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Analyses of Wear Mechanisms Occurring During Machining of the Titanium Alloy Ti-6Al-2Sn-4Zr-6Mo

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***Abstract*—**Titanium alloys like the modern alloy Ti 6Al 2Sn 4Zr 6Mo (Ti-6246) combineexcellentspecific mechanical properties and corrosion resistance. On the other hand,due to their material characteristics,machining of these alloys is difficult to perform. The aim of the current study is the analyses of wear mechanisms of coated cemented carbide tools applied in orthogonal cutting experiments of Ti-6246 alloy. Round bars were machined with standard coated tools in dry conditions on a CNC latheusing a wide range of cutting speeds and cutting depths. Tool wear mechanisms were afterwards investigated by means of stereo microscopy, optical microscopy, confocal microscopy and scanning electron microscopy. Wear mechanisms included fracture of the tool tip (total failure) and abrasion. Specific wear features like crater wear, micro cracks and built-up edgeformation appeared depending of the mechanical and thermal conditions generated in the workpiece surface by the cutting action.

***Keywords*—**Alloy 6246, machining, tool wear, optical microscopy, SEM, EDX analysis

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I. Introduction

THE alloy Ti-6246 (Ti 6Al 2Sn 4Zr 6Mo) is a high-strength, high beta-stabilized, (α+β)-alloy whose primary commercial application is rotating turbine engine components in general and especially in the aerospace industry. [1] The application temperatureis limited to 450°C as otherwise creep phenomena and surface oxidation occur. [2]Ti-6246has an excellent corrosion resistance which can be laid back to the TiO_2 layer on the materials surface.

Thermal and mechanical loadsproduced in the process zone by metal cutting actionare very important factors in machining. Both affect the quality of the components on the one hand and tool life on the other hand. The high temperature during metal cutting (locally up to 1000°C) and the high loads contribute to tool wear. For this reason it is very important to investigate the wear mechanisms to be able to optimize the cutting process in a second step. [3]

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II. Experimental

A. Tools materials and machining conditions

In our experimental study, bars of Ti-6246 alloy have been machined on a computer numerically controlled (CNC) lathe. Orthogonal cutting experiments have been carried out for four different depths (a_p) at eight cutting speeds (v_c). All machining operations were performed under dry conditions.

The cutting variable values were:

- a_p[mm]: 0.05,0.1, 0.15, 0.2
- v_c [m/min]: 20, 40, 60, 80, 120, 160, 200, 300

Standard cutting tools of SECO Company have been used. The cutting tools type TK 2000 (CNMA 120408) consist of a tungsten carbide (WC) body and several coating layers, namelyTi(C, N), Al_2O_3 andTiN [5].Thecoating layers were deposited by CVD (chemical vapor deposition).

For each cut a new edge of cutting tool was usedmeaning thatin total 27 cutting inserts were analyzed.

The worn toolshave been investigated from different directions, namely the flank face direction and the rake face direction.

B. Methods and instruments

The investigationof the wear mechanisms was carried out by the optical microscope Olympus GX 71, the stereomicroscope SSM-3E and a scanning electron microscope(Jeol JSM 7000F). The chemical composition was analyzed by means of an energy dispersive spectroscopy (EDS) detector of Oxford Instruments. [5] The data sets and images have been treated by the DinoCaptur, ImageJ software.

The roughness was measured by means of a confocal microscopes Plu neox, SENSOFAR.

III. Results and Discussion

Typical forms of tool wear were observed on all samples, namelynotch wear on the flank face was observed. In addition,abrasion was measured by an increasing flank wear land width (VB). On the rake face, crater wear,micro cracks and built-up edges (adhesion of Ti-6246 on top of the coating) have been found. Regarding tool life,VB is an important factoras large values would lead to the introduction of additional heat into the finished workpiece. This could lead to Oxygen diffusion into the workpiece and, hence, to α-casing. [1] The results of the flank wear land width analyses for each worn toolare summarized in Fig 1.

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This graph shows that with increasing $v_c$the flank wear land widthincreases. For a_p = 0.05mm, 0.1mmand 0.15mm VBis independent of the cutting depth whereasa sharp increase of VB is visible in case a_p = 0.2mm. It has to be stated that chip ignition occurred at 300 m/min and 0.15mm causing significant damage of the tool represented by steep rise of the flank wear land width.

