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Comparing the Performance of Diamond Coated and Uncoated Micro End Mills using Robustness Testing

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Abstract

The objective of this work is to compare the performance of uncoated micro end mills with micro end mills coated using various pretreatments and diamond coatings. Testing is conducted with 300-um-diameter, two-flute, carbide end mills cutting full-width slots in 6061-T6 aluminum. The comparison of these tools is conducted with a robustness test where the feed rate of the tool is increased every 5 mm of linear travel until catastrophic tool failure occurs. The outcomes from these tests are the maximum chipload, therefore material removal rate, and the maximum force experienced by the tool. It has been determined that tools pre-treated with an acid etch have a statistically lower maximum chipload than as-received tools. However, all other pretreatments and as-received tools had statistically equivalent maximum chiploads. Further improvements in the robustness testing method are needed to reduce data scatter and better test for differences in the tool coating methods.

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Keywords: Micro end milling; robustness; coatings; aluminum.

1. Introduction

Micro end milling has advanced significantly in the past decade as a practical and robust manufacturing process. More materials are being machined today than ever before, including extremely hard metals such as tool steels, powdered metals, stainless steels, and titanium [1]. Micro end mills have begun to be specially tailored with a range of coatings, for use with specific materials and substrates to improve cutting performance and life. Tools as small as 0.005 mm in diameter can now be purchased [1].

While micro end milling has made large strides in the past decade, significant research is still needed to improve the tool life and predictability of the tools' performance. One of the complications of machining with micro tools is the rapid degradation of cutting edge sharpness as tool sizes decreases [2]. One common way to increase longevity of the cutting edge and thus tool life is through the application of coatings on the surface of the tool. These coatings improve the performance of the tools by imparting properties of extremely high hardness and low friction coefficients that decrease the wear on the tools. Significant research has been done trying to improve hard wear resistant coatings using physical or chemical vapor deposition (PVD or CVD) on micro tools [3]. Many types of coatings have been evaluated on micro tools, including nano-crystalline diamond [4], cubic boron nitride [5], and titanium- and chromium nitrides [6,7,8]. However, current coating techniques for micro end mills can sometimes weaken the tools during pretreatment or can blunt the cutting edge, reducing tool performance [9].

Two metrics commonly used to evaluate the performance of micro end mills are tool wear and tool life. These metrics have been thoroughly treated by several researchers [10,11,12]. However, while tool life and wear tests are helpful

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in understanding the mechanics behind micro milling [4, 13, 14], these types of tests are often very time consuming and costly and are unsuitable for quick evaluation of tool performance. Many experimental repetitions are also needed because of the large uncertainty typically associated with micro end mill tool life. In an attempt to decrease the time required for the evaluation of micro end mill maximum chipload, the present work presents a milling test referred to as “robustness testing” that increases the feed rate of the mills by stepped increments. The goal of this test is to give the user a sense of allowable range of maximum feed rates and chiploads (at a given cutting speed and axial depth of cut) while reducing the overall time required for testing.

In this research, varying sets of pretreatments with different diamond and diamond-like coatings are used and compared in order to validate them against standard pretreatments used today.

2. Robustness Testing Methodology

2.1 Method

Robustness tests consisted of incrementally increasing the feedrate of micro end mills every 5 mm while milling until tool failure occurred. Tool failure entailed a gross fracture and removal of the fluted section that ended milling.

Two different methods were used to increase the feedrate of the tools. Initially, abrupt step increases in the feedrate were used. Later, analysis of the force data showed that the sharp step increase in feedrate caused the milling machine to decelerate to a feedrate of zero and then accelerate to the set feedrate at each transition. Therefore, a different step with a more gradual transition between feedrate settings was used in subsequent tests for the coating comparison to eliminate this effect.

2.2 Assumptions

This work assumes that wear is a purely abrasive process dependent on the forces experienced at the cutting edge and machining time and is dominated by abrasive edge blunting and flank wear mechanisms. Fracture-based wear mechanisms are not considered here due to their stochastic nature.

