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Frictional and wear behaviour of AlCrN, TiN, TiAlN single-layer coatings, and TiAlN/AlCrN, AlN/TiN nano-multilayer coatings in dry sliding

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Abstract

This paper examines the frictional and wear behaviour of AlCrN, TiN, TiAlN single-layer coatings, and TiAlN/AlCrN, AlN/TiN nano-multilayer coatings in dry sliding. Comparative studies on the coatings sliding in air and vacuum environment at different speeds provided important insight on the effect of oxidation and temperature on the frictional and wear behaviour of the coatings. Among all the single-layer coatings tested in vacuum, TiN gave the lowest coefficient of friction (COF), followed by TiAlN and AlCrN. This indicated that TiN was the most lubricous coating. At 10 m/min in ambient air in which oxidation took place, AlCrN gave the lowest COF, followed by TiN and TiAlN. Among the two types of nano-multilayer coatings tested in vacuum and air, the AlCrN/TiAlN produced lower COF. The characteristics of the COF produced by AlCrN/TiAlN and AlN/TiN in vacuum and air was similar to those produced by TiAIN and TiN, respectively. This showed that the COF of these nano-multilayer coatings was governed by TiAIN and TiN. AlCrN exhibited the highest wear resistance. TiAIN had the lowest wear resistance. TiAIN/TiN/AlCrN and AlN/TiN which exhibited similar wear resistance, had lower wear resistance than AlCrN but higher wear resistance than TiAIN. In air, increasing the speed from 10 m/min to 100 m/min resulted in a reduction in COF for all coatings, except AlCrN.

Keywords: coatings; friction; wear;

1. Introduction

The factors controlling the frictional behaviour of materials include mechanical stresses, temperature and oxidation phenomena. The complexity of sliding friction arises from the fact that all these three controlling factors are interrelated and influenced by load and sliding velocity as well as the sliding environment. The chemical composition has significant effect on the type and physical characteristics of the tribolayer formation which in turn control the frictional behaviour and thus
the wear rate of the coating [1,2]. This layer plays a protective role as it reduces material loss rate by reducing or eliminating direct contact of the two surfaces. In ambient environment, the type of layer formed is typically in oxide form, yielded from the reaction between the coating and oxygen. Hence, the partial pressure of oxygen during sliding is important for an effective oxidation process since the rate of oxidation is controlled by the diffusion of oxygen into the metal lattice. TiN was widely used as a coating material for cutting tool since the mid-sixties [3]. However, its poor oxidation resistance at high temperature is the main limitation for many applications. In recent years, AlCrN has been reported as a promising coating as it exhibited good hardness and better resistance to chemical breakdown than TiAlN, TiCN, and TiN coatings. It had been found that the high oxidation resistance of AlCrN was due to the formation of dense oxide mixture layers of Cr$_2$O$_3$ and Al$_2$O$_3$ at the surface, preventing further oxidation that could decompose the cubic AlCrN phase [4]. Many researchers demonstrated that AlCrN coating, which had been developed recently, gave better wear protection and exhibited lower friction coefficient than TiN and TiAlN coatings. Gant et al. [5] observed that in dry sliding under ambient air sliding, AlCrN produced lower COF compared to TiAlN and TiN, and the type of debris formed was governed by the atmosphere.

Mo et al. [6] concluded that hard chromium oxide formed as a result of tribo-chemical reaction of chromium with oxygen accounted for high abrasion resistance and low friction coefficient of AlCrN coating sliding in air. Liew et al. [7] had investigated the wear of uncoated carbide tools, and carbide tool PVD-coated with 2000 alternate layers of AlN and TiN (each layer 1.25 nm thick) and carbide tool PVD-coated with 0.5 µm TiN, 5.5 µm TiCN and 0.5 µm TiN in ultra-precision turning of stainless steel. It was found that the AlN/TiN nano-multilayer coated carbide tools exhibited higher wear resistance and produced better surface finish. More recently, Liew [8] found that TiAlN/AlCrN nano-multilayer coated tool exhibited higher wear resistance than the single-layer TiAlN coated tool in milling stainless steel. This paper aims to investigate the frictional behaviour of this single-layer coatings (AlCrN, TiN, TiAlN) and nano-multilayer coatings (TiAlN/AlCrN, AlN/TiN) under different sliding speeds in vacuum and air. The experimental results obtained in vacuum and air give valuable information on the role played by the formation of oxide on the friction coefficient and wear produced during sliding, and provide some explanation for the different in the wear characteristics of the coated cutting tools observed in machining.

