AC 2009-2503: MICROMACHINING EDUCATION AND RESEARCH AT TEXAS A&M UNIVERSITY

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Micromachining Education and Research at Texas A&M University

Abstract

The market trend for product miniaturization promotes research and education in micro manufacturing. Micromachining is an extension of conventional machining when chips are removed in micro/nano scales, but micromachining requires new knowledge, specially designed equipment, tooling, and additional knowledge for successful results. Common machining techniques for macro-scale machining often lead to inconclusive data and frustration when applying to micromachining.

This paper presents a synergistic effort that offers research and educational opportunities to students. Equipment and tooling are provided by industry, while resources are provided by university and National Science Foundation to both graduate and undergraduate students. The lab exercises are designed to complement research activities so that a broader impact can be achieved. The study presents the necessary conditions and infrastructure for successful micro machining. It characterizes how micromist would benefit micromachining, and predicts how micro tools would fail during services. It has been experimentally verified that micromist significantly improves tool life of microtools when compared to flood coolant and dry micromachining. Using the analogy of flow of the coolant over a rotating tool, computational fluid mechanics is used to optimize set up conditions that gives maximum lubrication and cooling effects at the cutting edges of a micromilling cutter. The optimal droplet size is calculated assuming it can penetrate the boundary layer of a high-speed rotating tool and reach the tool surface. Failure of microtools includes the adverse effects of spindle run out, tool deflection, and high cutting stress in micro machining. Dynamic response and laser displacement methods are used to characterize the equipment and setup. Finite element techniques are used to study and analyze the effects for different cutting conditions on the failure of microcutting tool. Experimental data on micromachining of 316L stainless steel are presented and confirmed with theoretical calculations.

Introduction

With the maturity and saturation of commercial products, new market trend predict waves of miniature products that packed with even more functional features. It is now appropriate to consider the future needs of production engineering from the perspective of product miniaturization. Micromanufacturing is multidisciplinary with customer needs and economics playing an increasingly important role. The precision and miniature products require diminishing component size, enhancing surface quality, tighter tolerances and manufacturing accuracies, reducing costs and diminishing component weight. Today precision machine tools under computer control can position a tool with sub-micron resolution and accuracy. Micromachining is the key to the manufacture of many advanced micro-electromechanical products for a variety of industrial and medical applications. The continuous demand for increased functionality, reduced size, small complex features on meso-scale components has led to the increase in research for micromanufacturing. The current silicon-based micromachining processes suffer from several inherent problems like high cost of sophisticated equipment, use of toxic chemicals, poor selectivity in material, and limitation to two-dimensional components. On the other hand, the tool-based manufacturing processes, e.g. micromilling, are capable of creating various three dimensional (3D) structures owing to the easily defined tool paths applicable to wide range of materials and simultaneously maintaining high accuracies in terms of tolerance to feature size. These advantages and applications led to the increased demand and focus in the field of conventional micromachining techniques.

Micromilling is the versatile machining process due to its flexibility and ability to produce complex 3D microfeatures. Attempt to perform micromilling using "rules of thumb" from established macromilling practices often lead to catastrophic fracture of microcutting tools. This paper (i) presents the research and educational program at Texas A&M University (TAMU), (ii) identifies necessary conditions for micromachining, and (iii) presents preliminary research result on micromilling of 316L stainless steel.

Education

Both graduate and undergraduate students are benefit from the collaborative support. Haas Automation provided a micromilling system OM2, Unist donated a cutting fluid atomizer to produce micromist, MA Ford provided microcutting tools, and NSF supported financially to participating students.

Micromachining is demonstrated to junior-level students after they have hands-on experience with macromachining. The senior-level students work in groups on specific micromachining projects to either collect research data, compare techniques for microtool setting, or produce microtooling for other research projects. Graduate students perform in-depth studies to compare micromachining options, optimize micromachining parameters, characterize micromist, or find limitation of fragile microcutting tools. All micromachining projects and equipment are proudly presented to high school students and visitors who often visit our Haas Technical Education Center.

