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Observation of Tool Life of Micro End Mills

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ABSTRACT

Prediction of mechanical machining tool life is an integral part of commercial manufacturing. Failure of micro end mills is still not well understood, and further work needs to be done to accurately predict tool life. The objective of this study is to observe the distribution of tool life for micro end mills under aggressive machining conditions without lubrication for 300-um-diameter micro end mills while machining 6061-T6 aluminum alloy. The average tool life was 3 to 7 times greater for the nanocrystalline diamond (NCD) coated micro end mills as compared with the uncoated (as received) tools. For both NCD coated and uncoated micro end mills the tool life increased as the cutting speed was increased from 32 to 48 m/min, suggesting the presence of a built-up-edge during machining. The variance in the tool life data was approximately an order of magnitude greater than what is expected in macro-scale machining.

INTRODUCTION

Micro end milling has become an increasingly prevalent manufacturing technique for creating high aspect-ratio features at the micro-scale. Continued commercialization of micro end milling is dependent on having a good understanding of manufacturing costs and tool failure predictability. Micro mechanical cutting tools tend to have a shorter time-to-fracture with wider variation than larger cutting tools. This difficulty is explored by Zdebski et al. [1] who uses a statistical approach to determine how normally distributed variation in tool rupture strength and machining forces will affect the tool life distribution. This work began to make sense of the wide scatter in tool life data for micro tools, but no practically applicable predictive models for tool life are currently available to the industrial community. The inability to predict micro end mill (micro drill) tool life severely limits the productivity of micro-machine shops and the market growth [10].

Tool life for micro end mills is defined here, following the definition in prior research [1,2,3,4,5], as gross fracture resulting in the loss of the tool cutting region. These fractures are commonly held to be the direct result of cutting forces exceeding a critical value based on the tool flexural rupture strength. However, the validity of this assumption also requires further investigation. Redefining tool life as a usable machining time prior to fracture would be useful to help prevent unexpected tool change and workpiece damage. At the macro-scale, well established standards exist for measuring tool wear [6] and determining useful tool life, but these