The goal is to test the “robustness” of the tool by determining the maximum chipload and force before tool fracture. The robustness is meant to be a measure of the structural integrity of the tool. Prior research has shown that cutting edge wear contributes significantly to the change in cutting forces experienced by the tool over extended cutting periods [14]. Therefore, the machining time to fracture was minimized to reduce the influence of wear on the maximum chipload and force.

2.3 Validation

A baseline set of experiments compared various pretreatments that are used on the micro end mills prior to coating with diamond for improved adhesion and growth. These tools were not coated. Among these, a standard pretreatment method using an acid etch procedure is known to cause damage to the tool integrity. This method uses Murakami’s reagent to roughen the tool surface followed by a Caro’s reagent to etch away the cobalt on the surface of the tool (pretreatment A in Table 1). The goal of these baseline experiments was to determine whether the robustness test is capable of accurately distinguishing tools that are structurally compromised.

Four different types of pretreatments were examined in addition to as-received micro end mills (Table 1). This included the standard acid etch and three variations of an industrially applied pretreatment (proprietary to NCD Technologies) that is believed to avoid tool degradation. The ambient temperature of pretreatments C and D was varied to determine if it had an impact on resultant tool strength or weakening. Five repetitions were performed for each type of tool pretreatment. These pretreatment methods were then used in the second round of experiments as the preparation before coating the tools with fine-grained diamond (FGD) or diamond-like carbon (DLC).

Tables 2 and 3 show the averages and standard deviations for the maximum chipload encountered by each type of pretreatment, as well as the ANOVA done on the data, respectively. The results showed a statistically significant difference in the maximum chipload found among the pretreatment conditions. This was because the etched tools displayed a much lower maximum chipload value than the untreated (as-received) tools. All other pretreatments (not including acid etch) showed maximum chipload values slightly above the as-received tools on average, but within error.

These results indicate that:

- The acid etch pretreatment reduces the structural integrity of the micro end mill and precipitates fracture at a lower chipload.
- The other pretreatments used do not significantly affect the integrity of the tool and are suitable for use.
- Robustness testing can effectively distinguish tool populations that have reduced structural integrity.

Table 1. Pretreatments

A	Standard acid etch
B	Standard NCD pretreatment
C	Lower temperature NCD pretreatment
D	Higher temperature NCD pretreatment
E	As-received tools

Table 2. Pretreatment Maximum Chiploads (μm/tooth)

	A	B	C	D	E	Overall
Averages	7.00	15.31	16.75	15.75	16.00	14.11
Std. Dev.	1.12	5.98	4.64	3.60	2.05	5.07

Table 3. Pretreatment ANOVA

Source	DoF	Sum of S.	M.Sum of S.	F-Stat
Treatment	4	2086900	521725	2.6156
Residual	19	3789936	199470	-
Total	23	5876836	-	-

3. Coated Tool Experimental Methods

3.1 Experimental conditions

304.8-µm-diameter (0.012 in.), two-flute, carbide, micro end mills (Performance Micro Tool, Inc. TS-2-0120-S) were used to cut full-width slots in a rectangular 6061-T6 aluminum workpiece (Table 4). A high-speed spindle (NSK-HES510) was mounted onto the spindle of a CNC milling machine (HAAS TM-1). Prior to micro milling tests, the surface is prepared through facing. Touch off was done using an optical magnification camera system. Force data was collected using a three-axis force dynamometer (Kistler 9256C2), National Instruments data acquisition hardware (NI PCI 6014), and LabVIEW software with a sampling rate of 60 kHz. The measurement threshold of the dynamometer is 0.002 N.

