MIST CHARACTERIZATION IN DRILLING 1018 STEEL

Ian Cole

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APPROVED:

Nourredine Boubekri, Major Professor
Reza Mirshams, Committee Member
Thomas Scharf, Committee Member
Leticia Anaya, Graduate Program Coordinator
Enrigue Barbieri, Chair of the Department of Engineering Technology
Costas Tsatoulis, Dean of the College of Engineering
Mark Wardell, Dean of the Toulouse Graduate School

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Minimum quantity lubrication replaces the traditional method of flood cooling with small amounts of high-efficient lubrication. Limited studies have been performed to determine the characteristics of mist produced during MQL. This study investigated the mist concentration levels produced while drilling 1018 steel using a vegetable based lubricant. ANOVA was performed to determine whether speed and feed rates or their interactions have a significant effect on mist concentration levels and particle diameter. It was observed that the concentration levels obtained under all four speed and feed rate combinations studied exceeded the current OSHA and NIOSH standards.

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CHAPTER I

INTRODUCTION TO MINIMUM QUANTITY LUBRICATION

Cutting fluids provide reduced friction between the tool and part, corrosion prevention of metal, the transportation of chips during machining and cooling for the workpiece. Furthermore, the coolant also provides a reduction in the dimensional variations between machined parts (Tasdelen et al., 2008; Fluid Application - MQL, 2006). Research has shown that the cost, filtering and waste removal of the coolant can be more expensive than the tool itself. As environmental regulations increase with the disposal of cutting fluids, the cost will inherently increase. Reducing the quantity of fluids used will have a positive impact on the environment and provide a reduction in the manufacturing cost (Dhar et al., 2006). To achieve these goals, an alternative to flood cooling is minimum quantity lubrication (MQL).

Minimum quantity lubrication, also referred to as near-dry lubrication or micro-lubrication (Khan et al., 2006), replaces the traditional method of flood cooling with small amounts of high-efficient lubrication (Dhar et al., 2006). This process has become a powerful tool when machining conditions are required to perform severe cutting, produce high efficiency and improve surface finish quality. The flow rate at which MQL operates is between 50-500 ml/h. This is approximately three to four times lower than the amount used in traditional flood cooling (Dhar et al., 2006). This decreased amount of lubricant utilized by MQL yields reduced cycle time in cleaning the workpiece/tool/machine and decreased occupational hazards (Khan et al., 2006).

The National Institute for Occupational Safety and Health (NIOSH) recommends that the exposure level that workers encounter from metalworking fluids should be limited to 0.5 mg/m^3 during a 10 hour day for a 40 hour workweek (Workplace Safety and Health – Metalworking

Fluids, 2012). The U.S. Occupational Safety and Health Administration (OSHA) states the permissible exposure level is 5 mg/m^3 based on an 8 hour workday (Metalworking Fluids: Safety and Health Best Practices Manual, 1999). However, it has been found in the past that the oil mist produced by traditional flood cooling methods in U.S. automotive parts manufacturing facilities range from levels of 20-90 mg/m^3 (Bennett et al., 1985). Workers are exposed to these fluids by direct skin contact from splashes or mist during the machining process or handling the tools, parts and equipment. Workers also inhale the mist by means of the fluid circulation system and the exhaust system in the room (Workplace Safety and Health – Metalworking Fluids, 2012). This contact can result in a number of health issues. Such concerns are dermatitis, acute and chronic respiratory diseases, skin cancer and other cancers (Final Report of the OSHA Metalworking Fluids Standards Advisory Committee, 1999).

The costs related to cutting fluids outweigh the price for the cutting tool. Furthermore, escalating the manufacturing expense is the disposal of the lubricant, which is greater than the purchasing price. Flood cooling constitutes 600 million gallons of usage in the metal working industry. Of that number, the United States alone accounts for 175 million gallons. The use of the coolant is 10% to 17% of the total manufacturing cost (Bandyopadhyay et al., 2009). Another economic issue is the recycling of the machined chips. Flood cooling requires the chips to be cleaned before reuse. With MQL, the chips are virtually dry and there will not be a large cleaning expense for recycling (Fratila et al., 2007).

Green manufacturing has become a global concern. During machining, the greatest source of environmental pollution arises from large amounts of coolant used during the cutting process. The environmental concerns within metalwork manufacturing are ozone depletion, global warming and pollution due to the coolant (Fratila et al., 2007). The selection of a cutting fluid for machining should not just be based on the cutting performance, but also on its secondary characteristics. These include biodegradability, oxidation stability, storage stability and water/soil/air pollution effects (Fratila et al., 2007). Currently, vegetable oils are the most effective means for lubricant. They are chosen over mineral oils for their ability to adhere to the metal's surface. Vegetable oils also have great friction reducing qualities, and they absorb heat when evaporated (Boelkins, 2009). The MQL machining with vegetable oils, opposed to flood coolant machining, have shown to reduce the average cutting temperature by 5% to 12% and still obtain dimensional accuracy (Khan et al., 2006). Using vegetable oils instead of mineral oils for MQL is more effective in milling, boring, drilling, turning, reaming, sawing and tapping (Tolinski, 2007). The application of these fluids is also environmental friendly.

