INTRODUCTION

Cutting fluids are widely used to cool and lubricate the cutting zone, to flush away chips, and to inhibit corrosion during machining operations such as drilling, turning, boring, grinding, and milling [Aronson et al., 1994]. Significant negative effects, in terms of environmental, health, and safety consequences are associated with the use of cutting fluids. Many of these are attributed to the production of mist during the machining process. The potential health effects of exposure to these cutting fluid mists have been the subject of numerous epidemiological studies. These studies have shown statistically significant increases in certain cancers [Hands et al., 1996], and have suggested that exposure to fluid mist may be associated with an increased risk of respiratory irritation, chronic bronchitis, occupational asthma and loss of lung function [Eisen, 1994].

In addition to these health related concerns, a variety of other negative effects of fluid mist: poor air quality, housekeeping safety issues, and environmental concerns [Marano, 1995] have prompted regulatory scrutiny by several organizations. Standards set by government agencies, such as the EPA and OSHA, as well as industrial organizations, establish maximum mass concentrations levels for airborne particulate matter less than a given size, e.g. 10 microns. Therefore, it is not only the mass concentration of mist produced that is of importance, but also the droplet size distribution.

In an effort to control cutting fluid mist production, ongoing work at Michigan Technological University (MTU) is aimed at developing numerical models which can be used to predict the mist produced during various metal working processes. In order to accomplish this, it is necessary to determine the mist formation mechanisms which occur during the machining process. Previous experimental work at MTU focused on identifying the machining conditions that significantly affect cutting fluid mist mass concentration. It was found that spindle speed has a dominant effect on the mist mass concentration of droplets less than ten microns in diameter [Gunter and Sutherland, 1999]. The work presented in this paper uses Design of Experiment techniques to further investigate mist formation during the turning process, and then examines the classical atomization theory in order to gain insight into the mist formation mechanisms that are occurring.

NOMENCLATURE

\[ \begin{align*}
D & \quad \text{droplet mean diameter, m} \\
K & \quad \text{wave number} \\
N_l & \quad \text{ligament number} \\
q & \quad \text{cooler flow rate, m}^3/s \\
R & \quad \text{workpiece radius, m} \\
Re & \quad \text{Reynolds number} \\
We & \quad \text{Weber number} \\
V & \quad \text{jet velocity at the nozzle exit, m/s} \\
\sigma & \quad \text{surface tension, N/m} \\
\mu & \quad \text{dynamic viscosity of the coolant, kg/(s\cdot m)} \\
\nu & \quad \text{coolant kinematic viscosity, m}^2/s \\
\rho & \quad \text{cooler density, kg/m}^3 \\
\omega & \quad \text{workpiece angular velocity, rad/s}
\end{align*} \]

MIST SIZE DISTRIBUTIONS

To determine the underlying process conditions that affect cutting fluid mist size distributions generated during a turning process, Design of Experiments (DOE) techniques were used to determine the most significant variable effects [DeVor et al., 1992]. Five variables were studied for this work, with each variable assigned a low and a high level: spindle speed (600 and 2000 rpm), workpiece diameter (63.5 mm and 104.8 mm), nozzle diameter (3.175 mm and 6.35 mm), cutting fluid oil concentration (5% and 20%), and location with respect to the lathe (front or back). A table-top lathe was used to turn the workpieces at the desired speeds. Cutting fluid was applied via a nozzle centered above the workpiece at a distance of approximately 100 mm and positioned orthogonally to the workpiece. The fluid flow rate was held constant (56.78 cm$^3$/s) for each test.

An Amherst Process Instruments Aerosizer Mach II particle measuring system was used to measure the aerodynamic particle size distributions in the range of 0.5 to 15 microns. Ambient particulate matter measurements were taken before each test with the Aerosizer, which was run for a total of three minutes. The lathe was started and the cutting fluid applied immediately after the ambient readings were taken.
Measurement of the cutting fluid mist generated also lasted for a duration of three minutes.

The ambient airborne particulate matter (e.g., dust, lingering cutting fluid mist droplets from previous tests) present in the air before each test is run can influence the measured size distributions of cutting fluid mist. Mist droplets can coagulate with or numberate around the ambient particulates, larger droplets settle out, and those ambient particles that do not combine with the mist droplets are counted by the Aerosizer and included in the mist distribution. Therefore, the size distribution of the cutting fluid mist does not provide an exclusive description of “pure” mist production. To mitigate this problem, at least in part, particle size distributions of the ambient air were measured before each test and then subtracted from the subsequent mist size distribution measurement. Although this approach does not filter out the effects of coagulation, nucleation, or sedimentation, it does provide a picture of the relative change in airborne particulate matter due to the generation of cutting fluid mist.

