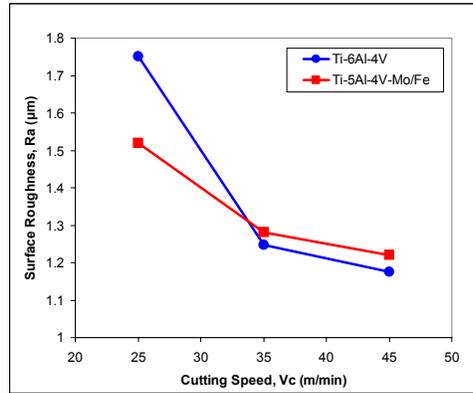


Figure 6 Surface roughness of drilled surface at various cutting speeds

### 3.3 Metallurgical alteration

The metallurgical alterations of the sub-surface of the drilled hole for Ti-6Al-4V and Ti-5Al-4V-Mo/Fe are shown in Figures 8 to 9 and Figures 10 to 11 respectively. It was observed that all the drilled sub-surface experienced plastic deformation during the drilling operation. Figure 8 shows evidence of surface damage on Ti-6Al-4V at cutting speed of 25 m/min after 7 minutes of drilling. After prolonged machining, plastic deformation of the work material becomes more severe. This phenomenon was worsened at higher cutting speed as shown in Figure 9, where the plastic deformation becomes more severe even after 3 minutes of drilling. These results could be due to the thermal, mechanical and chemical reaction at the deformation zone during high speed cutting.

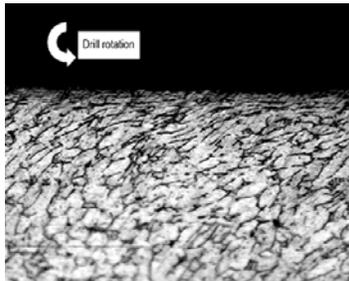


Figure 8 Microstructure of machined surface when drilling Ti-6Al-4V after 7 minutes at 25 m/min

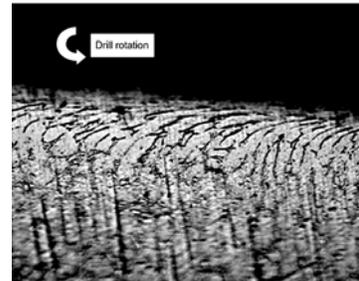


Figure 9 Microstructure of machined surface when drilling Ti-6Al-4V after 3 minutes at 45 m/min

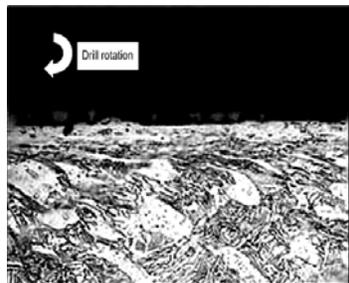


Figure 10 Microstructure of machined surface after drilling Ti-5Al-4V-Mo/Fe for 7 minutes at 25 m/min

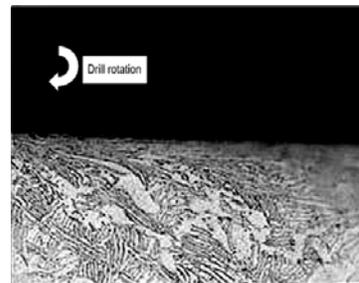


Figure 11 Microstructure of machined surface after drilling Ti-5Al-4V-Mo/Fe for 2 minutes at 45 m/min

Similar sub-surface alteration was also observed when drilling the low-cost titanium alloy at cutting speed of 25 m/min and 45 m/min as shown in Figures 10 and 11 respectively. In general the deformation follows the direction of the drill rotation. According to Che Haron<sup>(14)</sup>, the degree of deformation depends on the cutting conditions employed. Prolonged drilling with worn out cutting edges may have resulted in irregular sub-surface which includes surface tearing and severe plastic deformation.

