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Tribochemical Analysis of Metal Nitride Coatings Sliding Against Hardened Steel for Cutting Tool Applications

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Abstract

Evaluation of coating wear during machining is often complicated by the simultaneous occurrence of multiple failure modes such as chipping, flaking, and edge fracture. These co-existing mechanisms make it difficult to probe fundamental wear behavior. In this work, a pin-on-disc tribological test is employed as a proxy to study the tribo-chemical reactions relevant to steel machining by matching critical contact pressures and sliding velocities. Cemented carbide tools and hemispherical pins, all of which were coated with TiN, TiAlN, or AlCrN, were evaluated by machining as well as tribological tests under dry conditions. The resulting reaction products were characterized using micro-Raman spectroscopy on worn tool surfaces, machining chips, pins, and disc wear tracks.

Results reveal that Fe_3O_4 is the dominant oxide phase in both environments, with little Fe_2O_3 formation depending on the specific coating and local contact conditions. This close correspondence in oxide phases indicates that the tribo-chemical reactions of machining can be replicated under controlled laboratory conditions. Thus, pin-on-disc tribometry may be recommended as a practical, efficient method for evaluating coating performance and oxidative wear while bypassing the complexity of elaborate machining experiments.

1 Introduction

The inherent variables in machining processes make it challenging to isolate and study coating wear behavior. Monolayer coatings are usually applied to multipoint rotary cutting tools. In addition to regular wear, multiple failure modes get simultaneously activated. These include chipping, notching, gross flaking off of the cutting edges, corner crumbling, etc. [1,2]. When multiple modes of tool failure occur simultaneously, it interferes with the judgment of the wear resistance of the coating. Additionally, tool point runout effects lead to uneven cutting force loading of individual cutting teeth. So, it becomes difficult to generate uniform wear patterns on all the cutting edges as can be seen clearly in Figure 1.

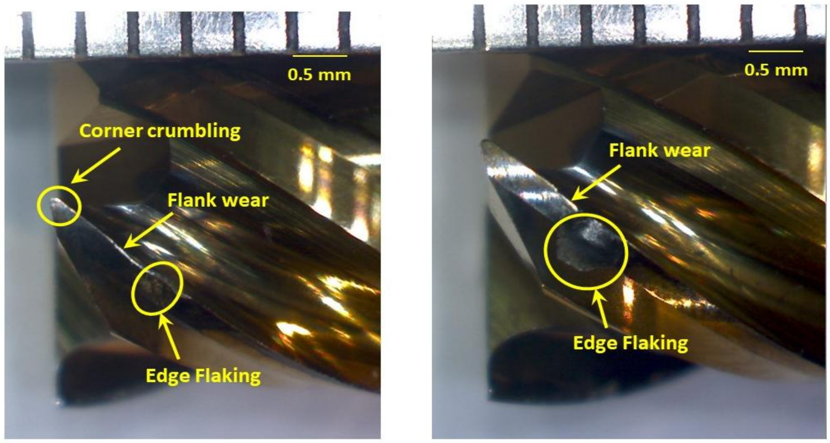

Figure 1: Multiple modes of tool failure on two different cutting edges of a solid carbide endmill resulting from machining mild steel.

Any test which could isolate pure wear from other non-wear types of tool failure would provide a desirable solution. For this purpose, we have used a suitably configured pin-on-disc tribological test [3]. A cylindrical pin with a hemispherical end is loaded on to a disc rotating at a given speed to create frictional sliding which results in wear. The test pin and cutting tool are made of the same material. Similarly, the disc and the workpiece to be machined are made of the same material. In our case, cemented tungsten carbide pins were coated with the thin film coatings whose wear resistance was to be tested. Ferrous discs were used to mimic the ferrous workpiece materials which the coated tools were designed to machine. The load was determined on the basis of the Hertzian contact pressure at the pin-disc contact zone, which was set to have the same order of magnitude of specific pressures encountered in machining steels, which is of the order of 2GPa [2, 4]. The sliding speed was matched to cutting speeds used in machining. For our tests we used a nominal sliding speed of 1.5 m/s which is a speed that is often employed in machining mild steels [2] as well as hardened steels [5]. Dry sliding experiments were conducted under ambient conditions to correspond to dry machining of steels, which is a common practice in industry [5]. Simultaneously, machining tests were also conducted on mild steel at the same cutting speed of 1.5m/s. Pins and cutting tools (endmills) coated with TiN, TiAlN, and AlCrN coatings, respectively, were used for the machining tests, as well as pin-on-disc tests. TiN, TiAlN, and AlCrN, represent three generations of coatings developed for cutting tool applications [6].