Literature Review

Micromilling has been considered an attractive alternative over other micromanufacturing processes due to its high flexibility and the ability to produce complex 3D features[1]. Initial works are focused on developing microcutting tools and micromachining systems. A microtool of Ø25 µm can be fabricated by scaling down of a macro-size cutting tool. A microlathe of 32 mm long is made but with limited capabilities in shape generation. Another system has a maximum dimension of 200 mm long, spindle speed of up to 15,000 rpm and is even equipped with a dynamometer to measure cutting forces during machining. A diamond tool is used successfully to machine a workpiece of Ø 0.3 mm. Although this microlathe can produce microscrews of Ø120 µm, the surface roughness is only comparable to that after macromachining [2, 3].

Other studies also contribute to development of micromilling process. Several aspects like the size effect, cutting force, minimum chip thickness, chip load, cutting speeds and feeds, surface roughness, cutter run out, cutting temperature, tool life, multiphase materials, microstructure effects etc., are studied. A higher surface roughness is resulted from machining with tungsten carbide end mills with an edge radius of 5 μm on soft material such as 1045 steel [4]. Other authors conclude that a machined chip is not formed after each cutting pass at low feed rates; they support their argument after measuring the chip volume and examining the distance between feed marks on machined surface [2].

Analytical techniques are used for design and analysis of microtools [6]. Some study the dynamics of micromilling, investigate the influence of spindle run out and tool flexibility. Tool failure mechanisms when micromilling aluminum, graphite, and steel are studied. The investigators redefine "tool wear" considering the size difference of a microtool from macrotool, i.e., wear as any macroscopic change of a tool from its initial state. The changes may be loss of material during cutting, adhesion of workpiece particles on cutting tool edge, or deformation of tool geometry after machining etc. Tool wear results as chipping of cutting edge in macromilling, but in micromilling a tool fails due to complete worn out of an edge or chip clogging on it. A small change at tool cutting edge may result in the tool failure. Chipping tool causes higher cutting force and cutting stress of the microtool. Tool failure due to chip clogging, which is highly difficult to predict, is very quick due to generation of high stresses reaching far beyond the endurance limit of the cutting tool [7]. Other study shows that tool failure in microdrilling is also due to chip logging [8]. Cutting force characteristics and tool vibration signals change slightly during microdrilling operation before tool breaks. The investigator extends the study to monitor the static component of cutting force through use of segmental averages and wavelet transformations in micro end-milling[7]. Failure of a tool occurs very quickly if the cutting force increases beyond the strength of the tool. When cutting force increases during cutting, it deflects the fragile tool. The deflection of the tool and the stress increases with time. The static component the force in the direction of feed will increase continuously until tool breakage. Experimental evidence indicates a tool failure due to increasing cutting force up to three or four times although cutting conditions are remained the same[7].

To evaluate tool life, a tool is traditionally used at constant speed until failure. This technique is time consuming if a speed is too slow to start with, and does not simulate the real machining practice. Concept of cumulative tool wear was developed with which a tool can be used at different cutting speeds until reaching the tool life criterion. The model for side milling was been derived mathematically and verified experimentally [9, 10] as:

$$\frac{1}{\lambda} QC = \sum_{i=1}^{k} \Delta t_i V_{ci}^{\frac{1}{n}} \quad ; \quad Q = 1.00 \tag{1}$$

$$\lambda = \frac{\text{tool - chip interaction time}}{\text{milling time}} = \frac{M.Arc\cos(1 - \frac{2a}{D})}{360°} \tag{2}$$

Where:

Δt_i	: machining time at cutting speed V_i
i, j	: discrete step
T_i	: tool life at cutting speed V_i
V_c	: cutting speed at the circumference
Q	: total accumulative damage
k	: number of machining passes

C, n : constants
a : width of cut (radial depth) in side milling
D : diameter of a milling cutter
M : number of teeth on a milling cutter

The "equivalent" tool life T_e: $$T_e = \sum_{i=1}^{k} \Delta t_i \qquad (3)$$

moreover, the "equivalent" speed V_e: $$V_e^{\frac{1}{n}} = \frac{\sum_{i=1}^{k} \Delta t_i V_{ci}^{\frac{1}{n}}}{Q \sum_{i=1}^{k} \Delta t_i} \qquad (4)$$

Experiments

The objective of the experiment is to study potential benefits and constraints of using micromist for cooling/lubricating of micro cutting tools.

