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Enhancement of Wet- and MQL-Based Machining of Automotive Alloys Using Cutting Tools with DLC/Polymer Surface Treatments

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Machining experiments using tooling prepared with thin perfluoropolyether (PFPE) lubricant films, which were applied to diamond-like carbon (DLC) PVD coatings, were compared to traditional tooling used in wet-machining conditions for the drilling of a cast aluminum-silicon B319 alloy. Multi-layered DLC + PFPE coatings show promise under minimum quantity lubrication (MQL) machining conditions of aluminum alloys. The positive impact on performance of this surface treatment is compared to wet machining by studying tool life, wear behavior and chip formation using coated cemented carbide drill bits. Cutting torque was measured in situ together with the characteristics of the chips. Also the chip cross-section microstructure was evaluated using a scanning electron microscope (SEM).

Keywords chip formation, DLC coatings, green machining, MQL, PFPE, tool life

1. Introduction

The use of cutting fluids in metal working operations is deemed to have a negative impact on the environment. Consequently, many environmental agencies are recommending that manufacturers reduce the volume and the toxicity of their cutting fluids and hence go toward green machining, which is also known as environmentally friendly machining.

To date, realizing dry machining in practice has remained a significant challenge, particularly during the drilling of lightweight automotive alloys (Ref 1, 2). In dry machining lightweight alloys like aluminum, which exhibit a high degree of plasticity, generate strong adhesive interactions with the tool materials and therefore have a strong tendency to form a built-up edge (BUE). BUE is known to be an underlying reason for high-cutting torque, poor surface finish, and short tool lifetime (Ref 2, 3). A variety of hard coatings, such as diamond and diamond-like carbon (DLC) have shown the ability to significantly reduce BUE formation and hence greatly improve dry cutting performance (Ref 1-3).

Dry machining of aluminum has proved to be an exceedingly difficult goal due to intensive adhesion of aluminum to the cutting tool. This difficulty is illustrated by the large reduction in performance from more than 10,000 holes/drill with wet machining to only 40 holes/drill with dry machining when all of the other conditions remain the same (Ref 4).

Machining under Minimum Quantity Lubrication (MQL) conditions has caught the attention of researchers as an alternative to the traditionally used flood coolant systems and dry machining conditions (Ref 5, 6).

Drilling under MQL conditions is favorable because of the size and distribution of the droplets of oil achievable in the specially prepared aerosols generated in the MQL unit. These fine droplets result in several physical advantages such as a high degree of surface wetting as well as the ability of the extremely fine particles of lubricant to reach poorly accessible regions and penetrate micro-cracks or pores on the workpiece surface and so better lubricate the cutting zone. The friction, and thus the transfer of heat from the chip/workpiece to the tool, is also reduced. This is extremely important for the machining of automotive alloys. Effective lubrication can also play a critical role in aiding the removal of the chips along the flute of the tool and out of the hole (Ref 6-10).

The results of applying five different categories of DLC coatings under dry machining conditions were studied in (Ref 4). Hydrogen-rich DLC coatings were found to work best under dry drilling conditions with aluminum.

When the process was changed to semi-dry MQL machining, hydrogen-free DLC films appear to work best (Ref 11-14). This was also confirmed by studying samples in a friction tester chamber. When water vapor was introduced into the friction tester chamber, both the coefficient of friction (COF) and the wear rate of the hydrogenated DLC films was found to increase (Ref 11-14), whereas COF and wear rate decreased for non-hydrogenated films as water vapor was introduced (Ref 15).

It has been a challenge to further improve the frictional properties of the DLC coating and reduce the adhesive interaction between the tool and the workpiece. The approach taken in this research was to investigate the impact of friction and adhesion through the application of nano-scaled layers (less than 4-8 nm) of anti-frictional polymer PFPE films. These films

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have recently been applied to other heavily loaded machining applications where they have demonstrated their ability to reduce adhesion (Ref 16).