There are two supply methods by which MQL delivers lubricant: external spray and through-tool (Boubekri et al., 2010). The most basic method that MQL operates with is by an external nozzle admitting air/oil mist to the tool and workpiece (Tolinski, 2007). This system is known as an external spray system. A coolant tank or reservoir supplies the coolant to nozzles via tubes during machining. The system can balance the coolant supply through adjustable coolant and airflow. The external spray system is portable, low in cost and is used for many machining processes (Boubekri et al., 2010). The second delivery system is the through-tool design with two different configurations for creating the air/oil mist. The first setup is external mixing or a one-channel system. The air and oil are externally mixed and then sent through the spindle and tool to the machined area. The advantages for externally mixed air and oil are low cost, simplicity, ease of service and adaptability to existing machines with high pressure. However, the disadvantages are the dispersion and separation of the air/oil mist after exiting the nozzle. Reducing to fine particles can be achieved, but much less lubrication is reaching the machined part. This will effect the performance of the machining (Boubekri et al., 2010). The second through-tool configuration is the internally mixed or two-channel system. The system uses two parallel tubes that deliver air and oil to a spindle where they are mixed. The mist is then delivered through the tool itself. The system allows for tools to be changed quicker during machining, but is difficult to maintain due to a more complex spindle (Boubekri et al., 2010).

There are currently many advantages that draw manufacturers to the MQL method. According to the Master Chemical Corporation, an MQL system can be adapted to machines that are not equipped to deal with flood cooling or high-volume coolant recovery. MQL also lowers the amount of mist and spray produced opposed to the amount produced during traditional flood cooling. MQL is also able to reduce or eliminate problems encountered with thermal shock during machining. This happens when the tool gains a significant amount of heat and is then cooled by the lubricant. MQL works very well with tools that are susceptible to tool failure by the flank when heat is generated. As stated earlier, this technique greatly reduces the consumption of coolant used, eliminates a large-scale recovery process and leads to a cleaner workplace and workpiece. Last, an MQL system can quickly be adapted to a flood coolant system when high lubricity fluid is needed during machining (Fluid Application - MQL, 2006).

Although MQL significantly reduces the consumption of coolant during machining, it does have disadvantages. First, this technique cannot remove chips from the workpiece as easily as traditional flood cooling does (Aoyama et al., 2008). Like flood cooling, it also creates a mist that is harmful for the body. The use of a vacuum system eliminates the mist created, but some manufacturers see this as excess electrical consumption. As of 2008, a new lean MQL system has been proposed and should greatly reduce the oil mist produced. This is called a direct oil supply system (Aoyama et al., 2008)

CHAPTER II

REVIEW OF MQL LITERATURE

Many experimental tests have been performed in order to determine the effects that minimum quantity lubrication (MQL) has on numerous variables when machining. These include the wear of the cutting tool, the cutting forces and the consumption of energy, the temperature of the workpiece and tool, the safety during machining, the pollutants produced and the vibrations associated the machine (Fratila et al., 2007). However, limited studies have been performed to characterize the mist produced under MQL. The following literature reviewed indicates that the use of MQL with drilling is as effective as flood cooling, if not more effective, when the drilling parameters are correctly chosen.

Davim, Sreejith, Gomes and Peixoto performed an experimental investigation in drilling to determine whether MQL would produce the same results as flood cooling (Davim et al., 2006). The researchers stated that the chips produced during drilling could restrict the flow of lubricant to the drill tip. Using a continuous supply of coolant would be wasteful during the process, and external MQL was chosen to mirror the same conditions as flood cooling. The group chose aluminum AA1050 as the material, and 5 mm diameter holes were drilled into 15 mm-thick discs. The drilling tools used were uncoated, helical K10 carbide with a 10% cobalt grade. The coolant used was an emulsion fluid Microtrend 231L. During the experiment, the flow rate of lubricant for MQL and flood cooling was 250 ml/h and 120,000 ml/h, respectively. The drilling parameters set for MQL were a cutting velocity of 75 m/min and a feed rate of 0.20 mm/rev. For flood cooling, the velocity was 90 m/min and a feed rate of 0.25 mm/rev. The quantity of lubricant, cutting velocity and feed rate were the three independent variables and their interactions considered when performing the analysis of variance (ANOVA). The specific outputs analyzed were the cutting power, specific cutting force and the surface roughness of the drilled holes. The ANOVA calculations showed that the cutting power, specific cutting force and surface roughness results did not show a significant difference when MQL and flood cooling were used. The results from their test concluded that when parameters are carefully chosen; MQL can perform the same as the traditional method of flood cooling (Davim et al., 2006).

