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Friction Studies of Coated and Uncoated Cemented Carbide in Controlled Environment

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Abstract—In this investigation, a controlled-environment tribological test device has been used to study the friction coefficients of several grades of commercially-available coated and uncoated cemented carbide cutting tools in a dry air environment at different environmental chamber pressures. Tests were run in the block-on-ring configuration. The results suggest that the friction coefficient is sensitive to the level of air present, with a noticeable rise in friction coefficient with decreasing pressure or increasing vacuum level. The uncoated cemented carbide sufaces resulted in the highest friction values, whereas the coated grades yielded somewhat lower values even after the coating was removed. The results suggest the importance of friction control in the design of coatings for metal removal processes.

1. Introduction

Cutting tools are an integral part of the manufacturing and finishing processes used by most all industries. To increase productivity and reduce costs, greater demands are being placed on cutting tools and the machinery associated with them. The incorporation of hard coatings has been shown to enhance tool life and improve machinability. Coatings such as TiC, TiN, Al_2O_3, and polycrystalline CVD diamond provide a hard wear-resistant interface that extends tool life and improves machinability [1]. Furthermore, increased productivity demands higher metal removal rates. It is well known that metal removal rates are higher in turning than even in rough grinding, therefore, the ability to turn materials (particularly hardened alloys) to near-finished size or eliminate any grinding steps would further reduce finished part costs. In addition, dry machining is being investigated as a possible means of eliminating the toxicological health risks associated with long-term exposure to metal cutting fluids [2].

The tribology of cutting tool interfaces varies considerably with the type of machining process, the materials being cut, and the cutting tool itself. At relatively low cutting speeds (such as in tapping), cutting fluids can lubricate by forming a chemically-reactive boundary film. This tends to reduce the tool face friction and thus the energy necessary to cut. At high cutting speeds (such as in single point turning), coincident with high metal removal rates, cutting fluids primarily dissipate heat. Friction behavior on the tool face has a strong influence on overall energy dissipation in the metal removal process. As noted by Shaw [3], a small change in tool face friction will cause roughly a three-fold change in energy dissipation at the shear plane (Fig. 1), where metal chip formation occurs, and thus will have a large effect on overall energy consumption. Furthermore, the temperature of the tool face plays an important role in metal cutting and tool life. In general, only 10% of the energy consumed in metal cutting is dissipated to the tool and the work, with the remainder being carried away by the chip. The temperature rise on the tool face equals the sum of the temperature contributions from the shear plane at the tool tip and the temperature rise due to friction on the tool face [4]. In general, it is most advantageous to have the point of maximum temperature on the tool face as far away from the actual cutting edge as possible, to maximize tool life. In some cases, high cooling rates and friction-reducing particle in the matrix can cause a chip to "curl" away from the tool face and thus decrease its overall contact length on the tool face. This has the effect of moving the point of maximum temperature closer to the cutting edge, and may actually reduce tool life [5]. Thus, controlled friction, not necessarily low friction (exclusively), is an important variable in designing the interfacial sliding system for cutting tools.

As the chip forms, the contact area nearest the cutting edge is characterized by a region of "sticking" friction, and then progresses to sliding friction at roughly the point of maximum tool face temperature (Fig. 1). During metal removal processes, the cutting conditions (temperature, pressure, speed, and lubrication) and the "environment" in this interfacial region contribute to the determination of the chip/tool face friction coefficient. Measurement of this friction coeffcient is difficult and prediction from first principles even more unlikely. At the cutting edge itself, high stresses (normal and shear) and temperatures develop as the chip forms and moves, and together with the close proximity of the workpiece to the cutting edge, raises questions regarding what the actual environment is at the cutting edge and then even further along the tool face until tool face/chip separation occurs. The actual environment, whether it be composed of solids, dissolved gases in the matrix liberated during the shearing process, ambient air, or a combination of the three, will play a key role in the interfacial friction or lubrication of the tool face/chip interface. Since it is difficult to facilitate interfacial friction control through external lubricants and/or coolants, engineered coatings that combine hard wear resistant materials with friction control agents delivered through internal (sacrificial) means may be potential candidates for new novel engineered coated cutting tool designs. The difficulty comes in designing the coated "system" without losing the desirable properties of each constituent. This, however, forms the basis for interesting future research.

