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Case Study

On the mechanism of tool crater wear during titanium alloy machining

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ABSTRACT

Tool crater wear is a major cause of accelerated tool failure during the machining of titanium alloy components. This paper presents a static diffusion couple method which replicates the complex reaction mechanisms occurring at the tool-chip interface during machining and is validated with dynamic turning trials. The diffusion couple tests are realised via the use of a bespoke vacuum compression rig. The rig consists of two graphite rods which secure the sample under a clamping load at the required temperature and pressure. Titanium alloys bearing a high molybdenum content are found to be less susceptible to TiC formation at the tool-workpiece interface. A TiC layer during machining coats and protects the tool from excessive crater wear therefore increasing tool life. Strong agreement was found between the diffusion couple technique and turning trial. This low cost test strategy will be used to design machinable titanium alloys and more compatible tools.

1. Introduction

With a shift in the aerospace industry towards the production of carbon fibre composite wing, empennage and fuselage aircraft structures, there has been a corresponding increase in the volume of titanium required for high strength forgings and fasteners. This is due to titanium's galvanic corrosion compatibility with carbon, compared to steel or aluminium. In the aero-engine compressor and fan sections there is an increasing move to design titanium alloys with lower densities, enhanced fatigue and ductilities for parts in the next generation of greener, more efficient engines.

Almost all titanium components are intensively machined and this is one of the costliest stages of the multi-stage manufacturing route. Therefore, titanium producers are striving to incorporate good machinability and manufacturability properties as part of their alloy design and product competitiveness.

For the current titanium alloy component machining, tool manufacturers do not offer different tooling solutions to customers based on the alloy chemistry or phase morphology of the billet material. However, it is common knowledge in the machining community that metastable β alloys are more challenging to machine than near α alloys with respect to both tool wear and workpiece surface integrity [1]. Machinists tend to adjust machining speeds depending on the titanium alloy chemistry. An alloy which is more difficult to machine is cut at a lower speed to avoid premature tool failure. Aside from adjusting machining parameters, there are few options available to optimise machining processes due to the reliance on uncoated WC-6%Co tool materials.

Tool wear is summarised as a combined effect of abrasion, plastic deformation, adhesion and chemical reaction between the workpiece and tool [2]. The latter resulting in diffusion bonding which leads to crater wear, severely limiting tool life and the economics of machining [3]. Hartung and Kramer [4] found that when machining titanium alloys at cutting speeds of 61–122 m min^{-1} the main limiting factor for tool life is crater wear. Flank wear does not play a role in tool life reduction until crater wear causes edge damage. Past this point, plastic deformation causes accelerated wear at the flank face of the tool. Numerous investigations have used costly and time consuming machining trials in order to try and understand diffusion wear mechanisms [5–9]. Recently, work has been carried out using static diffusion couples in order to study the chemical interdiffusivity between carbide cutting tools and titanium alloys [10–12]. These diffusion couple techniques aim to replicate the intimate contact between the tool and workpiece observed during machining. However, despite some success in identifying elemental diffusion and formation of interfacial reaction species, such work has yet to give these preliminary results any real application by way of directly relating them to tool wear or machining performance. Zhang et al. [10] investigated diffusion wear during high-speed machining of Ti-6Al-4V with uncoated WC-Co tools. The study presented a simplified model to analyse the diffusion of tool constituents towards the workpiece. The authors were able to

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suggest that the final concentrations of tungsten and carbon were much higher than that of cobalt at the same cross-section of the workpiece after the same time. The diffusion theory was then verified firstly by a diffusion couple experiment, and then by a high-speed milling trial. There is minimal information concerning the diffusion couple experiment other than showing basic X-EDS analysis of tool constituents at two different depths in the workpiece. The diffusion couples and machining trial were used to verify the mathematical model. The paper does not present the diffusion couple tests as a method of directly replicating tool crater wear observed in machining trials. Bhat et al. [11] used static diffusion couple tests to predict the crater wear rate of $AlMgB_{14}$ as a tool material. However, this material was far too brittle to be used to perform successful machining trials. Therefore, the findings from the diffusion couple tests could not be verified with machining trials. Jianxin et al. [12] investigated diffusion wear between Ti-64 and WC-Co tools, firstly with static diffusion couples and then with dry cutting. Various phases and reaction species were detected via XRD and EPMA. Vickers hardness values were also used as a method of detecting elemental diffusion. Poor agreement was observed between the diffusion couple tests and machining trial. Workpiece elements were not found on the rake face of the tool after machining. The work also fails to look at the microstructure of the titanium alloy. Any indication of change in the phase morphology at the subsurface of the titanium alloy could provide strong evidence of elemental diffusion.

In this paper we use a vacuum diffusion couple technique in tandem with outer diameter (OD) turning trials to determine the key mechanism for tool crater wear during the machining of titanium alloys. The rationale for using static diffusion couple testing is due to the nature of the sticking/seizure region observed at the tool-chip interface during machining. Fig. 1a illustrates the location of this region with respect to the sliding region.