An experiment on the analysis of temperature during the drilling of a titanium alloy (Ti6Al4V) was presented by Zeilmann and Weingaertner in 2006 (Zeilmann et al., 2006). The research was of interest because of the poor thermal characteristics that titanium presents during chip removal. Measurements of the temperature were produced by using thermocouples (type K) which have better results than those yielded by pyrometers, thermographs, calorimeters or thermoelectric measurements. The material used in the experiment was a 200x50x20 mm titanium alloy plate. The holes were drilled with 8.5 mm diameter drills and an MQL supply pressure of 3.5 bar. The MQL was supplied with an external spray and internally through the tool, thus requiring two different drills. Both drills had the same characteristics with a class type of K10, micro grains, 9.5% cobalt, a 6 degree clearance angle and three edges (type 125 drill for the internally cooled and type 105 drill for the externally cooled). The internally lubricated drills were not coated, but the externally cooled were uncoated and coated with TiAlN, CrCN and TiCN. The drilling parameters recommended by the manufacturer were for machining conditions under flood cooling. Zeilmann and Weingaertner chose the following new parameters: cutting speeds between 10-50 m/min and a feed from 0.1- 0.2 mm/rev. At a speed of 15m/min, the externally lubricated drills reached temperatures over 450°C and surpassed 500°C at a speed of 30 m/min. The internally supplied drills reached a temperature slightly above 150°C. The experiment revealed that lubricant supplied internally through the drill had temperatures that were more than 50% less than the drills with MQL supplied externally. For the external MQL supply, the uncoated drills showed the highest measured temperature, greater than 550°C, whereas no significant variations were shown between the drills with different coatings. The researchers noted that coated drills had a significant effect on the reduction of the workpiece's temperature (Zeilmann et al., 2006).

Key Engineering Materials published research performed by Rahim and Sasahara on the external MQL drilling of a nickel-based superalloy (Rahim et al., 2010). The scope of their experiments was to determine the difference that palm oil and synthetic ester lubricants had on the surface integrity of Inconel 718 or NiCr20TiAl. At the time of their research, few studies had been performed on the performance of drilling Inconel 718, and inadequate investigations had been performed with the use of MQL. The material used in the machining was a round bar with a diameter of 50 mm and a thickness of 20 mm. The average nominal hardness of the material was approximately 38 HRC. An indexable carbide drill was used to drill holes of 14 mm in diameter. The drill was coated with TiAlN, a point angle of 130 degrees, helix angle of 30 degrees and mounted on a standard tool shank. The drilling parameters used during the process were varying cutting speeds of 30, 40 and 50 m/min, and feed rates of 0.05 and 0.1 mm/rev. Both the palm oil and synthetic ester were externally supplied at approximately 10.3 ml/h. To examine the resulting surface, a vision based measuring machine and a scanning electron microscope (SEM) were used. The material was then sectioned, grind, polished and etched to observe the deformation and microhardness (tested under 50 lb load). Under palm oil lubrication, the surface roughness of the material decreased with higher cutting speeds, but increasing the feed rate raised the surface roughness value. The surface roughness was measured from 0.6 to 0.9 μm and 1 to 1.2 μm under feeds of 0.005 and 0.11 mm/rev, respectively. Synthetic ester produced a surface of roughness of 0.5 μm to 1.5 μm and 0.7 μm to 2.4 μm under feeds of 0.005 and 0.11 mm/rev, respectively. The drilling of the material also increased the hardness under the surface. The microhardness was observed to increase with faster cutting speeds. The researchers believed this was due from increased cutting temperature. Palm oil produced microhardness values of 411 to 444 Hv, and synthetic ester produced values ranging from 393 to 473 Hv. The sub-surface examination showed deformation of the microstructures under all testing conditions. The deformation was greater at higher cutting speeds. The use of palm oil vs synthetic ester during the MQL process exhibited better results in all observations. The researchers proposed that palm oil provides better lubricity that reduces friction force and thus decreases the cutting temperature. The synthetic ester had a density of 0.95 g/cm^3 and a viscosity of 19 mm^2s^{-1} at 40°C. The palm oils characteristics had a density of 0.91 g/cm^3 and a viscosity of 40 mm^2s^{-1} at 40°C (Rahim et al., 2010).

In 2009, Costa, Silva and Machado performed an experiment relating the burr formation in drilled holes to tool wear and the lubricating supply method published in the *Journal of Brazilian Society of Mechanical Sciences and Engineering* (Costa et al., 2009). The article stated that the removal of the burrs in precision machining could account for more than 30% of the total cost of the final piece. If the burrs are not properly removed, alignment of parts will not be accurate and injury to workers becomes a concern. The formation of burrs is influenced by three main parameters. These are the drill's geometry, properties of the material and the drilling process (cutting speed, feed rate and cutting fluids used). The experiments would allow for burr heights to be measured and relate the results to tool life. The researchers developed a procedure that would define tool life throughout the process. The drill's life was divided into seven stages: 1%, 18%, 36%, 50%, 64%, 82% and 98% of the machined holes. For each run, 21 holes were analyzed and the average burr height was assigned to the seven percentage levels of the machined holes. It was known that sharp drills produced relatively small burrs while dull drills produced the largest burrs. The drilling was carried out under dry, MQL and flood cooling conditions. Under MQL, vegetable oil and mineral oil were both supplied at 30 ml/hr. For flood cooling, mineral oil was supplied at 750 ml/hr, and synthetic oil was supplied at 1230 ml/hr. The drill used in the test was an 8% cobalt M42 HSS with a TiAlN coating, 10 mm diameter, 30 degree helix angle and 130 degree point angle. The coating had a 3300 HV hardness and a 0.4 friction coefficient against steel. The cutting speeds were performed at 45 m/min and 60 m/min and a feed rate of 0.25 mm/rev for all methods of lubricant supply. The material used for drilling was DIN 38MnS6 steel with dimensions of 100x100x30 mm. Holes were drilled through the 30 mm thick material and then repeated under each supply method and lubricant. The burr height was measured with a dial indicator at four spots per hole and averaged. From the experiments, the group was able to make conclusions and relate tool life and lubrication to burr formation. At the higher cutting speed of 60 m/min, the cutting fluids had little effect on the results and the average tool life was reasonably the same. The same could not be said for the results of the 45 m/min cutting speed. This proved that the lubricant was more efficient at decreasing tool temperature at lower speeds than opposed to higher speeds. At lower speeds, the tool was estimated to be over at 64%. The lower speeds produced twice the burr height of the faster speeds. This was due to the increase speed reducing the cutting force and reducing burr size. Also for the low cutting speed, dry machining produced the smallest average burr height, and the MQL systems with vegetable oil and mineral oil produced the largest heights after its 64% tool life. The 60 m/min cutting speed for dry machining produced the largest average height, but at 82% tool life the burr height reduced. The use of mineral oil and synthetic oils during flood cooling produced the same results under both cutting feeds. The MQL values used at this speed with mineral oil produced larger burr heights while vegetable oil produced the smallest burr heights. The study was able to confirm that the height and formations of burrs are associated with tool wear and the continued cutting with a worn tool, which is linked to the supply method of coolant (Costa et al., 2009).