In a second step,weinvestigated the crater wear and built-up edge formation.The crater wear on the rake face increased with the increasing a_p and the largest crater wear was found after machining atv_c 40m/min and 80m/min. Fig.2 shows a detailed image of the rake face of the worn tool (a_p = 0.15mm, v_c = 40m/min) showing severe crater wear.

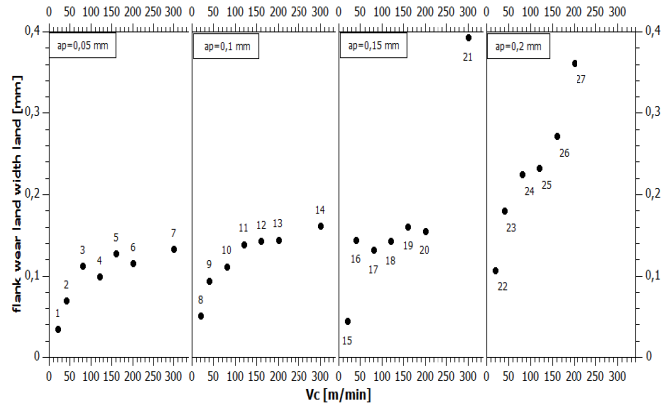


Fig. 1 Specific flank wear land width

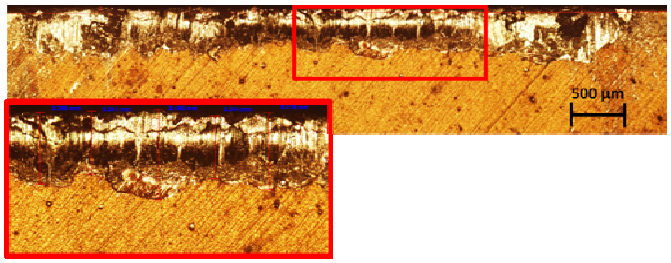


Fig. 2Details of the rake face of the worn tool (a_p = 0.15mm, v_c = 40m/min)

The build-up edges (material adhesion to the cutting insert) were found on all tools after the cutting experiments. Fig. 3showsa photo of the flank face of a worn tool with a built-up edge created on the rake face. Details of build-up edge are shown on fig.4a. Severe built-up edge formation was observed on tools machined in the following conditions: a_p: 0.05mm and 0.1 mm at v_c between 80m/min and 200m/min and at a_p 0.15mm and 0.2mm in the complete cutting speed regime investigated here.

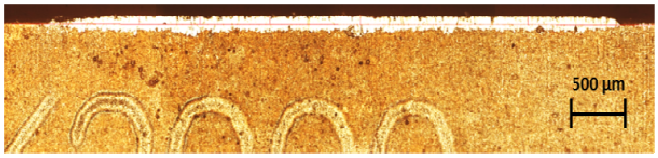


Fig. 3 Image of the flank face of a worn tool (a_p = 0.05mm, v_c = 80m/min)

In addition, micro crack formation has been observed on two tools, seeFig. 4b. The related cutting conditions were: a_p = 0.2mm, v_c = 160 m/min and a_p = 0.2mm, v_c = 200m/min.

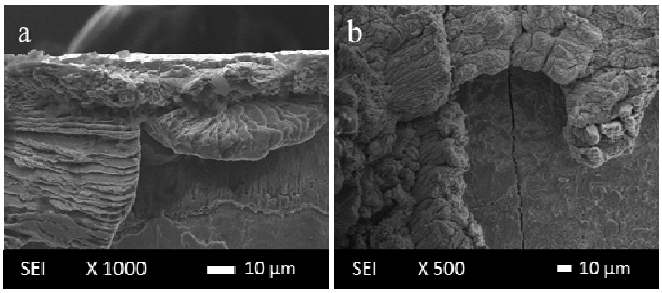


Fig. 4 SEM images of different wear mechanisms. a built-up edge formation, b micro crack formation

The build-up edges and the regions showing crater wear were further investigated by SEM EDX chemical analysis.

