Characterizing Performance and Impact of Nanocrystalline Diamond Coatings on Micro End Milling

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ABSTRACT

Currently, the standard material used for micro end mill tooling is sintered tungsten carbide with a cobalt binder. Its brittle nature coupled with the micro-scaled cutting features of the end mills often result in rapid tool degradation. Tool life and cutting performance can be significantly improved using a thin nanocrystalline diamond (NCD) coating. The high hardness (~90 GPa), low coefficient of friction (~0.2), and chemical inertness of diamond help reduce tool wear, adhesion of workpiece material, and overall cutting and thrust forces. This study measures the performance of hot-filament chemical vapor deposited (HF-CVD) diamond coatings on micro end mills. Tool performance is evaluated by dry milling full-width channels in 6061-T6 aluminum.

Previous research has shown that a 75% reduction in cutting forces can be achieved when applying a fine-grained diamond coating (500-600 nm diamond grains) to a 300 μm diameter end mill that is machining 6061-T6 aluminum. The fine-grained diamond coatings are 600-1000 nm thick, and occasionally suffer from significant (*i.e.*, large area) coating delamination that leads to a jump in forces followed by catastrophic tool failure.

To improve the diamond coating adhesion, a seeding technique with a higher concentration of nano-diamond particles is implemented. The higher nucleation density results in the synthesis of smaller grained (< 100 nm) and thinner continuous diamond coatings (100-300 nm) that can be classified as NCD. The cutting forces measured for NCD-coated tools are 50% less than for tools coated with fine-grained diamond. The delamination behavior improved for the NCD coatings: significantly smaller areas delaminate after which gradual increases in cutting forces and changes in the workpiece surface finish are observed.

INTRODUCTION

Micro end milling is an increasingly important micro-manufacturing process. As the direct scale down of macroscopic end milling, micro end milling is a material removal process that can generate high aspect ratio, three-dimensional features in a single step [1-3]. It is not limited to special clean room environments, and is compatible with myriad engineering materials such as polymers [4], metals and metal alloys [4, 5], pre-sintered and fully-sintered ceramics [6], and metal matrix composites [7].

There are several important challenges to overcome when scaling down end mills to microscopic sizes. Sintered tungsten carbide with a cobalt binder is brittle and the micro-scaled features of the end mills often result in rapid tool degradation [1, 2]. Also, due to their small diameter, micro end mills have low flexural stiffness and strength [8, 9]. Relatively small cutting forces can significantly bend the tool, negatively affecting the cutting process and potentially causing catastrophic tool failure [1, 2]. To avoid this, cutting forces must be maintained below a critical value by ensuring that the uncut chip thickness (*i.e.,* the chip load) remains sufficiently small. For many high-strength materials (*e.g.,* steel, titanium, etc.) the maximum allowable chip load is on the order of or less than the cutting edge radius [8, 9], which for typical micro end mills is <1.5 μm. This can result in material being removed by a rubbing or burnishing process rather than a cutting process, accelerating tool wear and producing a poor surface finish [1, 2, 9]. Also, any chips adhering to the tool will eliminate a path for chips to evacuate the cutting zone. This will result in a spike in the cutting forces, often leading to catastrophic tool fracture due to the low flexural strength of the tool.

Diamond coatings for micro end mills are promising because of their potential to eliminate many of the limitations currently hindering micro end mill performance and operational life. Previous micro drilling studies using HF-CVD diamond coatings indicated a threefold increase in the number of acceptable holes drilled in both printed circuit boards (typically a phenolic, glass fiber, and epoxy composite), and aluminum workpieces when compared to an identical uncoated tool [10, 11]. These machining improvements are due to many favorable mechanical and tribological properties that diamond coatings possess, such as high hardness, chemical inertness, low adhesion to aluminum, and low friction against aluminum [11-13]. The low adhesion to aluminum helps prevent chips from adhering to the flute surface, hence reducing tool clogging and associated sporadic force spikes [11, 12]. This,

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and the low coefficient of friction, reduces the forces exhibited on the cutting tool [13]. The high hardness reduces the rate of abrasive tool wear [1, 11-13].