In 2005, a study was published on the effect that minimum quantity lubrication has on the tool life of small twist drills in deep-hole drilling (Heinemann et al., 2005). The experiment carried out would reflect the results when MQL was supplied in a discontinuous flow versus a continuous supply. The material used was plain carbon steel (0.45% carbon) with the dimensions of 65x75x15 mm. Four types of twist drills with a diameter of 1.5 mm, a straight shank, wide chip flutes, parallel web, a 40 degree helix angle, 130 degree point angle and a split point web thinning were used. These attributes are recommended for twist drills in deep hole drilling. The characteristics of the drills are described in Table 1.

Table 1: Characteristics of Twist Drills

Twist Drill	Type	Coating
Drill 1	HSS	Uncoated
Drill 2	Co-HSS	Uncoated
Drill 3	Co-HSS	TiN
Drill 4	Co-HSS	TiAlN

Twist drills were drilled to a 10 mm depth at a cutting speed of 26 m/min and a feed rate of 0.28 mm/rev. In the first test, holes were drilled to a depth of 5 mm and the MQL supply of SETOL ST-SHAD 20A (synthetic ester + additives with 20% alcohol) was then stopped. This is due to that virtually none to little lubricant is able to penetrate this depth. The lubricant supply resumed once the drill penetrated the workpiece and began to withdraw. The second series of test used the same procedure but with two additional lubricants. These were SETOL ST-SHAD (synthetic ester + additives) and SETOL-SOE (oil-free synthetic lubricant with 40% water). The third test conducted was performed under dry conditions. An additional series of test were performed under a continuous minimum quantity supply of 18 ml/hr using only the uncoated HSS drill. The group concluded that discontinuing the MQL supply significantly reduced the tool life, whereas a continuous supply, even though obstructed, was beneficial for the tool life. This was especially evident with the uncoated drills during the continuous supply. The minimum quantity lubricant SETOL-SOE contributed to the longest tool life during a continuous supply. The researchers concluded this was because of its superior cooling capability and improved ability to penetrate the drilling bores. The dry drilling with all four drill types proved to achieve unsatisfactory tool life (Heinemann et al., 2005).

The *Journal of Brazilian Society of Mechanical Sciences and Engineering* published an experimental study relating the quality of MQL vs. flood cooling in the drilling of aluminum silicon alloy SAE 323 (Braz et al., 2003). The scope of the research was to measure the diameter and roughness of the holes, and the tool wear between the two lubricating supply methods. In this experiment, MQL supplied mineral oil at 10 ml/h with a pressure of 4.5 bars. The flood cooling supplied soluble oil, 4% oil concentrated in water, at a flow rate of 2.4 m^3/h. Two solid K10 carbide drills without coating were used. The first was a 10 mm diameter drill penetrating a 34 mm depth under both MQL and flood cooling conditions. The second drill was 20 mm in diameter penetrating 60 mm also under MQL and flood cooling conditions. These diameters were used in order to have a similar length to diameter ratio. The 10 mm drill used a cutting speed of 300 m/min and a feed rate of 0.1 mm/rev. The 20 mm drill was set at a speed of 450 m/min and a feed rate of 0.1 mm/rev. The 10 and 20 mm drills both used the pecking technique with depths of 5 mm and 10 mm increments, respectively. The flank wear of the tool was measured with an optical microscope with 50 times amplification. Surface roughness was measured with a portable surface roughness equipment, and the roundness was measured with electronic equipment using an LVDT sensor. Under MQL and flood cooling of the 10 mm diameter drills, no significant difference between the quality of holes and tool wear was observed. The 20 mm diameter drills under MQL demonstrated the same results as the 10 mm under MQL. The experiments did show that the 20 mm diameter drill under flood cooling was not possible because of tool failure. This was due to the flood coolant not possessing good lubricant capacity, which is needed for chip removal. The researchers hypothesized the flood cooling process with a 20 mm drill is possible if pre-drilled holes were made. The flank wear was also more evident in the 20 mm diameter drill tests under MQL; however, this was speculated by the increased cutting speed. It was determined that the MQL supply method was more efficient than flood cooling for this process (Braz et al., 2003).

