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Predicting chemical wear in machining titanium alloys via a novel low cost diffusion couple method

Oliver Hatt,[a]* Henrik Larsson,[b] Finn Giuliani,[c] Pete Crawforth,[d] Bradley Wynne[a] and Martin Jackson[a]

[a]*Department of Materials Science and Engineering, The University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK*
[b]*Division of Physical Metallurgy, Department of Materials Science and Engineering, The Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden*
[c]*Department of Materials, Imperial College London, London, SW7 2AZ, UK*
[d]*Advanced Manufacturing Research Centre with Boeing, Advanced Manufacturing Park, Catcliffe, Rotherham, S60 5TZ, UK*

* Corresponding author. Tel.: +44-780-268-5679; fax: +44-114-222-5943. *E-mail address:* o.hatt@sheffield.ac.uk

Abstract

Chemical wear during high speed machining of titanium alloys is a serious problem which affects the surface integrity of both the tool and workpiece. A low cost, novel diffusion couple method is presented which allows for thorough analysis of the tool-workpiece interface at the high temperatures reached during conventional machining operations. X-EDS analysis reveals that no less than seven distinct diffusion zones arise between Ti-6Al-4V and a WC-Co tool which are home to different phases and reaction species. Loss of cobalt binder coupled with a deficit of carbon results in a brittle η-phase leading to catastrophic fracturing of the tool. DICTRA is employed to thermodynamically model the diffusion mechanisms and verify the X-EDS results.

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1. Introduction

During machining of titanium alloys, the intimate contact between the workpiece and tool at temperatures above 800°C provide a high thermodynamic driving force for diffusion of tool material atoms across the tool-workpiece interface [1]. This theory is also valid for diffusion of workpiece atoms into the tool.

In titanium alloy machining; Ezugwu and Wang [2] summarised tool wear as a combined effect of abrasion, plastic deformation, adhesion, and chemical reaction between the workpiece and cutting tool. It has been observed that mechanical wear dominates at low cutting speeds while chemical reactivity between the tool and workpiece plays a more critical role at higher speeds. At higher cutting speeds, the relative contribution of chemical wear to the total wear increases exponentially, since the solubility and diffusivity follow an Arrhenius type of relationship with temperature [3].

Despite new coating technologies currently being developed to aid titanium machining [4], customers are still using the same 1930s technology [5] of uncoated straight-grade carbide tools for longer tool life and enhanced workpiece surface integrity. This same tool is used for all titanium alloys irrespective of phase morphology or chemistry. This is despite the fact that different classes of titanium alloys exhibit markedly different machining characteristics [6]. Many researchers recognise the important role of chemical wear during high speed machining operations [7-9] but fail to investigate these reaction mechanisms prior to costly machining trials. More recently, some researchers have attempted to replicate the machining environment with a variety of different diffusion couple methods [10,11].

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However, there is currently no recognized standard diffusion couple test which is reliable, informative and indicative of an industrial machining trial. This paper presents a novel diffusion bonding method which, when coupled with thermodynamic modelling can provide a strong indication of the complex reaction mechanisms at the tool-workpiece interface. This work will help the machining community to understand tool wear mechanisms at new levels of detail. Furthermore it could play a role in enhancing tool grade development for increased efficiency in titanium machining.

2. Experimental procedure

2.1. Materials

For this study, six titanium alloys were used ranging from near-alpha to metastable-beta classes:

- Commerically Pure Ti (CP-Ti)
- Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si-0.06C (Ti-834)
- Ti-6Al-4V (Ti-64)
- Ti-5Al-4V-0.8Mo-0.5Fe (Ti-54M)
- Ti-6Al-2Sn-4Zr-6Mo (Ti-6246)
- Ti-5Al-5Mo-5V-3Cr-0.6Fe (Ti-5553)

All were supplied in the as-forged billet condition from TIMET UK except Ti-5553 which was supplied by Messier-Bugatti-Dowty.

Tools were supplied by AB Sandvik Coromant of the grade H13A which is an uncoated tool containing 6 wt.% Co as the binder phase. This is the grade which is recommended to industry for machining of titanium alloys

2.2. Test rig

Fig. 1 shows the sample loaded on the thermomechanical test rig at Imperial College London. The rig consists of a furnace containing two graphite rods which compress the sample at a desired force and temperature under a vacuum of ~10^{-5} torr.

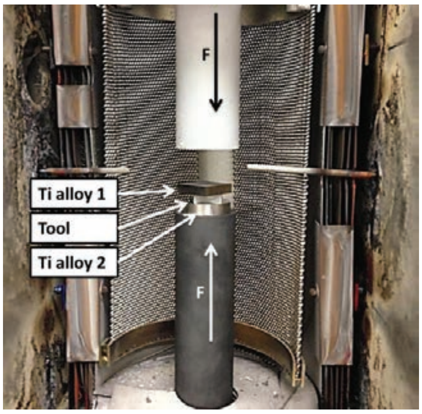

Figure 1. The thermomechanical compression unit at Imperial College London.

To reflect the high temperatures reached at the cutting zone during high speed machining, the furnace was set to 1000°C and the samples held for 2 h under a light clamping load of 150 N to help initiate an intimate bond.

2.3. Sample preparation and analysis

Each titanium sample was sectioned into a coupon measuring 20x20x5 mm and then subsequently ground and polished to a mirror finish. All samples and tools were then ultrasonically cleaned prior to furnace treatment. The samples were set up in a ‘sandwich’ fashion consisting of a tool with a titanium alloy on either side. This allowed for two alloys to be tested simultaneously. After heat treatment, the samples were carefully sectioned in half and cold mounted to help preserve the bond. They were once again ground and polished using standard methods. Microstructure analysis was carried out using SEM (Carl Zeiss EVO LS25) and X-EDS (Oxford Instruments).

2.4. DICTRA thermodynamic modelling

To verify and predict elemental diffusion and reaction species at the diffusion interface between the tool and workpiece, DICTRA was employed to simulate the diffusion couple between Ti-6Al-4V and the WC-Co tool. DICTRA is an add-on module to Thermo-Calc developed by Thermo-Calc Software AB, Sweden.

The thermodynamic database TCFE8 and mobility database MOBFE3 were ran using the homogenisation model. The simulation was programmed at 1000°C to match the experimental setup. However, in order to achieve sensible simulation times, the theoretical heat treatment time was set to 600 s and the grid size 200 µm.

3. Results and discussion

Fig. 2 shows micrographs of the interface of the six diffusion couples.

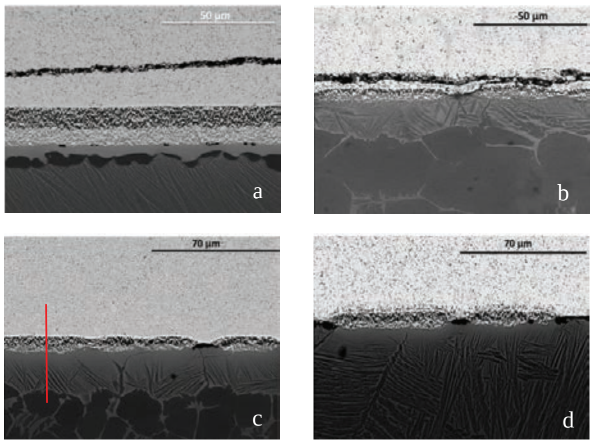

Figure 2.Backscatter SEM micrographs of the diffusion couple interfaces between the WC-Co tool and (a) CP-Ti; (b) Ti-834; (c) Ti-64 and (d) Ti-54M.