Wear 376-377 (2017) 115–124

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Experimental and theoretical study of the microscopic crater wear mechanism in titanium machining

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ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form
21 December 2016
Accepted 1 January 2017

Keywords:
Ti6Al4V
Turning
Crater wear
Tungsten
X-ray Diffraction
Diffusion simulations

ABSTRACT

Continuous turning of Ti6Al4V with uncoated WC-Co cutting tool inserts mainly results in crater wear on the rake face of the tool. The crater is located close to the cutting edge and increases in size with increased time in cut. The flank wear remains minor until the point when the crater reaches a critical size so that the edge deforms plastically and edge breakage occurs. To understand the crater wear degradation mechanisms, this study focuses on examining the worn tool at different stages, using both experimental and theoretical techniques, as well as under static and dynamic conditions.

A layer of adhered work-piece material is observed in the crater. The present study shows both experimental and theoretical evidence of carbon depletion of the WC in the crater and formation of W (bcc) at the interface during wet continuous longitudinal turning of Ti6Al4V. This has been demonstrated for the first time. In addition, indications of a carbon rich compound, possibly MC, where M=Ti, V and W, are also observed. These observations are verified by simulation of the diffusion process. Furthermore, diffusion simulations indicate that a liquid may form at the tool/chip interface in the crater zone during machining.

Turning is a dynamic process, however, to study the chemical driving forces in this system under static conditions, a means of verification of which phases will form is needed. Therefore, a diffusion couple consisting of the same materials is prepared and analyzed. Similar results are obtained for the diffusion couple as for the worn tool, indicating that the chemical wear is an important degradation parameter. The diffusion couple results are also compared to a numerical simulation of the diffusion process.

1. Introduction

Titanium alloys are used in a variety of different industries and applications, e.g., the aerospace industry, mainly due to the combination of high specific strength to weight ratio and good corrosion resistance. During titanium machining, high temperatures can occur at the tool chip interface due to the low thermal conductivity of titanium [1].

Machining Titanium alloys using different cutting speeds and feeds could result in different wear mechanisms dominating the wear on the cutting tool. As the speed or feed is increased the tool life is decreased, hence the wear rate increases [1–4]. Crater wear is regarded as the main wear type when machining titanium alloys, with uncoated WC-Co cutting tools, at moderate cutting speeds [1–3]. The crater wear is suggested to emerge due to high temperatures occurring at the tool/chip interface. Furthermore, the crater wear increases as a function of cutting speed, along with the temperature [4]. Kitagawa et al. [5] measured the temperature in the cutting zone and showed that the temperature increases both with increasing feed rate and cutting speed. This, in combination with the high chemical reactivity of titanium with most cutting tool materials [1] means that chemical wear limits the insert tool life [6,7].

Adhesion, diffusion and abrasive wear have been suggested by many authors to be the main degradation mechanisms [3]. However, the details behind the mechanisms are not yet fully understood. Hartung and Kramer [4] and Dearnley and Grearson [3] tried to explain the mechanisms more thoroughly by taking different aspects of the wear contribution into consideration. One attempt to explain the wear during titanium machining, by performing diffusion couple studies and diffusion simulations, was made by Hatt et al. [6], which indicated formation of TiC. They presented a method of producing diffusion couples and did some investigations of the diffusion between titanium alloys and WC-Co. The diffusion observed in diffusion couples was compared to computational diffusion simulations. However, they focused on simulated composition profiles and did not elaborate on the

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http://dx.doi.org/10.1016/j.wear.2017.01.104
0043-1648/

resulting phase formed according to the simulation. Clear pronounced diffusion bands could be observed with SEM/EDS. No link to machining tests was presented.

On the rake face, inside the crater, adhered or welded work-piece material has been reported [2,5]. The bonding between the adhered work-piece material and the WC-Co cutting tool is very strong as shown by quick-stop tests performed by Dearnley and Grearson [3]. Hartung and Kramer [4] suggested that this adhered layer limits the wear rate by changing the diffusion rate of the cutting tool constituents through the layer, thus limiting the diffusion wear. By using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS) and Auger Electron Spectroscopy, they showed that W, Ti and bound C and O could be found in the crater area of the worn and etched tools. These authors suggested that a chemical reaction takes place between the Ti-alloy work-piece and the cutting tool material forming an adherent layer of TiC at the rake face. TiC grains were suggested to be continuously removed from the cutting tool surface during machining and replenishing of TiC will probably occur by obtaining C from the WC grains in the cutting tool. Diffusion of chemical species from the tool to the work-piece material, through the tool chip interface, leads to wear on the rake face, which may increase the possibility of mechanical damage of the cutting edge [2]. Ezugwu and Wang [1] suggested that dissolution diffusion wear dominates on the rake and flank face for uncoated cemented carbides used for the turning of titanium alloys.