Bhowmick, Lukitsh and Alpas published an article in the *International Journal of Machine Tools and Manufacture* studying the different effects that dry machining, external MQL and flood cooling had on cast magnesium. Their research would focus on tool wear, cutting and force torque, temperature and surface integrity (Bhowmick et al., 2010). The workpiece material used in the experiments was a 60x10.16x7.62 cm die cast magnesium AM60 alloy plate with 6% aluminum. The hardness of the material was measured at 67± 8.0 kg mm^{-2} on a Brinell hardness scale. The drill used for the process was a HSS twist drill with a diameter of 6.35 mm and a Rockwell hardness of 64 ± 2.50 HRC. The drilling parameters were set at a cutting speed of 50 m/min and a feed rate at 0.25 mm/rev. Under dry, MQL and flooded conditions, the tool drilled 150 holes into the workpiece with an initial 19 mm blind hole. Two MQL coolants were studied.

The first was distilled water and the second was the fatty acid-based produced by Vogel. Both lubricants were supplied at 10 ml/h. Distilled water lacks lubrication and was chosen to determine how much lubrication is needed in the MQL drilling procedures. The flood coolant used was a mineral based oil set at 30 l/hr. Mineral oil was chosen because of its wide spread applications in machining magnesium. The torque and thrust generated during the drilling of each hole was measured with a non-contact, magneto-static torque sensor mounted to the base of the drill. The temperature was measured with an infrared thermometer. During the dry drilling experiments, the tool life was very short. Upon drilling the 79th hole, the drill seized to the magnesium and tool failure was defined. The dry drilling experienced a continuous increase in torque, and as the number of holes increased, the torque reached at prominent peak. The average torque during the drilling was 2.28 N-m for the first hole and 9.32 N-m for the 78th hole. The thrust forces were also high during the process. 102 N was measured at the first hole and 165 N for the 78th hole. The maximum temperature obtained was 200˚C. The MQL process produced no tool failures with both MQL coolants. Drilling with the fatty-acid based coolants produced a maximum torque that did not exceed 2.0 N-m. The maximum thrust force was 125 N with this coolant. The maximum temperature reached was 86˚C. During the MQL with distilled water, the torque ranged from 3.5 - 4.0 N-m. The thrust force was measured at 80 N for the first hole and 154 N for the 150th hole. Flood cooling produced similar results. The average torque was 2.08 N-m for the first hole and 2.75 N-m for the 150th. The maximum temperature obtained was 134˚C. The torque thrust was at 63 N for the first and 121 N for the last. Both of these measurements were within the range of the MQL process. The temperatures obtained were also very similar to those of the MQL with distilled water. The highest surface roughness measured was 46.8 ± 25.3 micrometers at the onset of drill failure during dry machining. The surface roughness values were 11.8 ± 2.2, 17.2 ± 2.4 and 12.9 μm ± for the fatty acid MQL, distilled water MQL and flood cooling, respectively. These results concluded that use of MQL could achieve the same results as that of flood cooling. Furthermore, the use of distilled water in MQL needed to be explored in a longer running process. The use of water-cooling with magnesium is generally avoided due to the formation of magnesium hydroxide and hydrogen gas (Bhowmick et al., 2010).

Summary of MQL Experimentations

The literature reviewed revealed that minimum quantity lubrication can be as effective as flood cooling. Utilizing MQL as an alternative to flood cooling depends on several factors. One of these factors is choosing the correct drilling parameters. This was evident in the study performed by Davim and his colleagues. The researchers compared the cutting power, specific cutting force and surface roughness results of drilled holes between MQL and flood coolant drilling. ANOVA calculations concluded that choosing the MQL drilling parameters carefully showed little variation in results between the two methods.

The correct lubricant used for the MQL drilling process also effects the surface integrity of the finished part as well as the tool's life. The studies reviewed experimented with different lubricants in order to determine which was the most efficient. These lubricants were vegetable oils, palm oils, mineral oils and synthetic esters. Many of the experiments used vegetable oils for their ability to adhere to a metals surface, friction reducing properties and the ability to absorb heat when evaporated. Another experiment confirmed that SETOL SOL (oil-free synthetic with 40% water) improved MQL drilling by producing reduced temperatures and its ability to penetrate greater bore depths. All researchers stated that vegetable oils are the most ecological friendly lubricant, but more research should be performed on which biodegradable lubricant is best for a specific material.

Using the same drilling parameters and lubricants for different materials will result in different surface integrity of the materials and fluctuating tool life. In order to reduce manufacturing cost and present a safer machining method, more research is needed to determine the correct drilling parameters and lubricants used when drilling with minimum quantity lubrication.

Conclusion

Limited studies have been performed to determine the quality of mist produced while drilling under minimum quantity lubrication. The objective of this study is to evaluate the concentration levels and particle diameters of mist during the drilling of AISI 1018 steel under two different speed and feed rates. Accu-lube 6000 is the chosen minimum quantity lubricant. A total of four treatments will be conducted, and the results will be compared to OSHA and NIOSH metalworking mist standards.

CHAPTER III

EXPERIMENTAL METHODS AND PROCEDURES

This section addresses the methods and procedures used to conduct this experiment. The drilling and data gathering equipment, cutting tool specifications and drilling procedure is also described. Additionally, the analysis used to conduct the design of experiments is explained.

