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Performance of coated- and uncoated-carbide tools when drilling titanium alloy—Ti–6Al4V

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Abstract

In this paper, the performance of uncoated-WC/Co and TiAlN–PVD coated-carbide twist drills were investigated when drilling titanium alloy, Ti–6Al4V. The effect of cutting speed on tool wear, tool life and surface finish of the hole when drilling using coolant were reported. Results showed that non-uniform flank wear, chipping and catastrophic failure were the dominant modes of tool failure for both coated- and uncoated-drills. It was found that at all cutting speeds tested, TiAlN-coated-drill significantly outperformed uncoated-drill in terms of tool life and surface finish. The highest tool life recorded for TiAlN-coated-drill was 7.8 min after drilling the 25th hole at the lowest cutting speed of 25 m/min and feed of 0.06 mm/rev. The effect of cutting speed on the performance of the uncoated-carbide drill was less significant at all cutting speed tested when all the drills failed prematurely with recorded tool lives of less than 1 min.

Keywords: Titanium alloy; Drilling; Carbide tool; Tool life; Surface finish

1. Introduction

Lightweight materials such as titanium alloys are now used in modern aerospace structure due to their best combination of metallurgical and physical properties. Each class of titanium alloy has their advantages and disadvantages. Titanium's advantages are high strength-to-weight ratio, low density, excellent corrosion resistance, excellent erosion resistance and low modulus of elasticity [1–3]. However, titanium and its alloy have poor machinability, this may be due to their high chemical reactivity with most cutting tools and therefore, have a tendency to weld to the cutting tool during machining, thus leading to chipping and premature tool failure. Its low thermal conductivity increases the temperature at the tool/workpiece interface, which affects the tool life. Its ability to maintain its strength at elevated temperature and its low modulus of elasticity further impairs its machinability [3].

Drilling process accounts for 40–60% of the total material removal processes and it is an essential technique in aerospace industries [4]. Holes come in many forms, where through hole is completely through the workpiece while blind hole is drilled only to a certain depth.

Nowadays, most of the carbide cutting tools are coated whether with CVD or PVD hard coatings. PVD–TiAlN-coated-carbide tools are used frequently in metal cutting process due to their high hardness, wear resistance and chemical stability, they offer benefits in terms of tool life and machining performance [5–8].

Most of the studies in machining of titanium and its alloys have been focused on turning and milling operations.

Most of these studies have concluded that straight carbide (uncoated-WC/Co) tool remains the best tool when turning [9,10] or milling [11,12] titanium alloys when compared to coated-carbide tools. However, the above result might not be applicable for drilling due to the complex nature of the operation.

Research on drilling of titanium and its alloy are limited and not widely reported. Sakurai et al. [13] have investigated the tool life, burr shape and chips formation under different cutting strategies. Fujise and Ohtani [14] conducted a machinability study of Ti–6Al4V using small drills of Co–HSS. Mantle et al. [15] have studied the effects of machining parameters in relation to tool life, hole quality, cutting force and workpiece surface integrity.

Dornfeld et al. [16] investigated the effects of tool geometry and process parameters on drilling burr formation of Ti–6Al4V using carbide drills with and without coolant and high speed

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Table 1
Chemical composition of Ti–6Al4V (wt.%)

Al	6.37
V	3.89
Fe	0.16
C	0.002
Mo	<0.01
Mn	<0.01
Si	<0.01
Ti	Bal.

Table 2
Mechanical properties of Ti–6Al4V

Tensile strength (MPa)	960–1270
Yield strength (MPa)	820
Elongation 5D (%)	≥8
Reduction in area (%)	≥25
Density (g/cm^3)	4.42
Modulus of elasticity (GPa)	100–130
Hardness (Hv)	330–370

cobalt drills without coolant. Syed et al. [17] recorded the hole quality with different types of drill bit (two helical flutes, straight flute and three flutes). Reports on the performance of new coated-tools when drilling titanium alloys are still lacking.

This work was carried out with the aim to evaluate the performance of both uncoated- and coated-carbide twist drills when drilling Ti–6Al4V at various cutting speeds. The effect of varying cutting speeds on tool wear, tool life and surface finish of the hole produced were investigated.

2. Experimental details

An annealed alpha–beta titanium alloy, Ti–6Al4V was selected as a workpiece material since it is the most commonly used grade in the aerospace industries. The chemical composition and mechanical properties of the material are shown in Tables 1 and 2, respectively. The workpiece was a rectangular plate of 102 mm × 104 mm with 20 mm thickness. The workpiece was premachined using a face milling cutter before mounting onto a Kistler piezoelectric dynamometer for forces measurement. The whole setup was then clamped to the machine bed as shown in Fig. 1. The cutting force data gathered in the drilling trials are not reported in this paper.

