Tool/Workpiece Chemical Transfer on Standard WC-Co Tool Inserts in Turning on Ti-6Al-4V

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ABSTRACT

This paper investigates the chemical wear behavior of commercially available uncoated cemented carbide cutting inserts when used to turn a common titanium alloy. Chemical interdiffusivity of WC-6%Co cutting tools with Ti-6%Al-4%V workpiece material was investigated under both dynamic (actual machining) and static (diffusion couple) conditions. Near-surface elemental composition mapping of the wear land of the used tools was carried out by means of energy dispersal X-ray spectroscopy (EDX) analysis. The cross-sectional chemical composition profile of the diffusion couple tool/workpiece boundary region was carried out by means of electron probe microanalysis (EPMA). Wear analysis on the cutting tools shows significant transfer of workpiece material to the surface of the tool as well as evidence of workpiece diffusion into areas on the tool showing less build-up. Both methods of analysis indicate a high degree of mobility of carbon atoms from the tool diffusing deeply into the workpiece/chip material.

1. INTRODUCTION

Titanium alloys are attractive materials due to their high strength-to-weight ratio, high hot hardness and exceptional corrosion resistance, resulting in increased usage in such diverse applications as aerospace engine components and biomedical implants. However, some of the very properties that make titanium alloys attractive also result in their being classified as difficult to cut materials, generating high tool failure rates and high machining costs. The low thermal conductivity of titanium alloys results in nearly 80% of the heat generated during cutting being conducted into the tool (vs. 50% when cutting steels), causing rapid tool breakdown /1/. Additionally, titanium is highly reactive at typical machining temperatures (upwards of 1000° C at the tool-chip interface), reacting strongly with almost every cutting tool material on the market.

The observed tool wear on inserts used to cut titanium alloys is a combined effect of abrasion, plastic deformation, adhesion and chemical reaction between the workpiece and the cutting tool. It has been observed that mechanical wear dominates at low cutting speeds while chemical reactivity between the tool and the workpiece plays a critical role in tool wear at elevated temperatures. 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 /2/. Typical industry cutting conditions are reported in the literature as being restricted to fairly low cutting speeds, frequently around 45 m/min /3/.

Chemical wear can be defined as the dissolution and diffusion of tool material into the workpiece or chip. It is tribochemical wear caused by the high temperatures generated during metal cutting /2/. With single-point turning tools, chemical diffusion effects dominate the rake face crater wear, while mechanical effects dominate the progression of flank wear.

Only limited success has been achieved in using coated cutting tools to machine titanium alloys, due to the reactivity of most hard coatings (TiN, TiCN, Al_2O_3) with the titanium workpiece /1,4/. Dearnaley and Grearson /5/ conducted an extensive study of chemical dissolution wear of a large number of cutting tool materials in the machining of a Ti alloy, and concluded that only the "straight" carbide grades and cubic boron nitride were possible candidates.

2. EXPERIMENTAL DETAILS

This paper presents the results of an investigation into the chemical diffusion behavior of a commercially available, uncoated cemented carbide with the popular alloy Ti-6Al-4V (Table 1). Elemental composition of the tool/workpiece diffusion zone was assessed on both actual worn cutting tools and furnace-fired diffusion couple specimens, resulting in an analysis of both static and dynamic diffusion phenomena.

2.1 Cutting Trials

2.1.1 Materials and Conditions

Single-point turning tests were carried out on a Hardinge Cobra 42 CNC lathe, on a sample of Ti-6Al-4V with a characteristic hardness of 29.7 HRC. The tools used were commercially available uncoated HU6C grade inserts from Stellram with a nominal hardness of 92.7 HRA and 1-3 μm average grain size. Their nominal composition is detailed in Table 2. The geometry used in this study was CNMP 432A.

The cutting trials reported here were performed at cutting speeds of 45 m/min (Tool 1) and 60 m/min (Tool 2), with a feed rate of 0.3 mm/rev and a depth of cut of 1.5 mm. At neither speed was the tool driven to failure. Maximum flank wear width on Tool 1 was 0.19 mm when cutting was discontinued after 8.6 min., and on Tool 2 was 0.28 mm when cutting was discontinued after 2.6 min. (The failure criterion was taken to be 0.4 mm maximum flank wear width.)