However, the nucleation and growth techniques used for conventional microcrystalline diamond (MCD) coatings for macro-scale cutting tools often result in coatings that are too thick (2 – 100 μm) for micro tools. These coatings would significantly increase the ~1.5 μm cutting edge radius, blunting the tool. As it is, the existing cutting edge radius of uncoated tools is larger than desirable, and increasing the cutting edge radius will negatively affect machining performance. MCD films, with grain sizes typically ranging from at least 100 nm up to several μm are also too rough for micro tools. In addition, they have inferior strength [14] and much higher friction [13] than NCD films. To take advantage of the best properties, nanocrystalline diamond (NCD) coatings for micro end mills are investigated here. By achieving high nucleation densities, we are able to repeatedly produce thin (~100 nm) continuous films with an average grain size of approximately 50 nm and a measured roughness of 30 nm on 300 μm diameter end mills. This work characterizes the cutting performance of these thin NCD coatings when dry cutting 6061-T6 aluminum.

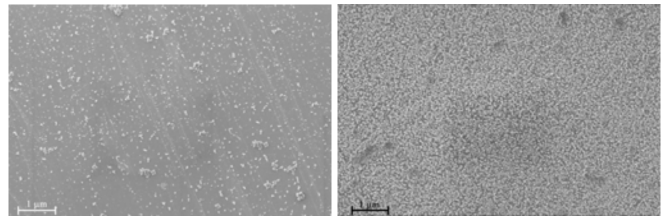
EXPERIMENTAL PROCEDURE

A. DIAMOND SYNTHESIS

Diamond coatings were synthesized on 300 μm diameter, two-flute, tungsten carbide (WC) end mills with an approximate cutting edge radius of 0.5 μm using hot filament chemical vapor deposition (HF-CVD). The micro end mills are a commercially available design (Performance Micro Tool, Inc.) and contain 6-8% cobalt (Co) binder located at the WC grain boundaries. Each tool is initially inspected via SEM for defects and is sorted based on the tool diameter. Defect-free tools are then subjected to a three step nanocrystalline diamond (NCD) synthesis process: etching, seeding, and diamond synthesis. A hydrofluoric based acid etch is used to selectively remove cobalt from the surface of the tool since cobalt inhibits the growth of diamond. Diamond nanoparticles are seeded on the tool surface to create nucleation sites for diamond growth. The tools are then placed into the HF-CVD vacuum chamber (base pressure 0.10 Torr). A mixture of 4% methane (flow rate 3.75 SCCM) and 96% hydrogen (flow rate 90 SCCM) at a pressure of 30 Torr flows over tungsten filaments at 2000°C, dissociating the gases which then impinge on the tool and react to synthesize diamond. A detailed description of the synthesis process is presented by Heaney *et al*. [15].

B. SEEDING

Nano-diamond particles are seeded onto the tool surface to help promote the diamond growth process and control where growth nucleation occurs [11]. Each of the seeded diamond particles produce a nucleation site for initial diamond growth, hence, a dense, uniform seeding procedure is ideal for producing thin, conformal diamond coatings. Typically,



(a) ***(b)***

Fig. 1 SEM image of the diamond nucleation density on a silicon substrate for: (a) DET diamond seed (b) UDD diamond seed.

diamond growth occurs in a columnar fashion [16], requiring extensive diamond growth to occur for complete film coalescence of a poorly seeded surface. The long growth time will often result in large-grained (~1 μm), thick diamond films (> 1 μm).

Mirco end mills were seeded using two different diamond seed solutions. The first solution was a mixture of a dry detonation nanodiamond powder (DET) composed of 20-50 nm diameter particles, dissolved in methanol. However, the dry diamond particles often agglomerated, resulting in diamond seeds 60-80 nm in diameter. The tool tips were suspended within the solution and ultrasonically treated to attach the diamond seeds onto the tool surface. This type of seeding method resulted in diamond particle coverage of 7.3% of the tool surface area as determined from SEM images (Fig. 1a). The other diamond solution consisted of ultra dispersed detonation (UDD) nanodiamond particles (25-30 nm) suspended in dimethylsulfoxide diluted in methanol. Seeding coverage for this method is approximately 59.8% (Fig. 1b). After 15 minutes of seeding, the tools were ultrasonically rinsed for 10 minutes in a methanol bath to remove large diamond particle agglomerations from the surface of the tool. Figure 1 compares the coverage of the two seeding methods on polished silicon samples. The smooth silicon allow for easy visibility of the diamond seeds.

