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COMPARISON OF MIST GENERATION OF MICRO-LUBRICATION AND FLOOD APPLICATION OF METALWORKING FLUIDS DURING MACHINING

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ABSTRACT

While cutting fluids have been used since before the mid-1800's, their use and formulation have changed dramatically over the years, for both performance as well as health and safety reasons. More recently, adverse health effects were reported in industries using cutting fluids, drawing renewed attention to methods for controlling occupational exposures to cutting fluids. In addition to the potential occupational hazards associated with cutting fluids, disposal of the used cutting fluids is also a concern to many machining operations. One approach to reducing the volume of fluids used in the machining process is micro-lubrication, also known as near-dry and semi-dry machining. Micro-lubrication provides the machining process with a very limited amount of cutting fluid. While the more traditional approach to cutting fluid application has been to flood the part and tool with fluid, with micro-lubrication, the fluid is applied as a mist, at flow rates that are usually several orders of magnitude lower than for flooding. The primary goal of this research is to determine how micro-lubrication, as a fluid application method, affects worker exposures to cutting fluid mists.

This project was conducted in conjunction with TechSolve, Inc. (formerly the Institute for Advanced Manufacturing Sciences, IAMS), and sponsored by the Illinois State Department of Natural Resources. TechSolve evaluated the effects of micro-lubrication on tool life, cutting forces, power consumption, and part quality, while the work described here focused on the mist generation potential of micro-lubrication.

The primary objective of this study was to determine the generation rate of respirable aerosols from the application of cutting fluids using micro-lubrication. Generation rates for flood application were also evaluated to put the micro-lubrication generation rates into perspective. The flood application processes used the same machining equipment, tooling and machining parameters as the micro-lubrication processes, the only differences being the method of fluid application and the flow rate. Two different machining processes were studied: milling and drilling. Six different fluids were evaluated, five different soluble oils and one straight synthetic fluid. The goal was to determine and compare respirable aerosol generation rates so that we can understand how micro-lubrication may affect occupational exposures to cutting fluids.

The results of this study showed that micro-lubrication resulted in significantly higher cutting fluid mist generation rates than flood application. Estimates of the workplace concentrations resulting from these generation rates showed that, for the process parameters studied, flood application would result in mist exposure concentrations below any applicable exposure criteria, while micro-lubrication would result in cutting fluid mist concentrations that would exceed many of the exposure limits. As a result of this data, facilities considering micro-lubrication should recognize the need for adequate cutting fluid mist controls, including machine enclosure, ventilation, and air cleaning. Micro-lubrication has many potential benefits, but the challenges associated with this fluid application method must be recognized and addressed before it is implemented.

INTRODUCTION

While metal cutting has been practiced in various forms dating back to ancient times, it has taken on a more critical role since the Industrial Revolution. It is during this time, the mid-1800's, that one of the first publications discussing cutting fluids appeared.[1] Perhaps the most comprehensive early work on cutting fluids was reported by Taylor in the early 1900's.[2] Since Taylor, cutting fluids have changed dramatically, for both performance as well as health and safety reasons. Some of the components in many early cutting fluids were identified as problematic, contributing to a variety of illnesses.

More recently, adverse health effects were reported in industries using cutting fluids, drawing renewed attention to methods for controlling occupational exposures to cutting fluids. These health effects include skin diseases, acute respiratory illnesses, and potentially, cancers. Cutting fluid mist is generated by the machining process, from splashing, and from the application of fluid to spinning parts and tools. The aerosol generated in the machining process may contain the components of the cutting fluid, as well as particulate from both the metal being cut and from tool wear. The components of the fluid can present a potential hazard to the worker along with any contaminants of the cutting fluid. For example, the cutting fluid can be contaminated with microorganisms and/or tramp oil. These contaminants can be as hazardous as any of the components of the cutting fluid, and may be extremely difficult to control.

In addition to the potential occupational hazards associated with cutting fluids, disposal of the used cutting fluids is also a concern in many machining operations. Several approaches have been investigated to address these disposal costs, including fluid maintenance programs to extend the life of the fluid, recycling programs to reuse the fluids, and dry machining to completely eliminate the cutting fluid. Another approach, and the topic of this current research, focuses on the application of the cutting fluid. Micro-lubrication, also known as near-dry and semi-dry machining, provides the machining process with a very limited amount of cutting fluid. The more traditional approach to cutting fluid application has been to flood the part and tool with fluid. With micro-lubrication, the fluid is applied as a mist, at flow rates that are usually several orders of magnitude lower than for flooding. But from an occupational perspective, how does micro-lubrication, as a fluid application method, affect worker exposures to cutting fluids? This is the primary question to be answered by this current research.

This project was conducted in conjunction with TechSolve, Inc. (formerly the Institute for Advanced Manufacturing Sciences, IAMS). TechSolve was sponsored by the Illinois State Department of Natural Resources, to evaluate the effects of micro-lubrication on tool life and cutting forces. One concern the Department had was the impact of micro-lubrication on occupational exposures to cutting fluids. The research described here was undertaken to address this concern.

Cutting Fluids and Micro-Lubrication

Cutting fluids serve several functions in the machining process. For some processes, the primary function is lubrication, while for others, it is cooling. In many processes, cutting fluids are also used for chip removal; in some facilities, a large portion of the cutting fluid pumped throughout the plant is for chip handling. In addition, cutting fluids may also provide corrosion protection for the newly machined surface of the part being produced. All of these functions have an impact on the process, from tool life and power consumption, to part quality and operability.

One of the primary driving forces behind the implementation of micro-lubrication is waste reduction. The fluid is atomized, often with compressed air, and delivered to the cutting interface through a number of nozzles. Because the fluid is applied at such low rates, most or all of the fluid used is carried out with the part. This eliminates the need to collect the fluid while still providing some fluid for lubrication, corrosion prevention, and a limited amount of cooling. Because of the low flow rates, coolant cannot be used to transport chips, meaning alternative methods for chip extraction must be implemented. However, the chips that are extracted should be of higher value since they are not contaminated with large quantities of cutting fluid.

Project Objectives

The primary objective of this study was to determine the generation rate of respirable aerosols of cutting fluids from the application of micro-lubrication. Generation rates for flood application of cutting fluids were also evaluated to put the micro-lubrication generation rates into perspective. The flood application processes used the same machining equipment, tooling and machining parameters as the micro-lubrication processes; the only differences were the method of fluid application and the flow rate. Two different machining processes were studied: milling and drilling. Six different fluids were evaluated, four soluble mineral oils, one soy-based soluble oil, and one synthetic cutting fluid. The synthetic fluid, used straight, was evaluated for using micro-lubrication only. The goal was to determine and compare respirable aerosol generation rates to understand how micro-lubrication may affect occupational exposures to cutting fluids. This information will be useful to facilities considering the implementation of micro-lubrication, so that mist collection needs can be adequately considered.

METHODOLOGY

The overall objective of this study was to determine the effect of fluid application, micro-lubrication or flood application, on cutting fluid mist generation. To achieve this goal, the mist concentrations from the machining process were measured and the generation rates calculated based upon a known air flow rate from the machine enclosure. Measurements were made using five different cutting fluids (four soluble mineral oils and one soluble vegetable oil) with two different machining processes (milling and drilling), with both micro-lubrication and flood application of the cutting fluids. A sixth fluid, a straight oil, was evaluated for milling and drilling with micro-lubrication only.

Cutting Fluid Mist Measurements

The cutting fluid mist concentrations from the studied machining operations were measured with a TSI Aerodynamic Particle Sizer (APS) Model 3320 (TSI, Inc., St. Paul, MN). The APS is a time of flight aerosol spectrometer which counts particles over a range of aerodynamic diameters from 0.5 to 32 μm. It samples at a total flow rate of 5.0 l/min; 1.0 l/min is analyzed, 4.0 l/min is filtered and supplied as sheath air to the sample stream. Time of flight aerosol spectrometers such as the APS, are based on the principle that the magnitude of a particle's lag in an accelerating air flow is directly related to the particle's aerodynamic diameter. The lag is determined by measuring the transit time required for a particle to pass through two laser beams perpendicular to the air flow. A timer measures the time between the two pulses generated by the particle passing through the two laser beams. The transit time is related to the aerodynamic diameter through a calibration with spheres of a known density.[3] The APS was calibrated prior to the start of this study.

Two diluters for the APSs, TSI Model 3302A (TSI, Inc., St. Paul, MN), were available to dilute the sample stream in the event that the sample concentration was high enough to saturate the detector. These diluters were capable of diluting the sample stream by a factor of 20 or 100, depending upon the nozzle installed. If additional dilution was needed beyond a factor of 100, two diluters could be used in series, providing dilution factors of 400, 2,000, and 10,000. The use of the diluters with the background samplers was not required.