The EDX point analysis of a built–up edge (a_p = 0.05mm,v_c = 20m/min) is shownon Figs. 5 and 6. The related chemical composition is listed in Table 1. As can be seen from Table 1, the EDX data confirmed that the unworn area (point 4) included titanium (approx. 42 at.%), nitrogen (approx. 46 at.%) and aluminum (approx. 11 at.%), the worn area included elements from the workpiece material. Points 1 and 3 representthe zones of built-up edges formation which consisted of Aluminum, Molybdenum and Zirconium and twice more Titanium compared to the unworn areas.

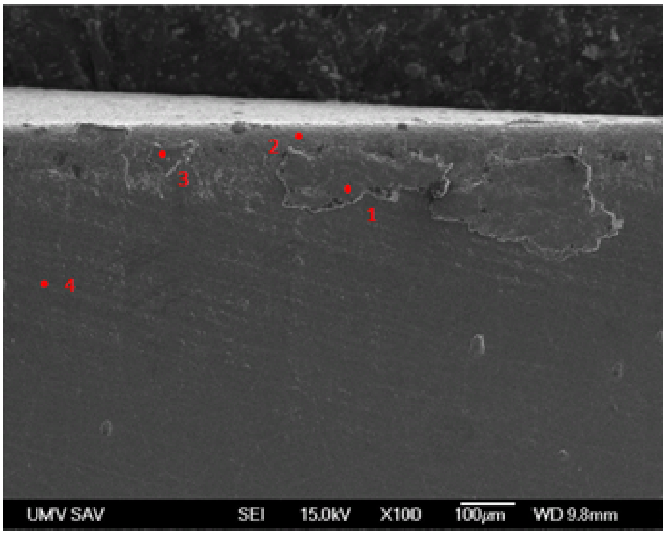


Fig. 5 The EDX point analysis of the worn tool

TABLE I
THE EDXDATA FROM THE POINT ANALYSIS OF THE WORN TOOL

v_c= 20m/min, a_p=0.05mm	Point 1 (at.%)	Point 2 (at.%)	Point 3 (at.%)	Point 4 (at.%)
C	-	22.52	-	-
O	-	37.43	-	-
N	-	-	-	42.42
Ti	85.18	29.48	83.93	46.39

Al	11.22	10.57	9.19	11.19
Zr	-	-	3.14	-
Mo	3.60	-	3.74	-

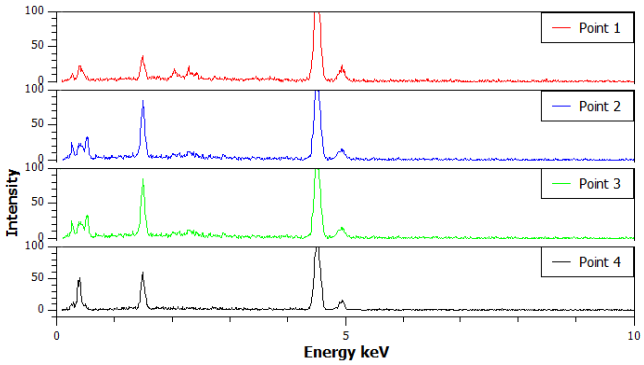


Fig. 6 EDX spectra of the points marked in Figure 6

Zones of crater wear (rake face of the worn tool, cutting conditions: $a_p = 0.1$mm, $v_c = 80$m/min) werealso investigated by EDX. The related EDX line analyses are presented in Figs. 7 and 8. The analysis showed that all elements are almost homogeneously distributed along the worn surface of the tool. Zirconium, Molybdenum, Tin, Titanium and Aluminum represented the Ti-6246 workpiece material. The presence of tungsten and nitrogen indicates a destruction of coating.