The larger diameter, less dense DET diamond seed requires a minimum growth time of 20 minutes to produce a completely coalesced diamond film. The long growth time is primarily attributed to the low nanoparticle density (Fig. 1a) and thus, a low density of nucleation sites. The low nucleation site density required extensive diamond deposition to occur before the diamond grains began to coalesce and form a continuous film. Fig. 2 contrasts the amount of growth required before film coalescence for low and high density seeding.

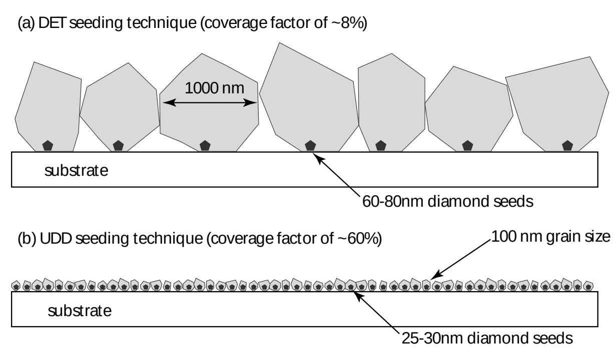
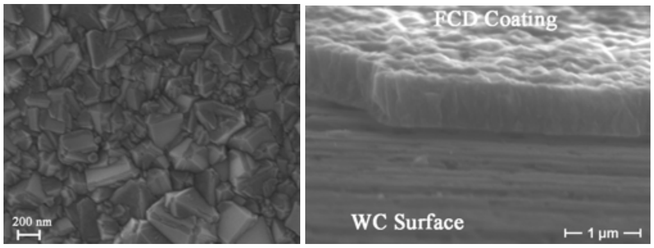


Fig. 2 Comparison of diamond growth for: (a) low nucleation density, (b) high nucleation density.



(a) (b)

Fig. 3 SEM micrograph of fine-grained diamond coating. (a) Top profile view. (b) Side profile view depicting a coating thickness of 650 nm.

This growth time resulted in a minimum coating thickness of approximately 600 nm, with most coatings being approximately 1 μm thick for complete coalescence. The long growth time resulted in diamond grains measuring between 500 nm – 1000 nm (Fig. 3).

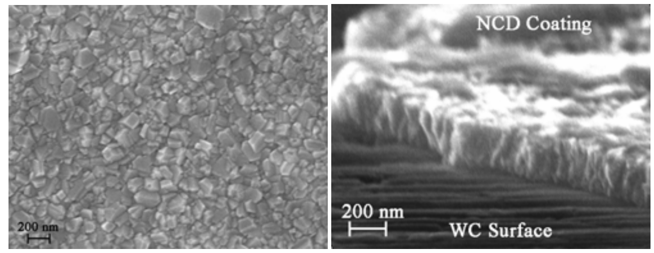
Typical DET-seeded diamond-coated tools experienced an increase in cutting edge radius of approximately 120% (measured via SEM), which resulted in an overall cutting edge radius of approximately 1.2 μm. Generally, tools that have experienced significant blunting from diamond coatings have broken immediately on contact during machining.

The high seeding density of UDD-seeded diamond requires a 5 minute growth time to achieve a completely coalesced coating. Coatings as thin as 110 nm have been grown with typical coatings between 200-300 nm thick with NCD grain sizes <100 nm (Fig. 4). The typical cutting edge radius of UDD-seeded NCD-coated tools is approximately 850 nm, which is approximately a 54% increase (measured via SEM) over the as-ground edge.