The APSs were controlled by separate IBM compatible computers, a Dell Dimension, 300 MHz, Pentium II desktop computer and a Dell Inspiron 3500, 350 MHz, Pentium II notebook computer (Dell Computer Corp., Austin, TX). Each computer ran the Aerosol Instrument Manager software, version 1.6 (TSI, Inc., St. Paul, MN), allowing remote access to the instruments' parameters so that the sampling process could be controlled appropriately. In addition, this software received, displayed, and recorded the aerosol data as measurements were being made. At the conclusion of a sampling run, the software also allowed the data to be exported to an ASCII text file, which in turn, could then be imported to other software packages for data analysis.

The machining center used in this study was equipped with an enclosure and mist collector. One APS was configured to sample from the mist collector ductwork using an isokinetic sampling probe, reducing aerosol losses in the sampling train. The probe was designed so that the air and aerosols in the exhaust stream entered the sampling probe at the same velocity as the air stream in the duct. The diameter of the sampling probe gradually increased to the diameter of the inlet of the APS. In this way, particle losses due to the changes in air stream velocity were minimized. The sampling probe was inserted through an elbow into a straight section of the exhaust ductwork. The sampling point was at the center line of the straight duct, more than 7.5 duct diameters (45 in, 1.15 m) downstream and 3 duct diameters (18 in, 0.46 m) upstream of any major air disturbance, in this case, two 90° elbows.[4] A simplified diagram of the sampling setup is given in Figure 1. A second APS was used to monitor general background particulate concentrations.

Temperature and Humidity Measurements

Temperature and humidity inside the machine enclosure was monitored continuously using one of two different instruments: a Rustrak® Model POD 29/03 temperature and humidity probe with a Rustrak Ranger II data logger (Rustrak, East Greenwich, RI); or a HOBO® H8 Pro Relative Humidity and Temperature Logger , Model Number H08-032-08 (Onset Computer Corporation, Cape Cod, MA). The Rustrak instrument was used for all sampling runs through August 30, 2000. Because of a malfunction with the temperature and humidity probe, the HOBO monitor replaced the Rustrak for all sampling from September 1, 2000, through the end of the study. The temperature and relative humidity data were collected to see what changes were occurring within the enclosure during machining. Following each day of sampling, the temperature and humidity monitor was downloaded to an IBM compatible computer using either the Pronto® software supplied with the Rustrak Ranger II data logger, or the BoxCar® Pro software supplied with the HOBO monitor.

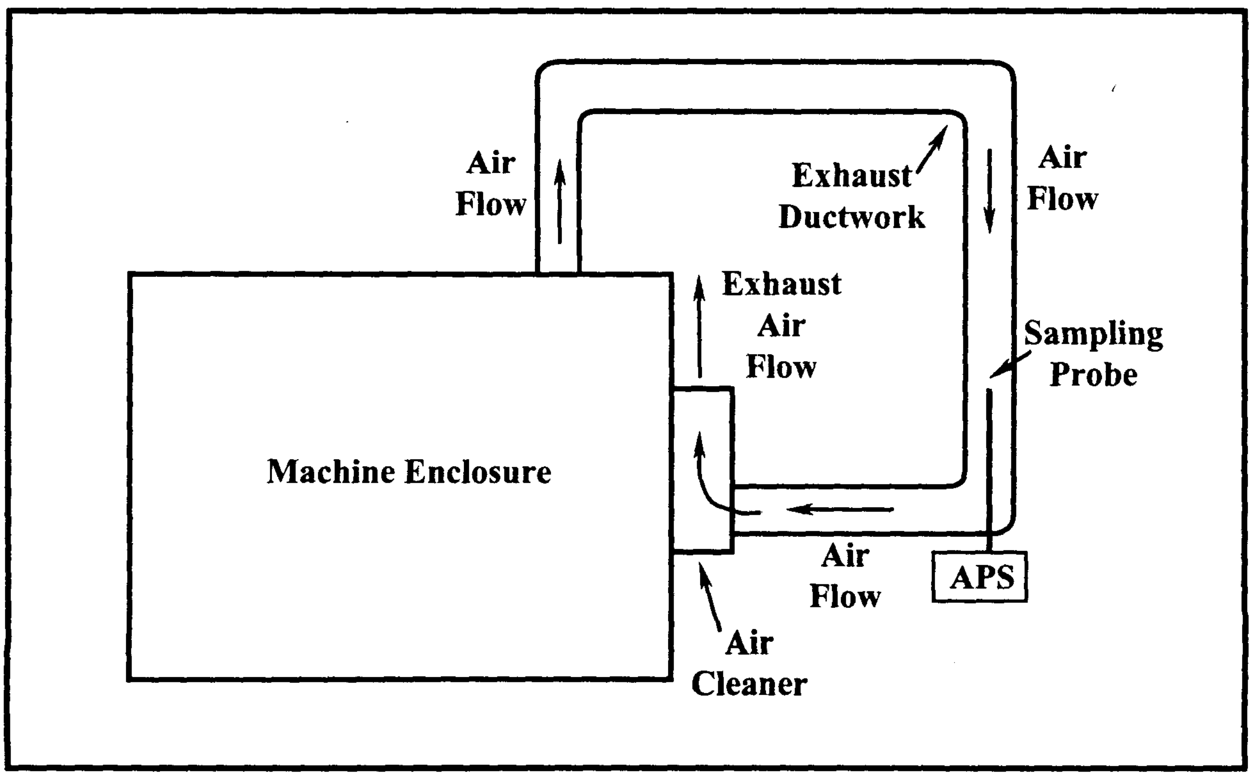

Figure 1. Diagram of aerosol sampling setup.

Instantaneous temperature and humidity measurements were made in the general laboratory environment at the start of each sampling run with a Fisherbrand catalog number 11-661-14 temperature and relative humidity monitor (Fisher Scientific, Pittsburgh, PA). Like the continuous monitor, these temperature and relative humidity measurements provided a means to track the conditions in the laboratory, in the event that major differences in the generation rates were seen from one run to the next.

Machine Enclosure Efficiency

The exhaust flow rate of the mist collector was measured by performing a pitot tube traverse at the sampling point in the ductwork.[4] The 10 point traverse was made with a Dwyer Model 166-12 pitot tube (Dwyer Instruments, Inc., Grandview, MO). A Neutronics model EDM-I electronic digital micromanometer (Neutronics N. A. Inc., Gainesville, GA) was used to measure the pressure drop across the pitot tube.

The effectiveness of the machine enclosure was evaluated by using a tracer gas, sulfur hexafloride (SF_6), and a monitor configured to detect this tracer gas.[5] This evaluation was accomplished by comparing the in-duct SF_6 concentrations when the tracer gas was released at the cutting interface with the concentrations when it was released directly into the exhaust duct. The concentration of SF_6 in the duct was measured with a Bruel & Kjaer (B&K) Multi-gas Monitor, Type 1302 (Bruel & Kjaer, Naerum, Denmark). The B&K is a photoacoustic gas monitor capable of measuring SF_6 concentrations down to the parts per billion level. The B&K was calibrated using standards prepared in gas bags from room air and 100% SF_6. The gas bags were first fully evacuated, and then filled with the appropriate volume of air using a 1 liter gas syringe. Then, using a gas-tight syringe, the appropriate volume of SF_6 was injected into each bag through an injection port. After the SF_6 was given sufficient time to diffuse throughout the bags, the inlet of the B&K was connected to the gas bag. The B&K recorded all concentration measurements. A four point calibration was performed with concentrations of 0, 2, 10, and 25 ppm. Three concentration measurements for each standard were averaged, and a linear regression was performed on these concentrations to determine a calibration equation.

The flow of the SF_6 to the machine enclosure was controlled by a MKS Model 247-C mass flow controller (MKS Instruments, Inc., Andover, MA). The flow rate of the SF_6 was verified by a Drycal Flow calibrator (SKC Inc. Eighty Four, PA). The mass flow controller set point was adjusted to provide a duct concentration of SF_6 of 15 ppm at 100% capture efficiency. Based on the duct flow rate of 14.36 m^3/min (507.2 CFM), as measured from the pitot tube traverse, the SF_6 was delivered at a flow rate of 0.215 l/min.