The purpose of the machining tests is to examine the tribo-chemical reaction products to compare with those produced in pin-on-disc tests. A correspondence amongst these strengthens the belief that the pin-on-disc test is useful in evaluating wear processes that might be encountered in machining. The worn surfaces of pins, as well as tools, were examined using micro-Raman spectroscopy, which is non-destructive, and can access complex geometries presented by the cutting tools (helical endmills). We hypothesize that a pin-on-disc test can simulate the tribo-chemical environment of steel machining with reasonable accuracy, if the contact conditions are carefully matched. The focus of this work is on the iron oxide phases (Fe_3O_4 and Fe_2O_3) produced at the interface. If these phases match across both processes, then the pin-on-disc test provides a simplified approach to study coating performance and oxidative wear.

While machining involves complex dynamics like intermittent contact and high strain rates, its interfacial conditions can be approximated through targeted tribological parameters. We acknowledge that this steady-state model bypasses the cyclic loading and localized flash temperatures inherent in dynamic chip formation. However, the goal is not a complete replication of machining, but a controlled isolation. The objective is to determine if interfacial oxidation is governed by local thermodynamics and kinetics rather than macroscopic deformation. This study utilizes a pin-on-disc setup to isolate the drivers of tribo-chemical reactions under dry conditions, specifically contact pressure (~2GPa) and sliding velocity (1.5m/s). We focus on tribo-chemical reaction products and aim to verify if oxide formation mechanisms remain consistent across both systems.

2 Experimental

Pin-on-disc experiments were conducted using a standard tribometer following ASTM G99. Cemented tungsten carbide pins (3mm dia) with hemispherical ends were coated with commercial coatings, namely TiN, TiAlN, and AlCrN, and tested against hardened HCHCR steel discs of hardness 55-58 HRC and surface roughness less than 1.6μm Ra.

A normal load of 10N produced a nominal Hertzian contact pressure of 2.8GPa evaluated using standard Hertzian stress calculations [7], that is comparable to stresses experienced by the tool flank and tool face under machining conditions [2,4]. Tests were conducted under dry sliding at a sliding speed of 1.5m/s for sliding distance of 1250m under ambient conditions.

Machining tests were carried out using TiN-, TiAlN-, and AlCrN-coated cemented carbide end mills to machine mild steel workpieces under dry cutting conditions at cutting speed 1.5m/s for a machined length of 70m, such that measurable tool wear developed. Worn tools and generated chips were then analyzed using Raman spectroscopy for comparison with tribological test results.

3 Raman Spectroscopy

Raman spectra were recorded using a Horiba LabRAM HR Evolution spectrometer having a 633nm red laser, a 100X objective, a range of 50-2000cm^{-1} for an acquisition time of 20-25 minutes. Spectra were obtained from several locations within worn regions to capture representative measurements of tribo-chemical reaction products.

The series of Raman spectra shown in Figures 2 – 5 are representative spectra measure directly on (i) cutting edges of metal nitride-coated tungsten carbide multi-point rotary cutting tools after machining a mild steel work pieces (Figure 2), (ii) the corresponding chips generated from the work piece during each of these machining processes (Figure 3), (iii) similar metal nitride-coated hemi-spherical pins tribo-tested against hardened HCHCR steel discs (Figure 4) and (iv) the corresponding wear tracks formed on the HCHCR discs (Figure 5). Several tens of spectra were measured on each of these samples in and around the cutting edge of the tools or around the middle of the tribo-contacted regions of the pins, as well as at several locations on the counter bodies, i.e. the machining chips and the wear tracks.