C. FRICTION TESTING

Friction measurements of diamond-coated and uncoated tungsten carbide (WC) spheres against flat 6061-T6 were made on a commercially available Falex pin-on-disk tribometer. The system uses an arm connected to a 'frictionless' gimbal to hold the pin sample. The normal load is applied via dead weight loading and the friction coefficient is measured using a force transducer attached to the arm of the system. The pin sample is held stationary while the disk below it rotates, inducing a frictional force that is measured by the system. The unit outputs an analog voltage representing the friction coefficient. This voltage is read by a National Instruments data acquisition card (PCI - 6036E) and recorded along with the ambient temperature and humidity level.

Polished WC spheres (1/8" diameter, Ra=4.5 nm, Rq = 9.6 nm), were used as the pin samples during the tribometry testing. The WC spheres were diamond-coated and tested against uncoated samples. However, the highly polished surface of these samples does not accurately represent the roughness and waviness of the WC end mills that is a result of the grinding process used to make them. A 1 N normal load with a sliding speed of 10 mm/s were used during the tests.



(a) (b)

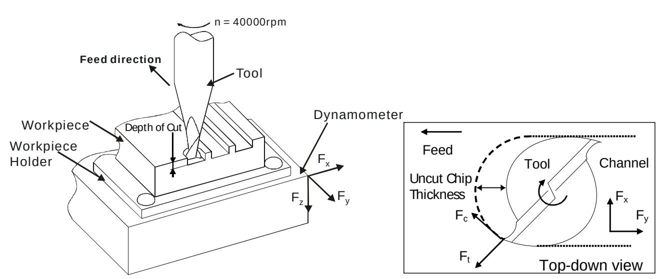
Fig. 4 SEM micrograph of NCD diamond coating: (a) Top profile view, (b) Side profile depicting a coating thickness of 270 nm.

D. MICRO END MILL TESTING

Fig. 5 illustrates the test setup used for the machining experiments. A high-speed spindle (NSK-HES500) with electric drive and ceramic bearings was mounted to the spindle of a CNC milling machine (HAAS TM-1). A constant spindle speed of 40,000 rpm and feed rate of 500 mm/min were used to dry mill full-width slots in 6061-T6 aluminum for all of the experiments (Table 1).

Forces acting on the workpiece were measured by a three-axis force dynamometer (Kistler 9256C2). The dynamometer was able to dynamically measure the cutting forces in the *x*, *y* and *z* axes. LabView software and National Instruments data acquisition hardware (NI PCI 6014) were used to record the force data at a rate of 60 kHz. Both uncoated and coated tools were tested in the same batch to ensure compatibility. A humidity control system was used to maintain a constant relative humidity of approximately 85% at the tool-workpiece interface.

The machining conditions used are shown in Table 2. The tests consisted of dry machining a single full-width channel 5 mm long and 100 μm deep, in a 50 mm x 50 mm x 4.8 mm 6061-T6 aluminum block. The workpiece was mounted on the dynamometer before its surface was prepared by facing with a one inch end mill to ensure flatness within 3 μm. Each tool was fixtured in the high speed spindle and then aligned to the workpiece using an optical magnification system. The alignment uncertainty was ± 10 μm in the z-axis, which corresponds to an uncertainty in the depth of cut.



(a) (b)

Fig. 5. Schematic of micro end milling: (a) 3D view of the experimental setup, (b) end view of the cutting process.

Table 1: Machining Conditions

Workpiece Material	6061-T6 Aluminum
Temperature / R.H.	~23°C / ~85%
Tool (end mill):	PMT Model TS-2-0120-S
Material	0.4 µm grain WC-Co
Diameter	300 µm (0.012 in.)
Flutes	2
Helix	30º
Spindle Speed	40,000 ± 500 RPM
Feed	12.5 µm/rev
Chip Load	6.125 µm
Coolant	None
Depth of Cut	100 ± 10 µm

RESULTS AND DISCUSSION

A. REDUCTION OF CUTTING AND THRUST FORCES

Heaney *et al*. [15] showed that a micro end mill coated with fine grained diamond (FGD, grain size ~500 nm) requires significantly less force to cut aluminum than bare tungsten carbide. For a 6.25 µm chip load, the main cutting and thrust forces are reduced from 2.14 N and 4.40 N to 0.49 N and 0.34 N, respectively, when adding an FGD coating to WC tools (Fig. 6). This force reduction occurs despite the fact that the relatively thick FGD coating (~1 µm) increases the cutting edge radius by 120%. Even smaller cutting forces are measured for thin (~200 nm) NCD-coated cutting tools. The NCD coatings further reduce the cutting and thrust forces to 0.18 N and 0.17 N, respectively (Fig. 6).