Fluorine-based lubricants like the PFPE group of polymers are widely used in practice under harsh environments. In the literature most of the attention is paid to the PFPE grades that are used for general tribological applications such as air bag triggering mechanisms in automobiles (Ref 16), bearings of spacecraft antenna arrays (Ref 16) and to lubricate the read head to disk interface in magnetic recording disk drives (Ref 17-19).

Far less attention has been paid to the application of these polymers to address the wear behavior of heavily loaded tribosystems prepared with these lubricious films. Also the maximum performance enhancement achieved for these PFPE films was limited by their thermal degradation under the high temperatures typically generated in the contact region of a cutting process (Ref 20).

However, some types of PFPE polymers have been specially developed for use in heavily loaded tribosystems such as those experienced during cutting. This is largely due to their improved thermal stability (Ref 20, 21). These films have been applied to reduce the sticking of aluminum and tool steels during drilling, tapping, or forming operations and have been found to improve tool life under wet conditions (Ref 22, 23).

The goal of this research is to transform dry cutting into a milder operating condition by doing the following:

– Improve the MQL cutting conditions;
– Enhance the lubricity of a DLC coating through the application of PFPE films.

2. Experimental

2.1 Sample Preparation

The experimental approach taken in this study focused on the adhesion of the workpiece material to the tool and the surface finish of the final hole.

A synthetic fluid for surface treatment based on perfluoropolyoxyalkane (0.5% solution of perfluorine polyester acid (R_f-CH_2OH) in Freon 113), which is also referred to as an epilam, was employed in this work. Epilams are multi-component systems, which contain fluorine-organic surface-active substances (fluorine-SAS) and controlling agents in various organic solvents (Ref 21). The epilamizing process involves applying the fluorine-SAS molecules on the surface of a frictional body. As a result, the epilamizing process forms a thin film of about 40-80 Å thick made from oriented fluorine-SAS molecules, which is fixed on the surface by chemo-sorption forces. This surface treatment has been found to lower the surface energy of the material and thus aid in retaining lubricants in the contact region during cutting. The maximum service temperature of this composition of PFPE was found to be around 450 °C (Ref 23), which is critical for semi-dry machining. Other properties of the PFPE surface treatment are summarized in Table 1.

The DLC drills were prepared with Balzers Triton coating, a-C:H coating that provides high hardness with a low-friction coefficient and thus gives good protection against adhesive wear and thus holds promise for MQL or dry working. These drills were then treated with the PFPE deposition process. The

Table 1 Physicochemical properties of the perfluoropolyether

Property	Value
Molecular mass, g/mole	2194
Density, kg/m^3	15.6
Thickness of the film, Å	40-80
Load-carrying capacity, Gpa	3-5
Maximum service temperature	450 °C

drills were cleaned with acetone, placed in a boiling fluorine-SAS-containing solution and kept at a temperature of 50 °C for 1 h. The process was run in a sealed container. After the PFPE film deposition, the tools were dried in a lab furnace at a temperature of 100 °C for 1 h. This drying process has been found to strengthen the chemo-sorption bond between the fluorine-SAS film and the treated surfaces (Ref 6).

To check the nominal quality of the deposited PFPE film, the wetting angle θ of an oil drop on the film was observed (Ref 17). The wetting angle θ is determined by measuring the contact angle that a liquid oil lubricant makes when in contact with the coated surface. The wetting angle value characterizes the ability of a liquid to form a boundary surface with a solid. The wetting angle θ should be equal to or more than 72° for this coating and an oil drop, having a diameter of 2-4 mm, should not move when the surface is tilted by 45°. In all cases, these conditions were met with the samples prepared.

2.2 Cutting Test Procedures

Wet machining experiments were first performed to provide a baseline for comparison for further experiments under 'green' or semi-dry (MQL) machining conditions. Tool life, wear behavior, and chip formation of the coated cutting tools were all compared. Approximately 1000 holes were drilled with two types of coatings (DLC; DLC + PFPE) and the progression in flank wear rate was compared. An OKUMA Cadet-Mate milling machine was used for the drilling tests.