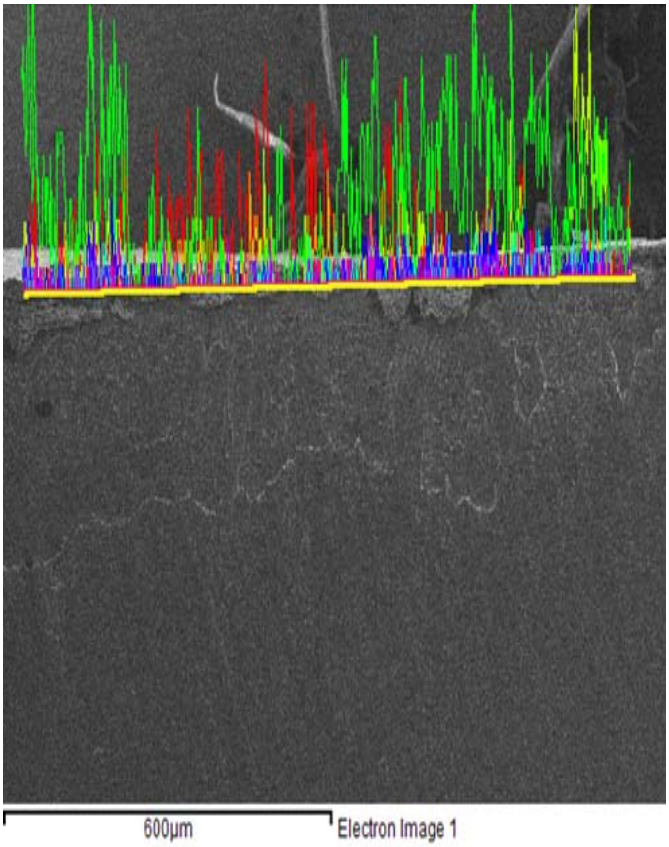


Fig. 7 The EDX linear analysis area

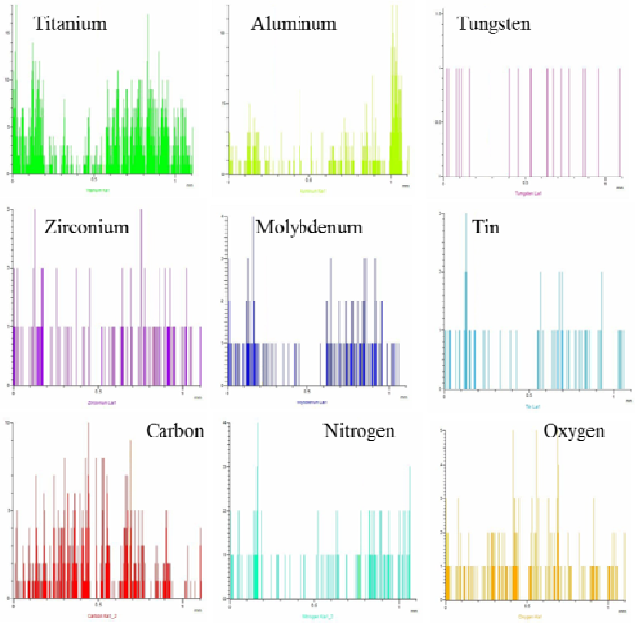


Fig. 8 The EDX line analysis of the worn tool

A chemical elements map of worn part of tool ($a_p = 0.05$mm,$v_c = 20$m/min) is shown on Figs. 9 and 10. The distribution of the elements tungsten and aluminum again signalizes adestruction of tool coating and a built-up edge formation. Other elements as Molybdenum, Zirconium and Tin were originating from workpiece material.

