Atomized Water and Oil Sprays as a Single Jet for Cutting Fluid Delivery in Micro-Milling

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In this paper, a new approach to deliver cutting fluids in micro-milling is presented. In this approach, the use of surfactants is eliminated with the ability to control the amount of oil and water spray delivered to the cutting zone. Water and oil are atomized independently into mists, and water and oil mists are mixed in the air before sprayed onto the cutting zone as a jet. The system is evaluated through micro-milling experiments, and the results indicate that the system is effective in cooling and lubricating the cutting zone.

1. Introduction

As demands for 3-dimensional (3D) miniature components increase, the micro-milling process is gaining more attention as a viable manufacturing process to satisfy the production requirements of components with micron to millimeter scale features for a wide range of engineering materials. However, it has been numerously stated in the literature that tool wear is a significant problem due to the limitations of tooling technology (large edge radii and poor geometry control) [1-7]. Thus, it is important to address the issue of rapid tool wear in micro-milling.

There are two main methods commonly taken to increase the tool life: coating and cutting fluids. For cutting fluids, conventional application methods are difficult to use for micro-milling due to high impact force associated with conventional methods [8]. Thus, either minimum quantity lubrication (MQL) approach is taken [9, 10], or different methods have been developed for application of cutting fluids in micro-milling [8, 11, 12]. Recently, atomization-based cutting fluid delivery method has been introduced for micro-milling [8, 13] and conventional turning as well [14]. However, although these methods employ different cutting fluid delivery approaches, they still used conventional cutting fluids, which contain surfactants and additives. Atomization of conventional cutting fluids leads to generation of mist that consists of fine droplets smaller than 10 μm in diameter and can be harmful to respiratory systems. Thus, elimination of harmful surfactants and additives will be important for continuous use of the atomization method for micro-milling.

Main roles of cutting fluids are to cool, lubricate, and flush away chips from the cutting zone. Because it needs to cool and lubricate, water and oil are both needed, and surfactants are consistently needed to emulsify water and oil. In this paper, a different approach is taken such that the use of surfactants is eliminated with the ability to control the amount of oil and water spray delivered to the cutting zone. In this approach, water and oil are atomized independently into mists, and water and oil mists are mixed in the air before sprayed onto the cutting zone as a jet. Essentially, two sprays are delivered to the cutting zone as one so that water droplets cool the cutting zone while oil droplets lubricate. Because two sprays are air mixed, no surfactant is needed, and the amounts of water and oil droplets are independently controlled so that ratio of their flow rates can be easily controlled.

2. A New Cutting Fluid Application System

2.1 System Concept

The concept of the system involves separate atomization of oil and water, mixing of the oil and water droplets in the air, and applying the mixture as a spray jet to the cutting zone. A schematic overview of the system is given in Fig. 1(a). Water droplets of 2-8 μm diameters are generated using an ultrasonic atomizer. Atomization by ultrasonic vibration is chosen for water because it creates quasi-monidisperse droplets with easy control of the flow rate [15, 16]. A compact ultrasonic atomization device has been designed and developed for micro-milling operations by our group [12]. Because vegetable-based oils cannot be atomized using ultrasonic vibration due to high viscosity, pressure atomization method is used to atomize vegetable-based oils. As shown in Fig. 1(a), as water and oil droplets are generated independently, they are carried by the carrier gas to the mixing chamber. In the mixing chamber, water and oil droplets get mixed in the air as they swirl around within the chamber. Then, the mixed droplets are carried to the nozzle. There is a tube at the center of the nozzle for the center gas to focus the droplets at the nozzle tip and create the spray jet. The nozzle tip is designed so that the droplets go through initial focusing. The center gas controls the spray jet velocity and thus the velocity control is very easy for achieving desired impingement dynamics of the droplets onto the cutting zone as well as effective flush-away of the chips.