The cutting torque was measured using a Kistler 9255B table dynamometer and associated charge amps and National Instruments data acquisition equipment. The surface finish of the drilled holes was measured using a Zygo Newview 5000 white light interferometer. Two types of 6.35-mm (¼ inch) cemented carbide twist drills from OSG, Japan, were employed to study wear behavior: solid cemented carbide drills for wet machining and custom made cemented carbide drills with two through holes to supply mist for the MQL machining.

The test involved drilling holes in 28 × 15 × 2.5-cm sand-cast B319 plates (Al-base, Si-5.5-6.5, Cu 3-4, Fe, Mg, Ni—less than 1 wt.%) with T6 heat treat (BHN500 hardness = 100). The cutting conditions were: speed 94 m/min; feed 0.13 mm/rev. Cutting tests were performed with and without pecking. Pecking was considered in an effort to improve the amount of lubricant in the cutting zone. Wet and MQL conditions are summarized in Tables 2 and 3.

For each coating and set of cutting conditions the flank wear was measured and plotted versus the number of holes drilled. The wear rate of the different coatings was compared after 1000 holes.

Surface morphology of the worn drills as well as the microstructure of the cross-section of the chips was analyzed using an analytical scanning electron microscope (SEM, Philips XL-40, 20 kV).

Table 2 Wet conditions

Lubrication	Commonwealth oil, commcool plus
Application	Flood
Total depth of cut	19 mm, blind hole

Table 3 MQL conditions

Lubrication	Commonwealth oil, mystie blue
MQL unit	AccuLube 02A0-DM0
Air pressure	100 PSI
Pecking cycle	4 mm peck with a full retract
Total depth of cut	19 mm, blind hole

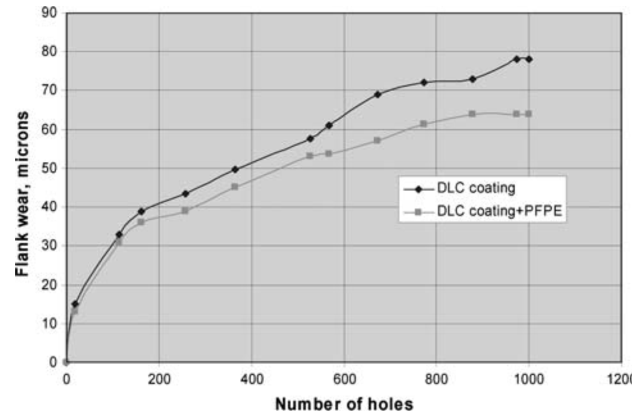

Fig. 1 Wear rate of the drill bits with DLC and DLC + PFPE coatings under the wet machining conditions after 1000 holes

3. Results

3.1 Wet Machining of Aluminum Blocks

The resulting wear rate for the drilling tests performed under wet machining with and without PFPE lubricant is shown in Fig. 1, showing reduced wear with the PFPE lubricant. A comparison of the cutting torque reveals an average torque of 4.30 Nm for a DLC drill and 3.71 Nm for the DLC + PFPE drill.

Images of the worn drills show that the PFPE film shifts the friction behavior to a milder condition as shown in Fig. 2. Overall a lower intensity of material pick-up was observed for the DLC + PFPE-coated drills after completing 1000 holes. The microstructure of the cross-sections of the chips showed that the PFPE-coated drills performed better than the drills without the PFPE treatment (Fig. 3). The drills without the PFPE treatment have intensive plastic deformation that occurred within the flow zone due to intensive sticking of the aluminum to the tool surface. Due to the sticking, low curling chips are formed under this condition (Fig. 3a). In contrast, a lower intensity plastic deformation within the flow zone can be observed for the drills with the PFPE deposition as shown in Fig. 3(b). Tightly curled chips are formed for the drills with PFPE films (Fig. 3b). A comparison of the surface finish of the drilled holes shows a better finish for the holes drilled with the DLC + PFPE coating at an R_a = 0.183 μm as compared to the drills with just the DLC coating having an R_a = 0.328 μm.