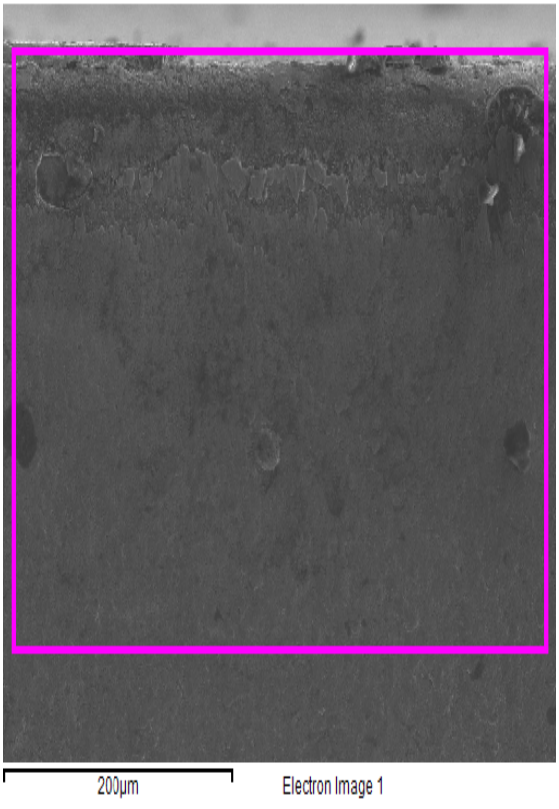


Fig. 9 The EDX mapping area

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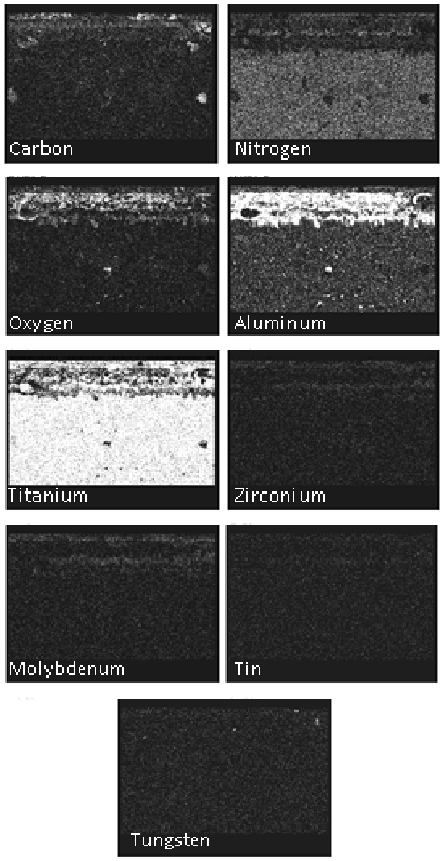


Fig. 10A chemical elements map

The roughness was measured by a confocal microscope at a distance of20µm fromthe edge of tool. As it is very difficult to analyze surfaces with high portion of sharp edges (larger than 70°), theresultspresented here are only to be taken as rough approximations. Fig. 11 shows the results of the roughness measurements. It is clearly visible that the surface roughness increases with increasing cutting speed for all cutting depths.

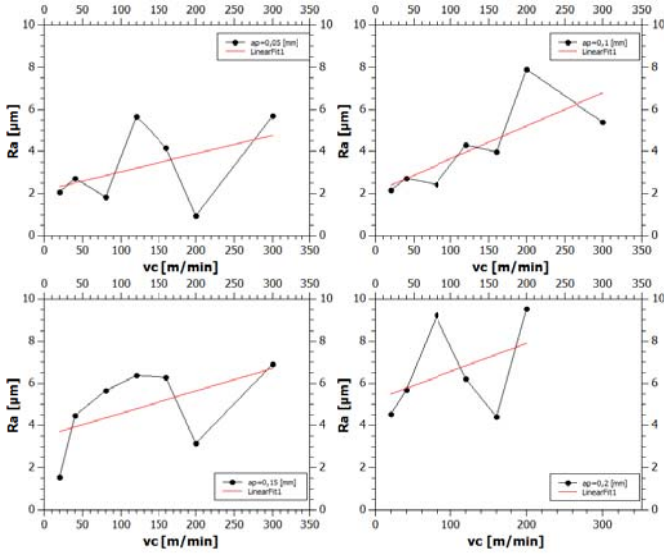


Fig. 11 Indicators of roughness

IV. Conclusion

In this paper, the wear mechanisms of cutting tools used during dry machining of the Titanium alloy Ti-6246 have been investigated. The following conclusions can be drawn based on the results:

Flank wear land widthincreased with increasing cutting depths and cutting speeds. This can be understood by the larger amount of energy introduced by the cutting action leading to higher temperatures in the cutting zone and, hence, to thermal weakening of the tool (as most of the heat produced will be dissipated into the tool due to Titanium's low heat conductivity). In addition, crater wear and build up edge were observed on the tools after all cutting experiments performed. Increasing temperatures in the cutting zone (as a result of the energy dissipation) ease chemical reactions between Ti-6246 and the tool leading to smearing and welding. These effects could be minimized by the use of cooling liquids during the cutting process. The roughness on rake face was increased with increasing cutting depths and with increasing cutting speeds. Due to the relatively low Young's modulus of Ti-6246 in combination with the high strength, large amounts of elastic energy are storedin the surface of the workpiece leading to vibrations and chatter. This results in lower surface quality and increased surface roughness.

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