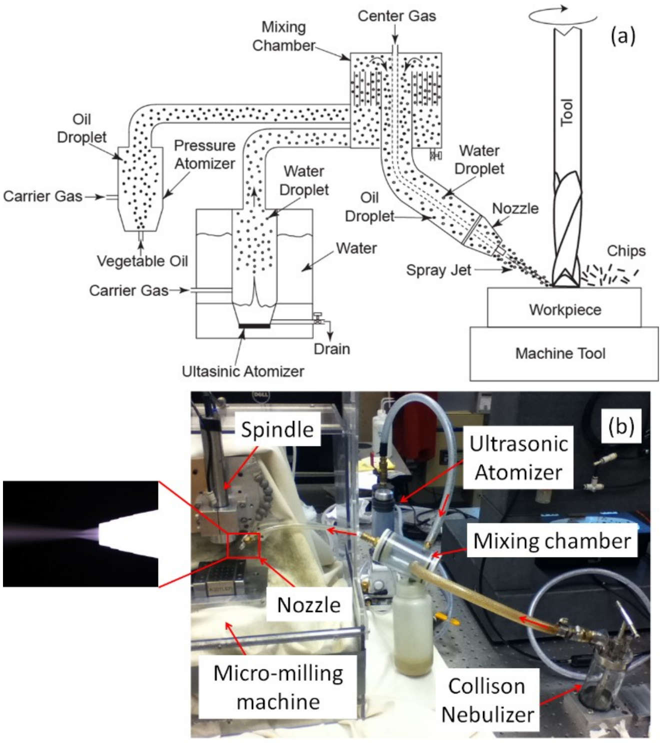

Fig. 1 (a) A schematic overview of the system that applies a mixture of oil and water droplets as a spray jet and (b) a photograph of the developed system.

As water and oil are atomized independently, mass flow rate of each can be controlled independently leading to precise control of the ratio of the amount of water and oil delivered to the cutting zone. Unlike other MQL methods, the system in Fig. 1(a) produces three major elements (water, oil, and jet) independently to satisfy the three roles of MWFs, that is, to cool, lubricate, and flush away chips. As the system can control the amount of each element independently, the appropriate mass flow rates and velocity can be tailored to the materials, tools and machining conditions. In addition, because water and oil droplets are not emulsified, there is no need for surfactants or emulsifiers. Also, because only the minimum quantity of vegetable-based oil and water are used, recycling and disposal of the fluids are not necessary, eliminating the need for additives such as biocides, and defoamers.

A photograph of the system set up on a micro-milling machine is shown in Fig. 1(b). As mentioned above, the ultrasonic atomizer was designed and developed in-house to atomize water. A Collison nebulizer (CN24, BGI Inc.) was procured and used to atomize oil. Canola oil was selected because it has been known to be effective for lubrication during cutting. The nozzle was developed in-house as well and mounted to be directed towards the cutting zone. A photograph of the spray jet from the nozzle is also shown in Fig. 1(b), which clearly shows the focused jet.

2.2 Experimental Setup

For micro-milling experiments, a custom built micro-machine tool (Alio Industries) with a spindle (NSK E800Z) with the maximum speed of 80,000 rev/min (RPM) was used, as shown in Fig. 1(b). Two-fluted micro end mills of 396 μm in diameter (Performance Micro Tools) were used for micro-milling operations. Cutting forces generated during micro-milling were measured using a Kistler MiniDyn 9256C1 dynamometer. Morphology of the generated chips, machined part quality, and burr formations were evaluated using an optical microscope (Olympus BXFM) and a scanning electron microscopy (SEM, Hitachi S4700).

The experiments were carried out with four fluid conditions: (a) ultrasonically atomized water, (b) nebulized canola oil, (c) water and oil mixture, and (d) nebulized 5% TRIM solution. Two different materials were considered for evaluation: Al6061 and Steel 1018. Full immersion slots were milled on both materials. Two feed-per-tooth (FPT) values of 0.3 and 1.0 μm/tooth were selected. Cutting velocities of 75 m/min (60,000 rpm) and 60 m/min (50,000 rpm) were chosen for aluminum and steel workpieces, respectively. For each new tool, total of 25 slots of 45 mm length were milled at the axial depth of cut of 150 μm for Al6061 and 50 μm for steel 1018.

3. Experimental Results with New System

3.1 Experimental Results for AL6061

For Al6061, two feed rates of 0.3 and 1.0 μm/tooth were chosen and a spindle speed of 60,000 rpm is selected. Using a new tool for each condition, 25 slots of 45mm length were machined at the depth of cut of 150 μm.

Figure 2 shows the peak-to-valley values of the resultant forces averaged for 25 slots at two different feed rates (0.3 and 1.0 μm/tooth). Note that oil only condition leads to better performance than the water only condition, and the best performance is achieved with the water and oil mixture. It is interesting that 5% TRIM solution performed the worst; this may be because this particular cutting fluid, being a general purpose metalworking fluid, is not best suited for micro-milling operations. Nevertheless, the results clearly show that performance is improved when the mixture is applied.

Figure 3 shows (a) SEM images of the generated chips and (b) microscope images of slots (25th slot) machined at the feed rate of 1.0 μm/tooth. The chip thickness measured for the chips shown in Fig. 3 are 3.97, 2.70, 2.73, and 6.91 μm for water, oil, water and oil mixture, and 5% TRIM conditions, respectively. Note that chip thickness is small for oil and oil and water mixture conditions, indicating low friction on the tool-chip interface. Machined slot images shown in Fig. 3(b) display similar results; less burrs are observed when oil and water mixture was used.