All of these factors indicate the favorable frictional conditions associated with the better lubricity provided by the DLC + PFPE coating under the wet drilling conditions.

3.2 MQL Machining of Aluminum Blocks

Semi-dry (MQL) machining experiments were also performed to investigate the tool life, wear behavior and chip formation of the coated cutting tools for comparison to the results performed under wet machining conditions.

Again 1000 holes were drilled under the MQL conditions both with and without the PFPE film deposition. Drilling with pecking showed some improvement with the number of holes produced being more consistent as shown in Fig. 4. Drilling with the current MQL conditions without pecking resulted in the same intensive wear rate as for dry drilling. It is questionable if the fine mist generated by the MQL unit used in this setup was reaching the cutting zone when pecking was not used. It is very difficult to speculate on the fluid in the cutting zone, but the improvement that comes with pecking is attributed to the opening of the cutting zone, which allows more coolant to enter periodically during cut. The further tool life improvement achieved with the application of the PFPE treatment on the DLC-treated drills is attributed to the ability of the PFPE to hold the available fluid in the cutting zone for a longer period of time. This is also evident from the cutting torque as shown in Fig. 5. It shows significant variation in torque without PFPE and increasing values after the running-in stage of wear as compared to the more steady torque values for the case with PFPE. The initially lower values for torque for the MQL DLC drill without PFPE are attributed to normal experimental variation with the trend in the data being the important result in this case. Overall the PFPE-coated drills generally performed better than the untreated ones. Also the average torque of 3.71 Nm as reported earlier for the wet DLC + PFPE drill is very close to the values shown in Fig. 5 for the MQL case with DLC + PFPE and pecking.

SEM micrographs of the worn surface of the drill and cross-sections of the chip shown in Fig. 6 exhibit the transformation of the cutting process to a milder friction condition. The DLC drills without the PFPE treatment have more intensive material build up, whereas the drills with the DLC + PFPE coatings showed a lower intensity of build up. A study of the microstructure of the cross-sections of the chip (Fig. 7) revealed that significant plastic deformation takes place within the flow zone due to sticking of aluminum to the tool surface for the drills with only the DLC coating, with a much lower plastic deformation for the drills with the DLC + PFPE coating due to their better lubricity as shown in Fig. 7. PFPE film deposition effectively lubricates the drill surface and promotes chip evacuation during cutting under MQL as well as under wet machining conditions.

4. Conclusions

An improvement in the frictional properties of cutting tools prepared with DLC + PFPE coatings was observed for MQL machining conditions of automotive aluminum-based materials by means of the deposition of the polymer-based lubricious films. Overall the PFPE surface treatment was found to reduce the cutting torque as well as increase tool life and improve the surface finish of the machined part. Investigations of the

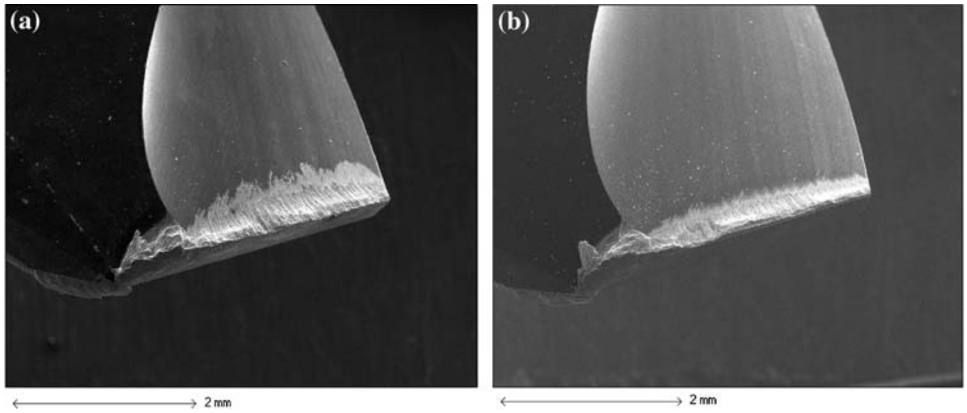

Fig. 2 SEM micrographs of the worn surface (after 1000 holes) of the drills with: (a) DLC coating; (b) drills with DLC + PFPE coatings after wet machining