The material chosen, 316L stainless steel, is popular for using in food equipment, pharmaceutical equipment, marine applications, medical implants, petroleum refinery equipment, turbomachinery, and electronics. The chemical composition of 316L is 0.03% C, 17Cr, 12Ni, 2.5Mo, balance Fe; its typical tensile strength is of 480 MPs (70 ksi), yield strength of 170 MPa (25 ksi), elongation of 35%, and hardness of 95 BHN or 217 R_B.

The cutting tools are provided by MA Ford. The tungsten carbide end milling cutters have:
- 2 flutes
- 8° back rake
- 30° helix
- Ø1.016mm (0.040 in) tool diameter
- Ø3.175 mm (0.125 in) shank diameter
- 2 mm (0.079 in) cutting length

All machining experiments are performed on the Haas OM2 CNC vertical milling system. The cutting conditions are:
- 10 µm/tooth (0.000,4 in/tooth) chip load
- 0.35mm (0.014 in) axial depth
- 0.56 mm (0.022 in) radial depth
- Climb (down) side milling.

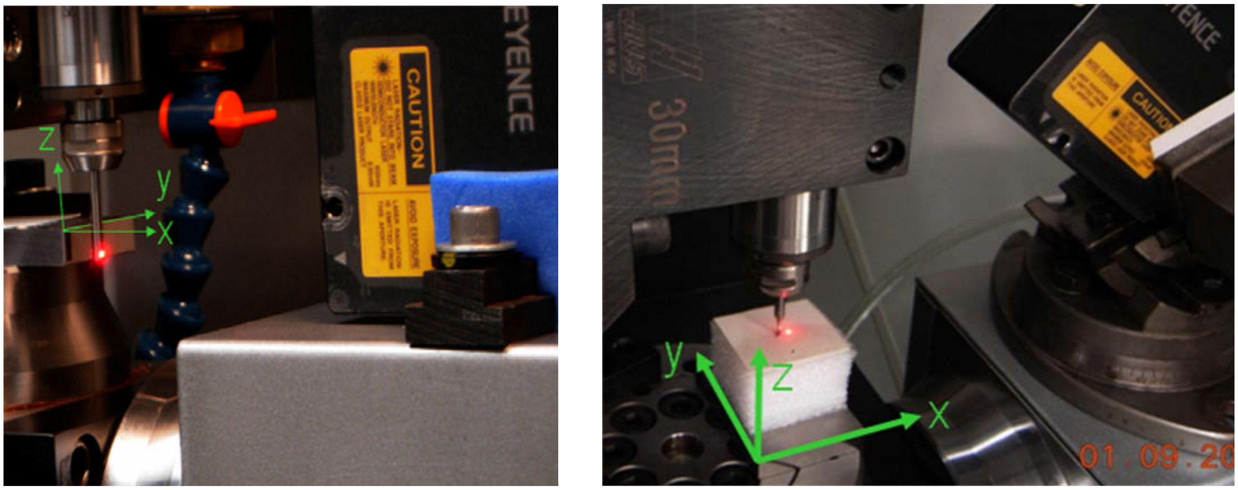
Variety of cutting fluids is used to compare their effectiveness:
- Dry
- Flood cooling: synthetic Blasocut 2000 Universal, 5:1 mixture
- Spray mist: 15% Blasocut 2000 Universal, 14 cc/min, 0.8 MPa, 30 mm @60° from z axis, 45° in x-y plane

- Micromist: UNIST Uni-MAX system, 2210EP oil, 0.022 cc/min, 30 mm @60° from z axis, 45° in x-y plane