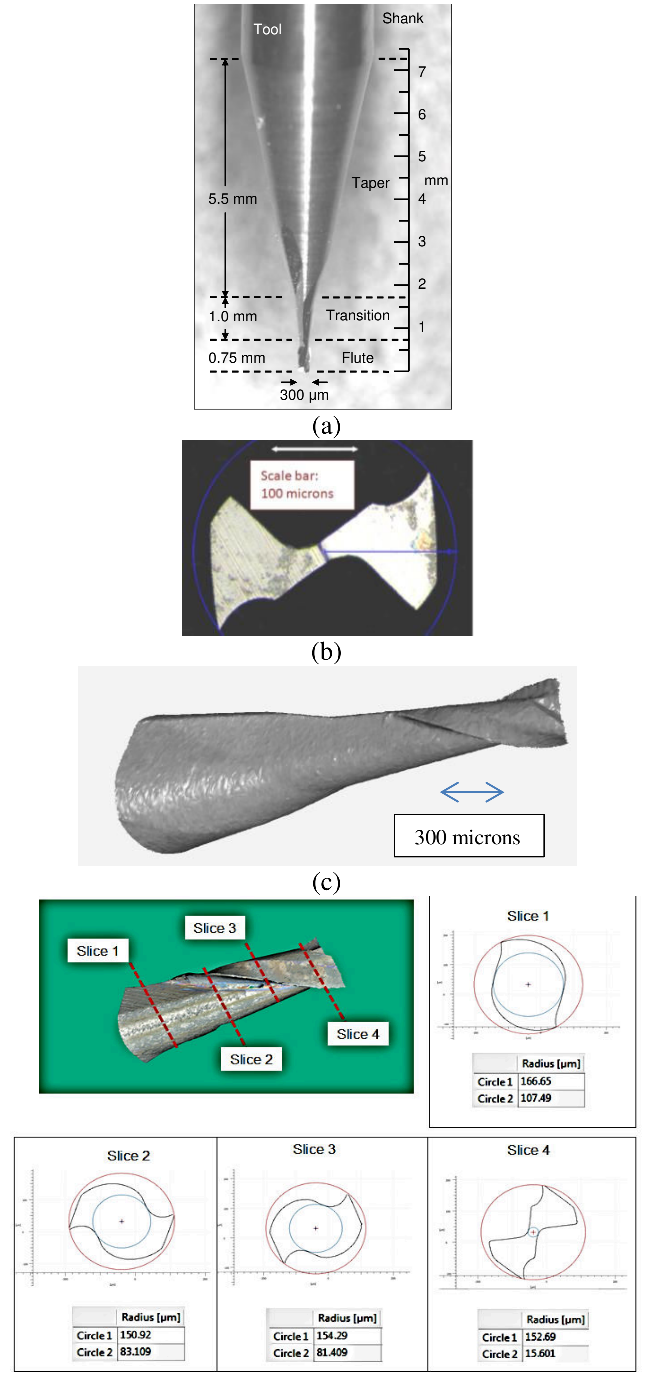


Figure 1: Optical metrology of a 300-µm-diameter, two-flute, WC end mill: (a) microscope image with dimensions incorporated,(b) 2D end view image, (c) 3D reconstruction, (d) cross-sections from 3D reconstruction

standards are not easily applicable to micro-machining operations. Several reviews of recent advances in micro mechanical machining [7-9] have touched on the advances made in understanding tool wear and life.

This study was undertaken in an attempt to start to address the need for industrially relevant micro end mill tool life data and to work towards a more commercially useful and applicable definition of tool life. This paper presents a method of measuring the time-to-fracture for micro end mills and compares the results for 300-um-diameter, two-flute, tungsten carbide with and without a nanocrystalline diamond coating at two different cutting speeds when machining 6061-T6 aluminum.

EXPERIMENTAL METHODS

Micro end milling tests were conducted on a three-axis CNC mill (HAAS TM-1) with a high-speed spindle mounted (NSK HES510). The high-speed spindle has an electric drive with composite bearings and is capable of 10,000-50,000 rpm. Commercially available tungsten carbide, two-flute, 300-µm-diameter, 450-µm-flute-length tools (Performance Micro Tool TS-2-0120-S) were used. The cutting edges were measured to have a radius between 1.0 and 1.5µm. Both untreated (as-received) and nanocrystalline diamond (NCD) coated tools were studied (Table 1). The NCD coatings were synthesized by NCD Technologies, LLC (Madison, WI). The NCD coatings were continuous, 200-nm-thick and contain 96% sp3 (diamond) bonds. Due to ultra-thin coatings used, there was very little impact on the cutting edge radius.

All machining was conducted on a 6061-T6 aluminum workpiece that was 12.7-mm-thick (0.5 in.), 304.8-mm-wide (12 in.), and 609.6-mm-long (24 in.) as shown in Fig. 2. Prior to micro end milling, the work-piece surface was face milled (Sandvik Coromant A490-032M32-08M face mill with 490R-08T308E-ML H13A inserts) at 3,000 rpm spindle speed, 500 mm/min feedrate, and 0.05 mm axial depth of cut. After facing the average "areal" surface roughness of the workpiece was Sa =200 nm (Table 1).

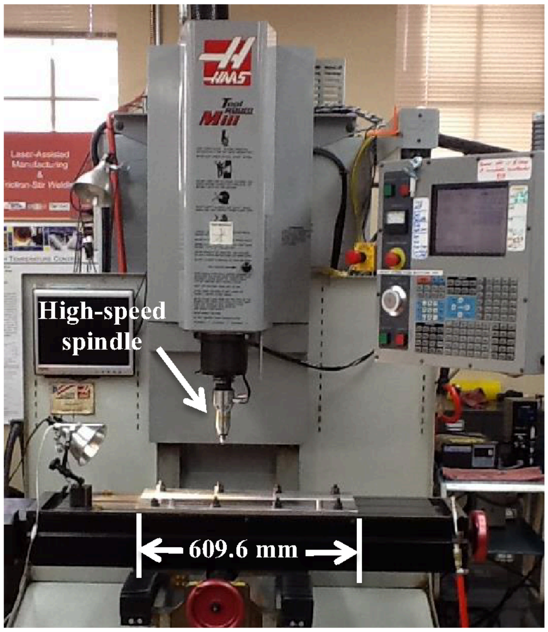


Figure 2: Image of experimental apparatus used for micro end mill tool life testing: workpiece is 609.6-mm-long and bolted directly to the mill table

All machining was done without the application of any metalworking fluid, i.e., dry. This was chosen to complement previous dry machining testing with NCD coated micro end mills. The workpiece surface was cleaned with acetone prior to micro end milling in order to remove any oil remnants from handling or facing.