Objective of Study

Measure the diameter of mist particles and concentration levels produced while drilling under various levels of speed and feed rates of AISI 1018 steel. The lubricant supplied through the MQL system is Accu-lube 6000. The results obtained will then be compared to current OSHA and NIOSH standards. The relationships between tool failure, particle size and concentration levels are also be analyzed.

Design of Experiment

This experiment uses a randomized factorial design for mist characterization. The speed and feed rates are the two independent variables. The speed and feed rates are measured in feet per minute (FPM) and inches per revolution (IPR), respectively. The particle size and the concentration levels of the mist produced are the dependent variables and are measured in micrometers (μm) and mg/m³, respectively. Table 2 displays the speed and feed rates used with their combinations.

Table 2: Experimental Design for the Speed and Feed Rate Combinations

Drilling Parameters		Cutting Speeds (SFM)	
		120	100
Feed Rates (IPR)	0.004	120, 0.004	100, 0.004
	0.003	120, 0.003	100, 0.003

Cutting Tool Specifications

The tool used is a high-speed steel drill with TiN/TiAlN multilayer coating as shown in Figure 1. The drill has a 118 degree point angle, a diameter of 0.5 inches, a straight flank, bright oxide finish and a maximum drilling depth between 1 - 1.5 inches. Guhring Inc manufactured the drills.

Figure 1: High Speed Steel Drill Bit
(Source: University of North Texas, Manufacturing Engineering Laboratory)

Workpiece Material

The material used in this experiment was 1018 steel. Alloy 1018 is the most available of cold-rolled steels. It is produced in round rod, square bar and rectangular bar. According to Eagle National Steel, the mechanical properties of this material are the strength, limited ductility and comparative ease of machinability. Table 3 depicts the mechanical and chemical properties of this steel.

Table 3: Properties of 1018 Steel

Mechanical Properties	Ultimate Tensile Strength (PSI)	63,800
	Yield Strength (PSI)	53,700
	Elongation	15.00%
	Rockwell Hardness	B71
Chemical Properties	Iron (Fe)	98.81 - 99.26%
	Carbon (C)	0.18%
	Manganese (Mn)	0.6 - 0.9%
	Phosphorus (P)	0.04% max
	Sulfur (S)	0.05% max

Drilling Equipment

Mori Seiki DuraVertival CNC machining center was used to perform the drilling operations under MQL. This machining center has a 30 tool storage capacity, a top RPM of 10,000 and 15 horsepower. The filtration system equipped to the machine was a LOSMA, Inc Darwin 2000M model. This model is a single-centrifuge filtration system used for air containing small quantities of particulate produced by the mist of soluble coolant or neat oils. The CNC's workspace is fully enclosed when in operation.

The machining center is equipped with an ECOSAVER KEB3 micro-lubrication system. This system was fitted to the CNC so that the lubricant was supplied externally through a nozzle. MQL supply air pressure can operate between 0.3 - 0.7 MPa and airflow ranging from 30 - 200 L/min. For this experiment, Accu-lube 6000 vegetable based lubricant was supplied under a flow rate of 11 ml/h. This lubricant is recommended for moderate-duty drilling and MQL systems. The attributes of Accu-lube 6000 are listed in Table 3.

Table 4: Properties of Accu-lube 6000 (Vegetable Based)

Characteristics	**Values**
Density	7.74 lbs/gallon
Appearance	Medium blue viscous
Specific Gravity	0.92
Viscosity at 40°C	8.9 cSt
Flash Point	418°F (214°C
Pour Point	. -40°F (-40°C
Sulfur	None
Chlorine	None
Silicone	None
VOC	Nil
Mineral Oil	0%
Water Solubility	Insoluble

DataRAM4

The mist produced during drilling is measured with a Thermodynamic DataRAM4.

Ambient mist concentrations are regulated by a Millipore filter. The filter is 37 mm in diameter and has a 0.8 micrometer cellulose ester membrane. During operation, the DataRAM4 processes the airborne particulate matter by a light scattering sensing configuration. The instrument has a measurement range from 0.0001 to 400 mg/m^3. The DR-4000 model is capable of storing 50,000 data points which include individual point averages and the median particle size (μm). The temperature and humidity at any given time can also be measured. When measuring particles in an enclosure, a non-electrostatic tube was connected to the DataRAM4 and ran into the enclosed space. Guidelines are applied when using this method for more accurate measurements of the mist particulates. These guidelines are:

1. Minimize the tube length from the Millipore filter to the DataRAM4, necessarily when running horizontal lengths.
2. Minimize the number of bends and angle changes of the tube.
3. Maximize the transport velocity by minimizing the tubing diameter.
4. Changes in tube diameter or couplings should be incremental in direction of flow.
5. Use non-electrostatic tubing.

Workpiece Preparation

A previous experiment left enough workpieces to complete one combination of speed and feed rates. In order to complete the three remaining combinations, additional 1018 steel was required. Two bar stocks measuring at 10 feet and 4 inches in diameter were ordered from a local material supplier. The bar stocks were loaded onto the rollers of the bandsaw and measured to a cutting thickness of 1.75 inches as in Figure 2.

