The effect of Titanium Alloy Composition and Tool Coating on Drilling Machinability

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Abstract

Excessive tool wear and poor machinability is observed in the machining of high strength, near- β titanium alloys when compared to $\alpha + \beta$ titanium alloys such as Ti-64. Tooling suppliers want to better understand drilling machinability in terms of (1) why alloy composition influences tool wear behaviour, (2) how this impacts part integrity and (3) the effectiveness of tool coating. This paper presents a novel approach to investigating the mechanisms by which tool wear and microstructural deformation occur in a range of titanium alloys, through the manipulation of the force experienced by the tool and work piece. The investigation compares and contrasts the drilling machinability of three important aerospace titanium alloys. Force feedback, tool wear and microstructural damage results highlight key differences when drilling different titanium alloys. Such findings will contribute to tool design, providing a better understanding of wear and machinability in near- β titanium alloy drilling.

Introduction

Titanium alloy utilisation for improved strength and reduced density within modern aircraft is vital within the aerospace industry. Ti-6Al-4V is used extensively and is responsible for the majority of tool and process optimization within titanium machining. [1,2] Aerospace companies have recognised that continued improvement will require investment into the use of other titanium alloys for more advanced components such as the use of Ti-5Al-5V-5Mo-3Cr (Ti-5553) in the Boeing 787 landing gear. Such near- β alloys are understood to be less machinable than $\alpha + \beta$ alloys but little progress has been made toward tool optimisation despite the varied material properties. [3,4] If the tool wear and subsurface damage mechanisms in titanium alloy machining are better understood, huge cost savings are possible through tooling and processes optimisation.

Titanium Drilling

Drilling is a complex machining process and is crucial in the production of aerospace components accounting for up to 60% of total material removal. Multiple types of holes are used within industry. Holes which go through the workpiece are referred to as 'through holes' while holes that only penetrate to a certain distance are known as 'blind holes'. Titanium alloys are often drilled using TiAlN-PVD coated carbide tools which are considered to have the best tool life and machining performance due to their high hardness, wear resistance and chemical stability. [7,8] Drilling titanium is not widely addressed and for such complex process, findings could be pivotal in improving titanium alloy machinability for all types of machining. [9]

TiAlN-PVD Coating for titanium machining

TiAlN physical vapour deposition (PVD) coatings are generally used to improve resistance to tool wear oxidation and thermal damage when machining. [10] Results on the effectiveness of TiAlN are inconsistent. In turning and milling Ti-64 TiAlN coatings have been outperformed by uncoated WC/Co inserts [11,12] but in drilling such coatings have been found to be superior in reducing tool wear and improving tool life in Ti-64. [8]

Titanium Machinability

Machinability is an ambiguous term but is often investigated through tool wear and part integrity analysis in relation to tool life, material removal rate, cutting forces, surface quality and chip quality. [2] Titanium alloys are considered to have poor machinability as low cutting speeds are required to reduce tool wear and maintain high quality. This is due to high strength, low thermal conductivity and high chemical reactivity with cutting tool materials. [13]

Molybdenum equivalency (Mo_{eq}) is a value which takes into account the effect of β stabilizing elements such as Mo, V, and Fe on the resulting microstructure. [2] It has been found that increasing the Mo_{eq} and hence the β phase content within titanium alloys improves fatigue and tensile properties. [14,15] For this reason aerospace companies have invested in alloys such as Ti-6246 and Ti-5553 for advanced components. Unfortunately, the increase in strength these alloys provides makes them harder to machine than conventional alloys, such as Ti-64. [16]

Machinability comparisons of Ti-64, Ti-6246, and Ti-5553 would provide an understanding of the relationship between increasing β phase content and alloy machinability.

