Flow Visualization and Characterization for Optimized MQL Machining of Composites

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Limited information is available on the effect of Minimum Quantity Lubrication (MQL) parameters (oil flow rate OFR, air flow rate AFR, nozzle orientation and distance from the cutting zone) on flow characteristics. Particle Image Velocimetry and Phase Doppler Anemometry flow visualization methods were used to define the optimal MQL jet for better penetration and cooling/lubrication; coherent, small magnitude number of vorticities, and small droplets of high velocity. Effect of flow characteristics on cutting forces, temperature, tool wear and geometric errors was examined in CFRP milling. Optimum AFR, OFR and nozzle distance from the cutting zone were established and compared to flood, pressurized air, and dry machining.

1. Introduction

Minimum Quantity Lubrication (MQL) is an emerging technology that proved to have technological, economic and environmental benefits in conventional and high speed machining of metallic and composite components [1-3]. Application of MQL in machining processes requires the droplet size of the spray to be small enough to penetrate the cutting zone [4], but greater than 5-10 μm, otherwise they become airborne fluid particles that cause health problems if inhaled [5].

In MQL machining, the droplet size and the velocity characteristics of the spray influence its cooling and lubrication capacity. This, in turn, affects the cutting temperature and forces, tool wear, and surface integrity [6].

Since limited information is available on the flow regimes in MQL, the main objective of this work is to study the effect of the MQL parameters; namely, the air flow rate (AFR), the oil flow rate (OFR), and the distance (L) from nozzle exit to the cutting zone, on the jet flow characteristics. This is carried out through flow visualization to determine the optimum MQL jet. The effect of the flow characteristics on machining performance was evaluated for Carbon Fiber Reinforced Plastics (CFRP), which is commonly machined under dry conditions, due to the negative effect of moisture absorption on its shear fracture toughness. Therefore, if optimized, MQL provides a viable alternative for improved performance, in terms of tool wear and part geometric accuracy.

2. Flow Visualization for Optimum MQL Jet
2.1. Definition of Optimum MQL Jet (Spray)

The MQL cutting fluid is disintegrated into small droplets when the aerodynamic and surface shear external forces exceed surface tension forces. Small droplets have a large surface area-to-volume ratio, thus have increased heat transfer through rapid vaporization. Therefore, water that has low boiling point and high latent heat of vaporization is mixed with small amount of oil, which acts as a lubricant. Due to the aerodynamic interaction between the spray and the surrounding atmosphere, vortices are generated in the spray. Higher jet velocity causes the vortices to be weaker, producing a more efficient atomized spray. In addition, it reduces the number of large droplets and narrows the range of droplet diameters, making the spray more uniform.

In machining, the optimum MQL spray should, therefore, be coherent (free of vorticity), and have smaller droplets and high axial velocity for better atomization and penetration of the cutting zone. The spray should also be axial (coinciding with the axis of nozzle), symmetrical and undisturbed.

2.2. Flow Visualization Setup and Measurement Principles

The complementary methods of Particle Image Velocimetry (PIV) and Phase Doppler Anemometry (PDA) were used to visualize and analyse the flow of the MQL jet. While PIV provides information on the velocity field, vorticities and the spray pattern, PDA measures simultaneously the droplet size and its velocity. A schematic of the experimental setup is shown in Figure 1. An external two-channel supply system was used to deliver the MQL cutting fluid, which is stored in an emulsion tank and pumped with a desired pressure through a nozzle in the form of an atomized jet or spray in the PIV or PDA measuring volume.

In the PIV setup, a double-pulsed laser (Nd:Yag) was used to project a pulsed laser beam of 1064 nm wavelength at 100 MHz. The pulsed laser beam is then transformed into a light sheet using a cylindrical lens, which illuminates the particles flowing through a cross section of the flow. The successive positions of the particles are captured and recorded using a Charge-Coupled Device (CCD) camera. The images of the illuminated tracers are then processed through image interrogation (to determine the displacement between two patterns of droplet images), image processing (to extract the instantaneous velocity vectors) and image post-processing (to validate and smooth extracted data).
In a second set of experiments, a PDA system was used (Figure 1). An argon-ion laser emits a laser beam, which is split into two beams by a splitter. Their intersection creates a measurement volume and forms a fringe pattern. When entrained droplets pass through the measurement volume, they scatter the light and create a beat (or Doppler) signal with a frequency linearly proportional to the particle velocity. The phase shift between these Doppler signals is a direct measure of the particle diameter.

