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Machining performance of TiN coatings incorporating indium as a solid lubricant

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ABSTRACT

The machining and wear performance of TiN-coated and patterned carbide inserts incorporating indium as a solid lubricant are reported in this study. Cutting tests were conducted by turning hardened 4340 steel in both lubricated and dry conditions. During turning, periodic flank wear measurements were made. The chips formed during cutting were examined by scanning electron microscopy, as the condition of the chip reflects the conditions obtained during machining. Inserts subject to dry machining were also examined using optical microscopy and X-ray photoelectron spectroscopy to determine the extent of damage on the rake surface as well as the degree of material transfer. The results showed indium to be effective in reducing flank wear during lubricated machining, but little additional benefit of patterning was observed. For dry machining, some degree of improvement was noted in the patterned sample, but the degree of lubricity brought about by the indium coating was not sufficient and the overall flank wear was higher than the lubricated tests. However, the wear and damage on the rake surface along the path of the chip was reduced by the presence of the In-containing microreservoirs. An additional test was conducted using an instrument that simulates temperature effects during machining, and it was found that the lubricity achieved by In coatings is lost above 450 °C. These results suggest that the use of indium is limited to below this temperature, and above this temperature transforms to a less lubricious indium oxide.

1. Introduction

Metal cutting processes have traditionally made extensive use of lubricating fluids. Recently, the economical and environmental disadvantages of using these fluids have become more pronounced. Their share in machining costs is high and management of the waste has become complex due to the environmental regulations. Elimination of the cutting fluids (dry machining) has been investigated as a potential solution and numerous research studies have been conducted, focusing on improving tool materials, tool coatings and/or finding tool geometries appropriate to conditions for dry machining [1–3]. In particular, improved tool coatings are sought that would help to negate the loss of some of the facilities provided by cutting fluids, namely cooling, lubricating and flushing the chips [1,2].

Coatings for cutting tools and other applications that require good wear resistance and low friction have observed steady advances for the last several decades, evolving from single layer/single phase coatings to multilayer/multiphase, gradient, superlattice, and composite coatings [4–7]. Composite coatings are multiphase/multiconstituent coatings that are tailored to combine the beneficial properties of several phases, such as combining a hard phase with a soft and lubricious phase. Examples of composite coatings based on natural phase separation during deposition include WC/Ag and TiC/Ag [4], CrN/Ag [5], DLC/Ag [6] and yttria-stabilized zirconia with gold [7].

While natural phase separation can occur in highly immiscible systems, the formation of amorphous or alloyed films instead can be a limitation to achieving the desired composite microstructures [8]. Recent efforts have been made to artificially create three dimensionally structured composite coatings for tribological applications. For example, Voevodin et al. [9] used a laser to cut a circular groove matching the center of the wear track in a functional gradient Ti–TiC–DLC coating, and then deposited MoS_2 in this groove. The purpose of this process was to provide a means for storage and replenishment of the solid lubricant. Pin-on-disk tests showed that this coating had a longer wear life than either the constituents alone or a MoS_2/Ti–TiC–DLC bilayer coating. In their more recent work, Voevodin and Zabinski [10] studied the effect of laser drilled 10 or 20 μm-sized-holes on the wear life of a TiCN coating. MoS_2 was applied to the surface of the hard coating after laser processing by either burnishing or magnetron sputtering. Several different geometries (area coverage and reservoir size) were examined in order to determine the optimum structure. The results showed that the reservoirs helped to improve the wear life by as much as one order of magnitude compared to the coatings without reservoirs. It was also found an optimum area coverage near 10% for their tribological system. Recently, we have explored a new approach for creating composite coatings in which microscopic beads are placed on the substrate and act as placeholders for microreservoir formation [11,12]. This approach is reviewed in detail in the following section. Results obtained with TiN/graphite composite

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Table 1
Coating description and fabrication parameters.

Sample name	Relative density	Diameter of the micro-beads (μm)	Application method	Area coverage
TiN	–	–	–	–
TiN–In	–	–	–	–
TiN–In5L	Lower	5	Spraying	1%
TiN–In5H	Higher	5	Submerging	3.8%
TiN–In10L	Lower	10	Spraying	1%
TiN–In10H	Higher	10	Submerging	2.3%

coatings showed significant improvements in friction and wear life compared to coatings without microreservoirs [11,12].

The goal of the present study is to examine the effects of solid-lubricant microreservoirs on the performance of TiN coatings during machining. Indium was selected as a solid lubricant due to its metallurgical incompatibility with Fe and Ni [13]. In addition, Fox-Rabinovich et al. [14,15] studied the effect of ion implantation of numerous elements on the wear resistance of the machining tools and found indium implantation gave the longest wear life (a 2.4-fold improvement in dry machining and 2.1-fold in wet machining). Coatings for the present study were fabricated on carbide cutting tool inserts with and without microreservoirs. The machining performance of these coatings was examined by measuring flank wear during turning operations. Tests were conducted both with and without liquid lubrication. Further evaluation, using X-ray photoelectron spectroscopy (XPS) and scanning electron microscopy (SEM), was carried out in order to explain the differences in the wear life of selected coatings. Finally, results of machining simulation tests are presented to further understand the results obtained.