The SF_6 was released at 0.215 l/min at two positions: near the cutting interface and at the entry of the enclosure exhaust duct. The capture efficiency at the duct entry was assumed to be 100%. SF_6 concentration measurements were made in pairs, with the tracer gas released at the cutting interface or at the entry of the exhaust duct. The order of the pairs was randomized, and a total of five pairs of measurements were made. Background SF_6 concentrations were measured before and after each duct or cutting position concentration measurement. Data from the B&K were downloaded to a personal computer for analysis.

The duct and cutting position concentration measurements were corrected for the background concentrations by calculating the mean of the before and after background measurements, and subtracting this value from the respective concentration measurement. Enclosure efficiency was then determined by the following:

$$E = \frac{C_{Cut}}{C_{Duct}} \times 100\% \qquad (1)$$

where: E = the enclosure efficiency,
C_{cut} = background corrected SF_6 concentration with SF_6 supply located near the cutting interface,
C_{Duct} = background corrected SF_6 concentration with SF_6 supply located at the duct entry.

The exhaust flow rate of the enclosure was calculated from the duct position concentration by the following equation:

$$Q_{Enclosure} = \frac{w_{SF_6}}{C_{Duct}} \qquad (2)$$

where: $Q_{Enclosure}$ = the air flow rate from the machine enclosure,
w_{SF_6} = the mass flow rate of SF_6 to the enclosure.

The exhaust flow rate determined by the pitot tube traverse was compared to the calculated flow rate from the tracer gas evaluation.

Machining Procedures

Mist generation was characterized for milling and drilling, using both micro-lubrication and flood application of the cutting fluids. The tests were conducted according to a published method for the evaluation of the effectiveness of cutting fluids, in a Tongil TNV-80 CNC vertical machining center.[6] Fluid for the flooding tests was pumped from a sump and collected for reuse. A special small volume work cell was constructed inside the machine enclosure to contain the fluid and to allow for more rapid fluid changes. The micro-lubrication tests were conducted using a three nozzle Unist mist application dispenser, model 25034 (Unist, Inc., Grand Rapids MI).

Sampling Procedures

The sampling procedures were designed to collect time dependent data from the APS, to determine the factors affecting the generation of cutting fluid mist. Equipment used in this study included the two APSs (with diluters if needed), an instantaneous temperature and humidity monitor, a continuous recording temperature and humidity monitor, two IBM compatible computers, and a video camcorder. The desktop computer controlled the APS monitoring background mist concentrations while the notebook computer controlled the APS measuring the in-duct aerosols. The camcorder was used to document the process activities such as machining start and stop times. The clocks on the two computers and the camcorder were synchronized manually to within less than one second. Both APSs were allowed to warm-up at least one hour prior to any sampling.

Using the Aerosol Instrument Manager software, the APSs were configured to record 2880 five second samples. This gave a sampling period of four hours, although sampling for a given test could be terminated earlier without the loss of data. If the diluter was used, a dilution file corresponding to the required dilution ratio was selected in the Aerosol Instrument Manager. This file contained the necessary values to calculate the size distributions accounting for the dilution of the sample stream. Particle size data were collected for aerosols between 0.523 and 20.535 µm. After setting the sampling parameters, the APSs were set to begin sampling at a specific time, several minutes before machining commenced. Both the in-duct and background APSs were configured similarly, with the exception of the use of the diluter.

Individual sampling sheets were used to document each machining test. The sampling sheet included entries for: date, fluid type, fluid concentration, sample start time, temperature, humidity, test identification number, in-duct sample filename, background sample filename, and machining process. The sampling sheet also included entries for sample numbers by pass or hole (i.e., first pass started during APS sample 30, fifth pass started during APS sample 74, etc.). Temperature and humidity measurements were made at the start of a test. In addition to the sampling sheets, additional notes were recorded for each machining test. This information included the machining start times, the passes or holes at which cutting force and tool wear measurements were made, and information on process upsets.

Like the APSs, the camcorder was started prior to the start of machining. The camcorder was used to document process upsets and the start and stop times for each pass or hole. Sample numbers for various passes or holes (usually every 4-6 passes) were recorded on the sampling sheets to ensure that start and stop times of the machining passes matched with the appropriate samples in the APS data file. Prior to the torque and cutting force measurements, the machining process was placed on hold to configure the data acquisition system for the dynamometer. After collecting the torque and cutting data, fluid delivery was halted and the tool was removed for wear measurements. The tool was then placed back into the machine, fluid application was restarted, and machining continued. Machining progressed with periodic torque, force, and tool wear measurements (as previously discussed) until the measured tool wear reached the pre-specified value. At that point, air sampling was discontinued, and the APS data exported to formatted text files. These data files contained particle count aerosol size distributions for each of the five second sampling periods.

Data Calculations

The text files containing the size distribution data from the APSs were imported into an Excel spreadsheet (Microsoft Corp., Redmond, WA), where additional calculations were made to convert the size distributions to generation rates. The data recorded from the APS consisted of a series of 5 second count distributions of particle size. While these files contained size data from 0.523 to 20.535 µm, the sizes of interest in this study were 10 µm and smaller. Therefore, the particle counts for each of 43 sizes ranges between 0.523 and 10.37 µm were included in these analyses. From the count distributions, particle volume was determined by calculating the volume of particulate for each size interval, and then summing all of the intervals for all sizes less than 10.37 µm, as shown in Equation 3. This gives the particle volume for each 5 second sampling interval.

$$V_{P_j} = \sum_{i=1}^{43} c_i \left(\frac{4}{3} \pi \left(\frac{d_i}{2} \right)^3 \right) \tag{3}$$

where: c_i = the particle counts for the i^{th} size range,
d_i = the midpoint diameter of the of the i^{th} size range,
V_{P_j} = the volume of the particles in the j^{th} sample.

The particle volume data were then converted to mass measurements by Equation 4.

$$M_{P_j} = V_{P_j} \rho \tag{4}$$

where: M_{P_j} = mass of particulate in the j^{th} sample,
ρ = density of the fluid, 1.0 g/cc.

The volume of air sampled for each measurement, V_S, was 8.33×10^{-5} m^3 (1.0 l/min for 5 sec). Equation 5, then gives the mean particle concentration for each 5 sec sampling interval.

$$C_j = \frac{M_{P_j}}{V_S} \tag{5}$$

where: C_j = mean concentration over the during the j^{th} sample.

To this point, both the in-duct and background measurements were treated the same, converting the size distribution data to concentration measurements. The background measurements were used to correct the corresponding duct measurements to account for other activities occurring in the laboratory. The magnitude of this correction was determined by calculating the mean of the lowest 10% of the background measurements over the duration of the sampling run. In plotting the background data, it was apparent that there was a baseline concentration of particulate, above which, the background concentrations normally remained. This calculation methodology provides an estimate of this baseline concentration and corrects for it.

The duct sample data were coded with a pass or hole variable, so that a specific sample could be associated with the number of the pass or hole being cut at a particular time. If no pass or hole was being cut during the collection of a particular sample, this variable was left blank. Each pass or hole had several particle volume samples associated with it, depending upon the length of time required to make the cut.

The duct sample data sets contained 5-second concentration measurements over the entire life of the given tool. For the determination of the generation rates, however, a selected sample of the concentration data from the middle of the tool's life was used. The main concern with using data from the entire life of the tool was that the samples at the beginning and the end of the tool's life would reflect aerosol generation during startup or process upset conditions. Data from the middle of the tool's life would better reflect the generation rate over the majority of the life of the tool. At the beginning of the tool's life, the tool's wear pattern is just being established, while at the end of tool life, the cutting forces are increasing with more heat being generated. These factors may impact the generation rate of the cutting fluid aerosols. The data in the middle of the tool's life, however, will be closer to steady-state, with wear patterns established and the cutting forces and heat generation being more consistent. For both the drilling and the milling tests, concentration data from the middle 11 holes or passes were used to calculate the mean concentration for the run.

In most instances, the data used for the mean concentration for the sampling run covered the period of time where tool wear measurements were made. When the tool was inspected for wear, the machine was not operating, no fluid was being delivered and the enclosure was opened. To address these conditions, two data points after the last pass before the tool inspection, and two data point before the first pass after tool inspection were included in the mean calculation. Data during tool measurements were excluded from the calculation, while data during tool movement between passes were included, as the enclosure was not opened, the tool was still turning and the fluid was still flowing to the tool. For example, assume a tool's life was 70 passes with tool measurements made every 10 passes. The data points included in the mean concentration calculation would include: two points before pass 30, all of the points during pass 30, two points after pass 30, two points before pass 31, all of the points for passes 31-40 as well as periods between these passes, and two points after pass 40.