Displacement is measured using the Keyence LKG laser, 70µm beam, 50 kHz sampling rate, 0.2 µm resolution. Tool life criterion is set at 50 µm and flank wear of a cutting tool is measured on an Olympus STM6 with 0.1 µm resolution. Tool fracture surfaces are observed with a JEOL JSM 6400 scanning electron microscope. Surface tension of cutting fluid is measured on a Sessile Drop Apparatus & FTA 188 Video Tensiometer. Multiple droplets are performed for satisfactory repeatability. Microdroplets emitted from the Unist system are collected on a cleaned 316L stainless steel sheet; their dimensions are then measured under the Olympus microscope to calculate the average air-borne droplets. Two-dimension simulation of micromist flow in the vicinity of a microcutting tool is performed using Fluent software using a solid cylinder as a simplified end-milling cutter. Finite element technique is used to evaluate the stress profile on a cutting tool. Run out of the machine spindle is measured with the Keyence LKG laser system. The laser beam is positioned at center of a Φ3 mm precision plug gage while it is rotating at different speeds. Tool offsets in x, y, and z directions are performed using the same laser system before machining (Fig. 1a and 1b).

Results and Discussions

Consistent spindle run out are observed when the spindle is running at steady state at different rotating speeds up to 50,000 rpm. Figure 2 shows the run out of ±1.5 µm on the Haas OM2 air spindle. If the run out were excessive, the displacement would bend a cutting tool during cutting and cause premature fatigue failure. Figure 3 shows the bending stress profile in a tool due to a run out amount equivalent to 34% of tool diameter. The maximum stress in this case would reach the tool flexural strength of 0.3 GPa.
Cumulative tool life data, calculated using equations (3) and (4), are plotted in Fig. 4. Dry micromilling of 316: stainless steel results in the lowest machinability following by flood cooling, spay mist, and micromist. Closed up examination using scanning electron microscopy indicates significant built-up edges and attrition failure of dry cutting tools (Fig. 5a). In contrast, a well-defined abrasive tool wear is seen on long lasting tools after spray mist or micromist cooling/lubricating (Fig. 5b). Micromist using 2210EP coolant/lubricant provides a significant improvement of ~10 times over dry machining of 316L stainless steel in this study. A specific condition of spray mist in macromilling of steel reduces burr formation, but provides similar machinability results as with flood cooling [11]. In another study of macromilling Ti 6Al 4V, the authors find a significantly improvement of tool life (~ 8 times) and a reduction of cutting forces when micromist is used [12].



(a) **(b)**

Figure 1. Measuring tool offset in (a) x and y directions and (b) z direction.

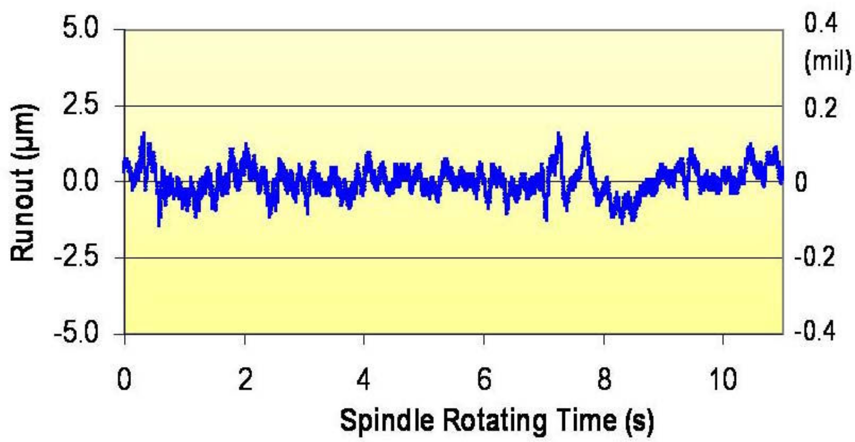


Figure 2. Run out of Haas OM2 air spindle at 10,000 rpm.