The measured size distributions were found to be bimodal in nature, suggesting the presence of more than one mist formation mechanism. The hypothetical particle size distribution in Fig. 1 shows the contribution of two different mechanisms to the distinct modes. It can be theorized that similar mechanisms define the cutting fluid mist distribution: the transfer of mechanical energy to the fluid as it impacts the machine tool and rotating workpiece results in larger droplets, while the mode associated with smaller drops is due to evaporation and condensation of suspended airborne droplets and/or the stripping of the oil droplets from the cutting fluid emulsion. Since the ambient particulate distribution is also characterized by a fine-particle mode (see Fig. 2), it can be theorized that the mist droplets or vapors nucleate around these particles, thus contributing to the corresponding mode on the “mist” distribution.

For some of the tests run at the low spindle speed (600 rpm), an interesting occurrence was observed. When the ambient size distribution is subtracted from the mist distribution, the resulting histogram is negative in some areas. The positive portions of the histogram can be referred to as “created” particles, the increased number of airborne particulate above the original ambient level due to the formation of cutting fluid mist. Likewise, the negative portions of the histogram can be thought of as “destroyed” particles, or particulate which existed in the original ambient measurement but were removed through the addition of mist droplets, most likely via mechanisms such as coagulation, nucleation, and/or settling. The presence of negative values in the mist-minus-ambient distributions serve to skew statistical quantities used to describe the data. Therefore, only the positive values were used for calculating distribution statistics (i.e., statistics associated with the total particles created). A representative distribution is shown in Fig. 2.

![Fig. 1: Hypothetical Bimodal Distribution (adapted from McClellan & Miller, 1997)](image)

![Fig. 2: Measured Particle Size Distributions (600 rpm)](image)

At the high level of spindle speed (2000 rpm), the presence of destroyed particles was much less prevalent, an example of which is shown in Fig. 3. This is due to the fact that the number of mist droplets generated is considerably greater than the number of ambient particles. Therefore, subtraction of the ambient distribution from the measured mist distribution has little effect on the histogram of created particles.
Fig. 3: Measured Particle Size Distributions (2000 rpm)

EXPERIMENTAL ANALYSIS

Since five variables were studied in this investigation, and each variable had a high and low level, a total of 32 tests were run. This design allows for the ability to observe the effects of changing factors individually while at the same time doing this at several different combinations of the other factors so that factor interdependencies can be properly revealed [DeVor et al., 1992].

Statistical analysis of the total particles created for each of the 32 tests was performed, and it was found that spindle speed is the only significant variable effect. The increase in particles is considerable -- by an order of magnitude or more -- and can be seen from a comparison of the histograms in Figs. 2 and 3. The test shown in Fig. 2 was run at 600 rpm, and the test shown in Fig. 3 was run at 2000 rpm.

While the total number of particles may be important from a health standpoint, as previously mentioned, the size of the particles produced is also of concern. Therefore, the effects of the five variables on mean diameter were also examined using DOE methods.

Two 3-factor interactions were found to significantly affect the mean diameter of particles created: the spindle speed/workpiece diameter/location effect, and the spindle speed/workpiece diameter/oil concentration effect. A geometrical representation of these interaction effects is shown in Fig. 4.

Examination of the spindle speed/workpiece diameter/location interaction (Fig. 4a) reveals the following:

- At the high spindle speed, the responses are approximately equal regardless of workpiece diameter or location.

- At the low spindle speed, responses are approximately equal at the negative location (i.e., behind the lathe), regardless of workpiece size. However, in front of the lathe, the mean diameter is significantly larger for the 2.5" workpiece and significantly smaller for the 4.125" workpiece.

Likewise, conclusions about the spindle speed/workpiece diameter/oil concentration interaction can be drawn from Fig. 4b:

- At the high spindle speed, the responses are approximately equal regardless of workpiece diameter or oil concentration.

- At the low spindle speed, responses are approximately equal except when the 20% oil concentration fluid is applied to the small workpiece, which results in a significantly higher mean diameter.

MIST FORMATION MECHANISMS

In order to identify the atomization mechanisms responsible for the generation of the droplets observed in the turning experiments, an examination of the classical atomization theory was undertaken. In a turning process, the cylindrical fluid film formed by an impinging jet is always unstable regardless of the value of the Reynolds number. The instability increases with increasing rotational speed and ribbing instabilities may form when the surface velocity reaches 0.05m/s [Campanella, 1984]. Three distinct liquid film disintegration modes; drop mode, ligament formation mode and film formation mode, which are similar to the disintegration mechanisms described for a rotating disk, occur in the turning process [Yue et al., 1996]. The disintegration mode which occurs depends on the rotational speed of the spindle. For low rotational speeds, as shown in Fig. 5, where the spindle speed is 600 rpm, the drop mode applies. This mode is governed by the balance between centrifugal and surface tension forces. At higher rotating speeds, as shown in Fig. 6 where the spindle speed is 2000 rpm, numerous very thin uniform ligaments are produced that subsequently breakdown into droplets. As the rotational speed is further increased, the liquid film
impinging fluid forms into ligaments which then break-up into droplets. Under these conditions, the drop diameter can be found from [Matsumoto et al., 1978]:

\[ D = 1.23 R \left( \frac{1}{N_f} \right)^{\frac{2}{7}} \left( \frac{\rho g}{4 \sigma R} \right)^{\frac{1}{7}} \left( \frac{\sigma}{\rho R^2 \omega} \right)^{\frac{2}{7}}. \quad (2) \]

