# Effect of Nanocrystalline Diamond Coatings on Micro-End Milling Performance

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#### ABSTRACT

The growing interest in high precision machining to fabricate miniaturized parts for medical devices, micro-satellites, and the optical industry with meso-scale machine tool systems (mMTs) requires high-performance micro-end mills with diameters ranging from 10 to 500 microns. This technology complements standard silicon-based microfabrication processes with its ability to directly produce true 3D structures with high accuracy, low cost, and short cycle time. One important aspect of micro-end milling which influences precision machining is the choice of tool materials. Presently, tungsten carbide (WC) with cobalt binder is widely used as a standard material. However, these tools suffer from a limited operational life and have difficulty in machining adhesive metals such as aluminum and copper. We have developed a new approach in growing a sub-micron thick coating of nanocrystalline diamond (NCD) on tungsten carbide micro-end mills using the Hot Filament Chemical Vapor Deposition (HF-CVD) technique. The sub-micron thickness of the coating minimally alters the radius of curvature at the cutting edge. NCD's high hardness (~ 80 GPa) and low friction coefficient (0.02 - 0.04) result in excellent wear resistance and lowered cutting forces, respectively. We have used this growth method to obtain uniform, conformal NCD coatings on 300 micron diameter WC micro-end mills. The performance of the uncoated and NCD-coated tools have been evaluated by performing dry slot milling experiments on 6061-T6 aluminum. A spindle speed of 40,000 rpm, depth-of-cut of 100 µm, and a feedrate of 500 mm/min (chip load =  $6.25 \text{ }\mu\text{m/tooth}$ ) were used as machining conditions. The initial test results show dramatic improvement in the tool integrity (i.e. corners not breaking off), extremely low wear, no observable adhesion of aluminum to the NCD-coated tool, and a significant reduction in the cutting forces ( $\sim 75\%$ ). The NCD-coated tool produced no burrs and a very uniform surface finish without the use of a metalworking fluid.

#### INTRODUCTION

Micro-manufacturing is a rapidly growing worldwide industry estimated at \$60 billion [1]. Micro-manufacturing is the process of creating features measured in micrometers [2, 3]. It is used in the production of small parts, miniaturization of common devices as well as well as producing packaging that links smaller devices, such as MEMS, to the macro world. As technology shrinks and the demand for smaller devices grows, the ability to precisely manufacture new and existing materials at small scales becomes increasingly more important [1-3]. One micro-manufacturing process that is growing in importance is micro end milling.

Micro end milling can generate three-dimensional features in a single step [1, 3, 4] out of a wide variety of materials beyond silicon-based compounds [3, 5, 6]. Polymers [7], metals and metal alloys [7-15], and pre-sintered powder ceramics [11] have been successfully machined by micro-end milling and has enabled the manufacture of biomedical components, micro-propellers, microfluidic devices, micro-heat sinks, micro-heat exchangers, and X-ray lithography masks [7].

There are several important problems to overcome when scaling down end mills from conventional to micro size. The main problem is that due to their small diameter micro tools have low flexural stiffness and strength. Relatively small cutting forces can bend the tool negatively effecting the cutting process and result in catastrophic tool failure [1, 12]. Therefore, in order to maintain cutting forces below a critical value the uncut chip thickness (i.e. chip load) must remain relatively small. For many higher-strength materials (e.g. steel, titanium, etc.) the maximum allowable uncut chip thickness is on the order of or less than the cutting edge radius of the tool ( $\sim 1.5 \,\mu$ m). This results in removing material by a rubbing or burnishing process rather than a cutting process, which both accelerates tool wear as well as produces a poor surface finish [8]. Another problem with smaller tooling is that tool wear has a greater effect on the cutting process [5]. Due to the low flexural strength any chips adhering to the tool in the flutes will eliminate a path for chips to evacuate the cutting zone and result in a spike in cutting forces, usually leading to tool failure.