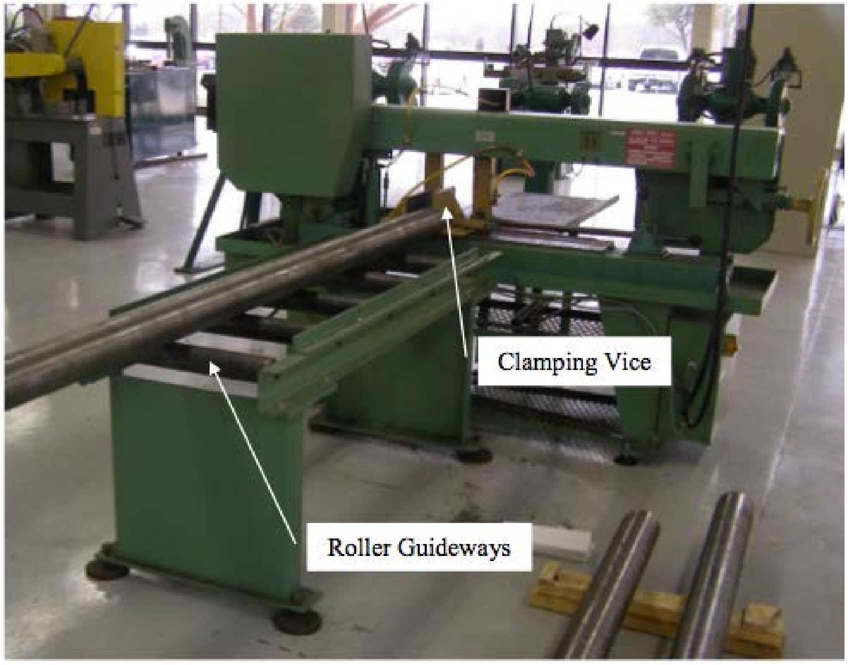


Figure 2: UNT bandsaw
(Source: University of North Texas, Manufacturing Engineering Laboratory)

The saw did not have an accurate way to measure the thickness precisely, so a steel ruler was used to acquire the needed thickness. Once the measurements were made, the bar stocks were made immobile by locking them into the bandsaw's vice. Turning the power button on and then activating the bandsaw would begin immediate coolant flow. After the rough workpieces were cut to 1.75 inches, a CNC lathe was used to remove excess material to produce a workpiece with a precise thickness of 1.5 inches. In order to accomplish this, both sides of the workpiece were faced. The sample was also turned to a diameter of 3.975 inches at a length of 0.75 inches. Additionally, a radius of 0.125 inches was machined to the edge. Figure 3 shows the final workpiece. The machining performed would allow for the workpiece to slide easily into the jaws of the CNC Mori Seiki and have a flush surface to seat properly within the jaws.

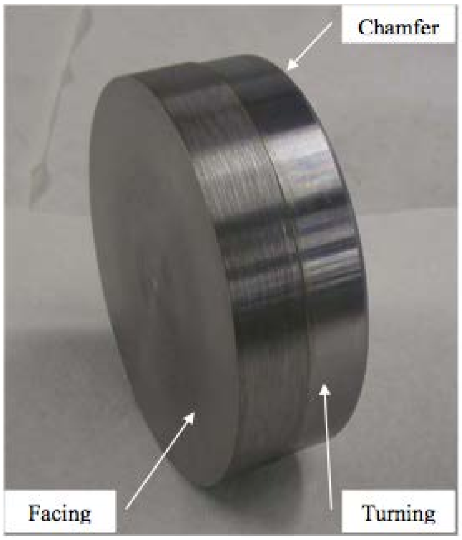


Figure 3: Final Sample
(Source: University of North Texas, Manufacturing Engineering Laboratory)

Drilling Process

A CNC program was written that would produce 30 center drilled holes and 30 drilled holes at a depth of one inch and a diameter of 0.50 inches per workpiece. Each hole drilled had a pecking cycle of 0.20 inches (five pecks per hole). The mister would automatically turn on once the drilling cycle had begun. At this point, the DataRAM4 was manually activated to start recording the concentration levels and particle diameters. The program was written to drill three consecutive holes, stop the machining process and turn the mister off. This process was done so that chip debris could be removed from the drill or readjusting the mister nozzle with the drill as necessary. The DataRAM4 was also manually paused during this stop. Once the user had resumed the drilling operations, the mister would automatically begin lubricating, and the DataRam was again activated to monitor the total particulate mass. This drilling process was repeated 10 times per workpiece.

Figure 4: DataRam 4 Installation
(Source: University of North Texas, Manufacturing Engineering Laboratory)

The DataRam 4 was positioned on a table next to the CNC. A hole was drilled into the side of the machine to allow the non-electrostatic tubing to enter the machining enclosure. The drilled hole was sealed with a rubber grommet so that the DataRam 4 only monitored the air quality within the CNC as shown in Figure 4.

Drilling Process

1. Turn the Mori Seiki CNC on and open the air pressure valves for the mister and CNC.
2. Fill the mister tank with Acculube 6000 or ensure that there is fluid within the tank.
3. Set the Data Ram 4 up.
    a. Attach the non-electrostatic tube to the instrument and place two inches within the CNC machine.
    b. Turn the DataRam on and zero initialize (approximately 300 or less seconds).
4. Choose a random combination of speed and feed rate.
5. Enter the speed and feed rates into the program from a given combination.
6. Secure a random workpiece in the jaws of the CNC and tighten.