The seized region exists where the frictional stress is constant and the sliding region exists where the coefficient of friction is constant [13]. These two regions exist simultaneously on the tool insert rake face during OD turning. The contact temperature and work material flow rate at the seized surface control the level of diffusion [14]. This is the first time that a diffusion couple technique has been directly validated by turning trials in order to successfully replicate tool crater wear in titanium alloy machining. Furthermore, it is hypothesised that formation of $Ti_2Co+\beta$ acts as a driving force for further diffusion, phase changes and reaction species formation.

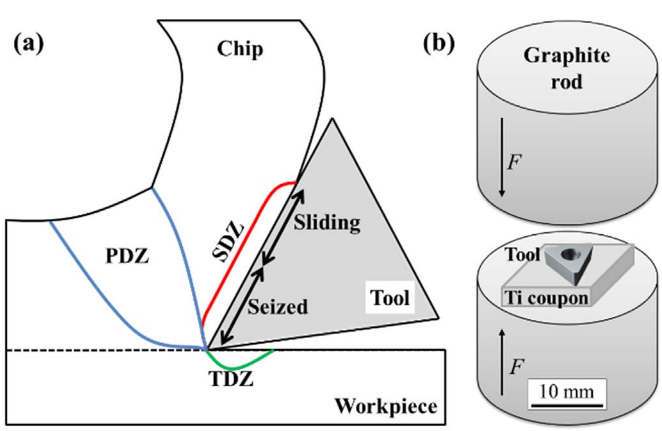

Fig. 1. (a) 2D schematic of orthogonal cutting showing the locations of the primary deformation zone (PDZ); secondary deformation zone (SDZ) and tertiary deformation zone (TDZ); (b) experimental setup of diffusion couple.

2. Experimental procedure

Two TIMET $\alpha+\beta$ titanium alloys in the as-forged condition were selected: Ti-54M (nominal composition in wt% is 5 Al, 4 V, 0.8 Mo, 0.5 Fe, bal. Ti) and Ti-6246 (6 Al, 2 Sn, 4 Zr, 6 Mo, bal. Ti), the latter being more β-rich. The β stability can be quantified by the molybdenum equivalent (Mo_{eq}) which takes into account the effects of various β-stabilising elements such as Mo, V and Fe [15]. Alloys with a higher Mo_{eq} value and a higher concentration of β phase at room temperature are generally regarded as more difficult to machine [16]. Machinability lacks a solid definition but tends to be assessed by a combination of the following criteria: tool life, material rate of removal, cutting forces, surface finish and chip shape [3].

The diffusion couple method (Fig. 1b) consists of two titanium alloy coupons (one of each alloy) sandwiching a Sandvik Coromant grade H13A tool. The coupons of Ti-54M and Ti-6246 are first polished to a mirror finish using conventional methods and ultrasonically cleaned in isopropanol. The H13A tool consists of a WC substrate with 6 wt% cobalt binder phase. The sample is secured via two graphite rods inside a vacuum furnace (10^{-5} mbar) and clamped with a constant load of 150 N at 1000 °C for 2 h before a furnace cool to room temperature. After heat treatment, all samples were carefully sectioned before standard metallographic preparation. It is recognised that in machining trials, pressures can obtain large values of 1–3 GPa. However, the clamping load of 150 N is used to promote strong contact between the tool and workpiece and intensify chemical reactivity. This is sufficient force to encourage diffusion to take place, and also sufficient force to eradicate any uncertainty that there is not sufficient contact between the tool and workpiece. The high pressures observed in machining trials can make atomic movement difficult, however investigations have shown how diffusion wear is the dominant tool wear mechanism in titanium alloy machining [21,22].

The same as-forged billets of Ti-6246 and Ti-54M were used for the OD turning trials. The tool inserts were the same type as used in the diffusion couple study and were mounted in a CoroTurn RC DCLNL 2020 holder which provided an effective rake and flank angle of 6°. Turning trials were carried out by the authors on a MAG Cincinnati Hawk 250 lathe. An exaggerated cutting speed of 120 m min^{-1} was used in order to increase the reaction kinetics and intensify chemical reactivity at the tool-workpiece interface. A 1 mm depth of cut was employed with a feed rate of 0.1 mm rev^{-1}. Each billet was machined for 180 s with the coolant Houghton Hocut 795B controlled at a concentration of 5%. Microstructural analysis was carried out using a Zeiss EVO LS25 scanning electron microscope with an accelerating voltage of 20 keV and a spot size of 3. Energy dispersive X-ray spectroscopy (Oxford Instruments) was used for quantitative elemental analysis. Light microscopy was done using a Nikon Eclipse LV150 with cross-polarised filters. Tool crater wear degradation was imaged using an Alicona InfiniteFocus instrument.

3. Results and discussion

3.1. Static diffusion couple

Fig. 2a and b show the microstructure of the diffusion couple interface between the WC-6%Co tool and the Ti-54M and Ti-6246 coupons respectively.

Ti-54M formed a strong diffusion bond with the WC-6%Co tool, yet Ti-6246 did not bond with the tool. The Ti-54M diffusion couple shows a complex interface with distinct diffusion zones and is discussed below together with X-EDS data in Fig. 3. The black line in Fig. 2a corresponds to the X-EDS line scan plot shown