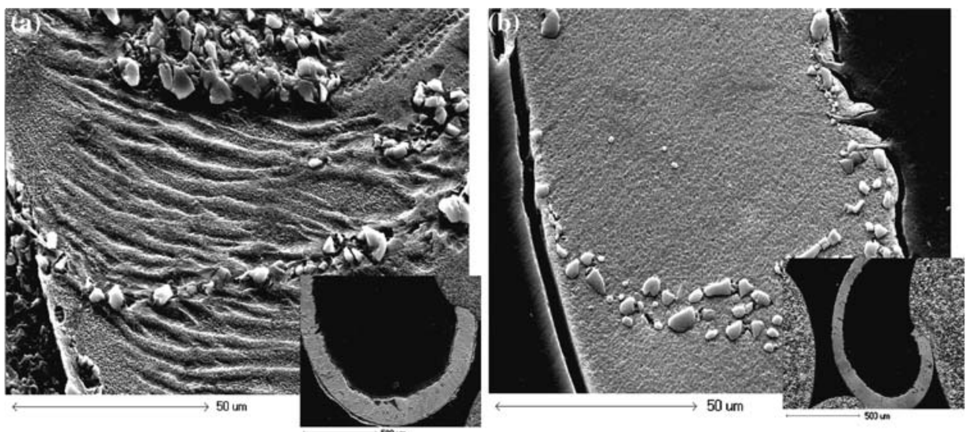

Fig. 3 SEM micrographs of the chips cross-sections after the wet drilling of aluminum (1000 holes): (a) without PFPE coating (DLC); (b) with PFPE coating (DLC + PFPE)

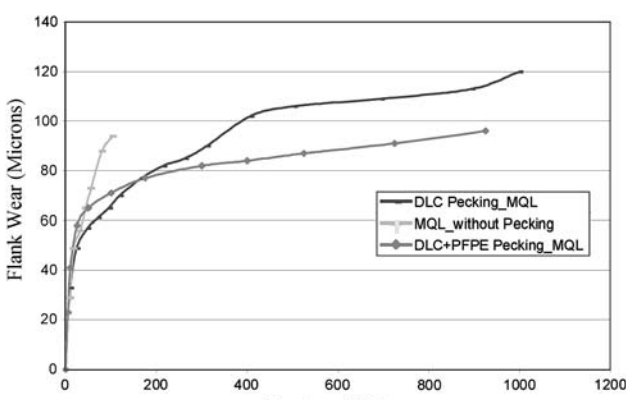

Fig. 4 Wear rate of the drill bits with DLC and DLC + PFPE coatings under conditions of MQL drilling of aluminum with and without pecking

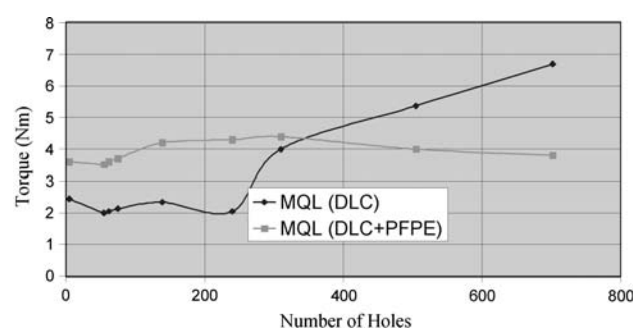

Fig. 5 Cutting torque during MQL machining of aluminum using cutting tools with DLC and DLC + PFPE coatings

microstructure of the cross sections of the chips indicate better lubricity at the tool/chip interface when multi-layered DLC + PFPE lubricating coatings were used.