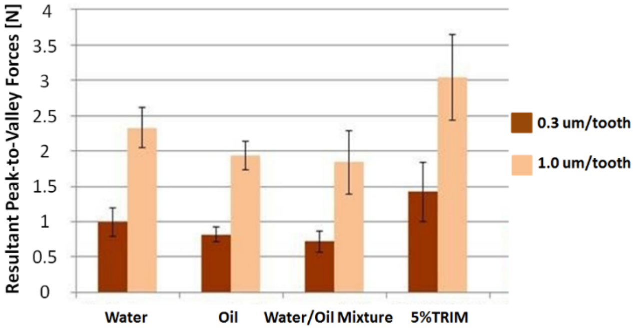

Fig. 2 Peak-to-valley values of ther resultant forces averaged over 25 slots

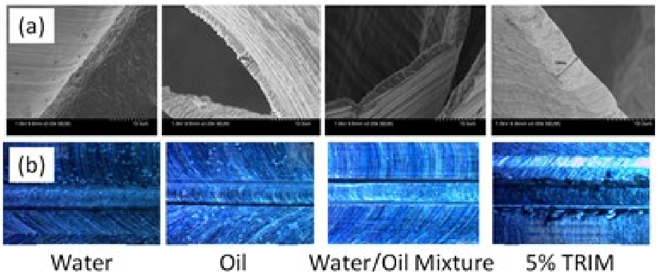

Figure 3. (a) SEM images of the generated chips and (b) microscope images of slots (25th slot) machined

Tool wear photographs were taken using an optical microscope to observe the cutting edge of the tool after 25 slots were milled. In Figure 4, tools' shapes with canola oil as cutting fluid obviously maintains the best. Hardly any wear is seen in the tip at both two feed rates. This verifies that canola oil behaves best in lubrication. At the feed rate of 0.3µm/tooth, tools with water, oil and mixture as MWFs all have very little tool wear while some wear is observed with 5% TRIM as coolant. At the feed rate of 1.0µm/tooth, the tool is seriously worn and even broken in the tip with distilled water condition. Substantial wear is also observed with the 5% TRIM condition.

Chips generated during slot-milling were carefully collected and examined to verify the chip morphology and thickness. Figure 5 shows the SEM photos of the chips generated at the feed rates of 0.3 and 1.0 µm/tooth with distilled water, canola oil, water and oil mixture, and 5% TRIM conditions. Morphologies of the chips generated with the conditions of canola oil and water and oil mixture are similar in shape, indicating that the oil component in the water and oil mixture contributed similar to the pure oil condition. Chips under distilled and water and oil mixture conditions are less curly than other conditions, indicating effective cooling during chip generation. It seems that chip curliness is the same with the canola oil and 5% TRIM condition, and cooling was not as effective as other conditions. The chip morphologies indicate that the water and oil mixture can provide both cooling and lubrication.

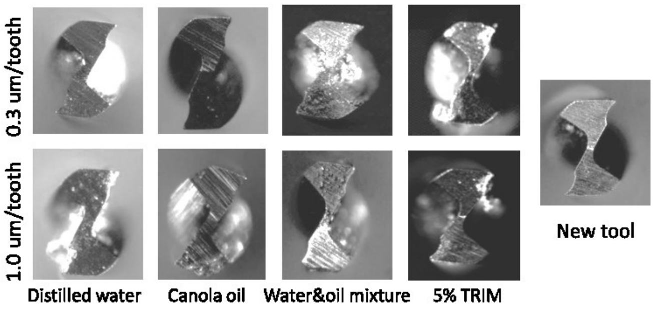

Figure 4. Tool wear photographs at different MWF conditions after milling 25 slots.

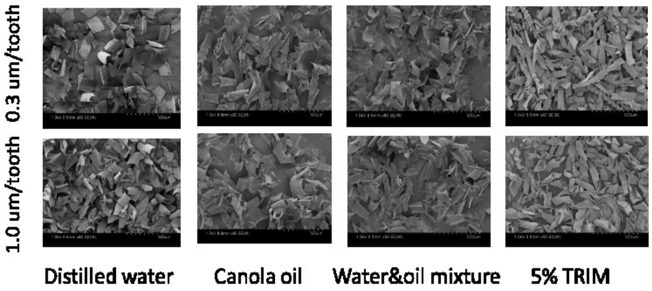

Figure 5. SEM photographs of generated chips (scale bar = 500 µm)

3.2 Experimental Results for Steel 1018

For steel 1018, two feed rates of 0.3 and 1.0µm/tooth are stilled used and a spindle speed of 50,000 rpm is selected since the surface speed is 60 m/min. For each new tool, as many as slots of 45mm length are tried to be cut at the depth of cut of 50 µm.