Titanium Drillability

Surface integrity in terms of residual stress, surface roughness, and microstructure plays an integral role in fatigue performance. [17] Work piece adherence to the cutting edge is called built-up edge (BUE), this can cause chipping and subsequently premature tool failure. [18] In the drilling of titanium alloys, wear mechanisms have been found to vary significantly. They are dependent on cutting parameters, tooling material, and titanium substrate composition. In milling and turning, BUE and abrasive wear is more prevalent in the machining of Ti-5553 compared to Ti-64, where the former tends to wear via adhesion. [3] Common failure modes in the machining of titanium alloys are nonuniform flank wear, notching, crater wear, chipping and catastrophic failure. [4,19,20]

Method

Experimental Setup

The three alloys, their nominal compositions, (Mo_{eq}) and classifications are stated in Table 1.

Table 1: Alloy Names, Classifications, (Mo_{eq}) and Nominal Compositions.

Alloy	Class	(Mo_{eq})	Nominal Comp. wt%
Ti-64	$\alpha + \beta$	-3.32	6Al 4V <0.4Fe
Ti-6246	$\alpha + \beta$	0.00	6Al 2Sn 4Zr 6Mo
Ti-5553	Near β	11.35	5Al 5Mo 5V 5Cr

In the experiment, 36 R846 6.9 mm diameter solid carbide TiAlN-PVD coated and 36 uncoated tools were used. These tools were provided by Sandvik Coromant (see Figure 1a). Tools were clamped using the hydraulic chuck shown in Figure 1b. The machine used was The Deckel Maho DMU60 monoBlock (Figure 1c). This machine was selected as it is representative of industry standards. Tools were clamped using a hydraulic chuck to limit tool run out. A 7% concentration of Hocut 795 coolant was supplied through the tool at 20 bars of pressure.

The hydraulic chuck and tool in Figure 1b were used with a Kistler spindle-mounted dynamometer. Kistler’s software package, Dynowear (Version 3.1.0) was then used to record the force in Z for each hole. A Clemex camera and Olympus SZX10 microscope were used to image the flank, corner and chisel wear on the tools. Images were taken before any holes were drilled, after the bedding in hole and at the end of each 10 hole set. A Walter Helicheck Pro Plus was used to measure tool geometry and check if tools were within industrial specification. Images of subsurface microstructural damage were taken using a Nikon cross polarised light microscope and a Zeiss scanning electron microscope (SEM).

Figure 1: (a) Corrodrill R846 with TiAlN-PVD Coating. (b) Hydraulic Corrochuck 930 and Kistler mount. (c) Deckel Maho DMU60 monoBlock.

Experimental Procedure

For each alloy two 25 mm plates were cut from cylindrical billets. In one plate, 110 through holes were drilled with coated tools and in the other 110 holes were drilled using uncoated tools. For every tool used, one bedding in hole was drilled at industry standard cutting parameters (Table 2). Cutting speed, V_s was kept the same for each tool and was varied from 32 to 48 m/min between tool 1 and 10. Drill feed penetration rates, V_f were varied between 208 mm/min and 283.4 mm/min for each tool. Figure 2 shows this graphically. The experimental setup provides a framework from which holes at similar forces and torques can be selected for microstructural analysis.

In addition to this, one blind hole was also drilled into each plate with the intention of investigating the damage propagation in the Z-axis of the drill. All blind holes were drilled with industry cutting parameters.

Table 2: Industry cutting parameters.

Alloy	V_s (m/min)	V_f (mm/min)
Ti-64	39.2	250
Ti-6246	41.6	272
Ti-5553	41.1	268

Figure 2: Diagram showing how penetration rate (mm/min) and cutting speed (m/min) were varied to create a variable matrix.

Experimental Analysis

Hole Sectioning

Holes that were selected for microstructural analysis, were sectioned from the titanium plates using wire electrical discharge machining (EDM). Once sectioned the holes were cut along the dimensions shown in Figure 3. The cross and perpendicular sections were then mounted in bakelite and ground using 400, 800 and 1200 silicon carbide grinding disks. Surfaces were then polished using a 0.05 μm SILCO colloidal silica suspension.

. **Figure 3:** Diagram of wire EDM sectioning of a through hole region.

Force and Torque Measurement

The force data from each set of 10 holes was exported from Dynowear to a Python based program provided by Sandvik. The program accurately compensates for thermal drift within the dynamometer. This is done by normalising the force measured at the start of each hole cycle. Figure 4 provides a graphical representation of this. The program was then used to measure average force over a one second period within the steady state cutting region. For every hole this average was taken at a depth of 5mm into the hole. Figure 5 shows typically where this data average is calculated for each hole.