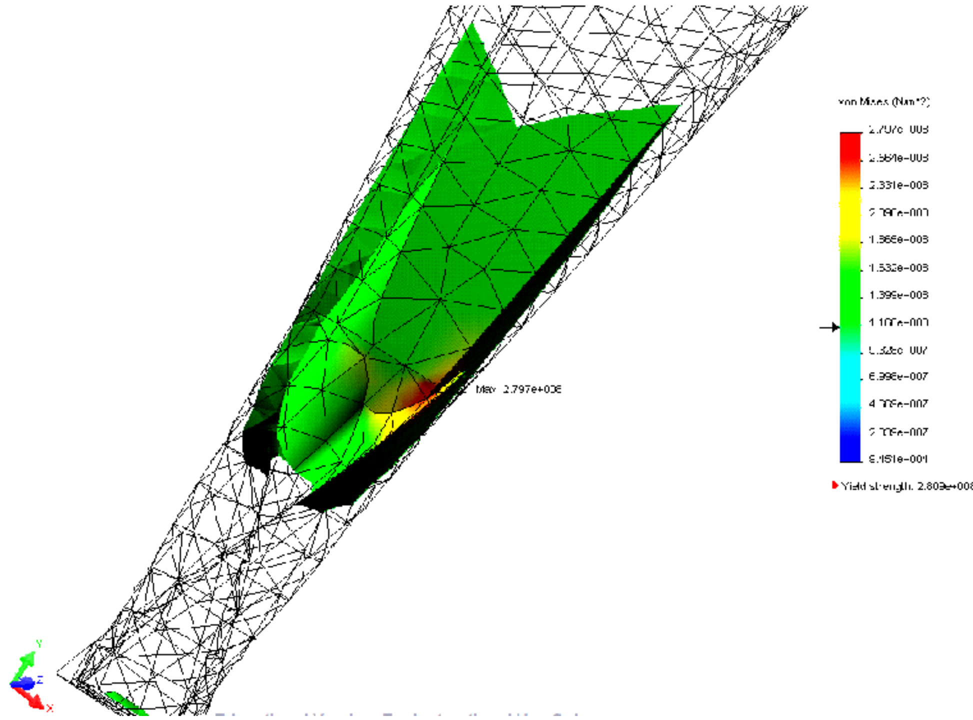


Figure 3. Bending stress on a cutting tool due to spindle run out. The maximum stress reaches flexural strength of the tool material when tool deflection is 0.34 mm (34% of tool diameter).

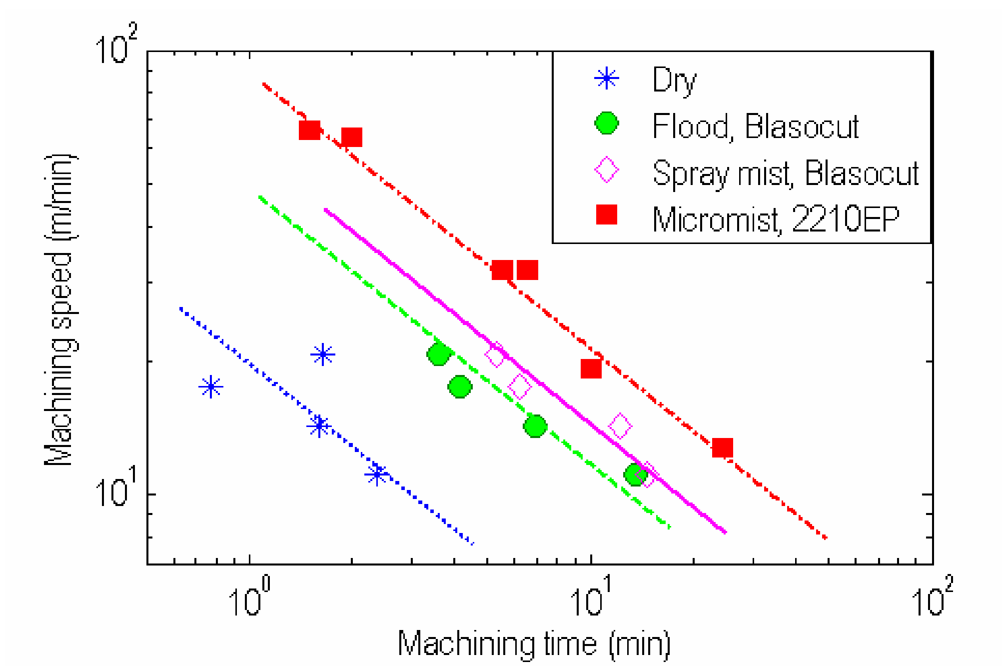
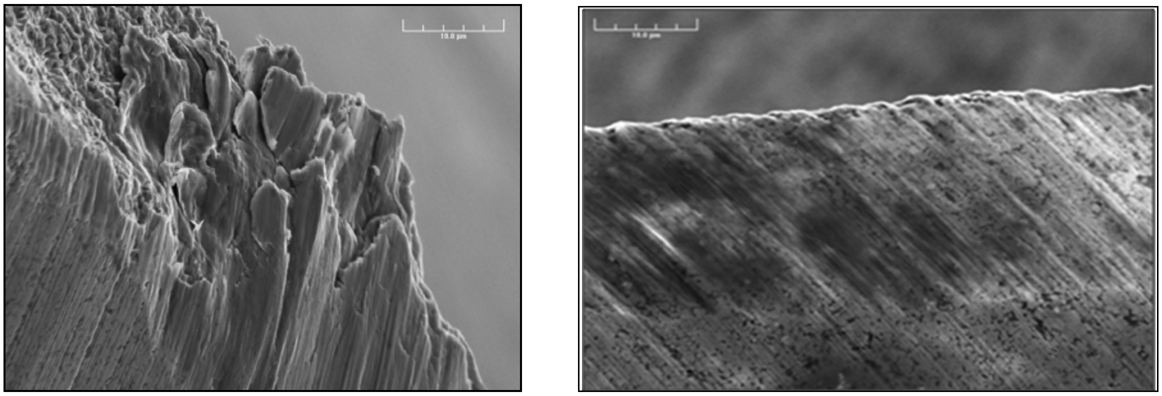