Drilling tests were carried out on a CNC machining center (MAHO700S) with varying cutting speeds of 25, 35, 45 and 55 m/min. The feed rate was kept constant at 0.06 mm/rev. Drilling trials were confined to through holes under

Fig. 1. Workpiece setup on the top of dynamometer.

Table 3
Mechanical properties of Ti–6Al4V

	Uncoated-carbide (WC/Co)	Coated-carbide (TiAlN–PVD)
Drill type	2 flute-twist drill	2 flute-twist drill
Drill diameter (mm)	6	6
Flute length (mm)	25	25
Overall length (mm)	70	70
Point angle (°)	120	120
Helix angle (°)	25	25
Grain size (μm)	0.5 (ultrafine)	0.5 (ultrafine)
Coating thickness (μm)	–	3
Hardness (kg/mm^2)	3700	3700
Tool run-out (μm)	2	2

the action of a 6% concentration of water-soluble coolant at a flow rate of 19.4 l/min.

Tool wear was measured at 10× magnification using a Nikon toolmaker microscope equipped with a digital readout device. A Zeiss HandyS (Model: E35A) with a cut off length of 0.8 mm was used to measure the surface roughness of the drilled.

The surface roughness (R_a) values of the 25th hole or the last hole that determined the tool life (tool failed) for each trial were recorded and compared.

The drills used in the experiments were uncoated-carbide and TiAlN–PVD-coated-carbide drills of 6 mm diameter. Both drills are from the K30/40 grade with similar substrate of WC/Co. The specification of both drills are given in Table 3.

Due to the limited and expensive workpiece material drilling experiment was stopped upon drilling the 25th holes or when any of the following criteria had reached:

(a) average non-uniform flank wear (VB2) ≥ 0.15 mm;
(b) maximum flank wear ≥ 0.2 mm;
(c) chipping ≥ 0.2 mm;
(d) fracture or catastrophic failure.

3. Results and discussion

3.1. Tool wear and tool failure modes

The development of flank wear curves obtained for both TiAlN-coated- and uncoated-carbide drills operated at various cutting speeds are given in Figs. 2 and 3, respectively. It was observed that during drilling with TiAlN-coated-drill, flank wear was observed to increase gradually when lower cutting speeds

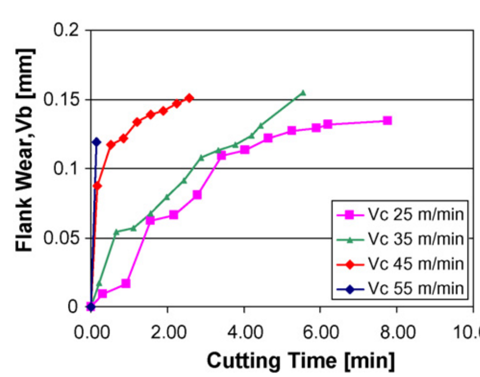

Fig. 2. Flank wear curves when drilling Ti–6Al4V using TiAlN-coated-drill at various cutting speeds.

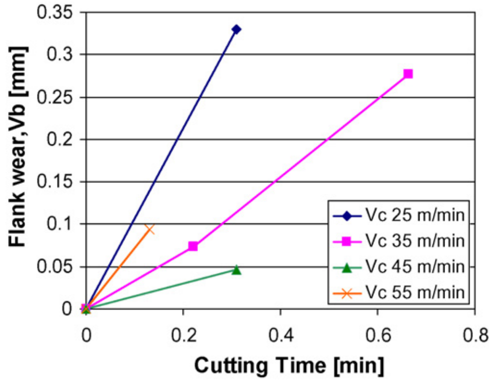

Fig. 3. Flank wear curves when drilling Ti–6Al4V using uncoated-drill at various cutting speeds.

of 25 and 35 m/min were employed. However, at higher cutting speeds of 45 and 55 m/min, the tool worn quite rapidly, resulting in a shorter tool life.

In contrast to the uncoated-carbide drill (Fig. 3), the drill worn very rapidly at all cutting speeds tested. Both drills experienced similar modes of failure throughout the trials. These were non-uniform flank wear, chipping and catastrophic failure. Figs. 4 and 5 show images of the above failure modes at various cutting speeds for TiAlN-coated- and uncoated-carbide drills, respectively. Chipping of the cutting edges was common at most cutting speeds, perhaps due to the immediate loss of sharp cutting edge especially with uncoated-drill. Attrition wear was observed to be the prominent wear mechanism operating at all cutting speeds on both tools. At the same time, the ability of Ti–6Al4V to retain its strength at elevated temperature during drilling also contribute to the resulting wear pattern of the drill.