All micro end mills were inspected for defects (e.g., broken cutting edges) and imaged prior to testing. 3D optical metrology (Alicona Infinite Focus with Real3D) was used to determine the cutting edge radii, outer diameter, and core geometry (Fig. 1d) of each tool. This data was used to determine if any of the variations in the measurable tool geometry had an influence on the test results.

The axial depth of cut for micro end milling was set after an optically observed touch-off. The touch-off accuracy is estimated to be ±3 µm. After the tool life tests, the actual axial depth of cut was measured with the optical metrology system.

The CNC mill and high-speed spindle were warmed up for a minimum of 40 minutes prior to micro end milling. The dynamic, radial run-out of the high-speed spindle was measured (Union Tool Co. OPTECH-RI-E) every morning to ensure that values stayed below 2.0 µm.

Micro end milling of full-width slots was conducted along the length (X-axis of the mill) of the workpiece until the tool fractured catastrophically. If the tool survived one 609.6-mm-long pass through the workpiece, it was returned to the beginning of the workpiece, indexed 500-µm in Y, and another channel was immediately started. Hence, all channels started at the same end of the workpiece. This process was continued until tool failure.

In this study the end of tool life occurs when the micro end mill catastrophically fails, i.e., the fluted section breaks off the shank. The authors recognize that this definition is not ideal and more research and discussion in the community is required to develop a more robust metric. This definition of micro end mill tool life was used here for the following reasons:

- The experiments require the least amount of time, effort, and money to conduct. Tools are run to failure without any interruptions. Cutting forces and tool wear are not monitored throughout the tests.
- These tests offer a relatively fast means of generating tool life data.
- An operator without specialized equipment can observe end of tool life.
- These experiments should be reproducible by any micro end milling practitioner.
- There is no international standard for tool life that can be directly applied to micro end mills.

It must be acknowledged that defining catastrophic failure as the end of tool life may add a significant amount of variance to the measured data. In addition to the variance that is already present in abrasive and adhesive wear mechanisms this metric adds the flexural strength of the tools and the onset of fracture. Several researchers have investigated the interdependencies of cutting forces, tool wear, and tool life by asserting that tool life (fracture) is the direct result of cutting forces exceeding a critical value based on the tool flexural rupture strength [1-5].

A. CONSTANT PARAMETERS

The micro end milling parameters that were held constant are given in Table 1. A relatively aggressive combination of axial depth of cut and chip load were chosen in order to reduce the length of time required to run each tool life test and collect data at higher material removal rates. The axial depth of cut was chosen to be 1/6th of the micro end mill diameter. This ratio is considered by many users to be the upper limit of the axial depth that should be used. The chip load (feed per tooth) was set at 30 μm. This value was chosen as 85% of the maximum chip load. The maximum chip load is defined by the feedrate at which the tool immediately fails catastrophically. With all other parameters (Table 1) held constant, this was determined to be 3 m/min. The maximum chip load test consists of increasing the feedrate (i.e., chip load) in increments of 0.1 m/min every 5 mm of linear distance without pausing until the tool catastrophically fails. 5 mm was chosen because it reduced the amount of time milling at each feedrate and acceleration occurred in a relatively small fraction of the 5-mm-length. Once the tool fails, the test is repeated at an initial feedrate that is one increment (0.1 m/min) below the previously measured maximum chip load. This helps verify the maximum chip load and minimizes the effect of tool wear on the results.

Table 1: Parameters held constant during tool life tests

Tool		
Material	Tungsten carbide with 6-8% cobalt	
Diameter	304	μm
Number of flutes	2	-
Flute length	450	μm
Helix angle	30	degrees
Rake angle	11	degrees
Workpiece		
Material	6061-T6 aluminum	
Initial surface roughness, Sa	200± 30	nm
Initial preparation	Surface cleaned with Acetone	
Cutting Parameters		
Feed per tooth	30	μm
Axial depth of cut	50 +1 / -6	μm
Metalworking fluid	None	-
Type of cut	Full width slot	-
Length of each channel	609.6	mm
Centerline spacing between channels	500	μm

Table 2: Parameters varied during tool life tests

Cutting speed	**31.60**	**47.88**	**m/min**
Spindle speed	33,000	50,000	rev/min
Feedrate	2.0	3.0	m/min
Coating	**NCD Coated**	**Uncoated**	**-**

B. VARIABLE PARAMETERS

The independent variables in these tests were the cutting speed (47.88 m/min and31.60 m/min) and the tool coating (uncoated and nanocrystalline diamond ‘NCD’ coated) as shown in Table 2. The feed rate was changed in order to maintain a constant chip load. The cutting speed variable was chosen because it has been estimated to be the most influential factor in tool life and wear. One example is J.B. Saedon who observed this in steel [11].