The cutting and thrust forces measured for the diamond-coated tools are more balanced, while the uncoated tools exhibit a thrust force that is twice the cutting force. This balance in forces indicates a more ideal cutting process with minimal ploughing, burring, or adhesion of chips in the flutes.

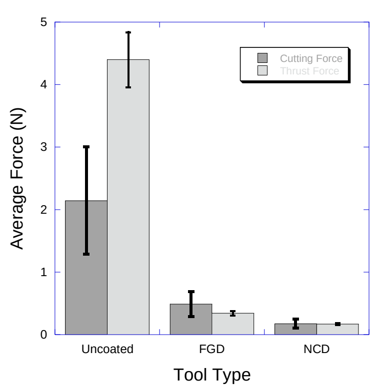


Fig. 6. Cutting and thrust force comparison between an uncoated, a fine grained diamond-coated, and a nanocrystalline diamond-coated end mills.

The lower magnitude in forces for diamond-coated tools means that the specific cutting energy is lower. Therefore, less energy is being converted into heat resulting in lower cutting zone temperatures.

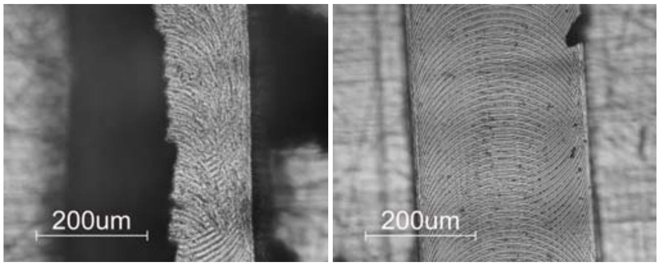
The reduction in forces between bare WC and diamond-coated tools (not attributable to burr formation or ploughing) is caused by a reduction in friction and/or adhesion. Here we present data showing the reduction in friction (Table 2). However, we also observe that dry end milling with the uncoated WC tools produces continuous chips from an interrupted cutting process. The only way this could occur is if a chip is created by the cutting edge, adheres to the flute face, and is then pushed along the flute by the next chip that is generated. In the process of pushing, the two chips are welded together. This process repeats itself creating a continuous chip. The diamond-coated tools do not produce these continuous chips since there is less friction and less adhesion of aluminum to the tool surfaces.

The cutting force reduction between the larger grained FGD and smaller grained NCD coatings can be attributed to the thickness and roughness differences. As mentioned previously, the FGD coating (~600 nm thick) results in a cutting edge radius of approximately 1.2 µm, whereas the NCD coating (~200 nm thick) results in cutting edge of approximately 0.85 µm. The increase in cutting edge radius, *i.e.*, a blunter cutting tool, will directly result in a higher cutting and trust forces. The exact relationship between cutting edge radius and forces will be determined in future studies by growing NCD coatings of various thicknesses, but the same roughness.

The tribometry tests verify the overall reduction of friction between an aluminum surface and a bare WC and diamond-coated surface. The bare WC surface produced a coefficient of friction of approximately 0.55, while the NCD-coated WC sphere produced a coefficient of friction of approximately 0.35 (Table 2). Data for the FGD-coated sphere is not available because the coating delaminated before sufficient measurements could be made. The difference in the surface roughness of the FGD and NCD coatings is presented in Table 2. Changes in surface roughness are known to correlate with friction coefficient for diamond films [13], therefore, it is expected that the friction coefficient of the NCD coating will be less than the FGD coating. More