In this work, a series of tests have been run on commercially available coated carbide cutting tools to investigate friction as a function of atmospheric pressure in a dry, pure air environment. It is anticipated that knowledge of the interaction between coating material and environment may help improve the design of coated systems for specific machining applications.

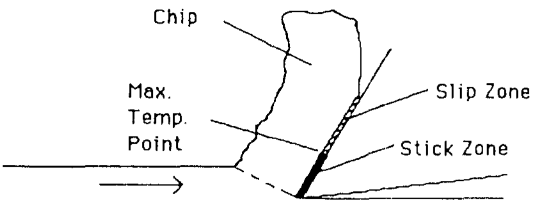

Fig. 1. Interaction of tool face and chip.

2. Experimental

A test device has been designed and constructed to enable controlled environment tribological testing in the horizontal block-on-ring configuration. The device consists of a stainless steel chamber containing the test specimens and load application mechanisms. A cross-section of the test chamber can be seen in Fig. 2. The ring specimen is mounted to a spindle that passes through a vacuum seal into the chamber. The loading arm also contains the block specimen holder (cutting tool insert) and is capable of both rotating and pivoting. The purpose of the loading arm rotation is to facilitate examination of the worn coating/cutting tool specimen utilizing spectroscopic ellipsometry or other optical techniques. The remainder of the test rig consists of a servo motor coupled to a torque meter (for heavy load applications), which is then coupled to a hollow drive spindle. The drive spindle has a slip ring at its far end, to facilitate power transfer to a resistance heater that can be used as an external heat supply to the ring specimen, if desired. For low-load ap-

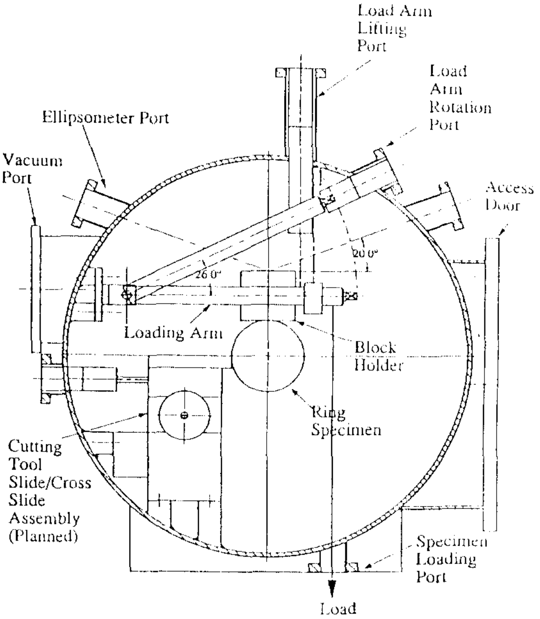

Fig. 2. Cross section of chamber interior components.

plications, a modified load arm may be used as can be seen in Fig. 3. Here, an integral pivot mechanism relays the friction force data to a load cell. A second load cell measures the applied normal load, transferred through a set of ceramic balls, to minimize exposure of the load cell to heat. Ring specimens are approximately 100 mm O.D., and of varying thicknesses and crown radii. Block specimens (tools) can be of varying shapes and sizes as well. The chamber itself is capable of controlled gas leakage; with a maximum achieved vacuum level of 5×10^{-8} torr.

The tests were run using annealed AISI 4130 steel rings with a 6 mm crown radius sliding against several coated tool surfaces. The load was 16 N, which translated to a maximum Hertzian contact pressure of 0.4 GPa. The sliding speed was 2.5 m/s. Tests were run by first pumping the chamber to approximately 2×10^{-7} torr vacuum and then backfilling with 2 ppm THC (total rydrocarbon) pure air (H_2O free). This essentially left the chamber filled with a clean nitrogen/oxygen mixture at atmospheric pressure. At that point, sliding tests were conducted for two minute intervals at each of the following pressures: 760, 1, 0.1, 0.01, 0.001, 1×10^{-5}, 1×10^{-6}, and 2×10^{-7} torr. Each test was repeated twice, and the average friction coefficients plotted.