2.3. Flow Characteristics of the MQL Jet

The selection of the optimum air and oil flow rates is critical to control the velocity and size of the droplets. If the air flow rate (AFR) is too small, the atomization process is incomplete, producing relatively large droplets of lower cooling ability. If AFR is, however, too high (or the oil flow rate OFR is too small), the relatively small droplet size creates a mist of lubricant in the air and leads to a higher internal pressure inside the droplets, making them unstable. This leads to poor wetting properties, and hence lower lubrication and thermal capacity. The goal of MQL is to use the minimum amount of oil needed to reduce friction and to improve tool life. However, too much OFR not only causes the chip to stick to the tool, but also defeats the main purpose of MQL. In a separate investigation using this 2-channel experimental setup [7], it was found that the mean droplet size D is proportional to (OFR/AFR)^1/2 and a wide range D can be obtained by varying 20 l/min to 35 l/min, and 10 ml/min to 25 ml/min, allowing us to define the optimum operating condition.

A total of 12 PIV tests were carried out for AFR= 20, 25, 28 and 31 l/min, and OFR= 10, 17.5 and 24 ml/min. Additional 8 PDA tests were conducted for AFR=25, 28 and 31 l/min and OFR=10, and 17.5 ml/min. In both sets of experiments, the measurements were taken at planes located at distances L=40, 60, and 80 mm from the nozzle exit. Figure 2 shows the PDA results for the average axial velocity distribution along the z-axis, measured from the central axis of the nozzle, for the combinations of the highest AFR/lower OFR (31 l/min, 10 ml/min), highest AFR/higher OFR (31 l/min, 17.5 ml/min), and lowest AFR/highest OFR (25 l/min, 17.5 ml/min). The results showed that by increasing AFR, the magnitude of the peak velocity increases and the axial velocity distribution becomes more symmetrical around the nozzle axis. To a lesser extent, the increase in OFR has similar effect. For all AFR/OFR combinations, the magnitude of the axial velocity decreases as the distance from the nozzle exit increases, due to the droplets collision and the external forces applied by the surrounding atmosphere. In addition, with the increase in the distance L, the peak of the axial velocity is shifted upwards, due to the air velocity gradient inside the nozzle, as confirmed by a separate CFD analysis. This effect is reduced by increasing AFR.
The increase in OFR causes, however, an increase in the number of vortices in all zones of the flow field, especially when AFR is low. These observations confirm that the combination of the highest AFR and the lowest OFR not only maximizes the jet axial velocity but also minimizes vorticity.

Figure 4 shows the variation of the mean vorticity magnitude (MVM) in various zones around the jet for the limiting cases of highest AFR/lowest OFR (31 l/min, 10 ml/min), and lowest AFR/highest OFR (20 l/min, 24 ml/min). Analysis of various cases indicated that the increase in AFR leads to a decrease in MVM, with nearly zero vorticity in zones 4 to 6 when AFR=31 l/min. As OFR increases, however, MVM increases remarkably.

The frequency distribution of the droplet size was examined for different combinations of air and oil flow rates, at planes located 4 cm and 8 cm from the nozzle exit, using the PDA technique (Figure 5). Analysis of the results showed that droplets with diameters in the range of 20-150 µm have the highest frequency. With the increase of the distance L, the size and number of the droplets increase due to the coalescence collision between the droplets, and due to the reduced axial speed. This negatively affects the spray atomization. To have an MQL jet with large number of small droplets, the same conclusion is reached again: high air flow rate and low oil flow rate.

The effect of the MQL parameters on the droplet diameter-velocity relationship is shown in Figure 6, for the highest AFR (31 l/min) when combined extreme levels of OFR (10 and 17 ml/min), at L= 40 and 80 mm. The results showed that as L increases, the number of droplets with larger diameters increases, especially at higher oil flow rates, since the spray is not well atomized. The results also showed that an increase in AFR results in an overall decrease in droplet diameter, with an increase in its velocity, due to the increase in the pressure drop across the nozzle.

### 3. MQL Machining of CFRP Laminates

#### 3.1. MQL Machining Setup

Slotting tests were performed to assess the effect of MQL parameters and different lubrication/cooling modes on the machining of CFRP laminates. The tests were performed on a 5-axis DMU-100P duo BLOCK® CNC Machining Center, at fixed spindle speed of 15,000 rpm, and feed of 1,500 mm/min, using helical 4-flute 1/4" uncoated tungsten-carbide end mills (SGS-30131). Megacrene 550® was used to make a 5% concentration emulsion for the MQL tests. Cutting forces, maximum tool temperatures and tool wear were evaluated for each cutting condition after 90 mm of cutting length, for a total length of 450 mm. Geometric and dimensional errors of machined surfaces were measured using Mitutoyo MACH806 CMM.