Figure 4. Tool life plotting for micromilling of 316L stainless steel. Feed 10 µm/tooth (0.000,4 in/tooth), 0.35mm (0.014 in) axial depth, 0.56 mm (0.022 in) radial depth.



(a) **(b)**

Figure 5. SEM picture of tool cutting edges after (a) dry machining and (b) spray mist cooling.

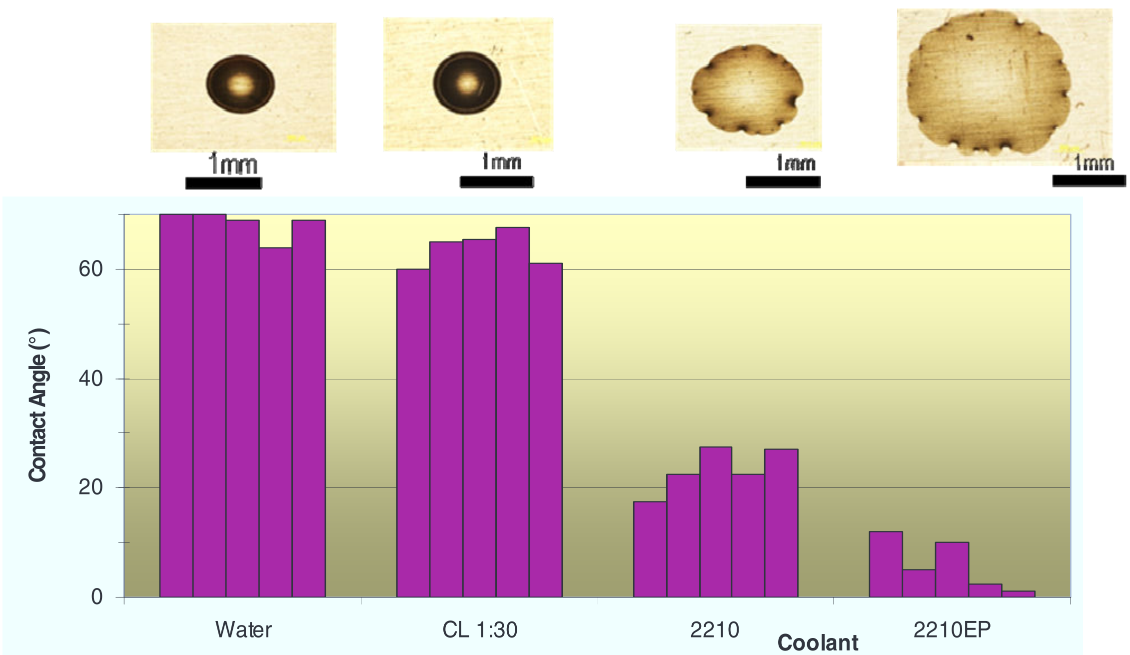


Figure 6. Wetting and contact angles of different coolants on 316L stainless steel flat plate. Five measurements for each fluid, drop volume 0.25 μL.