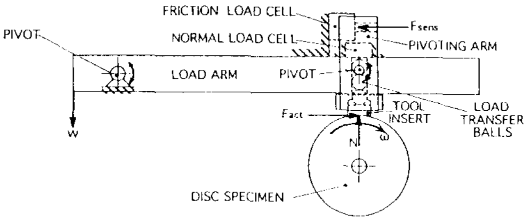

Fig. 3. Schematic diagram of experimental set-up.

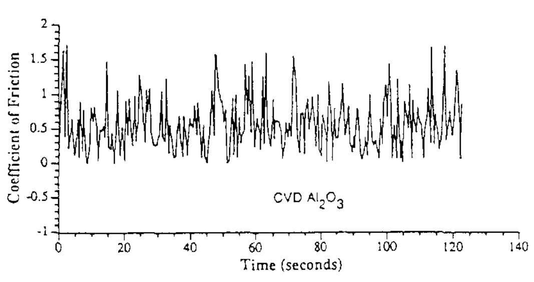

Fig. 4. Typical friction trace: 1×10^{-4} torr, CVD Al_2O_3.

The WC/Co (5.5-6% Co) tools were coated with PVD TiN; CVD TiC/TiCN/TiN, CVD TiCN/Al_2O_3/TiN; and CVD Al_2O_3. Tests were also run on uncoated WC/Co with and without 2% Ta for increased hot hardness. For this series of tests, the torque meter was used for friction determination. At the normal load of 16 N, friction torque values were at the low end of the torque meter sensitivity. This is believed to have caused the variation in the measured friction torque output, as can be seen in Fig. 4. This high level of friction torque variation at low loads disappears when using the modified load arm shown in Fig. 3.

3. Results and Discussion

A summary of the friction coeffcient value vs. chamber pressure can be seen in Fig. 5. It is apparent that the uncoated grades show the highest average friction coefficient values, initially at 0.5 to 0.6 (though somewhat high, recall that this system was first pumped to high vacuum and then filled with air