Diamond coatings for micro-end mills are studied because of their potential to eliminate adhesion, hence flute clogging, reduce the rate of tool wear due to their high hardness, and reduce the magnitude of cutting forces due to their low coefficient of friction. Conventional, polycrystalline diamond coatings that are currently used to coat macro-scale cutting tools are too thick  $(2 - 100 \ \mu\text{m})$  for micro tools because they significantly increase the cutting edge radius, blunting the tool. This is a problem because the existing cutting edge radius of uncoated tools is larger than desirable. Due to the size of the cutting zone and specifically the uncut chip thickness even micro-crystalline diamond (MCD) coatings, with a minimum thickness of 2  $\mu$ m are too thick for micro

tools. Therefore, in order to minimize the resulting cutting edge radius nano-crystalline diamond (NCD) coatings for micro-end mills are investigated.

Nano-crystalline diamond coatings have been investigated for dental micro-tooling [16]. The authors found that CVD diamond coated dental drills lasted longer and performed better when machining tool enamel. In this study we are evaluating the performance of NCD-coated micro-end mills when cutting aluminum.

#### **EXPERIMENTAL METHOD**

#### A. DIAMOND GROWTH

In this study nanocrystalline diamond (NCD) films are grown on 300- $\mu$ m-diameter, two-flute, tungsten carbide (WC) end mills with a shank length of 600  $\mu$ m. The tools are of a standard commercially available design (Performance Micro Tool, Inc.) and contain between 6 and 8 wt.% cobalt at the WC grain boundaries. All tools are initially inspected (by SEM) and sorted for defects and then by diameter with only defect-free tools used in this study. Diamond growth is a three step process: etching, seeding, growth. Table 1 quantifies the NCD growth conditions that are used in this study.

Table 1 NCD coating growth conditions	
Etching	
Acid composition	
50% HF	10 mL
Nitiric Acid	20 mL
DI Water	30 mL
Acid etching time	7 sec
Seeding	
Ultrasonic treatment with diamond powder	15 min
Ultrasonic cleaning with acetone	10 min
Growth	
Distance between tool and filament	3.5 mm
Methane/Hydrogen flows	4/95 sccm
Chamber pressure	30 torr
Growth time	45 min
Tool tip temperature	925°C

The WC tools are selectively *etched* in order to remove Co binder from the surface where it would catalyze the deposition of non-diamond-like carbon, which weakens the WC-NCD bond and limits diamond nucleation [16]. The solution concentration and etching time used in this study was determined from a parametric study to determine the shortest etch time for removing 95% of the Co from the surface: based on Auger electron microscopy measurements. To minimize the effect of etching on the tool life a micro positioner is used to etch only the first 500  $\mu$ m of the tool. This avoids weakening the grain boundaries where the flutes transition into the taper: the primary failure location.

**Seeding** is used to increase the nucleation density of the growing film and produce thin conformal coatings. An ultrasonic treatment of the tool in a nano-diamond (20 - 50 nm) powder and acetone solution is used. Ultrasonic rinsing in acetone to reduce the number of diamond agglomerations resulting in a smoother coating.

The etched and seeded tools are then *coated* with NCD using a hot filament chemical deposition (HF-CVD) system (Fig. 1). The HF-CVD system consists of a vacuum chamber (~30 torr) in which gasses are flowed over a hot tungsten (W) filament (~2000°C). The tool is positioned ~3.5 mm below the filament in order to experience radiative heating and be within the mean free path of the hydrocarbon radical produced by the hot filament. A mixture of precursor gasses, methane (CH<sub>4</sub>) diluted in an excess of Hydrogen (H<sub>2</sub>) is passed over the filament which dissociates the molecules into hydrocarbon radicals. These hydrocarbon radicals condense on the substrate and the diamond coating grows as the carbon species attach to the seeded diamond nuclei. The deposition is run long enough so that the nuclei can grow together to form a continuous coating.