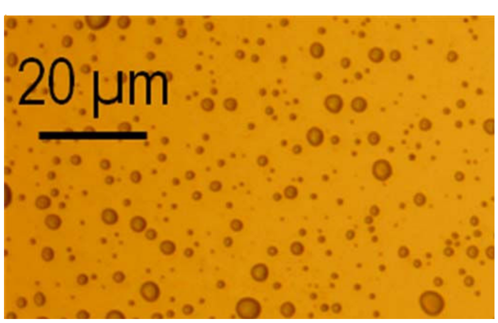


Figure 7. Microdroplets of 2210EP oil on 316L stainless steel. Stroke frequency 4-32 stroke/min, stroke length 0-3.6 mm, air pressure 3-4 bar.

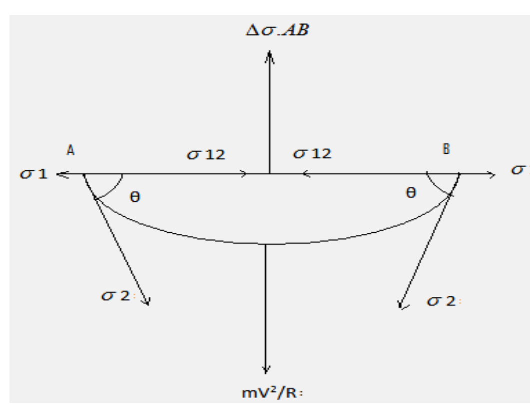


Figure 8. Free body diagram of a micro-droplet on a rotating tool.

Further investigation is performed to study the effect of micromist on tool life. Microdroplets of a cutting fluid must satisfy several conditions to effectively cool or lubricate a machining microtool at high rotating speed. The effective cutting fluid must:

a) Penetrate the boundary layer of a rotating tool,
b) Adhere to a tool surface despite centrifugal force, and
c) Wet the tool/chip interface to provide lubricating/cooling action.

Experiments have showed evidence of microdroplets of 2210EP penetrated the boundary layer and wet the Ø12.7 mm (1/2 in) and Ø3.17 mm (1/8 in) end milling cutters rotating up to 7000 rpm. The cutting speed is equivalent to that of the Ø1.016 mm (0.040 in) cutter in the study rotating at 89,000 rpm and 22,000 rpm respectively. Since the machine capacity of Haas OM2 is 50,000 rpm, it is postulated that microdroplets of 2210EP also penetrate and wet the Ø1 mm tool rotating at maximum speed. The fluid also favorably wets stainless steel compared to other fluid. The contact angle of 2210EP fluid on 316L stainless steel is less than 10° while that of water is 70° (Fig. 6). Dynamic analysis of microdroplet is performed to verify experimental results. Assuming the volume of in-flight microdroplets and those deposited on a plate are the same, i.e., neglecting the evaporation of the oil-based cutting fluid. By measuring the base radius and height of single microdroplet on a plate while omitting the coalesced larger droplets (Fig. 7), we can then calculate the in-flight droplet size. By equating the droplet volume, the radius R of in-flight microdroplet can be calculated from:

$$V = \pi h^2 \left[\left(\frac{h}{6} \right) + \left(\frac{r^2}{2h} \right) \right] = \frac{4}{3} \pi R^3 \qquad (5)$$

Where:

V	: volume of a microdroplet
r	: base radius of microdroplet on a flat plate
h	: height of microdroplet on a flat plate
R	: spherical radius of microdroplet in air

The airborne microdroplet diameter of 2210EP fluid is calculated from equation (5) to be ~0.4 µm for all tested parameters of the Unist micromist system. Free body diagram of a microdroplet on a rotating tool is shown in Fig. 8. A microdroplet is balanced between adhesion force due to surface tension and centrifugal force due to rotation. Using the Sessile Drop Apparatus & FTA 188 Video Tensiometer, the surface tension of 2210EP in air is measured to be 25.85, 25.85, 25.88, 25.90, and 25.90 mN/m. Figure 9 plots a curve representing the balance of two forces on a microdroplet. If the drop diameter is above this curve then adhesion prevails and it will not be separated from the tool due to centrifugal force. Since microdroplet diameter of Ø 0.4 µm is well above the curve for all speeds up to 50,000 rpm, the microdroplets of 2210EP will adhere and wet a cutting tool surface.