Table 4. Micro end milling parameters

Tool: micro end mill	
Material	Tungsten carbide with 6-8% cobalt
Diameter	304.8 µm (0.012 in)
Flutes	2
Flute length	450 µm
Helix	30°
Workpiece	
Material	6061-T6 Aluminum
Dimensions	50 × 50 × 5 mm
Initial Sa	200 nm ± 30 nm
Initial preparation	Surface cleaned with Acetone
Environment	
Room temperature	~ 23° C
Relative humidity	~ 14%
Cutting parameters	
Type of cut	Full-width Slot
Spindle speed	40,000 rpm
Cutting speed	38.3 m/min
Feed rate	100-2200 mm/min
Feed	2.5-55 µm/rev
Chipload	1.25-27.5 µm/tooth
Axial depth of cut	50 µm ± 5 µm
Metalworking fluid	None

3.2 Statistical Analysis

All experiments used one-way experimental layouts and were analyzed using analysis of variables (ANOVA). ANOVA aids in detecting differences between the means of several different types of treatments. It is done by calculating the degrees of freedom (DoF), sum of squares (Sum of S.), and mean sum of squares (M. Sum of S.) of the data set. From those values, an F-statistic (F-Stat.) is found which is then compared to a critical F-Stat. value to detect whether there are differences between the treatment types. The critical F-statistic value depends upon the degrees of freedom of the data and the confidence level desired. If the calculated F-Stat. is higher than the critical F-Stat., the null hypothesis that there is no difference between the groups is rejected [15]. A confidence level of 90% was chosen due to the high scatter expected with these types of experiments. For the method validation experiment using pretreatments only (§2.3), the critical F-Stat. was 2.266 while for the coating experiment (§4.3) the critical F-Stat. was 2.103.

The response parameters collected included maximum chipload, force experienced by the tool at fracture, and maximum amplitude of force experienced by the tool. Due to the large noise experienced by the pretreatment experiment due to the acceleration of the mill table, force analysis was not done on that experiment.

3.3 Diamond coatings

Two types of diamond coatings and three types of pretreatments were used for comparison to a baseline of uncoated (as-received) tools (Table 5). The acid etch pretreatment was not used since the predicted tool degradation was confirmed during the validation of the robustness test (§2.3). The standard proprietary pretreatment (NCD Technologies) was used along with a lower temperature version and a version using a modified process gas composition.

All of the pre-treated tools that were coated with fine grain diamond (FGD) were processed in a single batch. The FGD and diamond-like carbon (DLC) coatings were 500 nm – 1 µm thick. The FGD was deposited using hot filament chemical vapor deposition (HF-CVD) [4,5]. One set of tools (E in Table 5) was coated with DLC using glow-discharge plasma.

Table 5. Coatings	Pretreatement + Coating
A	Standard + FGD
B	Modified Gas + FGD
C	Modified Gas
D	Lower Temperature + FGD
E	Lower Temperature + DLC
F	As-Received Tools

3.4 Force Analysis

The x- and y-axis forces obtained from the three-axis dynamometer were post-processed in MATLAB by reducing signal noise using a Gaussian filter and calculating a resultant force from the filtered x- and y-axis forces. The difference between the maximum and minimum cutting force was calculated for each cutting pass and was used to find the amplitude of the resultant force oscillations. It is anticipated that this resultant force should start near zero, reach a maximum value, then return for each cutting pass because this a two-flute end mill cutting a full-width slot. Hence, there should be a near-zero minimum force during each cutting pass and non-zero values for the mean cutting force and the amplitude. The amplitude of the resultant force is taken for both teeth and displayed as red and green dots (Fig. 1).

A typical cutting force plot from robustness testing (Fig. 1) showed that during milling the resultant force oscillated between a maximum and minimum value for each cutting pass that were both non-zero. The green and red points in Fig. 1 show the amplitude of the oscillating resultant force, which was generally very consistent during tests and was under 0.1 N. The amplitude was tracked for each of the two cutting edges that were distinguished by color in the plots. The maximum resultant force experienced was collected for each sample, as well as the maximum amplitude for statistical analysis. The sudden drop in forces after 1.2 seconds (Fig. 1) is when the tool fractured. The vertical dashed lines indicate where the steps in feed rate occurred, starting with 800 mm/min and incrementing by 100 mm/min.