Figures 2 and 3 show scanning electron micrographs of the same tool before and after it is NCD-coated. The NCD coating covers the tool conformally and is between 0.5 and 1.5  $\mu$ m thick. The coating is thin enough that the striations created by the tool grinding process are still clearly evident surface features (Fig. 2b). One goal of using NCD coatings is to grown hard coatings that are thin enough so that they do not increase the cutting edge radius significantly. Even with a coating on the order of 1  $\mu$ m in thickness, as used in this study, the cutting edge radius does increase (Fig. 3). Coatings as thin as 200 nm have been grown and work is continuing to reliably grow thinner coatings.



Fig. 1 Schematic of hot-filament chemical vapor deposition (HF-CVD) chamber

# B. MACHINING TESTS

The end milling experiments were performed on a CNC mill (HAAS TM-1) equipped with a high-speed spindle (NSH-HES500). The high-speed spindle (5,000 – 50,000 rpm) is operated at 40,000 rpm for all of the experiments in this study. Therefore, chip load is controlled by the feedrate since the spindle speed is held constant. The workpiece is mounted on a three-axis piezo-electric force dynamometer (Kistler 9256C2). The absolute magnitude of the dynamic force data has an as-yet unspecified bias associated with it because the natural frequency of the dynamometer, with the workpiece mounted, is approximately 4 kHz and the forcing frequency of a two-flute end mill rotating at 40,000 rpm is 1.3



Fig. 3 SEM micrographs of cutting edge: (a) uncoated and (b) NCD-coated

kHz. Therefore, workpieces of identical mass are always used so that the data between different cutting conditions (i.e. tools) can be compared. The x and y data are used to calculate the thrust,  $F_t$ , and main cutting,  $F_c$ , forces acting on each flute (Fig. 4). Relative humidity is maintained between 90 and 95% in the machining zone because the friction coefficient of NCD is a function of humidity.



Fig. 4 Schematic of micro-end milling (a) 3D view of experiment, and (b) end view of cutting process

The machining tests consist of machining a channel 5 mm long and 100  $\mu$ m deep, in 6061-T6 aluminum. The nominal machining conditions are given in Table 2. An experiment is prepared by: mounting the workpiece on the dynamometer, facing its 50×50 mm surface to a flatness of 3  $\mu$ m, polishing the surface (R<sub>a</sub> = 130 nm), and aligning (i.e. zeroing) a tool using an optical magnification system. The alignment uncertainty is ± 5  $\mu$ m (z-axis: depth of cut). LabView software and National Instruments data acquisition hardware are used to record the force data at a rate of 60 kHz. Both uncoated and coated tools were run in the same test batch to ensure compatibility between tests.

The performance of the NCD-coated micro-end mill is compared to that of an uncoated micro-end mill with all other experimental parameters held constant. Comparisons of the cutting forces, adhesion of material, surface finish, chip morphology and tool integrity are compared in the following sections.

Table 2 Nominal machining conditions	
Workpiece material	6061-T6 aluminum
Room temperature	~23°C
Relative humidity	~85%
Tool (end mill):	
Material	0.4 µm grain carbide
Diameter	304.8 µm (0.012 in.)
Flutes	2
Helix	30 deg
Spindle speed	40,000 rpm
Feed rate	500 mm/min
Feed	6.25 µm/rev
Chip load	3.125 µm/tooth
Coolant	None
Depth-of-cut	$100 \pm 5 \ \mu m$

#### **RESULTS AND DISCUSSION**

#### C. CUTTING FORCES

Figure 5 clearly shows the reduction in the cutting forces resulting from coating the micro-end mill with NCD. Applying an NCD coating reduces the average thrust and main cutting forces between 75 and 90% for chip loads greater than the cutting edge radius (chip loads of 3.125 and 6.25 µm in this study). For a chip load of 1  $\mu$ m (less than the cutting edge radius) the average thrust force is reduced from 0.85 to 0.11 N when the NCD coating is applied, however, the average cutting force increases from 0.06 to 0.10 N. The change in the average cutting force for a 1 µm chip load is within the measurement uncertainty, therefore, the two measurements are treated as equal magnitude. For a chip load =  $1 \mu m$  the reduction of the average thrust force while the cutting force remains unchanged is evidence of the significant reduction in friction between the NCD coating and aluminum workpiece. The 87% reduction in the average thrust force for the NCD-coated tool is measured even though the cutting edge radius of the coated tool (~  $2 \mu m$ ) is larger than the uncoated tool (~ 1  $\mu$ m).