It is noted that the ligament number is the number of the wave associated with the maximum growth rate of the disturbance, i.e., \( N_f = K \), which is determined from Eqn. (1).

In order to estimate the drop size produced from a turning process, it is necessary to determine the percentage of the impinging fluid which forms into ligaments. The motion of the undisturbed liquid film is a result of the combination of the steady flow around the rotating cylinder and the gravity-induced secondary motion. In the case of low rotating speed, some of the liquid will drain off; while, a steady-state free-surface profile can be obtained provided the rotation rate is sufficiently large. Under the experimental conditions (5\% oil, \( \rho_i = 981 \text{ kg/m}^3 \), \( \mu = 1.061 \times 10^{-3} \text{ kg/s m} \), \( \sigma = 0.03 \text{ N/m, } R = 0.03175 \text{ m, } q = 0.9 \text{ gal/min} \)), a first approximation is to assume that all of the impinging fluid forms into ligaments and then droplets whose mean diameter can be predicted using Eqn. (2). For these conditions, the calculated droplet size versus rotating speed is shown in Fig. 6.

In the ligament formation mode many unstable liquid ligaments appear resulting from the disturbance at the edge of the film. The wave number \( K \) associated with the maximum growth rate of the disturbance can be found from Eqn. (1) [Kayano and Kamiya, 1978]:

\[ We = K^2 \left[ 3 + (8K - 3)St \left( 1 + \frac{1}{KSt} \right) \right] \quad (1) \]

where \( St = \mu^2 / (\rho \sigma R) \), and \( We = \frac{\rho \omega^2 K^3}{\sigma} \).

Disintegration of the ligaments at the circumference of the rim formed on the rotating cylinder is similar to the disintegration of ligaments on a rotating disk. When the jet flow rate is very low, it is assumed that all of the becomes thinner which in turn causes the ligaments to become thinner. The ligament lengths become progressively shorter until the liquid sheet directly disintegrates into droplets. The second mode, characterized by the formation of thin uniform ligaments, is called the ligament formation mode. It is this mode which is discussed in this paper since actual turning processes usually exhibit this disintegration mode.

![Fig. 5: Turning Operation at 600 rpm.](image)

![Fig. 6: Turning Operation at 2000 rpm](image)

![Fig. 7: Mean Diameter of Droplets versus Workpiece Rotational Speed](image)
secondary atomization resulting in smaller satellite drops. The number of satellite drops will increase with increasing atomization energy. Additional experiments will need to be conducted in order to obtain a more complete drop size information so that further models can be developed which will predict the drop size distribution and not just the mean size.

Unlike the analytical predictions, the experimental results show that a large amount of small droplets are produced, which reveals a bimodal size distribution. These small droplets are probably formed by two different mechanisms: evaporation/condensation mechanisms and the stripping of oil droplets from the cutting fluid emulsion. Due to high the temperatures in the cutting zone, some evaporation can occur with subsequent condensation around the particulate matter present in the ambient environment. Also, since the cutting fluid is an emulsion, a large amount of small oil droplets have probably been stripped from the fluid rather than produced by a classical atomization process [Romano, et al., 1998]. While normal emulsions have particle sizes approximately 2.0 to 50 μm in diameter, microlite emulsions, with a "pearlescent" look, have emulsion particle sizes of approximately 0.1 to 2.0 μm [Byers, 1994]. The mechanisms contributing to the small droplet formation may also include large droplet secondary disintegration and evaporation.

SUMMARY AND CONCLUSIONS

In order to determine the underlying process conditions influencing mist formation, a series of experiments were run to examine the effects of spindle speed, workpiece diameter, nozzle diameter, proximal location, and cutting fluid oil concentration on cutting fluid mist size distributions. This together with an examination of the classical atomization theory results in the following conclusions:

- Higher spindle speeds produce a larger quantity of drops in the 0.5 to 15 micron range.
- The observation of little variation in droplet size at high rotational speeds suggests that the atomization is highly influenced by the presence of the liquid sheet of uniform thickness.
- The smallest droplets are the most likely produced by stripping the oil droplets from the emulsion and from vaporization/condensation mechanisms since the classical atomization theory does not predict a bimodal droplet distribution.

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REFERENCES