Table 1

As-delivered chemical composition of Ti-6Al-4V workpiece

Chemical Composition of Workpiece (wt%)	
Al	6.21
V	4.08
Fe	0.20
O	0.18
Cu	< 0.01
N	< 0.01

Table 2

Cutting Tool Properties

Properties of Cutting Tools Used	
ANSI Designation:	CNMP 432A
Stellram Geometry:	3D (small radius)
Carbide Grade:	HU6C
Surface Condition:	Uncoated
Nominal Hardness:	92.7 HRA
Density:	14.94 g/cc
Composition:	6 wt% Co
	0.2 wt% Cr
	0.2 wt% VC
Grain Size:	1-3 mm

Table 3

Cutting Parameters

Cutting Parameters Used	
Speed (Tool 1): Speed (Tool 2):	45 m/min 60 m/min
Feed:	0.3 mm/rev
Depth of Cut:	1.5 mm

Rake face crater wear of about 0.5 mm width along the cutting edge was observed on both tools at the conclusion of cutting. *Figures 1* and *2* show optical microscope photographs of the wear land on each tool.

2.1.2 Energy Dispersal X-Ray Spectroscopy

A semi-quantitative analysis of near-surface elemental composition in the wear regions of each tool was performed with a Philips XL30 scanning electron microscope (SEM) with companion EDAX energy dispersive X-ray spectrometer (EDX). Scans of the wear regions were performed at 20 kV.

The EDX results showed a consistently high level of nitrogen at all points. Since neither the workpiece nor the tool contained any nitrides, and since N K-shell electrons have close energies to Ti L-shell electrons, a simplifying assumption was made for this paper that all of the reported N could be counted as Ti. Though there is, in fact, a small yet indeterminate quantity of N present due to atmospheric contamination, the amount of error introduced by ignoring it is not presumed to be significant enough to impact the semi-quantitative nature of this analysis. Throughout this paper, all elemental concentrations as found by EDX analysis are reported in values that take this uncertainty into account.

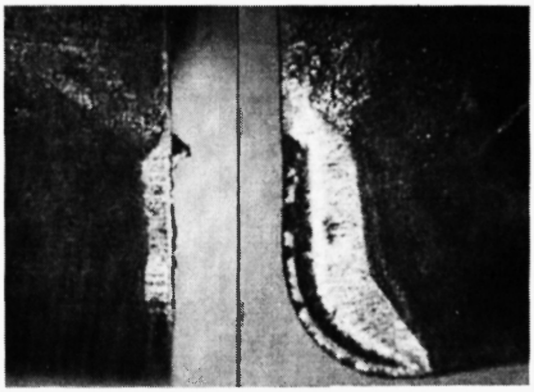

Fig. 1: Flank wear (left) and rake face crater wear (right) on Tool 1 (45 m/min)

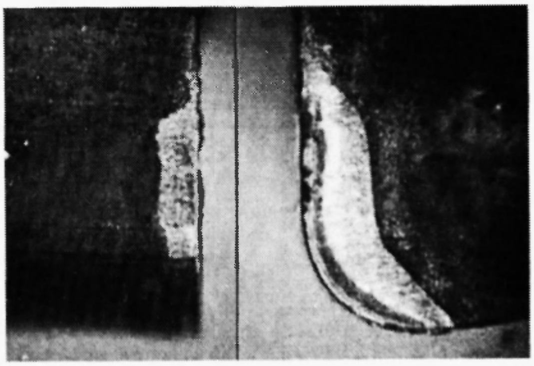

Fig. 2: Flank wear (left) and rake face crater wear (right) on Tool 2 (60 m/min)

2.2 Diffusion Couple Experiments

2.2.1 Materials

Cemented carbide cutting tool inserts of geometry RNG 42 and grade HA, compositionally similar to the HU6C tools used in the cutting tests, were obtained from Stellram Metalworking Products, La Vergne, TN. The Ti-6Al-4V alloy samples were cut from rods into discs of approximately 18 mm dia and 3 mm thickness. All samples were polished to a flat, mirror finish to ensure intimate contact during diffusion studies.

2.2.2 Diffusion Tests:

Prior to the diffusion test, each surface under contact was polished and ultrasonically cleaned. Special care was taken on a reproducible and uniform grinding and polishing procedure for both carbide and titanium alloy surfaces. Every surface was carefully polished using diamond paste. Non-optimized stacking of the metal-carbide-metal set up causes gaps in between the ceramic and metal slices, resulting in an increased reactivity /2/. Therefore, special care was also taken to avoid non-parallel ceramic and metal slices. Diffusion experiments were performed by pressing together polished specimens of carbide and Ti alloy, selected to provide calibration of the diffusion profiles generated at the two interfaces. The sandwich was held together within a Kovar^{TM} fixture as shown in Figure 3, and placed in quartz capsules. The capsules were evacuated and back-filled with argon prior to sealing. Diffusion experiments were carried out by placing the capsules in a furnace at 1000°C for 120hrs. 1000° C is the approximate temperature estimated for the tool tip during machining and an exaggerated time was used to exacerbate the interactions likely to take place during the actual cutting conditions. Since Kovar has a very low thermal expansion coefficient, heating at 1000° C allowed sufficient compressive pressure to be generated at tool/workpiece interfaces to ensure intimate contact, necessary for reliable interdiffusion. Thin alumina sheets were used as a diffusion barrier between the couple and the Kovar set-up to prevent interdiffusion at the interface. The temperature was monitored at 1000° C with a variation of ±1° C. The chemical reactivity was studied by accessing the extent of diffusion of species between two materials.