After determining the data to be included in the calculations, the mean concentration, $\overline{C}$, was calculated for the 11 passes (or holes) of the tool's life. This mean concentration was corrected for the background aerosols by subtracting the background concentration (as determined from the background calculation discussed above). This results in a mean concentration for the mid-life of the tool, which was then converted to a generation rate. For a given generation rate, the measured concentration will be a function of the generation rate and the ventilation rate diluting the contaminant. Therefore, for a given concentration and ventilation flow rate, the generation rate can be determined from Equation 6.

$$G = \overline{C} \cdot Q \qquad (6)$$

where: G = aerosol generation rate,

$\overline{C}$ = background corrected mean concentration for middle 11 passes (holes) of a given run,

Q = ventilation flow rate through the machine enclosure.

Calculations for each run were made to develop a data set that included the date of the sampling run, the machining process, the fluid application method, the fluid identification, and the generation rate. These data were then analyzed first to determine if there was a difference in the generation rates due to the fluid application methods, and then if there were differences between the fluids or the machining processes.

STUDY DESIGN

The primary factor of interest in this study is the effect of fluid application (micro-lubrication versus flood) on the cutting fluid mist generation rate. A secondary factor was the effect of the cutting fluid formulation (six different fluids). For the primary factor (fluid application method), the null hypothesis could be stated as follows:

H_{0_A} = The ratio of flood application to micro-lubrication generation rates is greater than 0.5.

The alternative hypothesis would then be:

H_{1_A} = The ratio of flood application to micro-lubrication generation rates is less than 0.5.

From the preliminary data, the ratio of flood to micro-lubrication generation rates was 0.25 or less. Therefore, a ratio of 0.5 was chosen as a reasonable value upon which to design this study. A ratio of 0.5 would indicate that micro-lubrication application of cutting fluid had a mist generation rate that was twice as high as flood application.

For the secondary factor, cutting fluid formulation, the null hypothesis would be the following:

H_{0_B} = The average ratio of flood application to micro-lubrication generation rates for a given fluid and machining process will not differ from the ratio for another fluid for the same machining process.

The alternative hypothesis would then be:

H_{1_B} = The average ratio of flood application to micro-lubrication generation rates for a given fluid and machining process would differ from the ratio for another fluid for the same machining process.

For study design purposes, to be considered different, the generation rate ratios would have to differ by at least a factor of 2 in order to be considered different.

Several conditions needed to be considered in order to design and carry out this study. Fluids could not be switched at random because of the cleaning needed for each fluid change. Second, the machining process could not be changed at random due to differences in the fixtures, dynamometers, and tools for milling and drilling. Therefore, the study was designed so that all tests of a given process were performed before switching to a different process. Within the process, all tests for a given fluid were performed before switching to a different fluid. Within the fluid, the fluid application method could be randomized in pairs. In addition to fluid, application method, and machining process, test timing (date, time) was also a concern. Conditions such as temperature and humidity could vary from day to day, even hour to hour. While the laboratory where the tests were conducted did have HVAC controls, small changes in the environmental conditions did occur. If the time of day or date of a test affected the generation rate, the study design would need to account for these differences. The study, therefore, was designed with micro-lubrication and flood application tests conducted in pairs. The order of the pairs were randomized, and each pair was completed on the same day, with one to three pairs of tests conducted on any given day. By completing each pair on the same day and randomizing the order of the pairs, the effect of changes during the day can be minimized. Five different fluids, all soluble oils, were tested in this flood application versus micro-lubrication evaluation. A sixth fluid, a straight synthetic, was also used for micro-lubrication application only. The data from this sixth fluid was not included in the flood versus micro-lubrication evaluation. Rather, it was evaluated only to determine if it was significantly different (in terms of mist generation) from the other fluids. Five replications of each pair for each fluid-process combination were conducted.

A series of preliminary tests were made to address two major concerns. The first centered on the evaluation of the test methodology, to determine if the methods would be capable of generating the type and quality of data desired. The second related to the study design, specifically, what number of replications would be needed to detect the desired differences between the mist generation rates of the two fluid application methods. These preliminary tests were conducted in conjunction with fluid evaluation tests conducted by TechSolve for projects not directly associated with this research. These tests provided an opportunity to test the study methodology while estimating the variability of the aerosol concentration data.

A total of 43 preliminary test runs were conducted in the Tongil machining center, with a variety of cutting fluids. Milling and drilling, with both flood and mist application, were evaluated. Although a large number of tests were conducted, many of the test results were discarded for the purpose of determining the sampling variability. Tests were discarded for a variety of reasons, including changes in the machining process (i.e. different tool insert material), limited samples for a particular fluid, process, or application method, or changes in the sampling methodology. At the end of the preliminary sampling, sufficient data were available for milling to estimate the sample variability of both flood and micro-lubrication application of the cutting fluid. These data also provided the basis of the test hypotheses. Due to resource limitations (a limited amount of machine time was available) additional preliminary sampling for drilling was not possible. However, for study design purposes, the variability of drilling, for both flood and micro-lubrication application were assumed to be similar to milling.

Several modifications to the sampling methodology were made over the course of the preliminary tests. Early testing illustrated the need to record process event continuously, rather than manually (note taking). To address this problem, video recording of the machining process was added to the test method. This allowed all start and stop times to be determined, along with process upsets and other significant events. Also in early tests, the APS instrument measuring background concentrations were located near the exhaust outlet of the air cleaner. To address the concern of the exhaust affecting the background concentrations, the background APS was relocated to the far side of the machining center, away from the air cleaner. Finally, major modifications were made to the sampling sheets used to record the process and sampling data for each run. Most of these changes concerned organization of the sheet or adding spaces for additional data such as temperature and humidity. The organizational changes were made to ease process data entry, reducing the amount of manual note taking required.

Of the 43 preliminary tests conducted, 15 were used to determine the number of replications needed for the study. The remaining 28 tests involved either sampling methods that were not effective, machining processes which were not to be tested, or fluids for which fewer than five tests were performed. The 15 tests, therefore, represented three different sets of conditions. Two sets, or ten tests, used flood application while the remaining set used micro-lubrication. Two different fluids were used for the three different sets; however, all the fluids were soluble oils. One fluid was used for the flood applications, while a different fluid was used for the micro-lubrication tests. In developing the study design, the differences between the fluids (in terms of their mist generation) was assumed to be negligible. This assumption would be evaluated in the analysis of the data from the full study.

The number of replications of each application pair was determined by evaluating the three sets of preliminary measurements made to determine the variability of the sampling data. These preliminary measurements were made following the sampling procedures outlined in an earlier section of this report. As mentioned, the primary goal of this study was to determine if there was a difference in mist generation rates between micro-lubrication and flood application of cutting fluids, while the secondary goal was to determine if there were differences between the mist generation rates of the different cutting fluids and between the different machining processes. The study design must attempt to meet these two goals, while at the same time, be feasible in terms of the laboratory time and resources required to carry out the study.

Sample size determinations were made through as series of calculations. A t-test was performed to determine the probability that the average flood to micro-lubrication ratio for a given process was less than 0.5. The calculations were made assuming mean ratios of 0.15, 0.25, and 0.35, with CVs of 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30. These values provide a full range (both high and low extremes) given the flood to micro-lubrication ratio and CV from the preliminary data. The results of these calculations showed that for flood to micro-lubrication ratios of 0.15 and 0.25, all the tested CVs had probabilities in excess of 0.99 for five replications. For a ratio of 0.35, all CVs except 0.25 and 0.30 had probabilities of 0.99 or greater. The two cases where the probabilities are not greater than 0.99 can be considered extreme cases for both the ratio and the CV. Based upon these results, five replications for each pair of application methods appeared to be adequate to achieve the primary goal of this study, assuming that there was not excess variability over time.

RESULTS

Study results are given in two sections: enclosure efficiency and aerosol measurements and generation rates. The results of the enclosure efficiency tests were needed to perform the required calculations for the cutting fluid mist generation rates. If the results indicate enclosure efficiencies significantly different than 1.0, the cutting fluid mist generation rates would be adjusted to account for aerosol losses from the enclosure.

Enclosure Efficiency Results

A series of tests were conducted to determine the efficiency of the enclosure of the Tongil machining center. As discussed earlier, measurements were made in pairs, with one measurement made with the SF_6 released at the cutting interface, and the other measurement with the SF_6 released into the exhaust ventilation duct. Using Equation 1, the enclosure efficiency for each pair of measurements was made, resulting in five efficiency values. For the Tongil machining center, the mean efficiency was 98.04%. A t-test of the duct and cutting position concentration was performed to determine if the efficiency of the enclosure was different than 100%. If the differences in the duct and cutting position concentrations were statistically significant, the enclosure efficiency could be said to be different than 100%, and the mist generation data would need to be adjusted. For the Tongil machining center, the t-test results showed no statistically significant differences between the duct and cutting position concentrations ($P(T \geq t)=0.3269$). Because of this result, no correction for enclosure efficiency was made to the cutting fluid mist generation rate data collected in this study.