2. Experimental

The frictional and wear behaviour of AlCrN, TiN, TiAlN single-layer coatings, and TiAlN/AlCrN, AlN/TiN nano-multilayer coatings was investigated using a Ducom TR-20EV-M3 ball-on-disc tester. Tests were carried out at 10 and 100 m/min at a constant normal load of 5N for a sliding distance of 200 m in ambient air and vacuum (1× 10$^{-5}$ Pa). However, if the steady-state coefficient of friction had not been achieved at this distance, the tests would be continued until it reached 800 m. Uncoated cemented carbide balls were used to slide on coated carbide discs. Cemented carbide discs (6wt% Co and 94% WC; grade ISO K10) with a hardness 1600 HV was used as the substrate material for the coatings. Prior to coating deposition, the specimens were polished to a surface roughness of less than 0.04 µm. The PVD-coatings were deposited by Sumitomo Electric, Japan. The hardness of the AlN/TiN nano-multilayer coating (200 alternate layers of AlN and TiN, each layer 1.25 nm thick) and TiN was 3900 and 2500 HV, respectively. The hardness of the TiAlN/AlCrN nano-multilayer coating (1000 alternate layers of TiAlN/AlCrN, each layer 5 nm thick) was 5100 HV, considerably harder than TiAlN and AlCrN single-layer coatings which had a hardness value of between 3200-3300 HV. The thickness of the single-layer coatings was 3 µm. The ball-on-disc apparatus enclosed in a chamber can be evacuated to a pressure of 1x 10$^{-5}$ Pa by a diffusion pump backed by a single-stage rotary pump. The COF was continuously measured throughout the tests by a load cell.

3. Results and Discussion

3.1. Running-in process

Figures 1-4 show the variation of the COF (coefficient of friction) with sliding distance for all types of coatings in vacuum and ambient air under different sliding speeds. A notable feature of the results obtained in vacuum is the sharp increase followed by a rapid drop in the COF to a low prevailing steady-state value in the initial stage of sliding. This reflects the nature of the running-in process which rapid wear occurs. In air, such abrupt drop in COF either did not take place or was not evident. In air, the distance required to reach the steady-state COF was greater than that required in vacuum. The sliding distance to achieve the steady-state COF increased with speed. The tests involving AlCrN, TiN and
3.2. Steady-state coefficient of friction

Among all the single-layer coatings tested in vacuum, TiN gave the lowest steady-state COF, followed by TiAlN and AlCrN. This indicated that TiN was the most lubricous coating. In ambient air, it could be expected that the coatings reacted with the oxygen and humidity to form a tribofilm on the coatings, resulting in higher COF [6,9]. Therefore, the COF was no longer governed by the lubricity of the coating itself but by the type of oxide formed. In air at 10 m/min, AlCrN gave the lowest steady-state COF, followed by TiN and TiAlN.

In vacuum, the reduction in the COF due to increased speed from 10 m/min to 100 m/min could be attributed to the softening of the coatings brought about by increased temperature. In air, increasing the sliding speed from 10 to 100 m/min resulted in a reduction in the COF in all tests except for the test involving AlCrN in air where the COF increased to the value exhibited by the TiAlN.

Among the two types of nano-multi layer coatings tested in vacuum and air, AlCrN/TiAlN produced lower COF. There was a great similarity between TiAlN and AlCrN/TiAlN in terms of the distance required to produce the steady-state COF and the value of the steady-state COF produced during sliding in air and vacuum. The same similarities were also observed between AlN/TiN and TiN. These show that the COF of AlCrN/TiAlN and AlCrN/TiAlN was governed by TiAlN and TiN, respectively.