#### 4. Conclusions

The conclusions drawn from the study when drilling Ti-6Al-4V and Ti-5Al-4V-Mo/Fe alloys with WC/Co carbide drill at various cutting speeds are as follows:

- i. Ti-6Al-4V alloy system possessed superior machinability property than Ti-5Al-4V-Mo/Fe alloy during the drilling operation due to the better tool life performance as a result of lower flank wear rate of the drill.
- ii. Non uniform wear and chipping at the cutting edges were the dominant tool failure modes when drilling both titanium alloys at various cutting speeds tested
- iii. In general the surface roughness of the drilled surface on both alloys, improved with increase in cutting speeds.
- iv. Severe plastic deformation of the drilled sub-surface was observed on both Ti-6Al-4V and Ti-5Al-4V-Mo/Fe alloys when drilling at all cutting speeds tested.

#### 5. Acknowledgement

The authors would like to express their appreciation to the Research Management Centre (RMC), UTM and the Ministry of Science, Technology and Innovation, Malaysia for their financial support for the above project through the IRPA funding 03-02-06-0086 EA001 – vote no. 74122.

#### References

- (1) Konig, W., Applied Research on the Machinability of Titanium and Its Alloys, Proc. 47<sup>th</sup> Meeting of AGARD Structural and Materials Panel, September 1978, Florence, CP256, London, (1979), pp. 1-10.
- (2) Machado, A. R., and Wallbank, J., Machining of titanium and its alloys – A Review, Proc. Instn. Mech. Engrs., Vol. 204, (1990), pp. 53-60.
- (3) Ezugwu, E. O., and Wang, Z. M., Titanium Alloys and Their Machinability – A Review, Journal of Material Processing Technology, Vol. 68, (1997), pp. 262-274.
- (4) Komanduri, R. and Von Turkovich, B. F., New Observations on the Mechanism of Chip Formation when machining Titanium Alloys, Wear 69, (1981), pp 179-188
- (5) Hartung, P. D. and Kramer, B. M., Tool Wear in Machining Titanium Alloys, Annal of CIRP 32(1), (1982), pp 65-69.
- (6) Kosaka, Y., Fanning, J.C. and Fox, S.P. Development of Low Cost High Strength Alpha/Beta Titanium Alloy with Superior Machinability, 10<sup>th</sup> World Conf. on Titanium Ti-2003, Hamburg, Germany, July 2003.
- (7) Sakurai, K., Adichi, K., Ogawa, K., and Niba, R., A Study on drilling of Ti-6Al-4V by TiN Coated Drills, Int. Conf. on Recent Advances in Science and Engineering of Light Metals, (1991), pp. 803-808.
- (8) Sakurai, K., Adichi, K., Ogawa, K., and Niba, R., Drilling of Ti6Al4V, Journal of Japan Institute of Light Metals, Vol. 42, No. 7, (1992), pp. 389-394.
- (9) Mantle, A. L., Aspinwall, D. K., and Wollenhofer, O., Twist Drill of Gamma Titanium Aluminide Intermetallics, Proc. of the 12<sup>th</sup> Conf. of the Irish Manuf. Committee, (1995), pp. 229-236.
- (10) Arai, M. and Ogawa, M., Effects of High Pressure Supply of Coolant in Drilling of Titanium Alloy, Journal of Japan Institute of Light Metals, , Vol. 47, No. 3, (1997), pp. 139-144.
- (11) Fujise, K., and Ohtani, T., Machinability of Ti-6Al-4V Alloy in drilling with Small Drills, Proc. of the Fourth Int. Conf. on Progress of Cutting and Grinding. October 5-9. Urmqi and Torpan, China, (1998), pp. 49-54.
- (12) Sharif, S. and Rahim, E. A., Performace Evaluation of Coated and Uncoated Carbide Tools when Drilling of Titanium Alloy, Proceedings of the 3<sup>rd</sup> Int. Conf. on Advanced Manufacturing Technology (ICAMT 2004), May 11-13, Malaysia, (2004), pp 203-208
- (13) Zlatin, N. and Field, M. Procedures and precautions in Machining Titanium Alloys, 2nd Int. Conf. on Titanium, Cambridge, Massachusetts, 1972, pp. 489-504.
- (14) Che Haron, C. H., Tool Life and Surface Integrity in Turning Titanium Alloy, Journal of Materials Processing Technology, Vol. 118, (2001), pp. 231-237.
- (15) Jawaid, A. Sharif S. and Koksai S., Evaluation of wear mechanism of coated carbide tools when face milling titanium alloy, Journal of Materials Processing Technology, 99, (2000), pp. 266-274.