In general, these tens of spectra measured on the tools or the pins may be grouped into three different kinds. Firstly, spectra measured at locations that lie far away from the cutting edge of the tools or those measured far away from the middle of the tribo-contacted region on the pins, exhibited characteristic optical and acoustic phonon bands that are readily assigned to the crystalline metal nitride coating. These spectra also closely resembled the spectra measured on pristine, untested tools/pins, indicating that at these locations the coating is completely intact. Secondly, spectra measured at some locations along the cutting edge of the tool or in the middle of the tribo-contacted region on the pins showed no characteristic Raman bands indicating complete wear of the coating, exposing the underlying tungsten carbide surface. These locations typically appeared shiny under an optical microscope. Thirdly, a group of spectra that showed a completely new set of intense Raman peaks that are not characteristic of the metal nitride coatings. These new peaks are readily assigned to the two major oxide phases of iron, namely Fe_3O_4 (Magnetite) and Fe_2O_3 (Hematite) [8-10], that have been deposited onto the tool/pin surface from the ferrous counter body as a consequence of machining process/tribological-testing. In the Raman spectra shown in Figures 2 – 5, we focus our attention mainly on these iron oxide phases deposited on the surface of tool or pin, as well as those formed on the counter body, namely the chips from machining and the wear track formed on the disc. Therefore, only select spectra that showed characteristic peaks of either of the major iron oxide phases are displayed in these figures.

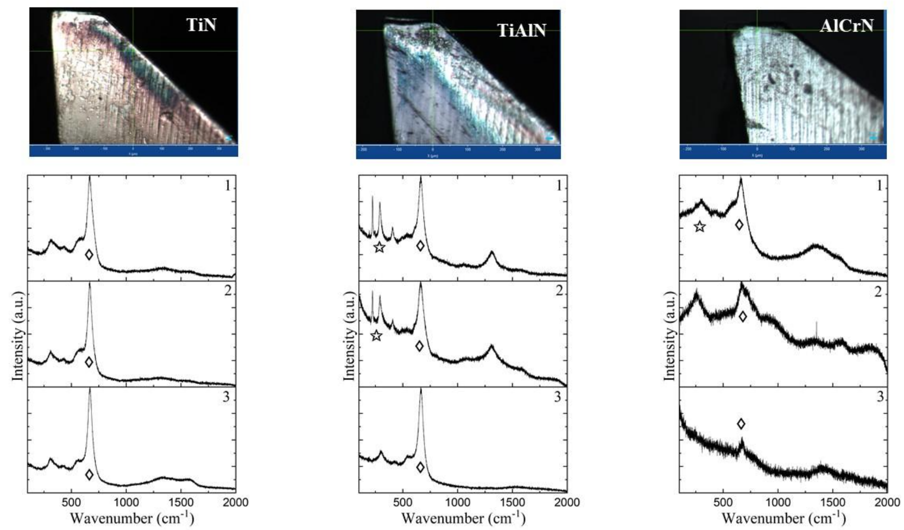

Figure 2: Optical images of cutting edges of metal nitride-coated tungsten carbide cutting tools showing the extent of coating wear after cutting a mild steel work piece using cutting parameters as described in the text and selective Raman spectra measured on these tools showing the dominant presence of Fe_3O_4 (◊) on the tool surface. Characteristic peaks of Fe_2O_3(☆) phase is also seen at few locations.