Another contributing factor to the brittle failure of the cutting edge, could be due to the low modulus of elasticity of titanium alloys which can cause vibration and chatter during drilling. As observed from Figs. 4 and 5, chipping was the dominant mode of failure for both coated- and uncoated-drills at most cutting speeds.

However, close observation of the worn out drills in both figures showed that under the same cutting speed, TiAlN-coated-drills suffered less damage when compared to uncoated-drills. This suggests that the hard coating material protects the tool and manages to substantially reduce the wear rate of the substrate.

3.2. Tool life

Results on tool life when drilling Ti–6Al4V using coated-TiAlN and uncoated-carbide drills are given in Fig. 6. Uncoated-carbide tool recorded very short tool lives, all less than 1 min as when drilling Ti–6Al4V at all cutting speeds. The maximum tool life for uncoated-tool was 0.664 min at cutting speed of 35 m/min. Lowering the cutting speed to 25 m/min did not improved the tool life, in fact the tool life was reduced further to 0.31 min. This is due to the premature tool failures on uncoated-drills which include chipping and tool breakage as shown in Fig. 5.

Results showed an outstanding performance of the coated-drill when compared to uncoated-drill. The longest tool life of 7.8 min was recorded for coated-drill when drilling at the lowest cutting speed of 25 m/min. Although drilling was performed up to the 25th hole, the resulted flank wear (VB2 = 0.135 mm) was still below the limiting value. At similar cutting speed, uncoated-drill failed catastrophically as shown in Fig. 5a with a recorded tool life of 0.31 min. This indicates that an increased of 2416% was achieved by TiAlN-coated-tool as compared to the uncoated-tool when drilling Ti–6Al4V at the same cutting

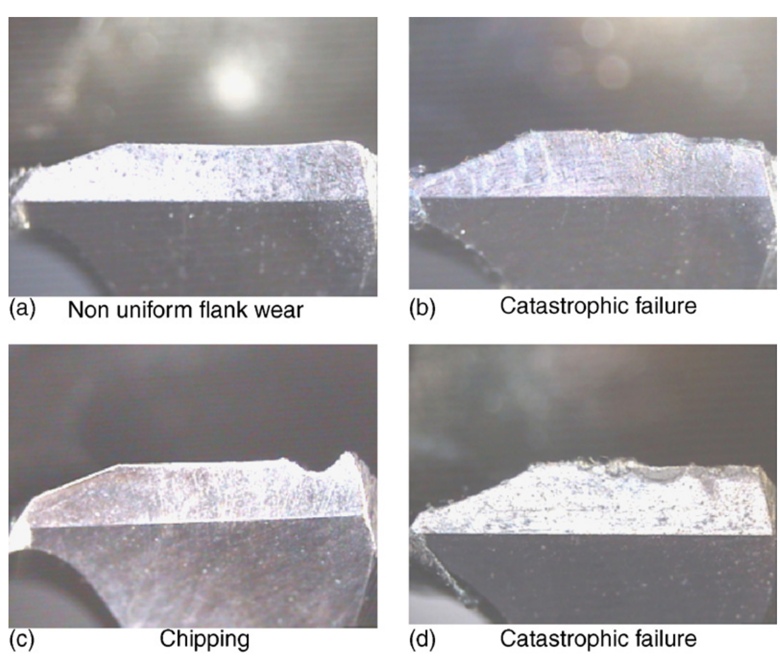

Fig. 4. Wear on TiAlN-coated-drill when drilling Ti–6Al4V at feed rate of 0.06 mm/rev and cutting speed of: (a) 25 m/min, (b) 35 m/min, (c) 45 m/min and (d) 55 m/min, respectively.