Imaging both sets of tools after machining shows that the uncoated tools had large aluminum chips adhering to them (Fig. 6). EDS was used to confirm that the chips were aluminum. The uncoated tools also showed wear in the form of broken cutting tips. Nanocrystalline-diamond-coated tools, where the coating remained intact, showed no evidence of adhered aluminum and no wear (Fig. 6). This is evidence that the chips encounter less resistance in traveling up the flutes and away from the cutting zone on NCD-coated tools. This will result in lowering the cutting forces.

The thrust to cutting force ratio changes from < 1 to unity with the application of an NCD coating on the micro-end mill (Fig. 5). The uncoated tool has a much larger thrust force compared to cutting force, which is representative of a grinding, rubbing, or plowing action rather than cutting. The coated tool has a force ratio of unity, within the uncertainty limits, which is indicative of cutting with a chip load that is similar in magnitude to the cutting edge radius. The force ratio of unity for



Fig. 5 Average cutting forces for NCD-coated and uncoated tools



Fig. 6 SEM images of WC micro-end mills after cutting 6061-T6 aluminum: (a) uncoated and (b) NCD-coated

the coated tools also suggests that plastic deformation in the primary shear zone is more dominant than for the uncoated tool where friction and elastic deformation of the workpiece make the main contribution to the process forces.

# D. SURFACE FINISH

The bottom of the machined channels were imaged with a white light interferometer to compare the surface roughness produced by the uncoated and NCD-coated tools. The bottom of the channel machined by the uncoated tool did not have a uniform texture and the advancing side of the channel had a large burr running the length of the channel (Fig. 7, left). The non-uniform surface roughness suggests a significant amount of heat generation causing adhesion and smearing throughout the cutting process. The tool, or material adhered to the tool, is rubbing the workpiece surface. Smearing results in higher forces and adhesion can result in increased tool wear by delamination of tool material. The NCD-coated tool made uniformly periodic surface feature (Fig. 7, right) as seen in typical end milling applications.

The uncoated tool produces significant burring. There is a series of burrs along the top edges of the channel. However, the size of the burrs is greatest on the side where the cutting edge is advancing in the feed direction (Fig. 7). Chips or material adhering to the tool flank also have a tendency to adhere to the advancing side of the channel approximately half-way down the wall when cutting with an uncoated tool.

Aluminum is particularly susceptible to burring during micro-end milling due to the relatively large thrust forces acting on a warmed workpiece. The NCD-coated tool does not produce any significant burring, suggesting that the cutting process is much cooler and less of a ploughing action is produced by the cutting edge.

Area ( $200 \times 200 \mu m$ ) measurements and calculation of the average, RMS, and peak-to-valley surface roughness parameters revealed that the NCD-coated tool produced smoother surfaces than the uncoated tool for all three chip loads studied (Figs. 8 and 9). Average surface roughness decreased by 35, 32, and 12% for chip loads of 1, 3.125, and 6.25, respectively. Root-mean-square roughness decreased by 23, 31, and 12%, while peak-to-valley decreased by 13, 21, and 15% for the same chip loads.