4 Results and Discussion

The spectra measured directly on the cutting edge of metal nitride-coated cutting tool after machining corresponding mild steel work pieces are shown in Figure 2. In all these spectra, a dominant presence of Fe_3O_4 phase of iron oxide may be inferred from the characteristic (A_{1g}) peak at around 670cm^{-1} [8]. In some spectra measured on the tools the presence of small amounts of Fe_2O_3 may also be seen from the characteristic sharp peaks at 220 and 250cm^{-1}, these peaks arise from the A_{1g} and E_g modes, respectively [8,10]. The presence of Fe_2O_3 also showed some dependence on the nature of the coating, with TiAlN and to some extent AlCrN coated tools showing slightly higher amounts of Fe_2O_3 compared to TiN coated pins, which predominantly consisted of Fe_3O_4. In Figure 3, Raman spectra measured on the corresponding chips formed from the ferrous work piece during machining are plotted. These spectra exclusively show the presence of Fe_3O_4 phase, with very little or complete absence of Fe_2O_3 phase, irrespective of nature of meta nitride-coated tool used.

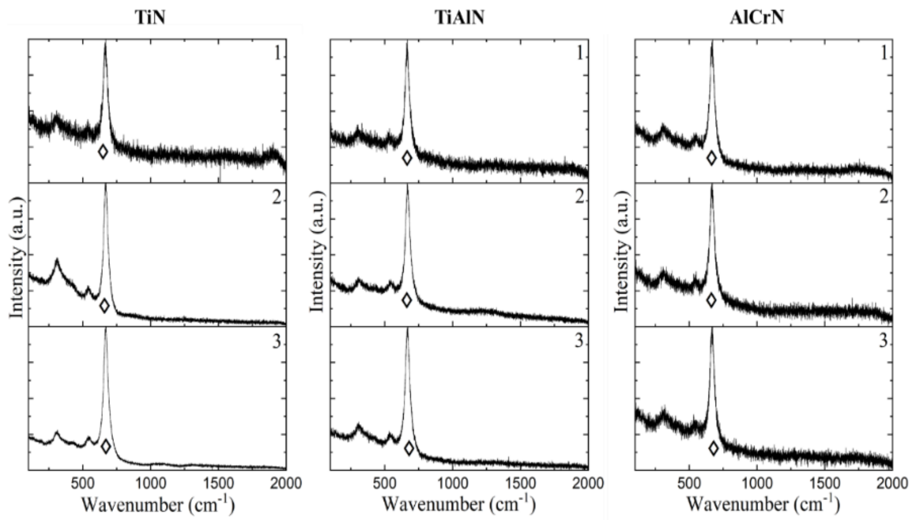

Figure 3: Few representative Raman spectra measured on chips formed during machining of a mild steel work piece using metal nitride-coated tungsten carbide cutting tools. The spectra almost exclusively show the presence Fe_3O_4 (♢) phase on the chip surface. Peaks characteristic of Fe_2O_3 are very weak or completely absent in these spectra.

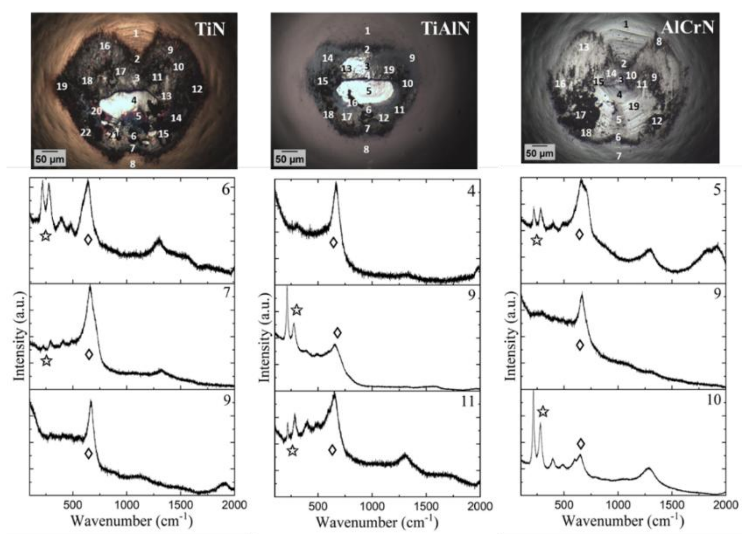

Figure 4: Images of tribo-tested metal nitride-coated tungsten carbide pins (left: TiN, middle: TiAlN and right: AlCrN) showing the extent of coating wear and a few selective Raman spectra measure on these pins showing the characteristic peaks of the two iron oxide phases, Fe_2O_3(☆) and Fe_3O_4 (♢). Only spectra showing the presence of iron oxides are shown here. The numerical indices alongside the spectra refers to the nominal locations from where spectra were acquired.