The 2D simulation result in Fig. 10 shows velocity contour of a flow surrounding a rotating cylinder [the simplified end milling cutter]. A stagnant zone (zero air velocity) is near the 12 o'clock position of a rotating cylinder. This location should not be the contact zone for tool and workpiece since microdroplets will be suspended and do not have momentum to penetrate the boundary layer of the tool. Further micromachining study is necessary to verify this.

There are constraints for using micromist in machining. Forming micromist from an arbitrary fluid could raise environmental concerns since excessive airborne microdroplets could contaminate the air or damage sensitive electronic instruments. Correct selection of a fluid and minimum amount of micromist should be used for environmental and economical reasons. Applying of micromist in some machining operations [for example gun drilling], is difficult since the cutting tool tip is completely shielded in a workpiece and micromist does not help to flush out the chips.

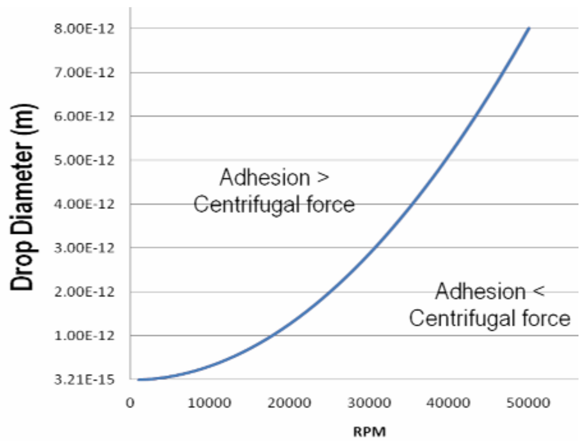


Figure 9. Balance of adhesion and centrifugal force on a 2210EP microdroplet

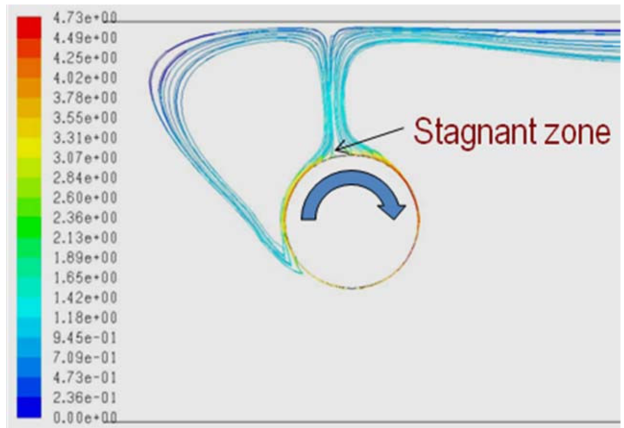


Figure 10. Simulation of flow across a rotating cylinder. Ø1 mm (0.04") cylinder @4000 rpm clockwise, airflow at 0.65 m/s (25.6 in/s) from left to right.

Conclusions

Both graduate and undergraduate students have been benefit from the collaborative support. Micromachining of 316L stainless steel using Ø 1mm (0.040 in) carbide end mills were investigated. This study showed:

1) Tool failure modes of the tools include chipping, attrition, and abrasive wear depending on type and how cutting fluid is applied.
2) Micromist significantly improves tool life when applied properly. Dry machining is not recommended due to built-up edge, tool chipping, and attrition.
3) The cumulative wear models apply for macro/micro machining in absence of tool chipping/delaminating.
4) Macromachining parameters (speed, feed, depth of cut…) cannot apply to micromachining. Experiments at macromachining parameters verified catastrophic failure of fragile microtools and damage to a workpiece.
5) Submicron droplets of air-borne cutting fluids may raise health and environmental concerns.
7) There is an optimal orientation to apply atomized micromist on a rotating tool. The tool and workpiece contact zone should not be at the stagnant area of flow mist.

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