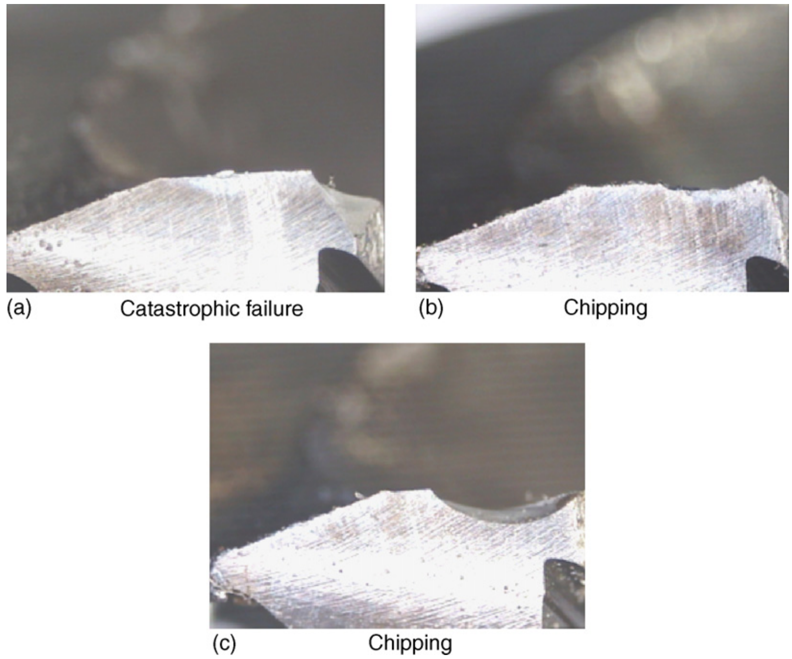

Fig. 5. Wear on uncoated-carbide drill when drilling of Ti–6Al4V at feed rate of 0.06 mm/rev and cutting speed of: (a) 25 m/min, (b) 35 m/min and (c) 45 m/min, respectively.

speed of 25 m/min. This result contradicts the findings of previous researchers when turning [9,10] and milling [11,12] of titanium alloys. These researches found that uncoated-carbide (WC/Co) tools outperformed coated-carbide tools as when machining at low cutting speed as far as turning and milling are concerned.

This phenomenon might be due to the formation of a micro-thin oxide layer Al_2O_3 as a result of the reaction between the TiAlN and the oxygen in the surrounding air. As this layer is created, it provides thermal insulation for the cutting tool. In addition, Al_2O_3 can also acts as a solid lubrication thus reducing the friction between workpiece/tool interface hence prolonged the tool life [8].

Results also showed that cutting speed had a proportional and linear effect on the tool life of TiAlN-coated-drill. Reducing the cutting speed tends to increase the tool life of the coated-drill. However, at the highest cutting speed of 55 m/min, the tool life dropped significantly to 0.131 min, which is the same for uncoated-drill. Therefore, it can be suggested that uncoated-drill should not be used for drilling of Ti–6Al4V.

3.3. Surface roughness

Fig. 7 shows the surface roughness values (R_a) of the final hole when the tool criteria were met for each test. It is evident that TiAlN-coated-drill produced better surface finish at most cutting speeds when compared to uncoated-carbide drill. The R_a values obtained for coated-tool lied between 0.7 and 1.0 μm, while for the uncoated-carbide drill the range was between 0.7 and 1.3 μm. The wear pattern of the coated-tool may have an influence on the surface roughness since the damage on the cutting edge was less when compared to uncoated-tools. Results also showed that cutting speed affects the surface finish of the hole. Both tools produced lower R_a values at higher cutting speeds. The R_a value was slightly increased when cutting speed was reduced to 25 m/min for both tools. This could be the effect of chatter or vibration which usually occurred at

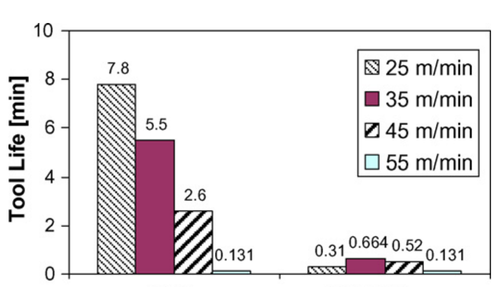

Fig. 6. Tool life performance comparison between uncoated- and coated-carbide drills at feed rate of 0.06 mm/rev.

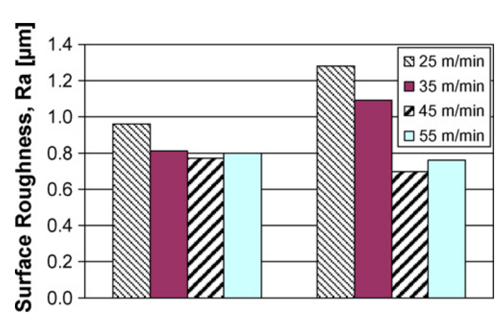

Fig. 7. Surface roughness (R_a) of the last hole drilled using coated- and uncoated-drills at various cutting speeds.

this cutting condition especially when titanium machining is concerned.

4. Conclusion

The main conclusions that could be drawn from this investigation are as follows:

(1) The dominant failure modes for both TiAlN-coated- and uncoated-carbide tools when drilling Ti–6Al4V are non-uniform flank wear, chipping and catastrophic failure;
(2) Highest tool life was obtained with TiAlN-coated-drills when drilling at cutting speed of 25 m/min;
(3) TiAlN-coated-carbide drill outperformed uncoated-drill at all cutting speeds both in terms of tool life and surface roughness of drilled surface when drilling Ti–6Al4V;
(4) Uncoated-carbide drill is not suitable to be used for drilling Ti–6Al4V at cutting speed of 25 m/min and above due the rapid wear of the cutting edge.

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