C. ADDITIONAL VARIABLES

Several experimental variables were measured for each tool life test but not actively controlled (i.e., no closed-loop control) by the authors. These include:

- ambient temperature
- humidity
- high-speed spindle temperature
- workpiece flatness
- workpiece temperature
- workpiece surface roughness
- axial depth of cut
- time of day that the test was conducted
- tool diameter
- tool axial flute length
- tool core diameter
- tool cutting edge radius (at the tip).

The authors did their best to hold many of these variables constant through open-loop control. E.g., the same face milling conditions were used for all tests in an attempt to maintain a constant initial surface roughness. These additional variables were compared with the tool life results to determine if variations in them had a measurable effect on tool life. During an initial set of experiments, which are not presented in this paper, the only additional variable that correlated with tool life was the time of day. The tool life was longer for tests conducted in the afternoon as compared with tests conducted in the morning. Multiple changes were made to the testing procedure: (1) the warm-up time for the CNC mill and high-speed spindle were increased, (2) incandescent lighting of the workpiece was replaced with LED lighting, and (3) the micro end mills were not left to idle at speed in the high-speed spindle between touching off and starting the tests. After making these changes the correlation between testing time of day and tool life was eliminated. Unfortunately, these changes were all made at the same time; hence it is not possible to attribute the change to just one of them.

The original incandescent light increased the workpiece surface temperature by 8 K in two minutes as measured by a K-type thermocouple attached to the aluminum workpiece. The micro milling process only raised the workpiece temperature by 1 K during each tool life test. After replacing the incandescent light with an LED no temperature rise could be attributed to the spot light.

The compressed air that flows through the high-speed spindle does not stop when the spindle rpms go to zero. When the spindle isn't rotating, the flowing air will cool the spindle down to room temperature in 20 minutes. Hence, the spindle may require a new warm-up cycle prior to each experiment to maintain consistent outcomes.

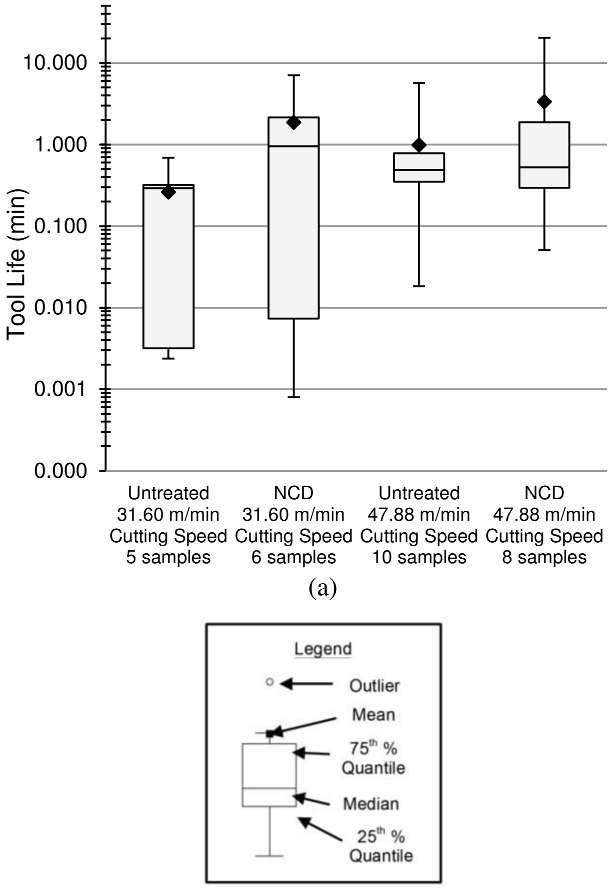
A variable that should be monitored in the future is vibrations in the workpiece and high-speed spindle to determine the effect of other lab equipment and external sources (building HVAC, cars, trucks, train, etc.).