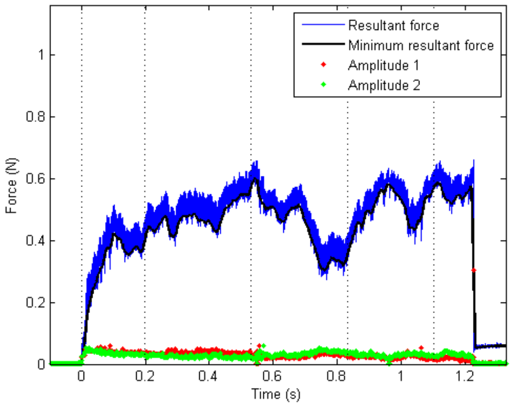


Figure 1. An example of collected force data.

4. Coated Tools Results and Discussion

4.1 Force data

A characteristic pattern for most of the force data was observed (Figs. 1 and 2):

1. An increase in the force amplitude from 0 N to approximately 0.05 N in under 10 tool rotations. This corresponds well to the time for full tool immersion. During this stage, the minimum resultant force remained close to zero (Fig. 2a).
2. After the tool fully engaged the workpiece, the resultant force amplitude consistently remained below 0.1 N and showed little variation. However, the minimum force value increased from near 0 to approximately 0.5 N in the first 0.5 s of machining time (Fig. 2b).
3. Over the course of the robustness test, the minimum resultant force is non-zero and remains relatively constant with seemingly stochastic fluctuations that do not correspond well with steps in feed rate (Fig. 1).
4. The force immediately drops to zero at fracture (Fig. 1).

The increase in forces after full tool immersion was unexpected and indicated tool dynamics or rapid wear. After the forces reached a quasi-equilibrium state, there was also little visible change at different feed rates, which was unexpected.

One notable exception to this pattern was coating condition B, which showed a period of reduced forces during the first 0.15s of cutting (Fig. 2c). This implied a possible improvement in cutting followed by a delamination event.

4.2 Channel appearance

The channels were examined to learn more about the conditions of cutting to help interpret the force data. It was found that an irregular cutting pattern was predominant throughout the tests indicating that unstable cutting was occurring. Also, cutting patterns inside some channels indicated that edge fracture may have also been occurring during the process leading to imbalanced cutting between the two cutting edges. This did not correlate well with any particular set of tools.

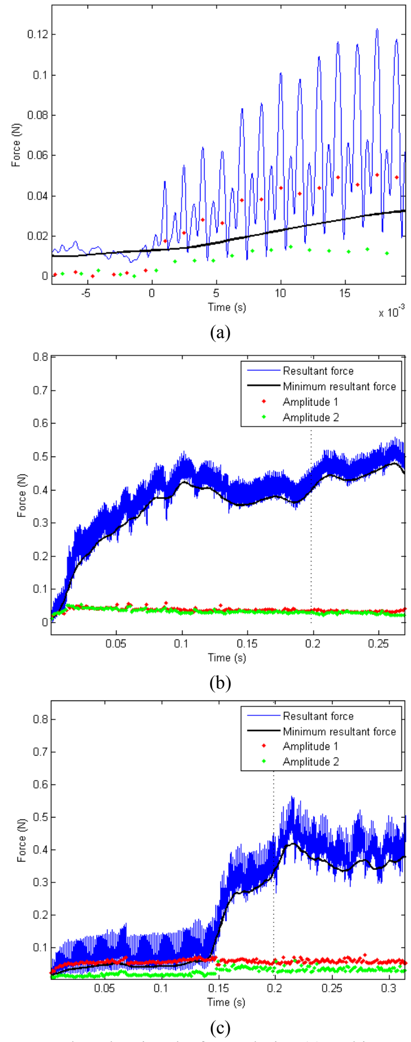
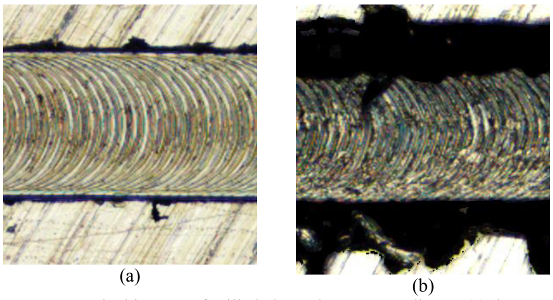


Figure 2. Force data showing the forces during (a) tool immersion and (b,c) during the first 0.3 s of cutting.