Table 2: Tribometry Results against 6061-T6

Coating	Bare WC	FGD	NCD
Thickness	–	>600 nm	100-300 nm
Grain Size	–	500-1000 nm	20-100 nm
Ra	4.5 nm	27.4 nm	17.6 nm
Rq	9.6 nm	32.5 nm	22.2 nm
µ	0.55	–	0.35



(a) *(b)*

Fig. 7 White light interferometric images of end milled channels in 6061-T6 aluminum using: (a) uncoated end mill, (b) FGD-coated end mill.

tribology tests will be conducted to verify this as the friction coefficient will directly impact the force needed to move the chip along the rake face of the tool.

B. TOOL AND WORKPIECE COMPARISON

Previous results have indicated significant amounts of aluminum adheres to the cutting edges and tool flutes for uncoated WC tools, while the diamond-coated tools exhibited very little to no workpiece adhesion. In several instances, the aluminum adhesion on the uncoated tools led to either complete tool fracture, or partial fracture of a cutting flute. In addition, the milled channels for the diamond-coated tools exhibited little burring and produced a highly patterned, uniform bottom surface, while the uncoated tool produced significant amounts of burring and a sporadic surface finish (Fig 7).

C. TOOL INTEGRITY

Diamond-coated WC end mills show significant improvement in both cutting performance and surface finish when compared to bare WC end mills under dry machining of aluminum. However, these performance gains are only experienced as long as the diamond coating survives. In several instances during testing, the diamond coating delaminated during milling. As found previously, upon delamination, tools with the thicker and larger grained FGD coating either return to a state of performance similar to an uncoated tool, or suddenly catastrophically fail. In either case, coating delamination occurs almost instantaneously with very little indication of coating failure beforehand. These coating failures are easily seen in an abrupt increase in measured force exhibited by the tool on the workpiece (Fig 8).

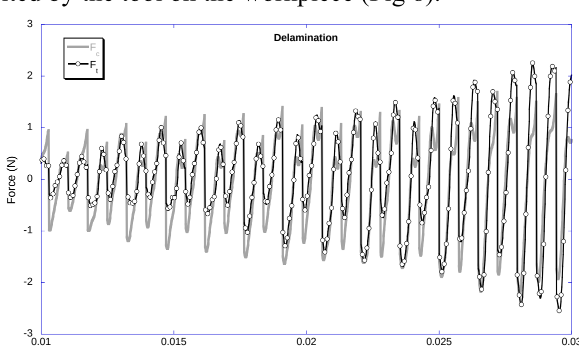
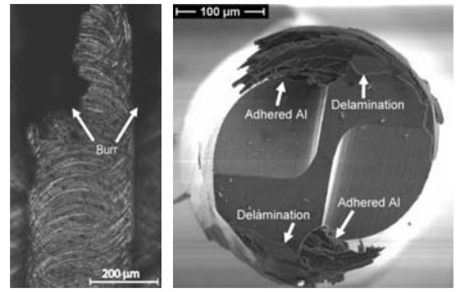


Fig. 8 Measured cutting and thrust force during delamination of a FGD-coated end mill.



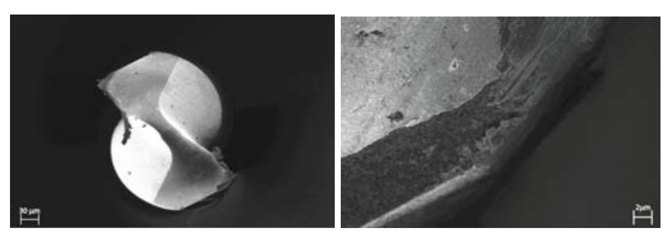
(a) *(b)*

Fig. 9 (a) White light interferometric image of milled aluminum channel during NCD coating delamination (b) SEM image of delaminated NCD-coated micro end mill.

Further examination of the milled channel reveals a clear location where delamination of the FGD-coated tool occurs. The channel in Fig. 9(a) depicts such a scenario where the FGD-coated tool delaminated approximately halfway through the imaged section of the channel. Before delamination, the mill produced a clean, uniform channel with very little burring. After coating delamination, burring of the workpiece immediately began. In addition, the channel bottom produced a very sporadic surface topography. This happened in approximately 80% of the tests conducted under the conditions used in Table 1.