RESULTS

Comparison of tool life for the tool groups tested at cutting speeds of 31.60 m/min and 47.88 m/min showed that the average tool life was lower for the 31.60 m/min group (Table 3). This was true for both the uncoated and NCD coated micro end mills (Fig. 3). The NCD coated tools showed higher average tool life values, 75th percentile values, and maximum life values in both cutting speed groups compared to the untreated tools. The box-and-whisker plot of the tool life data (Fig. 3) indicates that the NCD treated tools have a larger interquartile (IQ) range for both cutting speeds. The IQ range is the distance between the 25th and 75th percentiles. The source and significance of this is still unclear. However, the mean value of tool life for the NCD coated tools was 3.4 times greater than the mean tool life for untreated tools at a cutting speed of 47.88 m/min. The NCD coated tools lasted 7 times longer on average than untreated tools at a cutting speed of 31.60 m/min (Table 3).

An important observation of the box-and-whisker plots (Fig. 3) is that the mean tool life is sometimes above the 75th percentile, not near the median value. This indicates that the few very long run times, sometimes operating over 6 times longer than the average, significantly affected the mean.

The onset of tool failure (fracture) point was identified during machining by the sudden lack of any discernable machining marks on the workpiece. Several of these tools were examined to confirm that the fluted section of the tool was lost. Fig. 4 shows an optical and SEM evaluation of a typical fracture surface. The surface morphology is consistent with intergranular brittle fracture and looks to have propagated from the cutting edge in the upper right in Figs. 4(a) and 4(b). This failure mode would be consistent with a brittle material under high amplitude cyclic loading and appeared to be consistent for several tools that were evaluated. It should be noted that this characterization was not exhaustive. Characterization of an untreated tool that was tested under similar



(a)

(b)

Figure 3: (a) Tool life data for uncoated and nanocrystalline diamond coated (NCD) micro end mills (b) Box-Whisker plot legend.

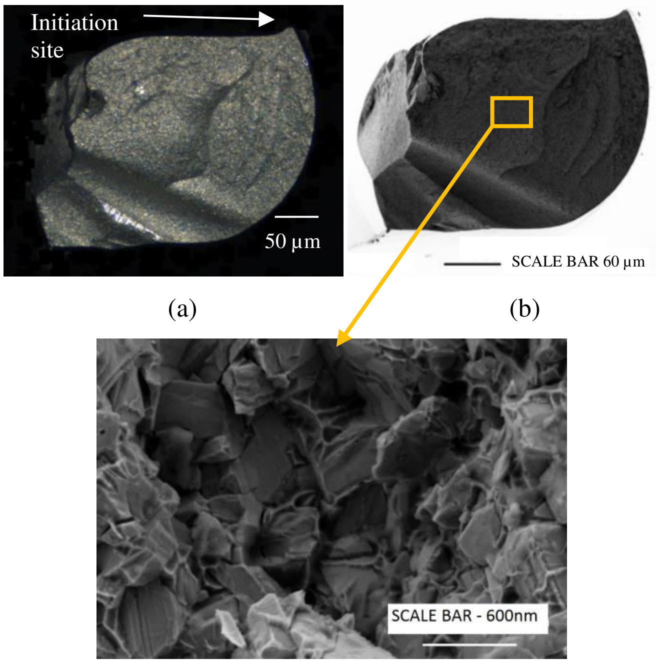
Table 3: Micro end mill tool life results (Fig. 3)

Cutting Speed	31.60 m/min		47.88 m/min	
Coating	**None**	**NCD**	**None**	**NCD**
Mean (min)	0.26	1.87	0.99	3.35
Variance [log (tool life)]	7.57	16.96	2.21	3.34
Max. (min)	0.69	7.06	5.69	20.32
75th % (min)	0.32	2.14	0.78	1.88
Median (min)	0.29	0.95	0.49	0.53
25th % (min)	0.003	0.01	0.35	0.29
Min. (min)	0.002	0.001	0.02	0.05

NCD = nanocrystalline diamond

conditions, but was not run to failure (Fig. 5) showed that a significant amount of aluminum adhered to the tool. It is not possible from this characterization to see if the adhered aluminum is indicative only of adhered chip material or if there is a stable built-up-edge underneath.

The distribution of tool life results are shown against linear (Fig. 6a) and logarithmic (Fig. 6b) axes. Macro-scale tool life experiments commonly vary by ± 20% [12]. The distribution of tool life data in this study shows something closer to a normal distribution when plotted on a logarithmic scale, but additional data and statistical analysis are needed to compare the initial results to a lognormal distribution.