Chip Load = 6.25µm Fig. 7 White light interferometric images of 6061-T6 aluminum channels cut with uncoated WC and NCD-coated tools

#### E. CHIP MORPHOLOGY

When micro-end milling 6061-T6 aluminum with uncoated tools with a chip load of  $6.25 \,\mu\text{m}$  long continuous chips (Fig. 10) are frequently formed and even remain attached to the tool 20% of the time. These long chips have not been seen for

any of the feedrates/chip loads when using NCD-coated tools. One



Fig. 8 Comparison of surface roughness for channel bottoms cut with uncoated and NCD-coated tools



Fig. 9 Comparison of peak-to-valley height for channel bottoms cut with uncoated and NCD-coated tools

reason for this is that aluminum does not adhere to NCD coating and can easily exit the cutting zone, thereby, not providing a surface for the next chip to weld to. Another reason is the lower cutting temperatures with NCD-coated tools resulting in less pliable chips.

Figure 11 shows chips generated with an NCD-coated tool (left) and uncoated tool (right) at three chip loads used in this study. The lack of adhesion to and smoother nature of the NCD-coated tool is evident by the smooth and defect-free surfaces of the chips generated by an NCD-coated tool. This is compared with the chips generated by the uncoated tool which are not as uniformly smooth on the bottom surface and show evidence of adhesion having occurred at some point in the chips path. At a chip load of  $3.125 \,\mu\text{m}$  the NCD-coated tool produces segmented chips of uniform size and morphology, whereas the uncoated tool produces smaller chips of varying morphology. At the largest chip load (6.25  $\,\mu\text{m}$ ) both tools produce segmented chips, however, unlike the small uniformly shaped chips generated by the NCD-coated tool the

uncoated tool produces longer chips, frequently continuous, chips.



Fig. 10 SEM of continuous chip from dry cutting 6061-T6 aluminum with uncoated WC tool (40,000rpm, 500mm/min, 100mm depth-of-cut, 6.25µm chip load)

NCD-coated Uncoated



Chip Load 1 µm



Chip Load 3.125 µm



Chip Load 6.25µm Fig. 11 Comparison of chips generated while cutting 6061-T6 aluminum channels with uncoated and NCD-coated tools

### F. TOOL INTEGRITY

The NCD coating is significantly harder than the 6061-T6 aluminum that is machined in this study. Therefore, no abrasive wear is expected or seen. The lack of evidence of any aluminum adhering to the NCD coating after machining tests where the coating remained intact suggests that adhesion remains small under all machining conditions and adhesive wear is unlikely. However, it cannot be ruled out at this time. Figure 12 shows an NCD-coated tool after a cut during which a portion of the coating delaminated. The cutting tips have broken off and aluminum is adhered to the rake face of the tool and inner portion of the flutes where it is assumed no more NCD coating exists. Acid etching the aluminum off of the tool will be attempted to verify this assumption. From Fig. 12 it is clear that delamination initiates near the cutting edge. What is still unknown is whether delamination of the NCD coating from the WC substrate, by adhesive or fatigue wear, was the first event. It is also possible that the WC tip of the tool weakened by fatigue, broke off and removed NCD coating in the process.

The delamination process is sudden and occurs the length of the cutting edge. Figure 13 shows images of sections of channel where the cutting forces jumped to higher values and where the burrs formed by an uncoated tool are suddenly generated by a tool that was NCD-coated. Therefore, once a section of NCD coating delaminates the cutting performance of the micro-end mill is similar to an uncoated tool.



Fig. 12 SEM micrograph showing coating delamination



Chip Load = 1µm Chip Load = 3.125µm Fig. 13 White light interferometric images of 6061-T6 aluminum channels where NCD-coating delamination occurred

## CONCLUSIONS

The machining performance of NCD-coated 300 µm end mills is significantly improved over uncoated tools. This is shown by decreases in cutting forces between 75 and 90%, reduced surface roughness, uniformly segmented chips, and no burrs being formed during cutting of 6061-T6 aluminum. It is important to determine how long a NCD coating lasts and

why it delaminates because once it does detach from the tool the cutting performance reverts to that of an uncoated micro-end mill.

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