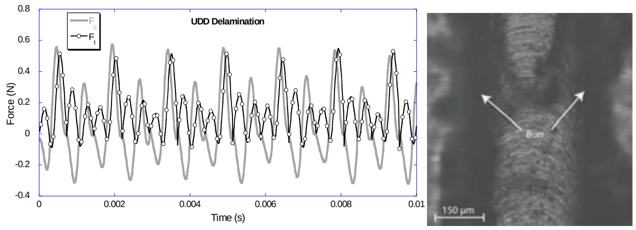
Coating delamination is also apparent upon further inspection of the FGD-coated end mills using an SEM (Fig. 9b). Large portions of the tool coating are fractured from the tool tips and cutting edges, and continue along the flank face of the end mill. Aluminum workpiece material has adhered to the underlying WC tool surface, resembling the tool condition and performance of the uncoated end mills tested previously. In several instances, the tool would catastrophically fracture immediately after coating delamination. The vast propagation of the delaminated coating throughout the tool suggests a weak adhesion between the WC tool surface and the FGD coating.

Some of the smaller grained and thinner NCD-coated tools exhibit coating delamination over significantly smaller areas. Delamination was observed in approximately 40% of the tests. Fig. 10 shows a typical example of how NCD coating delamination is restricted to the high stress areas of the cutting tips and edges. The failure does not propagate further along the faces of the tool. This raises the possibility that the underlying WC structure failed, taking the coating with it, meaning the event is tool fracture, not delamination, so we refer to it generically as "tool wear". The high wear areas



(a) *(b)*

Fig. 10 SEM image of: (a) delaminated NCD-coated end mill, (b) worn flank face edge of end mill with areas of adherent aluminum



(a) ***(b)***

Fig. 11 (a) Measured cutting and thrust force from a delaminated NCD-coated end mill, (b) White light interferometric image of milled aluminum channel from a delaminated NCD-coated tool.

along the flank face of these end mills have also experienced loss of the NCD coating (Fig. 10).

The cutting force traces do not provide clear evidence of when the tool wear event occurred (Fig. 11a). The peak magnitudes of the forces remain relatively constant throughout the test cut. Inspection of the workpiece channels after milling also produces the same inconclusive results (Fig. 11b). Therefore, the tool wear either occurred rapidly upon the tools first contact with the workpiece, or resulted in very little change in the cutting forces. The delaminated NCD-coated tools produce a uniform surface finish with little indication of any workpiece smearing, but an observable amount of burring is apparent throughout the length of the cut. Overall, the amount of burring is not as considerable as the amount created by an uncoated end mill.

CONCLUSIONS

It has been demonstrated that thin diamond coatings (100 nm – 500 nm) significantly reduce cutting forces for micro end mills dry cutting aluminum compared to bare tungsten carbide tools. Using fine grained diamond (0.1 – 1 µm grain size; 0.5 – 1 µm thick) and nanocrystalline diamond (10-100 nm grain size; 100-200 nm thick) coatings results in cutting force reductions of 75% and 88%, respectively, compared to bare tungsten carbide. The cutting force reduction between tungsten carbide and diamond is attributed to the lower friction coefficient and adhesion with aluminum. The cutting force improvement between the fine grained diamond (FGD) and nanocrystalline diamond (NCD) coatings is attributed to a reduction of the cutting edge radius (thinner coating) and reduced surface roughness and associated friction due to the smaller grained diamond. Diamond-coated tools produce cleaner, burr free channels with very little work piece adhesion to the surface of the tool. When FGD coating delamination occurs, it happens over large areas of the tool surface, and can be detected in the cutting force data. Tool performance returns to that of an uncoated tool, and in some instances results in immediate tool fracture. Wear of NCD-coated tools occurs locally at the cutting edges, does not result in a noticeable change in cutting forces, and does not change the characteristics of the aluminum channel that is cut.

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