One noticeable exception to the previously described channel appearance was for coating condition B (Table 5). The beginning of the channels showed very regular circular cutting paths at the expected chipload indicating stable cutting conditions. There was also very little burring, compared with significant burring shown for other conditions. This then rapidly changed to an irregular condition similar to the other tools. A comparison between a channel produced by Tool B (Table 5) and an uncoated tool is shown in Fig. 3. The beginning of the channel cut by Tool B, which shows evidence of stable cutting, corresponds to the region of low minimum resultant force shown in Fig. 2(c). Neither the low minimum resultant force nor evidence of stable cutting was found in any of the other tool coatings. The lack of burr formation during the beginning of Tool B tests (Fig. 3a) changed to significant burr formation after the forces increased (Fig. 2c) and resembled the burr formation shown for Tool F in Fig. 3(b).



(a) (b)

Figure 3. Optical images of milled channels corresponding to (a) the beginning of a channel for condition B and (b) the generally observed cutting pattern.

4.3 ANOVA

4.3.1 Maximum chipload

Tables 6 and 7 show the averages and standard deviations for each coating as well as an overall average and standard deviation. The analysis of variance (ANOVA) for the experiment is listed as well.

No statistically significant difference was found between any of the tools. This was due to similar averages and fairly high standard deviations. However, all of the tools with coatings had average [maximum] chiploads 2.75-4.5 µm/tooth higher than the uncoated (as received) tools. The one other uncoated tool that received a modified pretreatment (tool C in Table 5) had an average [maximum] chipload similar to the as-received tool (tool F in Table 5). All of the coated tools performed similarly, and had standard deviations of approximately 5 µm/tooth (Table 6).

Table 6. Coating Maximum Chiploads (µm/tooth)

	A	B	C	D	E	F	Overall
Averages	15.00	16.75	12.75	17.50	16.75	12.25	15.17
Std. Dev.	4.92	5.27	2.71	4.76	5.27	1.63	4.45

Table 7. Maximum Chipload ANOVA

Source	DoF	Sum. of S.	M.Sum of S.	F-Stat.
Treatment	5	522444	104489	0.7521
Residual	24	3334444	138935	-
Total	29	3856889	-	-

4.3.2 Maximum force

The maximum resultant force experienced at any point by the tools were recorded. If the tool broke, that maximum force was almost always experienced immediately prior to catastrophic failure. However, if the tool ran a second pass, the maximum force experienced at any point in the first run was the force used. Both the maximum force and the two neighboring peaks were averaged for each data point. The resultant force (blue line in Figure 1) is the overall force acting upon the tool in the x-y-plane at any moment in time. It oscillates between high and low peaks that correspond to the cutting loads experienced by the individual teeth of the micro end mill. Tables 8 and 9 show the averages and standard deviations for each treatment (Table 5).

No trends could be discerned from comparing the conditions against one another since the F-Stat (1.3362) was lower than the critical value (2.103). It should be noted that there was also no discernable correlation between the maximum chipload and the maximum resultant force.