From the tracer gas measurements, the air flow rate through the machine enclosure can be calculated from Equation 2. In Equation 2, C_{Duct} was determined by calculating the mean concentration from the five duct concentration samples for each enclosure. The Tongil machining center's calculated exhaust air flow rate was 14.44 m^3/min (510.0 CFM). This compared closely to the pitot tube traverse flow rate of 14.36 m^3/min (507.2 CFM). The pressure drop measurements for the pitot tube traverse are also given in Appendix D.

Aerosol Measurement Results

The aerosol data from the APSs were exported by the APS software to text files, which were then imported into individual Excel spreadsheets. Data for particles smaller than 10.37 µm were included in the calculations of the mist generation rates as earlier outlined in the Methodology section of this report. For the analysis of the data from this study, all data were log transformed, and residuals from the fitted models supported the log normality of the data. Three different models were developed to evaluate the collected data. Similar models were used to evaluate flood and micro-lubrication separately, as well as the ratio of flood to micro-lubrication. All three models took the form of the following:

$$\ln(\text{determination}) = \mu + \alpha_{\text{process}} + \beta_{\text{fluid}} + \alpha\beta_{\text{process*fluid}} + \text{error} \tag{7}$$

where: μ = overall mean,

$\alpha_{process}$ = process effect, milling or drilling,
β_{fluid} = fluid effect, fluids 1-5 for flood and ratio models, 1-6 for micro-lubrication model,
$\alpha\beta_{process*fluid}$ = interaction between process and fluid effects, and
error = random components.

For all three models, the initial form of the error term was as follows:

$$\begin{aligned} \text{error} = a_{rep} + b_{rep,process} + c_{date(fluid,process,rep)} \\ + d_{rep,fluid} + e_{rep,fluid,process} + \text{residual} \end{aligned} \tag{8}$$

where: a_{rep} = randomly chosen replicate effect,
$b_{rep,process}$ = randomly chosen process over replicates effect,
$c_{date(fluid,process,rep)}$ = randomly chosen date of measurement effect,
$d_{rep,fluid}$ = randomly chosen fluid over replicate effect,
$e_{rep,fluid,process}$ = randomly chosen fluid-process interaction over replication effect, and
residual = residual variability after accounting for the above effects.

Proc Mixed in the statistical analysis program SAS[7] provided estimates for the fixed effects in the model, as well as estimates of the variance components of the random effects. Likelihood methods were used to reduce the number of terms in the error expression. A solution for each of the three full models (flood, micro-lubrication, and the ratio of flood to micro-lubrication) was determined. A Wald test was performed, whereby components of the error expression were removed from the model if they were not significantly different from 0 at the 5% level. Only those components yielding a statistically significant result, as well as the residual term, were retained in the model. For the flood analysis, all the error components except the residual were eliminated, and the resulting model was as follows:

$$\ln(\text{flood}) = \mu + \alpha_{process} + \beta_{fluid} + \alpha\beta_{process*fluid} + \text{residual} \tag{9}$$

For the micro-lubrication model, all of the components except $c_{date(fluid,process,rep)}$ (randomly chosen date of measurement effect) and the residual were eliminated. Therefore, the model for micro-lubrication was as follows:

$$\begin{aligned} \ln(\text{Micro} - \text{lubrication}) = \mu + \alpha_{process} + \beta_{fluid} + \alpha\beta_{process*fluid} + \\ c_{date(fluid,process,rep)} + \text{residual} \end{aligned} \tag{10}$$

Like the flood application, all terms except the residual were eliminated from the model for the ratio of flood to micro-lubrication, and was reduced to the following:

$$\ln(\text{ratio}) = \mu + \alpha_{process} + \beta_{fluid} + \alpha\beta_{process,fluid} + \text{residual} \tag{11}$$

The Wald test used here is intended for large samples. However, the replicate components for this study are not based upon a large sample. Therefore, two alternative data analysis methods were evaluated to see if a better test was available and to determine how well the initial test evaluated the data. One alternative was to treat the random effects included in the original model as fixed effects. Using similar methods to eliminate terms which are not statistically significant, this alternative approach leads to flood and micro-lubrication models which included more statistically significant terms than the original model. The model for the ratio of flood-to-micro-lubrication was the same. A major limitation with this approach, though, is that there is no reason to assume that the test of the factors when treated as fixed is equivalent to the test treating them as random. The result of this alternative approach, while yielding different models in two of the three cases, did not alter the findings regarding the cutting fluid mist generation rates for micro-lubrication and flood application.

The other alternative approach evaluated the effects of replication without including replication in the model. Because the second replication was not a full replication, this alternative approach evaluated the study data with and without the second replication data, and compared the two results. For most of the comparison of interest, there was little difference in the conclusions from the two different analyses. The result of this approach, that replication variability is unimportant compared to the variability of other factors studied, suggests that the initial approach to the analysis of the data in this study is appropriate and the models from this approach are the ones used to estimate the cutting fluid mist generation rates for micro-lubrication and flood application.

Figure 5 shows the estimated cutting fluid mist generation rates for each fluid, machining process (milling or drilling), and fluid application method (flood or micro-lubrication). This figure also includes bars showing the 95% confidence interval about the estimated generation rate. The axis of this chart is shown on the log scale, and the chart graphically illustrates the differences between the micro-lubrication and the flood fluid application methods. Values for the data displayed in Figure 5 are given in Table 2 for drilling and Table 3 for milling. Unless otherwise indicated, significance is at the 5% level.

This study was designed to test two different sets of hypotheses. The primary hypothesis was whether the mist generation rates for flood and micro-lubrication were statistically significantly different. Table 4 gives the results of the ratio of flood application to micro-lubrication generation rates for the each fluid during drilling and milling, while Figure 6 shows a chart comparing these ratios. The ratios were all significantly different from 1.0, indicating that flood application and micro-lubrication result in significantly different cutting fluid mist generation rates.

Table 5 gives the results of the multiple comparison tests (Bonferroni method) conducted on the flood application to micro-lubrication ratios to evaluate the secondary hypothesis, that individual fluids were significantly different from each other. The results of the multiple comparison tests showed that, for milling, none of the fluids were statistically significantly different from the others. For drilling, however, several of the comparisons showed significant differences.

Comparisons between machining operations were also made. Table 6 shows the results of these comparisons. Comparisons were made between milling and drilling for a given fluid and fluid application method. This comparison was made to help determine if differences in generation rates were due to the fluid, the fluid application method, or the machining process.

Table 2. Geometric mean cutting fluid mist generation rates with 95% confidence intervals for the six different cutting fluids during **drilling** with micro-lubrication and flood application of cutting fluid. Fluids with the same letter under "Significant Difference" are not significantly different.

Fluid No.	Micro-lube Generation Rate (mg/min)			Flood Generation Rate (mg/min)		
	Geometric Mean	Confidence Interval	Significantly Different	Geometric Mean	Confidence Interval	Significantly Different
1	9.51	7.31-11.99	A	0.0102	0.0052-0.0199	D
2	9.52	7.52-12.26	A	0.0134	0.0076-0.0236	D
3	5.14	4.10-6.72	B	0.0147	0.0075-0.0286	D
4	9.45	7.60-11.66	A	0.0085	0.0046-0.0156	D
5	13.33	9.90-18.02	A	0.0052	0.0025-0.0111	D
6	121.34	89.84-163.89	C	NA	NA	NA
NA – Not Applicable; data not collected for this condition.						

Table 3. Geometric mean cutting fluid mist generation rates with 95% confidence intervals for the six different cutting fluids during **milling** with micro-lubrication and flood application of cutting fluid. Fluids with the same letter under "Significant Difference" are not significantly different.

Fluid No.	Micro-lube Generation Rate (mg/min)			Flood Generation Rate (mg/min)		
	Geometric Mean	Confidence Interval	Significantly Different	Geometric Mean	Confidence Interval	Significantly Different
1	8.91	7.22-11.89	AB	0.0820	0.0420-0.160	D
2	9.73	8.27-12.20	AB	0.0869	0.0472-0.160	D
3	7.15	5.36-9.76	B	0.0708	0.0363-0.138	D
4	10.56	8.49-13.11	AB	0.0896	0.0459-0.175	D
5	13.19	10.81-16.70	A	0.0923	0.0473-0.180	D
6	73.62	58.03-95.24	C	NA	NA	NA
NA – Not Applicable; data not collected for this condition.						