3.3. Comparison of steady-state coefficient of friction

Mo and Zhu [10] obtained a COF of 0.6 in sliding of AlCrN in air using a Si3N4 ball at a nominal load of 5 N and speed of 0.48 m/min. At a higher speed of 5 m/min, a higher COF of 0.8 was obtained. The increase in the COF with speed for AlCrN was also observed in this study. In another tests carried out in air at a nominal load of 5 N and speed of 10 m/min, the same authors obtained a COF of 0.75 and 0.8 for AlCrN and AlTiN, respectively. In sliding at 6 m/min and 10 N load in air, a COF of 0.6, 0.2 and 0.05 was obtained for TiAlN, TiN and AlCrN, respectively [5]. Although these values were different from those obtained in this study (probably due to the difference in the balls used [11]) but the order of the COF was the same as that obtained in this study using the speed of 10 m/min (Figure 1(b)).

![Graph](a) ![Graph](b)

Fig. 1. Variation of coefficient of friction at 10 m/min in dry sliding for the single-layer coatings in (a) vacuum and (b) air.
Fig. 2. Variation of coefficient of friction in dry sliding at 10 m/min for the nano-multilayer coatings in (a) vacuum and (b) air.

Fig. 3. Variation of coefficient of friction in dry sliding at 100 m/min for the single-layer coatings in (a) vacuum and (b) air.

Fig. 4. Variation of coefficient of friction in dry sliding at 100 m/min for the nano-multilayer coatings in (a) vacuum and (b) air.
3.4. Worn Profile

In air at 10 m/min, a worn surface with a depth of 0.25 µm was produced on the TiAlN coating (Fig. 5(a)). The same environment produced worn surfaces with a depth of about 0.1 µm on the TiN, AlCrN/TiAlN and AlN/TiN coatings (Fig. 6(b)-(d)). AlCrN exhibited the least wear with depth less than 0.05 µm (Fig. 6(a)). TiAlN suffered the most severe wear as a result of long running-in process and high steady-state COF. AlCrN/TiAlN produced similar steady-state COF and duration of running-in process as TiAlN but suffered less severe wear because it had higher wear resistance due to it high hardness. The worn surfaces produced on TiN, AlCrN/TiAlN and AlN/TiN at 10 m/min in vacuum had depth of less than 0.05 µm. However, the worn surface on the TiAlN coating exhibited higher depth of between 0.05-0.1 µm (Fig. 5(b)). The difference in the depth of the worn surfaces produced on all coatings at 100 m/min in air and vacuum could not be distinguished. All worn surfaces had a depth of less than 0.05 µm (Fig. 5(c) and (d)).

![Fig. 5. Wear of the TiAlN produced after 200 m sliding distance in (a) air at 10m/min, (b) air at 100 m/min, (c) vacuum at 10 m/min and (d) vacuum at 100 m/min.](image_url)

![Fig. 6. Wear of (a) AlCrN (b) TiN (c) AlCrN/TiAlN and (d) AlN/TiN produced after 200 m sliding distance at 10 m/min in air.](image_url)
3. Conclusions

The frictional and wear behaviour of AlCrN, TiN, TiAlN single-layer coatings, and TiAlN/AlCrN, AlN/TiN nano-multilayer coatings in dry sliding were studied. Among all the single-layer coatings tested in vacuum, TiN gave the lowest coefficient of friction (COF), followed by TiAlN and AlCrN. This indicated that TiN was the most lubricous coating. At 10 m/min in ambient air in which oxidation took place, AlCrN gave the lowest COF, followed by TiN and TiAlN. Among the two types of nano-multilayer coatings tested in vacuum and air, AlCrN/TiAlN produced lower COF. The characteristics of the COF produced by AlCrN/TiAlN and AlN/TiN in vacuum and air was similar to those produced by TiAlN and TiN, respectively, suggesting that the COF of the nano-multilayer coatings was governed by TiAlN and TiN. The COF and wear reduced with increased speed, except for the test involving AlCrN in air where the COF increased with increased speed. This needs further investigation. In air at 10 m/min, the wear resistance of the coatings can be well distinguished. AlCrN exhibited the shortest running-in process and lowest steady-state COF was found to have the least wear. TiAlN suffered the most severe wear as a result of long running-in process and high steady-state COF, and relatively low hardness in comparison to the nano-coatings. TiN, TiAlN/AlCrN and AlN/TiN which exhibited similar wear resistance, had lower wear resistance than AlCrN but higher wear resistance than TiAlN.

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References