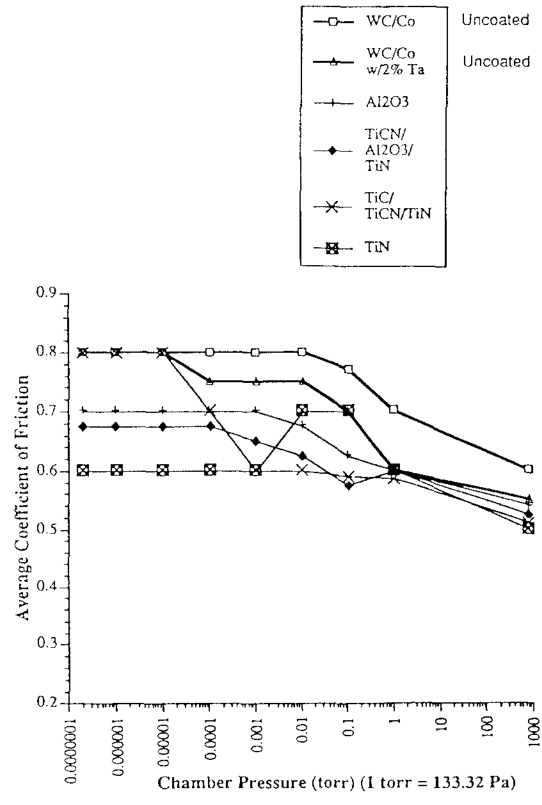

Fig. 5. Average coefficient of friction

having no H_2O vapor), then reaching 0.8 at elevated vacuum levels. For uncoated WC/Co, it appears that the 2% Ta reduces the friction coefficient up to approximately 1×10^{-5} torr, after which both uncoated grades tend to equate. For the coated specimens, coating life was in the range of 8 to 10 minutes, with the coating being removed at pressures of 10^{-2} to 10^{-3} torr. As seen in Fig. 5, not all friction traces ended up at the uncoated friction level (0.8), as in the cases of TiN, $TiCN/Al_2O_3/TiN$, and Al_2O_3. In the case of TiN, the friction level increased and then decreased above 0.01 torr. For most all materials, no change in friction was observed as the vacuum level exceeded 10^{-4} to 10^{-5} torr. The most significant change (increase) in friction occurred between 1000 and 0.01 torr.

As noted in [6], normal and shear stresses on the order of 1 GPa, coupled with chip velocities of 0.5 m/s and elevated friction coefficients, can equate to interfacial temperatures in excess of 650°C. Given that oxygen and nitrogen are present in the chamber, it is quite feasible that a tribochemical reaction occurs under the conditions of sliding. This situation may also occur in metal cutting processes, although as mentioned earlier, the actual environment may be more diffcult to define, particularly in high speed continuous cutting processes.

In order to differentiate the potential tribochemical mechanisms that operate across the tool face, it is necessary to run similar investigations under tighter test conditions. Thus, a particular coating material (non-composite coating) must be run in non-mixture environments (inert, oxdizing, etc.), at select pressure levels to develop a more thorough understanding of what is occurring. In addition, tribochemical analyses of the worn surfaces and transfer films (if any) will further aid in explaining the operating mechanisms of these tribosystems. Another potential active process is the formation of gaseous species due to the extreme condition of sliding. Whether or not there are any gaseous species formed, and how gaseous species impact tool face friction is another area of investigation. The desired outcome of this work is to gain a more thorough understanding of the mechanisms of interfacial friction in metal cutting. This knowledge may then by used to engineer specific coatings for optimal cutting of specific materials, or possibly even a wider range of materials. It may also be possible to design a controlled-environment test methodology under select conditions that serves as a tool for comparative studies of coating life and coating quality. This may then be useful in reducing the amount of test machining that must be done as part of the quality control and certification process.

One of the most recent developments in coated cutting tools is the use of polycrystalline diamond coatings, applied by various techniques. Another coating material that is receiving considerable interest is the cubic phase of BN, the second hardest material behind diamond. BN does not have diamond's chemical and thermal limitations, and thus is an important candidate coating material for cutting tools. Understanding the frictional characteristics of these materials under simulated cutting conditions will allow tool manufactures to maximize their utility in metal cutting processes.

With a properly engineered sliding interface, it may be possible to design a coating that combines the attributes of a low-friction interface away from the cutting edge, minimizing overall energy dissipation, while at the same time ensuring proper cutting edge protection for long tool life. These aspects will be important when searching for solutions to difficult applications such as machining hardened alloys as well as experiments in dry machining; and forms the basis for future research.

4. Conclusions

(1) A controlled-environment block-on-ring test apparatus has been designed and construced and has been applied to the study of coated cutting tools. Tests were conducted in pure air at various vacuum levels.

(2) The friction coefficient varied with vacuum level and with coating material, as expected. Friction values for the uncoated substrates were higher, in general, than the coated ones. Friction remained relatively constant when the vacuum level exceeded 10^{-5} torr.

(3) Friction coefficient values for some of the coated tools did not elevated to equated to those of the uncoated tools after the coating was worn through. This suggests the possibility of a tribochemical reaction between the gaseous species present in the chamber, the 4130 rings, and/or the coating material itself.

(4) To gain a more thorough understanding of the

friction mechanisms that operate along the cutting tool interface, it is necessary to characterize the actual operating environment along the cutting edge and maintain tighter control over the test conditions.

(5) Improved understanding of the friction mechanisms at the cutting tool interface may aid in the development of engineered surfaces capable of overcoming some of the more diffiult machining processes such as dry machining and the machining of hardened alloys.

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