Following the diffusion treatment, the Kovar assembly was disassembled and the sandwich was cold mounted in epoxy. The mounts were sectioned with a metal-bonded diamond cut-off saw operating at low speeds, and polished metallographically. The samples were examined by SEM and optical microscopy, to determine the extent of diffusion.

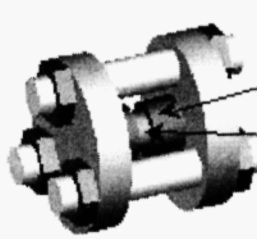

Fig. 3: Diffusion Couple in Kovar^{TM} Assembly

2.2.3 Electron Probe Microanalysis (EPMA):

A detailed study of the interdiffusion zones and concentration profiles was performed using an Electron Probe Microanalyzer (Model JXA-8200) at the High Temperature Materials Laboratory of Oak Ridge National Laboratory, under a User Program Agreement. The reactivity of a metal-ceramic combination, in this work defined as the thickness of the interaction layer on the carbide side of the interaction couple, was determined from the composition depth profiles across the diffusion interfaces. The instrument parameters were as follows: accelerating voltage was maintained at 15kV; compositional readings were taken at an interval of 2 microns. X-ray elemental distribution maps of individual elements were also recorded. However, due to space limitations, these maps will not be presented in the paper, but discussed in general terms to explain the observed results.

3. RESULTS AND DISCUSSION

3.1. Dynamic diffusion

The rake face of both worn inserts exhibited a typical crater wear land of approximately 0.5 mm width along the cutting edge, widening out past an "elbow" near the nose of the tool. Inside the crater was a zone primarily consisting of deposited workpiece material along the rise opposite the cutting edge, visible in the SEM photos of Figures 4 and 5 as a dark zone labeled (a). The lighter remaining zone of the crater area, labeled (b) in the figures, consisted of tool material with significant amounts of workpiece elemental diffusion. Along both cutting edges there are tenacious bits of workpiece chip debris clinging to the tool, labeled (c) in the figures.

On Tool 1, tested at 45 m/min, zone (a) mechanically deposited workpiece material was shown, smeared into the crater by the flowing chip, concentrated on the crater's chip departure slope furthest from the cutting edge. This dark deposit contains significant tool diffusion constituents, and consists of 65-80 wt% Ti. The

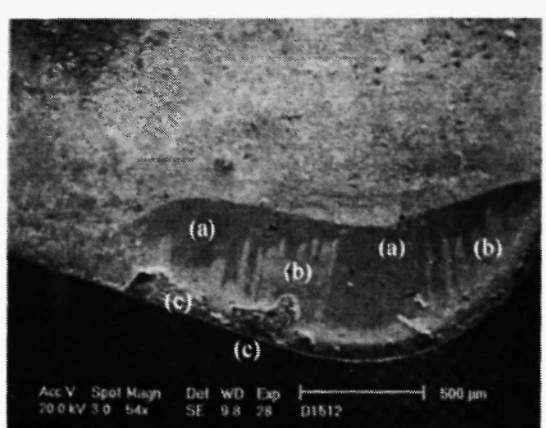

Fig. 4: Crater wear on rake face: Tool 1 (45 m/min)

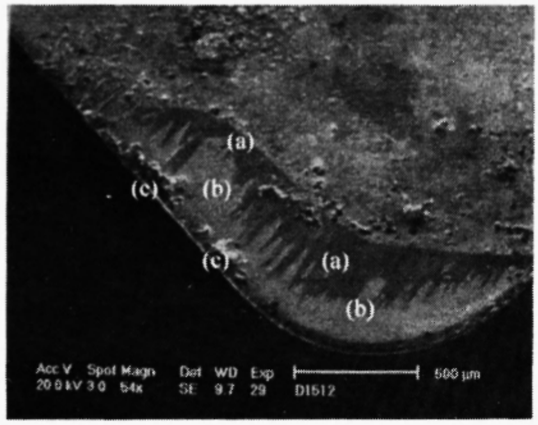

Fig. 5: Crater wear on rake face: Tool 2 (60 m/min)