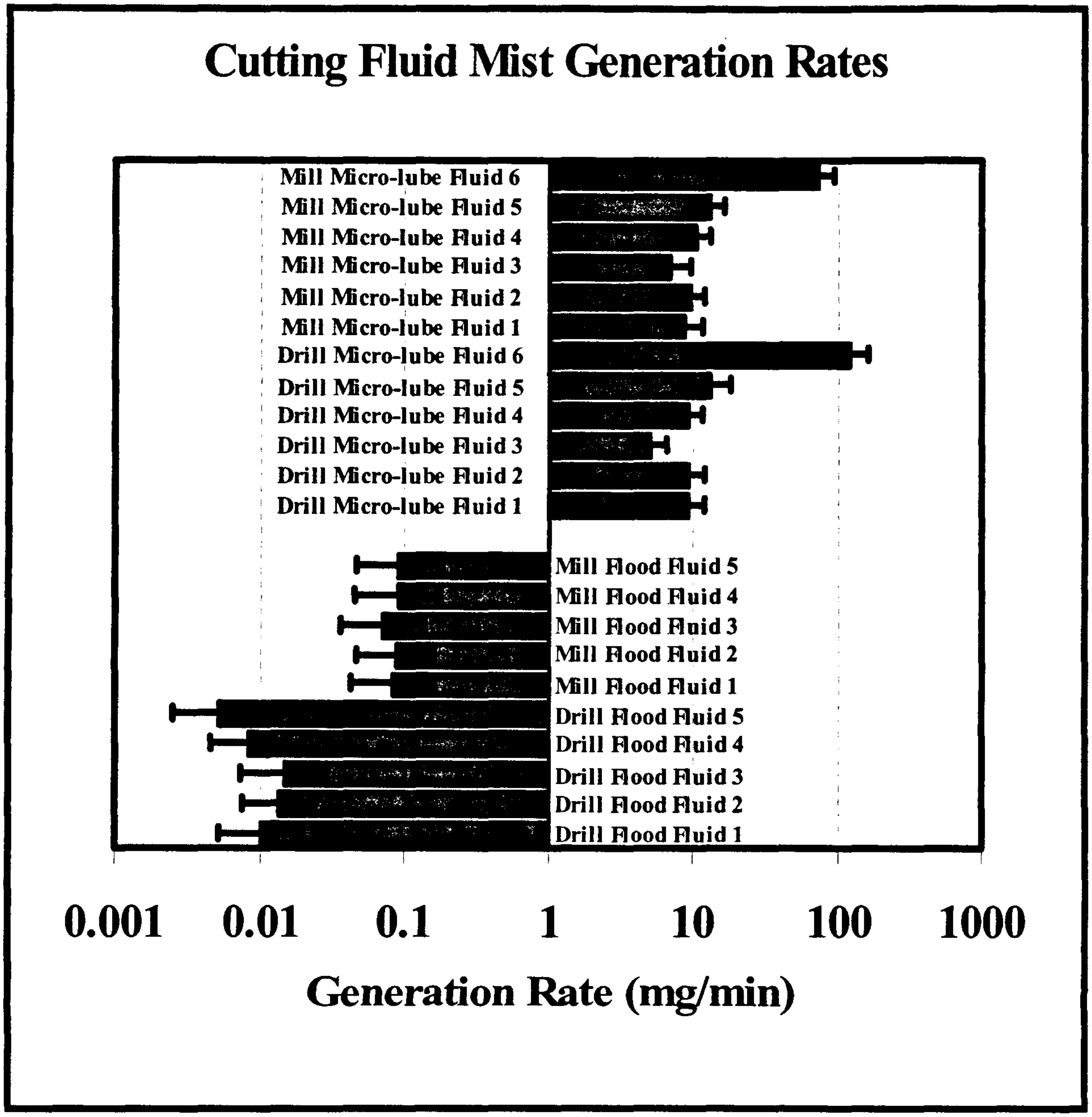

Figure 5. Estimated cutting fluid mist generation rates for the six different fluids, during milling or drilling, in micro-lubrication or flood application. The 95% confidence interval about the estimates are also shown.

Table 4. Flood application to micro-lubrication cutting fluid mist generation rate ratios for fluids 1-5.

Fluid No.	Drilling			Milling		
	Ratio Flood to Micro-lubrication	Lower Confidence Interval	Upper Confidence Interval	Ratio Flood to Micro-lubrication	Lower Confidence Interval	Upper Confidence Interval
1	0.0011	0.0005	0.0021	0.0092	0.0046	0.0183
2	0.0014	0.0008	0.0025	0.0089	0.0048	0.0167
3	0.0029	0.0014	0.0057	0.0099	0.005	0.0197
4	0.0009	0.0005	0.0017	0.0085	0.0043	0.0169
5	0.0003	0.0001	0.0005	0.007	0.0035	0.0139

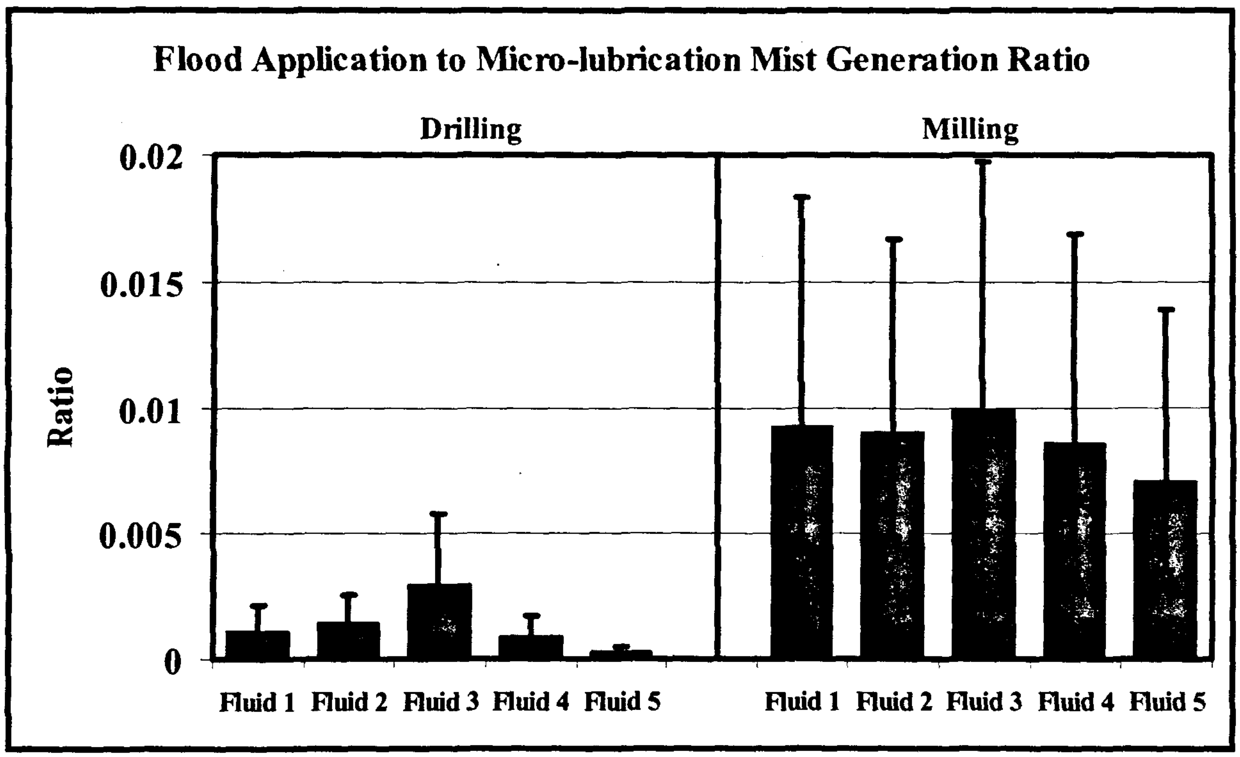

Figure 6. Flood application to micro-lubrication cutting fluid mist generation ratio for fluids 1-5 with 95% confidence interval shown.

Table 5. Results of multiple comparison tests of flood application to micro-lubrication ratio of cutting fluid generation rates.