(a) (b)

(c)

Fig. 4: (a) Optical and (b) SEM characterization of typical surface morphology of a fractured micro end mill far outside the cutting region. (c) SEM image at fractured surface.

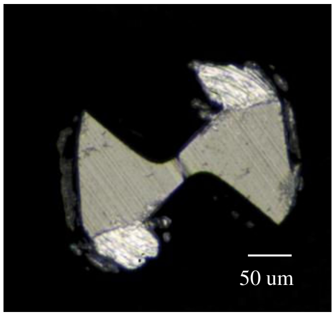
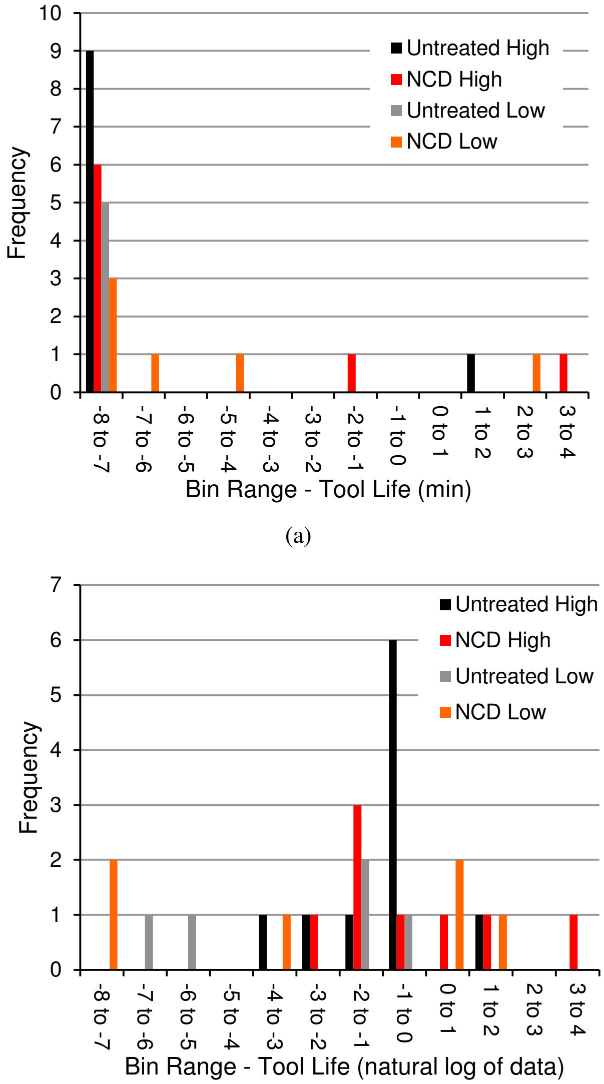


Fig. 5: Optical characterization of an untreated micro end mill showing the significant amount of adhered material at the cutting edges.

ANALYSIS

The cutting speed (31.6 m/min and 47.88 m/min) and the tool condition (uncoated and NCD coated) were the controlled variables during the machining trials. The trends in the resulting tool life data were analyzed after conducting experiments with 5 to 10 replicates.



(a)

(b)

Figure 6: Histogram of tool life results: (a) original data, and (b) natural log of tool life data (log normal).

A. CUTTING SPEED

End mills operating at the lower cutting speed experienced a shorter average time to fracture. This trend is the opposite of what Taylor's tool life equation predicts. This is because Taylor's tool life applies to the linear portion of the tool life curve (Fig. 7), where abrasive wear dominates and there is no built up edge. If a similar tool life curve is valid for micro end milling of 6061-T6 aluminum, this suggests that the selected machining conditions may have been within the build-up-edge (BUE) zone where increased cutting speed can lead to increased tool life. The other possibility is that the curve in Fig. 7 does not hold for cutting at the micro-scale.

Either way, significantly more testing needs to be performed to determine how further changes to the cutting speed will affect the tool life, and careful characterization of tools prior to catastrophic failure should show if there is evidence of a BUE. In addition, testing on other less adhesive alloys (e.g., steels) needs to be conducted to determine how pervasive the observed trend is.