Diffusion of Ti into the WC-Co has been reported, where diffusion couples have been analyzed [2,6]. The diffusion occurring between Ti6Al4V and WC-Co up to 800 °C was studied by Jianxin et al. [2]. By analyzing diffusion couples prepared at different temperatures with SEM, X-ray diffraction (XRD) and Electron microprobe analysis (EPMA) they could verify that W and Co diffuses into the Ti6Al4V work-piece material and that Ti diffuses into the WC-Co tool material already at a temperature of 400 °C. The penetrating depth in the diffusion couple increased with increased temperature. The result was compared with dry cutting experiments using uncoated WC-Co cutting tool. The rake face of the tool was severely worn after machining at 60 m/min and Ti, Al and V were detected inside the crater. This was concluded as evidence for diffusion wear, however, they did not tell if adhered material was visible in the crater or if it was removed before analyzing.

The novelty of this study is the application of a combined approach, studying the actual cutting operation, static diffusion interaction and diffusion simulations, all of this combined with high resolution SEM and compositional imaging as well as microfocus XRD.

2. Method

2.1. Machining

Longitudinal turning of Ti6Al4V was performed in a RNC600 lathe at a cutting speed of 70 m/min, feed rate 0.2 mm/rev and 2 mm depth of cut using cutting fluid (9% water-oil emulsion). The cutting tool holder used was a C5-DCLNL-35060-12 equipped with a CNMG120408-SM insert in grade H13A (Sandvik Coromant). H13A is a commercially available uncoated WC-Co cutting tool containing 6% Co, often used for titanium machining. The work-piece material used was a 170 × 700 mm bar of Ti6Al4V (OREMET) with chemical composition according to Table 1.

The inserts were machined for one minute intervals until end of tool life. The worn inserts were investigated by light optical microscopy (LOM) and SEM at different stages before cross-section polishing was made. An Alicona Infinite focus equipment was used to measure the size and depth of the crater.

Table 1
Chemical composition of the work-piece material Ti6Al4V according to the material specification provided by material supplier OREMET.

Element	Mass-%	Element	Mass-%
Aluminum	6.17	Vanadium	4.03
Iron	0.21	Oxygen	0.18
Carbon	0.03	Nitrogen	0.011
Hydrogen	0.003	Yttrium	< 0.001
Others Each	< 0.10	Others total	< 0.40
Titanium	BAL[a]		

[a] BAL = Balance to obtain 100%.

According to Hartung and Kramer [4], the temperature in the cutting zone, at 61 m/min, for uncoated tools, corresponds to 780 °C. Our cutting speed is higher (70 m/min), resulting in 940 °C and furthermore, our feed is higher, 0.2 mm/rev compared to 0.15, which further increases the temperature and pressure. Thus, we determine that the temperature in our operation is very close to 1000 °C. Kitagawa et al. [5] also measured the temperature during continuous turning as a function of feed and cutting speed. Their data lead us to the conclusion that the temperature, at our conditions (continuous turning, 70 m/min, 0.2 mm/rev), also gives a temperature very close to 1000 °C.

2.2. Diffusion couples

Diffusion couples were prepared by mounting together a polished sample of the work-piece material Ti6Al4V with an H13A insert in a special clamp to increase the contact between the materials. The surface of the insert was ground flat on the rake side and polished step-wise with 9 μm and 1 μm diamond paste. Due to difficulties of establishing an adequate chemical bond between the materials the temperature was selected to enhance reaction and diffusion. Thus the sample was heat treated in stationary argon atmosphere at 1410 °C for 60 min, a significantly higher temperature and longer time than can be expected during the cutting process. After the heat treatment, cross-sections were prepared. For images at high magnification, the sample was also polished on a soft cloth, using a slurry containing very fine SiO_2 particles, (Buehler MasterMet).

2.3. Cross-section preparation

The worn cutting tool insert and the diffusion couple sample were cut, embedded in conductive resin and the cross sections were then polished. The resulting material removal was estimated to 1 mm, initiated from the flank side as presented in Fig. 1.

2.4. X-Ray diffraction

XRD measurements of worn inserts, before and after etching to remove the adhered work-piece material, were performed on a Bruker Discover D8 diffractometer with Davinci design, equipped with a IμS Microfocus Source (CuK_α radiation, $\lambda = 1.5418$ Å, 50 kV, 1.0 mA), an Eulerian cradle and a Våntec-500 2D area detector. A laser-video positioning system was used for alignment of the sample. Diffraction data was collected in the $31° < 2\theta < 51°$ angular range for the insert with adhered work-piece material. For the etched sample an angular range $25° < 2\theta < 100°$ was covered. The XRD patterns were analyzed with the DIFFRAC EVA (Bruker) and High Score Plus (PANalytical) software.

2.5. Diffusion simulations

Simulations of the inter-diffusion process, occurring both in the worn tool and the diffusion couple, were performed on the basis of