Table 1 shows the total number of slots machined before tool failure when steel 1018 was used as the work material. Note that tool failed earlier for all conditions at the feed rate of 0.3 µm/tooth; this is due to increased ploughing and rubbing at the low feed rate. At both feed rates, water and oil mixture condition led to the most number of slots machined, compared to other cutting fluid conditions. It is interesting that the water only condition led to better performance compared to the oil only condition. This indicates that with steel 1018, temperature increase was more likely significant, and cooling capacity was important to improve the cutting process and tool life. When both water and oil are applied together, cooling and lubrication were both effectively achieved. This shows the capability of the system in controlled application of water and oil for different materials and cutting conditions.

Table 1. Total number of slots machined under different conditions before tool failure.

Cutting Fluid Condition	Feed Rate [µm/tooth]	Total Number of Slots Machined
Water	0.3	13
	1.0	25
Canola oil	0.3	8
	1.0	24
Water & oil mixture	0.3	15
	1.0	34
5%TRIM	0.3	4
	1.0	9

Tool wear photographs taken under a microscope are shown in Figure 6. The new tool is on the right for comparison. Because of tool failure, tool wear was observed after machining two slots at each feed rate condition. The tool wear phenomenon is more obvious with steel as indicated in Figure 6. It is evident that the minimum tool wear is observed when the mixture of water and oil is applied. Note the tool at the feed rate of 1.0μm/toot; only small tool wear was observed when the mixture of water and oil is used compared to other fluid application conditions.

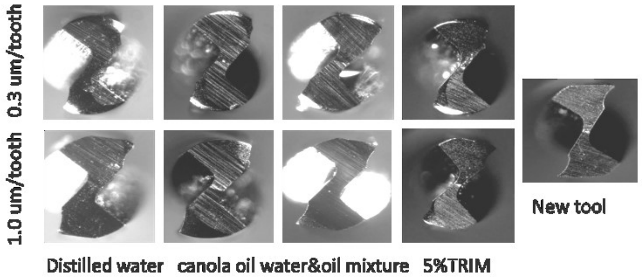

Figure 6. Tool wear photographs at different MWF conditions after milling 2 slots of Steel 1018.

Top burrs are also observed of the 1st and 2nd slots for all the fluid application conditions at the feed rate of 0.3μm/tooth, and they are shown in Figure 7. It shows that the slots have the least amount of burrs with water and oil mixture as MWF. The canola oil condition leads to a little more burrs than the mixture condition. On the contrary, a big amount of burrs and coarse edges are observed with 5% TRIM as cutting fluid. The distilled water condition led to the most amount of burrs. The results indicate that both cooling and lubrication are important when machining Steel 2018, and the water and oil mixture was effective in temperature reduction as well as lubrication.

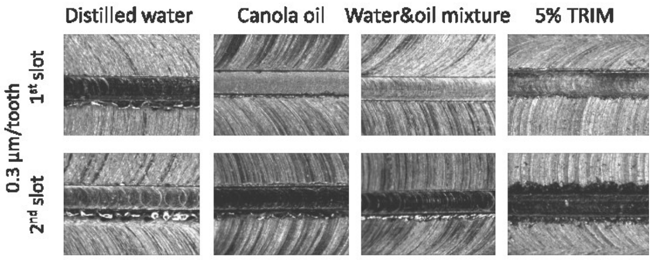

Figure 7. Photographs of burrs formed on top surfaces of the machined slots.

3. Conclusions

A new cutting fluid system to apply air-mixed water and oil sprays as one spray jet to the cutting zone has been designed and developed. The system requires no surfactant or emulsifiers because water and oil are mixed in the air. The system was evaluated using micro-milling experiments, and the results of experiments show that the cutting zone can be effectively cooled and lubricated. Among four different kinds of cutting fluids, the mixture of distilled water and canola oil behaves best in almost all aspects including reducing cutting forces, tool wear, and slots' burrs. This may due to the combination of both cooling and lubricating characteristics of the mixture. The mixed jet of independently atomized water and oil sprays has a prominent advantage, which is, any ratio of oil and water droplets in mixture can be achieved by changing the mist velocity of low gas pressure from the atomizer and the spray velocity of high air pressure from the center tube in the nozzle.

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