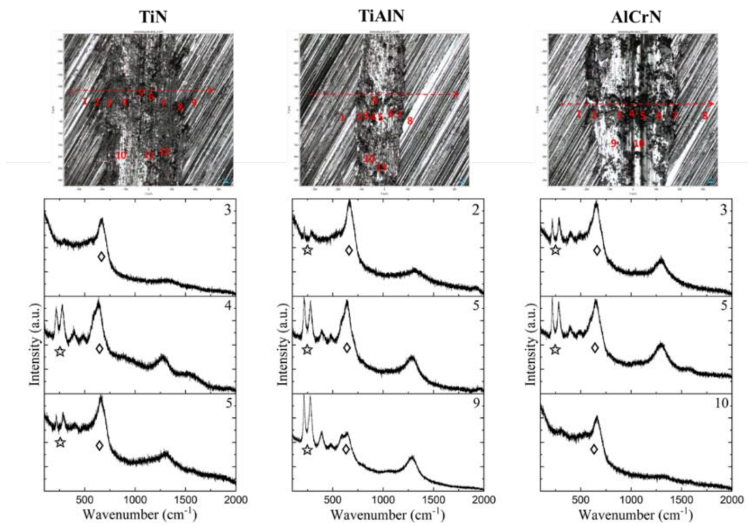

Figure 5 Images of the wear track formed on the HCHCR disc after tribo-testing against corresponding metal nitride-coated tungsten carbide pins (left: TiN, middle: TiAlN and right: AlCrN) and representative Raman spectra measured on these tracks showing the characteristic peaks of the two iron oxide phases, Fe_2O_3(☆) and Fe_3O_4 (◊). The numerical indices alongside the spectra refers to the nominal locations on the track from where spectra were acquired.

Similar observation can be made from the spectra plotted in Figure 4, wherein Raman spectra measured on metal nitride-coated pins tribo-tested against hardened steel disc (HCHCR) are plotted. The spectra show close correspondence with the spectra measured on the tools indicating the presence of predominately Fe_3O_4 phase on the surface with the appearance of Fe_2O_3 at some locations. Spectra measurements on the corresponding wear tracks are presented in Figure 5. Spectra were measured at various locations along a line encompassing the wear track. No Raman peaks were observed on spectra measured on locations outside the wear track (not shown in the figure), whereas spectra measured at locations within the wear track exhibited characteristic iron oxide peaks. Fe_3O_4 was once again the most dominant of the two oxide phases observed on the tracks as well with varying amounts of Fe_2O_3 also seen along with it.

From these sets of data, it is clear that the nature of the interfacial oxide generated during the machining operations and those generated during tribo-testing bear a striking similarity with Fe_3O_4 being the dominant iron oxide phase generated at the interface in both these processes. Minute differences in the composition of the two oxide phases (Fe_2O_3 and Fe_3O_4) on the nature of the coating are also observed. This requires further curve fitting analysis of the spectra that we intend to present in detail elsewhere in the near future. Nevertheless, the similarity of the nature of tribo-chemical reactions occurring at the interface during machining and tribology are evident from the data presented here.

5 Conclusion

The present study shows that pin-on-disc tribological tests, when carried out under contact conditions similar to machining, can reproduce the main tribo-chemical reactions that occur at the tool–workpiece interface during steel machining. Raman analysis indicates that Fe_3O_4 is the dominant oxide phase formed in both machining and tribological tests, while smaller amounts of Fe_2O_3 are also observed depending on the coating used.

The similarity in oxide phases formed in both cases suggests that interfacial oxidation is mainly controlled by local temperature and reaction conditions rather than by the processes specific to machining. These results indicate that pin-on-disc testing can serve as a simpler and more controlled method to study coating behavior and oxidative wear processes relevant to machining applications.

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