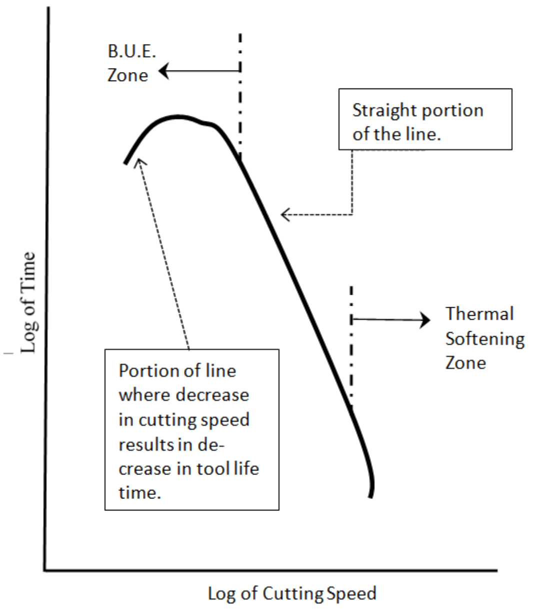


Figure 7: Qualitative representation of tool life curve [13]

B. BUILT-UP-EDGE

A significant amount of research has sought to explain the phenomenon of built-up-edge (BUE) during metal cutting. This phenomena is usually observed at lower cutting speeds. Due to the small diameter of micro end mills, the limit on commercially available spindle speeds, and the finite cutting edge radii that can be produced BUE is bound to be a regular occurrence in many micro-mechanical machining operations. Waldorf et al. [14] performed a study examining BUE formation while machining 6061-T6 Al and determined that a stable BUE, nicknamed a "dead metal cap", which adheres to the tool and remains stationary while the process attains steady state best matched the test results. Kountanya and Endres [15] verified BUE with a high magnification visual study of micro-orthogonal cutting using a blunt tool. Weule et al. [16] also conducted fly cutting tests with a blunt tool on SAE 1045 with varying cutting speeds. Their tests confirmed that stable BUE forms at low cutting speeds.

Increasing the cutting speed is the most common method of reducing the built up edge and moving into the linear portion of the tool life curve (Fig. 7). The primary limiting factor in increasing cutting speed is spindle rotation speed. The operating conditions used in this study employed the maximum capability of the high speed spindle. In order to test if the tool life trend changes with higher cutting speed, further testing will have to be performed with a higher speed spindle or larger diameter end mills.

C. NCD COATING

Figure 3 and Table 3 show that the average tool life of NCD coated tools was greater than that of uncoated tools. The improvement in tool life is 7 fold at the lower cutting speed (31.6 m/min) and 3.4 fold at the higher cutting speed (47.88 m/min). Within the tests for each cutting speed the maximum, 75th percentile, mean, and median tool life are greater for the NCD coated tools as compared to the uncoated tools. However, within the replicates all types of tools at both operating conditions some tools experienced very short tool lives. Lowering the cutting speed from 47.88 m/min to 31.6 m/min reduced the average life of untreated tools by 74% and only 44% for the NCD coated tools. This suggests that the NCD coated tools are less sensitive to the cutting speed.

The fact that NCD coated tools experienced longer tool life at higher cutting speeds suggests that the operating conditions lay within the built up edge (BUE) portion of the Taylor's tool life curve (Fig. 7). Further investigation is required to verify that a BUE was forming on the tools. Future studies must also determine if any BUE was forming directly on the NCD coating or on a region that experienced delamination. Despite the likelihood of BUE being present it is known that NCD coated tools benefit from improved chip clearing due to their low adhesion in the flutes [4]. Improved chip clearing resulting from NCD coating in the flutes can explain the ability to maintain cutting forces below the fracture threshold longer than the uncoated tools.

D. VARIANCE

The variance of tool life measurements on these micro end mills are an order of magnitude larger than the variance expected during macro-scale cutting tests [12, 13]. The reasons for this larger variance must still be investigated. However, one aspect is certainly the difference in tool life criteria. In these micro end milling tests tool fracture defines the end of tool life and this will be sensitive to the tool geometry and small imperfections at the cutting edge.

CONCLUSION

This study showed that when micro end milling 6061-T6 aluminum higher cutting speeds will most likely lead to longer tool life. This was the case for both uncoated and NCD coated tools between 31.6 and 47.88 m/min. This suggests that a BUE is forming on all tools at these cutting speeds, however, more research is required to confirm this. At 31.6 m/min and 47.88 m/min cutting speeds the NCD coating helped to increase the tool life 7 times and 3.4 times, respectively. The variance in tool life data was approximately an order of magnitude larger for these micro end mill tests than what is expected from macro-scale cutting tests.

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