Figure 7 shows the experimental setup, with the tool (1) moved upwards for clarity. A vacuum system (2) was used to collect the CFRP dust generated during cutting, without affecting the application of MQL (3). The CFRP test samples were multidirectional (0°-45°-90°-0°) woven laminate, 6.35 mm thick (4). Cutting forces were measured using a 4-component Kistler 9272 dynamometer (5). A FLIR ThermoVision A20M infrared (IR) camera (6), with a spatial resolution of 2.7 mrad, was used to measure the temperature of the tool and the surrounding CFRP material. The tool emissivity was calibrated within the measured temperature range; ε = 0.34. The IR temperature measurement error is estimated to be 5%.

#### 3.2. Effect of MQL Parameters on Machining Performance

The effect of MQL parameters on the machinability of CFRP was evaluated and compared to dry cutting and pressurized air cooling (at a flow rate = 31 l/min). Three MQL combinations were tested at conditions corresponding to the lowest and highest air

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**Figure 4** Mean Vorticity Magnitude (s⁻¹) by zones for different air and oil flow rates

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**Figure 5** Droplet size frequency distribution at (a) L=40 mm and (b) 80 mm

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**Figure 6** Correlation of droplet diameter and velocity for different air and oil flows and distances from the nozzle exit

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**Figure 7** Experimental setup for slotting of CFRP panels
and oil flow rates used in the flow visualizations tests. These conditions are identified in Figures 8 and 9. Figure 8 shows the measured maximum temperature at the tool tip for various lubrication/cooling modes throughout the cut (0-450 mm). In this set of tests, flood cooling was not applied, since it obstructs the IR temperature measurement. It can be noticed that the maximum temperature obtained with pressurized air cooling, at the end of the cut, is higher than dry cutting and all MQL combinations by up to 25%. This can be attributed to the effect of pressurized air and rubbing the CFRP dust against the tool and the possibility of re-cutting the dust. Various MQL combinations showed the same performance in terms of the tool temperature (within ~ 7% variation). The optimum MQL condition of highest AFR (311/min) and lowest OFR (10 ml/min), established by flow visualization, produced slightly higher temperature, when compared to the combination of lowest AFR/highest OFR (AFR=20 l/min and OFR=24 ml/min).

The mean force in the feed direction near the end of cut, under pressurized air cooling, was about 15% less than other cooling modes due to the resin softening effect. The feed force for all MQL conditions and those for flood and dry cooling were within 7% of each other. It is interesting to note that forces resulting from MQL machining were less than those obtained in flood machining. This suggests that the flood coolant was not as effective as MQL in penetrating the cutting zone.

Figure 9 shows the progressive flank wear measurements under MQL and dry machining, as well as pressurized air and flood cooling. When compared to other modes of lubrication/cooling, MQL causes a reduction in the tool wear by 20-30%. This can be attributed to the jet atomization and improved penetration. Among the MQL test conditions, lower tool wear was observed for the optimum spray conditions predicted by flow visualization; highest air flow rate (AFR = 311/min) and lowest oil flow rate (OFR = 10 ml/min). For this combination, a 17% reduction in the flank wear was reached, when compared to other MQL conditions. This confirms that a favourable jet is associated with lower droplet size, higher droplet velocity and lower vorticity. As expected, this promotes the droplet penetration, evaporation and hence, increasing the rate of heat transfer from the cutting zone. Additionally, the slightly higher tool temperature obtained for this condition (Figure 8) caused thermal softening of the resin to the point of reducing the tool wear. It is worth noting that flood machining resulted in higher tool wear than MQL. The results presented in Figure 9 strongly suggest the use of MQL in machining of composites over dry machining, which is the current practice of the industry.

Examination of the dimensional and geometric accuracy of machined surfaces showed that the optimum MQL condition (AFR = 31 l/min and OFR = 10 ml/min) produced the most stable width of cut throughout the cutting distance and it was the only condition that satisfied the tolerance requirement of ±10 µm. At the end of the test (cutting length of 450 mm), the straightness and parallelism requirements of maximum error of ±12 µm were only satisfied by this optimum MQL condition and flood cooling.

4. Conclusions

PIV and PDA flow visualization showed that the optimum MQL spray can be achieved with the combination of high air flow rate (AFR) and the low oil flow rate (OFR), when the nozzle placed as close as practically possible to the cutting zone. This combination promotes the breaking mechanism of the droplets, providing good atomization; large number of small droplets at high axial velocity. It also produces a more coherent jet with less vortex formation that has better penetration into the cutting zone.

Slotting tests were performed on CFRP laminates to investigate the effect of the MQL parameters on the machining performance, as compared to flood and dry cutting. The performance was evaluated in terms of maximum tool temperature, cutting force, tool wear and machining accuracy. Using MQL, the flank wear is reduced by the 30% compared to pressurized air and 22% as compared to dry and flood coolant. The MQL combination of high air flow rate and low oil flow rate produced the longest tool life and the least machining error. These findings are in agreement with flow visualization and analysis results.

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References