workpiece alloying elements Al and V are also present, with a 7-9 wt% relative concentration of Al (an over abundance given its 6 wt% concentration in the workpiece) and 2-3 wt% relative concentration of V (a slight depletion given its 4 wt% concentration in the workpiece). Diffused tool constituents W and C comprise an average of 8 wt% of the examined zone, with a heavy preferential diffusion of C. Some 20-50 times more C atoms than W atoms are present within this zone. On Tool 2, tested at 60 m/min, the composition of zone (a) is similar to that of Tool 1, though the atomic ratio of C to W is increased to 40-70 times.

Thus the combined mechanical and diffusion effects of chip flow in zone (a) result in a built up layer within the crater that consists primarily of vanadium-depleted workpiece material including preferentially diffused aluminum (from the bulk chip) and carbon (from the tool). Carbon's preferential diffusion into the chip over that of tungsten appears to increase with speed.

Zone (b) of Tool 1 consists of an exposed diffusion zone with a workpiece-to-tool weight ratio of about 2:3. Due to preferential diffusion, C exists in the diffusion zone in excess of its stoichiometric 1:1 ratio for WC, exceeding the amount of W present by 10-30 at%. No apparent mechanical deposition occurs within this zone.

On Tool 2, tested at the higher speed, zone (b) contains less of the workpiece constituents than at the slower speed, with a workpiece-to-tool weight ratio down to about 1:4. The preferential diffusion of C again appears to increase with speed, as the number of C atoms in this diffusion zone is about twice that of W.

The tenacious bits of chip debris adhered to the cutting edge of Tool 1 were found to contain as much as 13 wt% C and were depleted by about half their expected V content on average, confirming general diffusion trends observed in both zones within the crater wear land.

A similar semi-quantitative EDX analysis was performed on randomly collected chip samples from the test runs on both tools, and they were found to contain about 10 wt% C, with concentrations marginally lower on the chips from the faster cut. Tungsten was found to have diffused into the chips in only trace amounts, less than 0.25 at%.

3.2. Static diffusion

The diffusion couple provided some of the most remarkable microstructural features observed in the present study. As shown in Figures 5 and 6, the diffusion profiles exhibit some of the strangest compositional variations along the interdiffusion pathway. The reaction zone clearly shows the evidence of a strong affinity between the cemented carbide tool and the Ti alloy. Coming back to Figure 6, the most significant feature of the microstructure is the presence of discrete islands of what are clearly TiC particles. The phase formed is confirmed to be $Ti_{0.6}C_{0.4}$, which is a thermodynamically stable phase. Such islands of titanium carbide are formed all long the interface in a regular manner, and vary in size from a few microns to over 100 microns. A detailed observation of the diffusion profiles of Figure 7 suggests that the strong chemical reactivity of Ti leads to a decomposition of WC, and the carbon that is released diffuses rapidly along the grain boundaries of the alloy to react with titanium. An increased concentration of cobalt was also observed at the interface, suggesting the formation of the *eta* phase in the tool surface.

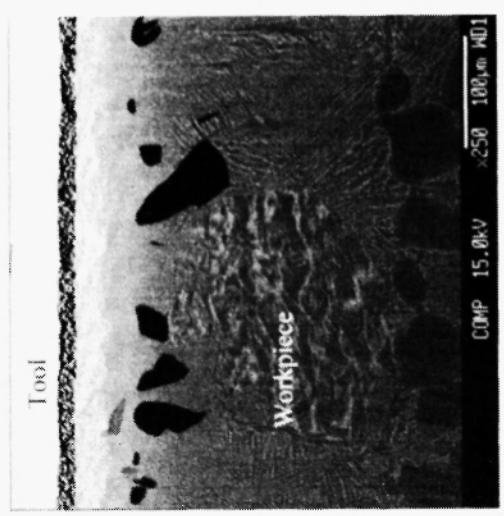

Fig. 6: Reaction zone of Ti-6Al-4V after diffusion test with WC-6%Co

Another remarkable feature of this diffusion couple is that there is a clear indication of diffusion of titanium into the tool surface, and the formation of a (W,Ti)C phase. This is a thermodynamically stable phase, often observed in TiC-coated cemented carbide tools /6/. The diffusion profile in this region shows a variation in the concentration of Ti and W, indicating that Ti diffuses considerably below the surface of the tool. It is not clear at this point how this occurs, and more work is clearly needed to understand this remarkable behavior.