In this article a cutting tool with multi-layered DLC + PFPE lubricating coating showed a moderate wear rate under conditions of MQL with pecking. Although the wear rate is slightly higher under MQL conditions with pecking compared to straight wet machining, the resultant torque is similar.

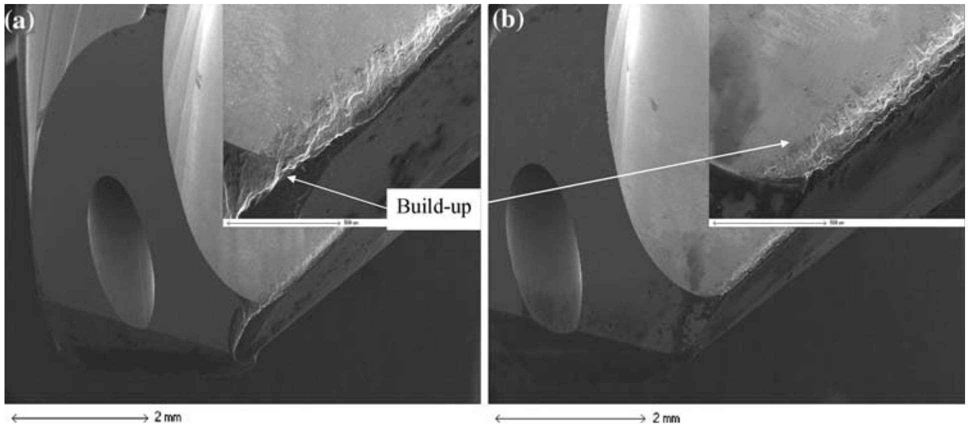

Fig. 6 SEM micrographs of the worn surface (after 1000 holes) of the drills with: (a) DLC coating; (b) drills with DLC + PFPE coatings after MQL machining

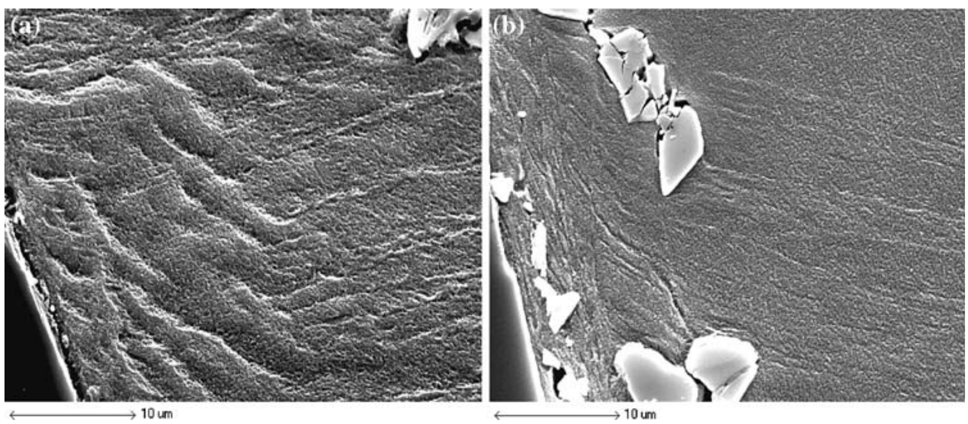

Fig. 7 SEM micrographs of the chips cross-sections after the MQL drilling of aluminum (1000 holes): (a) with PFPE coating (DLC + PFPE); (b) without PFPE coating

Overall the multi-layered DLC + PFPE coating shows promise during wet and MQL machining of aluminum alloys. Future work will focus on improving the MQL setup to achieve better wetting of the contact zone to eliminate the need to peck during the drilling cycle.

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