Fluid A	Fluid B	Drilling			Milling		
		Fluid A Ratio	Fluid B Ratio	Significantly Different?	Fluid A Ratio	Fluid B Ratio	Significantly Different?
1	2	0.0011	0.0014	No	0.0092	0.0089	No
1	3	0.0011	0.0029	No	0.0092	0.0099	No
1	4	0.0011	0.0009	No	0.0092	0.0085	No
1	5	0.0011	0.0003	Yes	0.0092	0.007	No
2	3	0.0014	0.0029	No	0.0089	0.0099	No
2	4	0.0014	0.0009	No	0.0089	0.0085	No
2	5	0.0014	0.0003	Yes	0.0089	0.007	No
3	4	0.0029	0.0009	Yes	0.0099	0.0085	No
3	5	0.0029	0.0003	Yes	0.0099	0.007	No
4	5	0.0009	0.0003	Yes	0.0085	0.007	No

Table 6. Comparison mist generation rates of milling and drilling by fluid and fluid application method.

Fluid No.	Flood Application			Micro-lubrication		
	Milling	Drilling	Significant Difference	Milling	Drilling	Significant Difference
1	0.0820	0.0102	Marginal	8.91	9.51	No
2	0.0869	0.0134	Yes	9.73	9.52	No
3	0.0708	0.0147	No	7.15	5.14	No
4	0.0896	0.0085	Yes	10.56	9.45	No
5	0.0923	0.0052	Yes	13.19	13.33	No
6	NA	NA	NA	73.62	111.85	No

DISCUSSION

The analysis of the data collected in this study showed statistically significant differences between the mist generation rates for micro-lubrication and flood application of cutting fluids for the five different fluids, in both milling and drilling. For milling, micro-lubrication had a mist generation rate of 100 to 140 times the generation rate for flood application, depending on the cutting fluid. The differences for drilling were more pronounced, with micro-lubrication generation rates being 340 to 3,300 times the rates for drilling, depending on the cutting fluid. The flood application-to-micro-lubrication mist generations rate ratios were all significantly different from and less than 1.0. The smaller ratios indicate a greater difference between flood application and micro-lubrication. Fluids were compared by evaluating these flood application-to-micro-lubrication generations rate ratios against each other, by machining process. As shown in Table 4, for drilling, Fluid 5 was significantly different than all of the other fluids, with the flood application-to-micro-lubrication generation rate ratios being lower (the difference between flood application and micro-lubrication was greater). Fluid 3, in drilling, was significantly different than Fluids 1, 4, and 5. For Fluid 3, the flood application-to-micro-lubrication generation rate ratios were greater than the ratios for the other fluids (differences between flood application and micro-lubrication were not as great). For milling, none of the flood application-to-micro-lubrication generation rate ratios were significantly different.

The data collected in this study differed from the preliminary data collected for the purposes of the study design. First, the relative standard deviations for the flood data were much higher, approximately 50%, than those measured in the preliminary tests, less than 25%. The relative standard deviations for the micro-lubrication data were close to the relative standard deviations in the preliminary tests. As a result, the power of the experiments would be diminished, meaning that the differences between the generation rates for flood application and micro-lubrication would need to be greater than the factor of 4.0 assumed in the study design. In fact, the smallest micro-lubrication to flood generation rate ratio was 100, much larger than anticipated. The reasons for the higher relative standard deviation for the flood data are unclear, but could have been due to a number of related factors. During the collection of the preliminary data, few activities occurred in the machining laboratory which would have contributed to higher background levels. Although the data were corrected for background aerosol levels, the background concentrations varied substantially during any particular sampling run. The mist generation rates during flood application were extremely low; the effects of background concentrations could have been substantial. During micro-lubrication application, however, mist generation rates were much higher, making the effects of the varying background concentration inconsequential. The low mist generation rates during flood application could also have been affected by certain cycles of the machine, namely the application of way oil. The way oil on this machine was applied pneumatically and could have contributed to the mist concentrations measured by the APS sampling from the ventilation ductwork. Because the oil was applied within the enclosure, the way oil aerosols would not have been measured by the background APS. And like the background concentrations, the generation of way oil aerosols, while potentially significant during flood application, would have been a minor component in the aerosols measured during micro-lubrication.

Comparisons of the individual fluid generation rates within the fluid application method yielded some intriguing results. Comparisons were made within the machining process (milling or drilling) as well as across the processes. The comparisons included within process, (comparing each of the fluids for a given process, milling or drilling, and a given fluid application method, flood or micro-lubrication), within fluid (comparing milling to drilling for a given fluid and given fluid application method), and within fluid application method (comparing one fluid to another across machining processes).

For flood application, five fluids were evaluated (Fluids 1-5 only; Fluid 6 was not used in flood application). As shown in Table 2, within drilling, none of the generation rates for a given cutting fluid was significantly different from any other generation rate. The results for milling, shown in Table 3, were similar. The comparison of milling to drilling for a given fluid yielded a much different result, as shown in Table 6. For all fluids, milling had a mist generation rate that exceeded drilling generation rates in tests at the 5% significance level. On average over all fluids, the ratio of drilling to milling generation rates during flood application was about 0.10.

For micro-lubrication fluid application, six fluids were evaluated. As shown in Table 2, within drilling, Fluid 6 and Fluid 3 were statistically significantly different from each other and from the other fluid generation rates (adjusted p-value$\leq$0.05). Fluid 6 had a higher mist generation rate than the other fluids, while Fluid 3 had a lower generation rate than all the others. For milling, shown in Table 3, the results showed that the mist generation rate for Fluid 6 was statistically significantly higher than the other five fluids, while the generation rate for Fluid 3 was statistically significantly lower than the rates for Fluids 5 and 6. Unlike flood, the comparison of milling to drilling for micro-lubrication for a given fluid, shown in Table 6, showed no statistically significant difference in mist generation rates for Fluids 1-5. For Fluid 6, the results are significantly different at the 5% level, with drilling being about 60% higher than milling.

What do the results of these comparisons mean? In looking at the comparisons between milling and drilling by fluid application method, the generation rate during micro-lubrication appears to be independent of the machining process. Alternatively, during flood application, milling tended to result in higher generation rates than drilling. In comparing the flood application-to-micro-lubrication generation rate ratios, drilling resulted in much lower ratios than milling or greater differences between flood application and micro-lubrication. The lower ratios, however, were not due to higher generation rates during micro-lubrication, but rather, lower generation rates for drilling during flood application. There were no significant differences between the generation rates for drilling and milling with micro-lubrication, suggesting that the contribution to the mist generation rate from the machining operation is limited. Most of the mist generated during micro-lubrication appears to derive from the fluid application equipment. During flood application, however, machining operation did have an impact, with several fluids having a statistically significant difference between milling and drilling. These differences are even more profound considering the relative standard deviations for flood application were much higher than for micro-lubrication (about 50% versus about 12%).

It is also important to put these generation rates into proper perspective. Stating that a fluid, used with a given machining process and fluid application method, has a certain generation rate, does not easily translate into what a worker's exposure might be. With a few assumptions, equilibrium concentrations can be estimated for the generation rates with the following equation.[8]

$$C_{t_2} = \frac{KG}{Q}\left[1 - e^{\left(\frac{-Q}{KV}(t_2 - t_1)\right)}\right] + C_{t_1} e^{\left(\frac{-Q}{KV}(t_2 - t_1)\right)} \tag{12}$$

where: C_{t_2} = Concentration at time t_2
C_{t_1} = Concentration at time t_1
t_1 = Time 1
t_2 = Time 2, later than time 1
K = Mixing factor
G = Generation rate
Q = Ventilation volumetric flow rate
V = Volume of room or enclosure.

The mixing factor, K, takes into account the inefficient mixing present within a room or enclosure. Perfect mixing corresponds to a mixing factor of 1. In an industrial setting, mixing factors will usually range from 3 to 10, with 3 being well mixed and 10 being poorly mixed. If t_2 is allowed to approach infinity, C_{t_2} becomes the equilibrium concentration, C_{eq}, and Equation 7 can be reduced to the following:[8]

$$C_{eq} \approx \frac{KG}{Q} \tag{13}$$

For this calculation, assume a ventilation rate (Q) of 1000 CFM (28.31 m^3/min) and a mixing factor of 5, moderately well mixed. In a small manufacturing facility, these assumed values would be reasonable. In a larger manufacturing facility, the ventilation rate will be much higher, but the mixing factor may also be somewhat higher. In addition, larger facilities will have multiple machines operating at any given time, increasing the generation rate by some factor. Table 7 gives the equilibrium concentrations for the estimated generation rates for each combination of fluid (Fluids 1-6), machining process (milling or drilling), and fluid application method (micro-lubrication or flood).