Table 4

Averaged EDX results at 20.0 kV on Tool 1(45 m/min)

		Ti (K)	Ti (L)*	Al	V	W	C	Co	O
Zone (a)	Wt%	60.5	18.6	5.3	2.3	2.5	5.4	0.2	5.0
	At%	35.0	36.6	5.5	1.3	0.4	12.4	0.1	8.7
Zone (b)	Wt%	16.1	19.3	2.1	0.8	54.9	4.3	1.5	1.2
	At%	13.2	53.9	3.0	0.6	11.7	13.9	1.0	2.9
Chips: Adhered	Wt%	58.1	18.3	3.9	1.9	3.0	9.3	0.6	5.0
	At%	36.6	30.8	3.7	1.1	0.4	19.2	0.3	7.9
Chips: Loose	Wt%	48.0	25.8	5.1	1.7	1.4	9.0	0.2	8.8
	At%	23.2	41.9	4.4	0.8	0.2	17.0	0.1	12.5

* EDX labels this column as N, though it consists of mostly Ti L-shell results.

Table 5

Averaged EDX results at 20.0 kV on Tool 2 (60 m/min)

		Ti	Ti (L)*	Al	V	W	C	Co	O
Zone (a)	Wt%	55.8	22.3	5.7	2.3	1.9	6.1	0.5	5.3
	At%	30.2	41.1	5.5	1.2	0.3	13.0	0.2	8.6
Zone (b)	Wt%	5.9	11.1	2.3	0.7	64.9	9.3	2.9	2.9
	At%	5.2	33.5	3.6	0.5	14.9	32.6	2.1	7.6
Chips: Loose	Wt%	53.6	23.8	5.6	2.5	1.2	6.4	0.3	6.7
	At%	28.4	41.5	5.2	1.2	0.2	13.1	0.1	10.3

* EDX labels this column as N, though it consists of mostly Ti L-shell results.

4. CONCLUSIONS

After assessing both the static and dynamic diffusion phenomena between tool and workpiece, the following general observations can be made:

1. Tungsten carbide tools decompose at machining temperatures, resulting in a high level of carbon diffusion into the workpiece/chip.
2. Titanium from the workpiece also diffuses in significant quantities into contact zones on the tool, with the lighter alloying element aluminum preferentially diffusing over the heavier alloying element vanadium.
3. The use of conventional tungsten carbide cutting tools on Ti-6Al-4V machined components has the potential to contaminate the machined surface of the part. Such contamination could compromise the wear and corrosion resistance of the finished part. This phenomenon is currently under investigation.

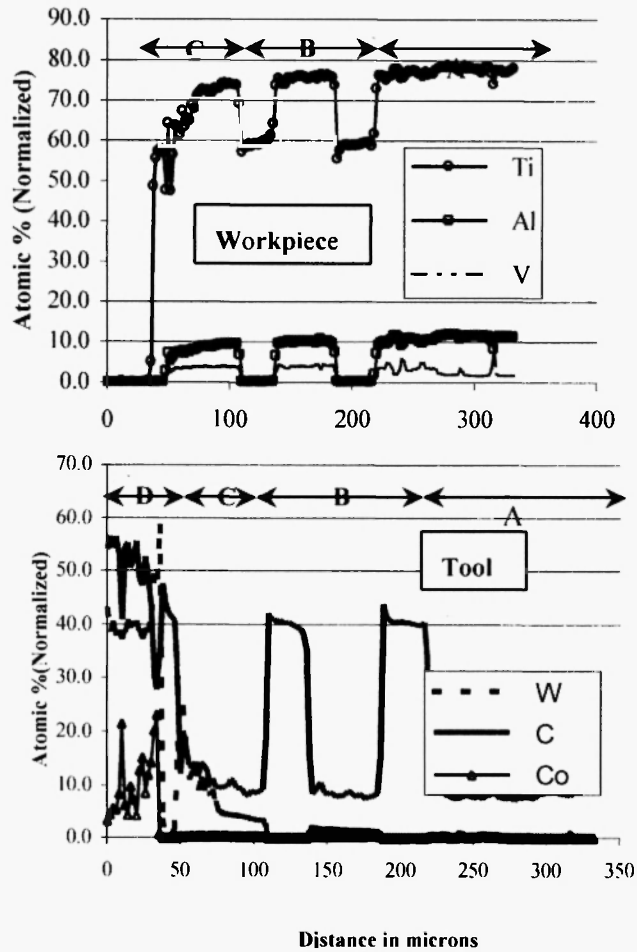

Fig. 7: Chemical Interdiffusion Profile for WC-Co vs. Ti-6Al-4V

5. ACKNOWLEDGEMENTS

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