Table 8. Coatings Maximum Force Experience (N)

	A	B	C	D	E	F	Overall
Averages	0.623	0.623	0.715	0.699	0.695	0.713	0.678
Std. Dev.	0.116	0.070	0.027	0.060	0.063	0.061	0.076

Table 9. Max Force ANOVA

Source	DoF	Sum of S.	M.Sum of S.	F-Stat.
Treatment	5	0.0410	0.0082	1.3362
Residual	24	0.1474	0.0061	-
Total	29	0.1884	-	-

4.3.3 Maximum force amplitude

Also recorded from the force data was the maximum force amplitude experienced at any point by the tool. The amplitude of the resultant force is taken for both cutting edges and displayed as red and green dots in Figures 1 and 2. The data point recorded in Table 10 and used in the analysis of variance in Table 11 is the highest red or green point for any given test. Occasionally, when the tool broke, the amplitude would spike due to the extremely sudden drop in resultant force. For this analysis, those points were disregarded and the next largest amplitude was used.

No trends could be discerned from comparing the average maximum amplitudes against one another.

Table 10. Coating Maximum Force Amplitude (N)

	A	B	C	D	E	F	Overall
Averages	0.172	0.225	0.167	0.184	0.165	0.156	0.178
Std. Dev.	0.041	0.075	0.029	0.026	0.032	0.023	0.044

Table 11. Maximum Force Amplitude ANOVA

Source	DoF	Sum of S.	M. Sum of S.	F-Stat.
Treatment	5	0.0127	0.0025	1.1662
Residual	24	0.0524	0.0022	-
Total	29	0.0652	-	-

4.3.4 Force vs. Chipload

Various linear regressions were performed for the coating experiments comparing maximum chiploads against maximum force and force amplitude (Figs. 4 – 5). The data shows significant scatter, and an attempt at various fits showed very low R^2 values indicating that there is no discernable trend.

From cutting theory, it was expected that the force would increase with the chipload. The lack of correlation may be due in part to the observation that the tests appeared to be in an unstable cutting regime. Long chips were observed during the process, indicating that the chips from discontinuous cutting fused together in the flutes. It is possible that the forces required to push these chips along the flute does not correlate with chipload.

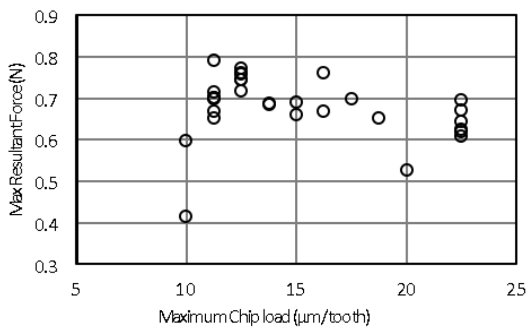


Figure 4. Maximum resultant forces as a function of maximum chipload.

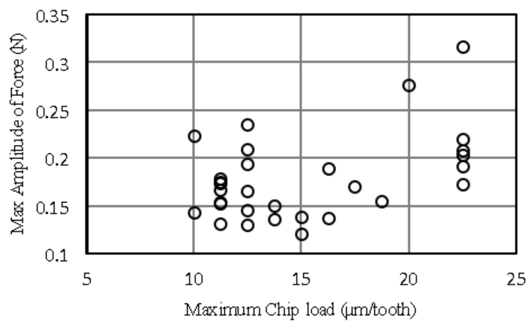


Figure 5. Maximum force amplitude as a function of maximum chipload.

5. Conclusions

The results of the robustness tests show that except for the standard two-step Murakami and Caro's acid etching the pretreatments do not weaken the micro end mills. Hence, the robustness test effectively distinguished a tool population known to be weaker. No significant difference was seen between coated tools when compared to uncoated tools suggesting that the tested coatings do not weaken the micro end mills.

Lower forces and minimal burr formation at the beginning of the test was observed for the tools with a modified gas pretreatment and coated with fine-grain diamond. After approximately 0.15 s these forces increased, as did the burr size to magnitudes observed in all other diamond coated tools.

Observation of the channels, forces, burrs, and chips indicates that the robustness testing that was carried out has significant limitations. The unstable cutting, large scatter in the data, and lack of correlation between the maximum chipload and maximum resultant force suggests that chip adhesion and flow in the flutes dominated. Modified coatings and/or the use of metalworking fluid may produce data from which trends can be more easily determined.

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