In reviewing the concentrations presented in Table 7, several things become evident. First, the concentrations during flood application of cutting fluids are all relatively low, 0.0160 mg/m^3 or less. These concentrations are well below both the current OSHA Permissible Exposure Limit (PEL) for mineral oil mist of 5.0 mg/m^3 TWA[9] and the NIOSH REL of 0.4 mg/m^3 thoracic

Table 7. Equilibrium cutting fluid mist concentrations for given cutting fluid mist generation rates.

Fluid Number	Machining Process	Fluid Application Method	Generation Rate (mg/min)	Equilibrium Concentration (mg/m^3)
1	Drill	Micro-lube	9.36	1.65
		Flood	0.0102	0.00180
	Mill	Micro-lube	9.27	1.64
		Flood	0.082	0.0145
2	Drill	Micro-lube	9.60	1.67
		Flood	0.0134	0.00237
	Mill	Micro-lube	10.05	1.77
		Flood	0.0869	0.0153
3	Drill	Micro-lube	5.25	0.927
		Flood	0.0147	0.00260
	Mill	Micro-lube	7.23	1.28
		Flood	0.0708	0.0125
4	Drill	Micro-lube	9.71	1.66
		Flood	0.0085	0.00150
	Mill	Micro-lube	10.55	1.86
		Flood	0.0896	0.0158
5	Drill	Micro-lube	13.36	2.36
		Flood	0.0052	0.000918
	Mill	Micro-lube	13.44	2.37
		Flood	0.0923	0.0163
6	Drill	Micro-lube	121.3	21.43
	Mill	Micro-lube	74.34	13.13
Mixing factor = 5 Ventilation flow rate = 1000 CFM				

particle mass or 0.5 mg/m^3 total particle mass.[10] Second, the concentrations during micro-lubrication for the soluble fluids (Fluids 1-5) are all relatively high, ranging from 0.927 to 2.37 mg/m^3. These concentrations were all above the NIOSH REL, approaching the OSHA PEL. Finally, for the synthetic fluid used straight, the mist concentrations were estimated to be 21.43 mg/m^3 and 13.13 mg/m^3 for drilling and milling, respectively. These levels are both well above both the NIOSH and the OSHA exposure criteria. These calculated concentrations suggest that worker exposures to cutting fluid mists may be a problem when using the micro-lubrication fluid application method.

There are several limitations to the data collected in this study, the primary being the limited variation in the machining parameters. Only milling and drilling were evaluated, and then only with a single set of machining conditions. Of the various machining parameters such as spindle speed, depth of cut, feed rate, metal hardness, metal type, etc., spindle speed is the one variable which may well have a dramatic impact on the cutting fluid mist generation rate. The spindle can act as a spinning disk atomizer, generating aerosols as the fluid is sheared from the surface of the tool. At the slow spindle speeds addressed in the study, aerosols generated in this manner would have been primarily larger particles, greater than 10 µm. The effects of process parameters affecting heat generation were also not evaluated. In addition to spindle speed, other parameters affecting the generation of heat include tool geometry, metal removal rate (both feed rate and depth of cut), and metal hardness and type. The generation of heat is a concern since evaporation and condensation of the cutting fluid is a mechanism of cutting fluid mist generation.[11] If a process generates more heat than was produced in this study (i.e., during machining under severe conditions), cutting fluid mist generation rates would be expected to increase due to the evaporation and condensation of the fluid sprayed into the cutting zone.

So what do these limitations mean to this study? Strictly speaking, the generation rates reported here apply solely to the fluids tested under the machining conditions specified in the test methodology. However, given the magnitude of the differences in the cutting fluid mist generation rates between the two fluid application methods, micro-lubrication would be expected to result in higher cutting fluid mist generation rates than flood application for most milling and drilling applications. Similarly, many other machining processes such as turning and boring, will likely behave in a similar fashion. Care should be used, however, when trying to extend these results to operations that are very different than milling or drilling, such as grinding operation. In addition, while it is easy to say that micro-lubrication results in a greater cutting fluid mist generation rate than flood application, the magnitude of the differences may vary greatly from one machining process to another.

CONCLUSIONS AND RECOMMENDATIONS

Based upon the data collected in this study, there are tremendous differences between the mist generation rates for micro-lubrication and flood application of cutting fluids. Under the conditions tested, micro-lubrication had cutting fluid mist generation rates 340 to 3,300 times the rates for flood application when drilling, and 100 to 140 times the rates when milling. While the machining conditions for the tests in this study would not be considered severe (relatively low RPM and metal removal rates), differences between flood application and micro-lubrication cutting fluid mist generation rates would be expected until machining conditions became much more aggressive, with significantly higher RPMs and metal removal rates.

The evaluation of the six different cutting fluids also showed some statistically significant differences. Fluid 6, the straight synthetic fluid, had generation rates that were much higher than the soluble oils evaluated. The estimated cutting fluid mist concentration calculations, shown in Table 7, showed that this fluid would likely result in workplace concentrations exceeding the current OSHA PEL and the NIOSH REL. There were some differences between the other soluble fluids as well, although none of the generation rates for these fluids were close to the generation rates for Fluid 6 in either drilling or milling. For milling, there were no statistically significant differences in the flood application-to-micro-lubrication ratios. For drilling, the ratio for Fluid 5 was significantly smaller (the difference between flood application and micro-lubrication was greater) and the ratio for Fluid 3 was significantly greater than Fluid 4 and 5 (the difference between flood application and micro-lubrication was smaller for Fluid 3). The primary conclusion from this analysis is that there are differences from one fluid to the next, but more significantly, some types of fluids, as demonstrated by Fluid 6, may result in extremely high worker exposures.

Like so many others, this study raises quite a number of questions that warrant further investigation. Chief among these is the issue of machining parameters and their effects upon mist generation. In this study, only a single set of machining parameters was evaluated for each machining process (milling and drilling). The effects of such parameters as cutting speeds, metal removal rates, tool geometry, material hardness, and metal type, could not be evaluated. Many of these factors may have impacted on the cutting fluid mist generation rates. Cutting speeds, particularly those associated with highspeed machining, may well contribute to higher mist generation rates for both micro-lubrication and flood application of cutting fluids. Material may also have an impact on mist generation, as the heat generated by the machining process will depend, among other things, upon the metal being machined. Greater heat generation may result in high rates of evaporation and condensation of the cutting fluid, which in turn, could lead to a higher mist generation rate. Further research into some of these areas would help place the results of this current study into a better perspective.

Another area for additional research is on the micro-lubrication equipment. The lack of statistically significant differences between milling and drilling during micro-lubrication suggests that the primary source of mist generation comes not from the machining process, but from the delivery of the cutting fluid through the application equipment. A single unit, the Unist equipment, was used in this study. Another micro-lubrication unit will be part of a limited evaluation by TechSolve in the near future. This second unit is a much more complex device than the Unist unit, but its effect on cutting fluid mist generation is unknown. In addition to evaluating other micro-lubrication equipment available on the market, further research on the design of the units is also needed. For example, would it be possible to develop a micro-lubrication unit that did not generate mists of less than 10 μm, while at the same time, delivering similar machining performance? Most of the micro-lubrication units allowed for the adjustment of the fluid flow rate, and could operate at a range of air pressures. (Many, if not most of the units, required shop compressed air to deliver the fluid to the cutting zone.) What effects would fluid flow rate and air pressure have on the cutting fluid mist generation rates? The list of potential research topics focusing on the micro-lubrication delivery units could be substantial.

The magnitude of the cutting fluid mist generation rates should be of concern. The estimated workplace concentration calculations showed that while all of the fluids applied using flood application resulted in concentrations below the NIOSH REL and the OSHA PEL, all of the fluids applied using micro-lubrication resulted in concentrations exceeding the REL, with several approaching or exceeding the PEL. Because of the high mist generation rates associated with it, machining facilities interested in implementing micro-lubrication should also make provisions for adequate machine enclosure, exhaust ventilation, and air cleaning.[12] Air cleaning will be vitally important, as this equipment will be required to handle heavy mist loadings. Due to the size of the mist, the air cleaners also need to have high aerosol removal efficiencies.

Micro-lubrication represents an opportunity to reduce the amount of cutting fluid being disposed, while potentially providing improved machining performance. It represents a departure from the more traditional flood application of cutting fluids, exemplifying the idea of "doing more with less." These process improvements, however, appear to come with their own set of challenges. While micro-lubrication would reduce the potential for occupational exposures to biologically contaminated fluids (micro-lubrication fluids are not recycled), micro-lubrication may also dramatically increase the potential for occupational exposures to cutting fluid mists. These challenges need to be adequately addressed so that the advantages of micro-lubrication can be realized without jeopardizing the health and safety of the workers operating these machining processes.

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