Figure 4: Graphical representation of the drift compensation algorithm for (a) force and (b) torque data frm a hole drilled in Ti-64.

. **Figure 5:** Graphical representation of the place where force and torque measurements were recorded for a hole drilled in Ti-64.

Results and Discussion

Forces in Z axis of the drill

Figure 6 shows the Z forces for all drilled holes plotted against feed per revolution, which is a combination of cutting speed and cutting feed. The lowest and highest feed per revolutions are the least and most extreme cutting conditions tested in terms of material removal rates, respectively. Forces increase as the drilling conditions become more extreme. For each alloy the coated tools experienced the highest Z forces and the highest overall forces were recorded for Ti-5553. The lowest forces were recorded for Ti-64. The black horizontal line in Figure 6 indicates which holes have been sectioned for microstructural analysis at similar forces.

Figure 6: Force in drilled direction(Z axis) plotted against feed per revolution.

Tool Wear Analysis

Figures 7,8a and 8b show the flank face, rake face and margin of tools respectively. The images are of the tools after the first 11 holes for each of the six alloy plates. The coated tools can be seen on the left side of each figure and uncoated tools are on the right. The presence of BUE on the tool flanks is apparent in all cases and obscures the level of flank wear on each tool. Notch wear is visible for the coated Ti-64 tool and chipping was observed on both coated and uncoated tools used on Ti-5553. The dark regions on the flank face are associated with the heat at the cutting interface. In all cases, this wear scare is larger on uncoated tools indicating the tool may be at higher temperatures during the cut. Alternatively, the coating may be masking the scar. On the rake faces of the coated tools used in Ti- 64 and Ti-6246, wear appears to be adhesive in nature. For coated tools in Ti-5553 and all uncoated tools, wear looks to be a combination of adhesion and abrasion. The wear differentiation here has been recorded in milling and turning. [3] On the uncoated tools the wear is highly abrasive. In both coated and uncoated cases, the wear increases in severity from Ti-64 to Ti-6246 to Ti-5553 which corresponds to an increase in alloy (Mo_{eq}) and tensile strength. Some chipping is visible on the rake corner for tools used to machine Ti-5553. In turning such chipping has been observed and attributed to chip flow. [20] The final condition of the margins and outer corners of the tools are similar for coated and uncoated tools. In the case of Ti-64 and Ti-6246 there is minimal material adhesion on the edge. In sharp contrast, the tools used to machine Ti-5553 have large amounts of adhered material. This suggests that poor chip evacuation is causing chip flow damage on the rake corner in the form of chipping.

Figure 7: Images of tool wear on the flank face after the first 11 hole set in each alloy.

Figure 8: Images of tool wear on (a) the rake face and (b) the corner and margin after the first 11 holes in each alloy.

Microstructural analysis

Figure 9a compares light micrographs of the hole wall perpendicular to the Z axis of the drill. They show microstructural damage caused to material due the rotation of the drill at feed forces of 1600 N. Figure 9b shows backscattered SEM magnification of the polarised images. In Ti-64 there is extensive twinning at the hole wall. There is very little damage visible in the Ti-6246 and Ti-5553 micrographs. However, some plastic deformation is apparent in the backscattered electron images. Ti-6246 has a larger plastically deformed layer and both microstructures appear swept in the cutting direction.

Figure 9: (a) Polarised light micrographs for holes made using uncoated tools in Ti-64, Ti-6246 and Ti-5553. (b) Backscatter SEM images of hole wall made using uncoated tools in Ti-64, Ti-6246 and Ti-5553.

Conclusions

- Forces in the drilling direction increase with alloy strength and (Mo_{eq}).
- Higher forces and alloy strength correspond to an increase in tool wear and a decrease in damage depth within the machined surface.
- Tools that are coated in TiAlN display different wear characteristics to uncoated tools.
- Chipping on the outer corner of tools used in Ti-5553 appears to be caused by chip flow over the margin.

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