2. Experimental

In this study indium was used as a thin film overlaying the TiN-coated carbide inserts, several of which were patterned to incorporate 5 or 10 μm diameter microreservoirs within the TiN coating. A novel method has been devised to fabricate these patterned coatings [11,12]. The first step in this process is to apply ceramic beads (borosilicate glass micro-spheres produced by Duke Scientific Corporation) to the surface by spraying on a solution containing the beads. The carrier solvent (high-purity ethanol) is allowed to dry leaving a random distribution of beads on the surface. The samples are then placed in the sputter coating system and coated with TiN to a thickness of approximately 1–2 μm. The next step involves removal of the beads by sonication. Beads break away from the surface leaving microreservoirs in the coating. In the final step indium is applied to the surface by sputter deposition. This indium coating is effectively a blanket layer, but generally follows the contours of the microreservoir morphology. The previous studies [11,12] used steel substrates, while in the present study polished SPG 422 type cemented carbide inserts were used as substrates.

In addition to the method described above, a modified "submerging" or "dipping" process was devised to increase the density of the micro-reservoirs on the surface. In this method, the substrates were submerged into a homogeneously mixed bead-ethanol suspension by means of a perforated container that allows the mixture to flow in and out. The micro-beads that settled onto the rake surface of the insert substrates were drained without disturbing bead settlement. The excess ethanol evaporated quickly and the beads became immobilized with their layout fixed. Samples denoted "*lower density*" were fabricated by spraying micro-beads, whereas samples labeled "*higher density*" were fabricated by submerging the insert into a bead-ethanol suspension. Table 1 gives a list of the samples examined. The first two samples (TiN and TiN–In) are control samples and do not have microbead reservoirs. The last four samples listed have microreservoirs, made either with 5 or 10 μm diameter beads and different densities resulting from the application method. As noted above, the submerging method gave a higher bead density and area coverage in comparison to the spraying method. The area coverage

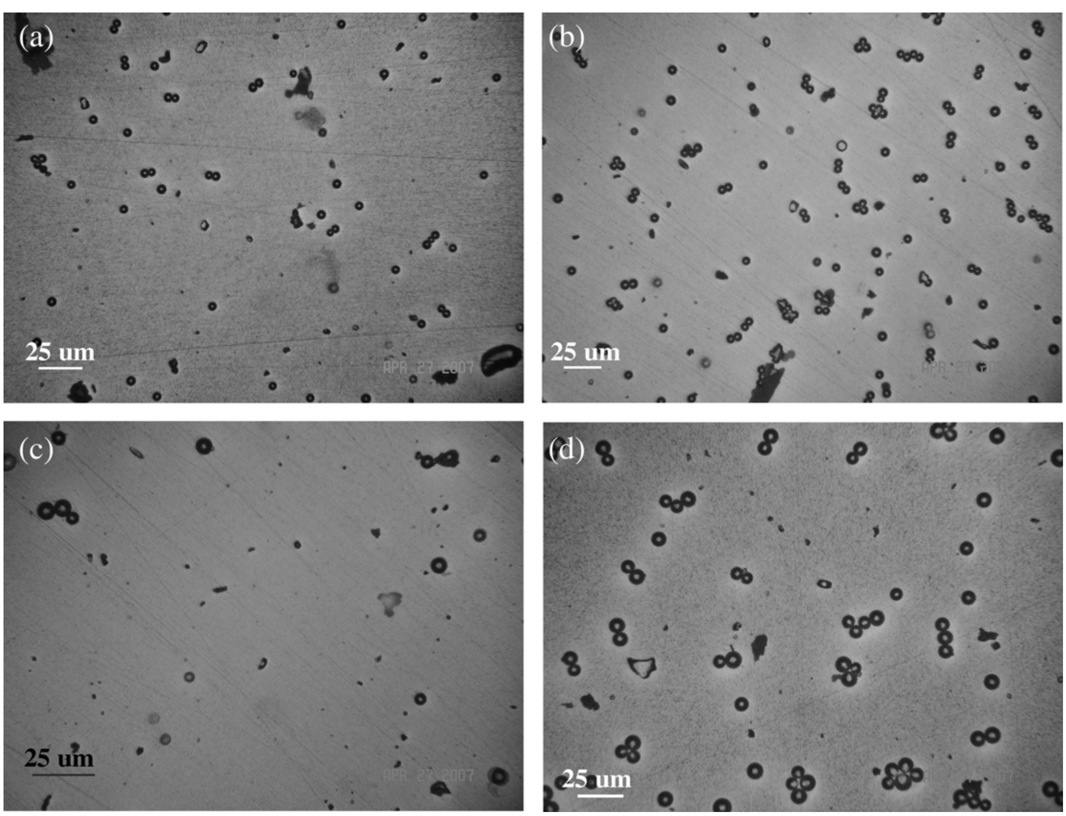

Fig. 1. Optical microscope images of the rake face of the insert specimens after removing the micro-beads from the surface, leaving empty reservoirs behind. (a) 5 μm, spray method; (b) 5 μm, immersion method; (c) 10 μm spray; (d) 10 μm immersion.