7. Set the tool offsets for the center drill and HSS drill.
8. Place the mister 6” away from the drill bit at a 45 degree angle. Aim the mister on the lower quarter inch portion of the drill bit.
9. Perform the initial spot drilling for thirty holes on a given workpiece.
10. Activate the DataRAM4 to record total particulate mass once the drilling cycle begins.
11. Temporarily pause the DataRAM4 once the three holes have been drilled. The program allows for three consecutive holes to be drilled and then stops.
12. Clean any debris from the drill and readjust the mister if necessary.
13. Activate the DataRAM4 once the drilling operations have resumed.
14. Perform steps 10 - 13 an additional nine times. This will produce a total of 30 holes per workpiece.
15. Stop recording information on the DataRAM4 once all 30 holes have been drilled. Take note of the tag number applied to that workpiece.
16. Remove the workpiece from the CNC jaws.
17. Repeat steps 4 - 16 until tool failure occurs for the selected speed and feed rate. Tool failure is defined in Chapter III under the Tool Failure Criteria section.
18. Repeat steps 1 - 17 for the additional three combinations of speed and feed rates.

Figure 5 shows a workpiece after all 30 holes were completed.

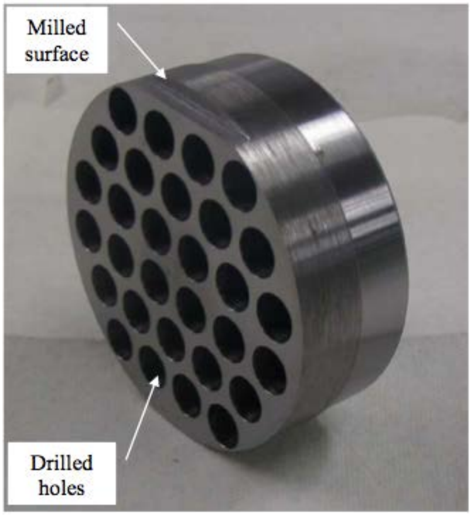


Figure 5: Drilled Workpiece
(Source: University of North Texas, Manufacturing Engineering Laboratory)

Tool Failure Criteria

Every 10th hole's diameter was measured with a digital vernier caliper. Determining tool failure was recognized by one of the following criteria:

1. Three consecutive diameters greater than or equal to 0.51 inches.
2. A diameter measured less than the first hole's diameter.
3. Sudden or abrupt tool failure during the drilling process.

Once any of these conditions were met, drilling for that speed and feed rate combination would end.

Data Collection

The DataRAM4 was configured so that a data point was recorded every second. After 30 holes were drilled into a workpiece, the DataRAM4 was stopped and the data was saved internally to the machine. The DataRAM4 was then connected to a computer to access the saved files. The resulting files produced were in Excel format. A tag number was assigned to each file, and each tag represented 30 holes. The last workpiece varied in hole number depending on when the tool failed. The concentration levels and particle diameter were then averaged for each individual workpiece. These values were then inputted into Design Expert in order to perform the analysis of the data.

Data Analysis

Analysis of variance (ANOVA) was performed in order to determine which factors, speed, feed rate or their interactions, had a significant effect on the particle size or concentration level of the mist. The statistical program, Design Expert, was used in order to perform the calculations. The steps used to conduct the analysis were:

1. Organize and input the data obtained from MQL drilling and monitoring with the DataRam 4.
2. Evaluate the resulting F values to determine the significance of the models obtained for mist concentration and particle diameter as well as the significance of the independent variables speed rate, feed rate or their interactions.
3. For each regression model, determine whether the R-squared and adjusted R-squared indicate a reliable predictor. Perform transformations if necessary.
4. Plot graphs representing the normality of residuals for concentration levels and particle diameters.
5. Plots graphs representing the constant variables of residuals versus predicted for the concentration levels and particle diameter.
6. Create histograms depicting the frequency of concentration levels and particle diameters.
7. Plot graphs representing the data trend of mist concentrations and particle diameters for each combination of speed and feed rates.
8. Plot a correlation analysis graph between concentration levels and particle diameters for each combination of speed and feed rates.

CHAPTER IV

ANALYSIS AND RESULTS

This section addresses the results obtained from the analysis of variance. Additionally, each speed and feed rate combination is explained in its own subcategory. Design Expert was used to produce the ANOVA results and normal probability plots. Excel was used to graph the histograms, correlation analysis and the data trends of the concentrations and particle diameters for the treatment combinations.

Hypotheses

1. Null hypothesis: Speed and feed rates do not have a significant effect on the particle size and concentration levels of mist produced during MQL drilling.
2. Alternative hypothesis: Speed and feed rates do have a significant effect on the particle size and concentration levels of the mist produced during MQL drilling.

Normal Plot of Residuals

A normal probability plot is used to demonstrate whether the data set approximates a normal distribution. Plotting with residuals yields a more accurate assessment of the ANOVA results. Residuals are the differences between the observed and predicted responses.

Figure 6 displays the normal plot of residuals for the mist concentration. The normal probability plot indicates a reasonable linear pattern for the center of data. However, there are a few points scattered around the centerline. These points are viewed as reasonable data since they are not a far departure from the centerline or follow a specific curve.

Plots from Design Expert are used to show the constant variance for the mist concentration. Figure 7 shows that there is constant variance of the residuals versus the predicted. The plot shows that the data does not follow a particular trend, thus indicating constant variance.

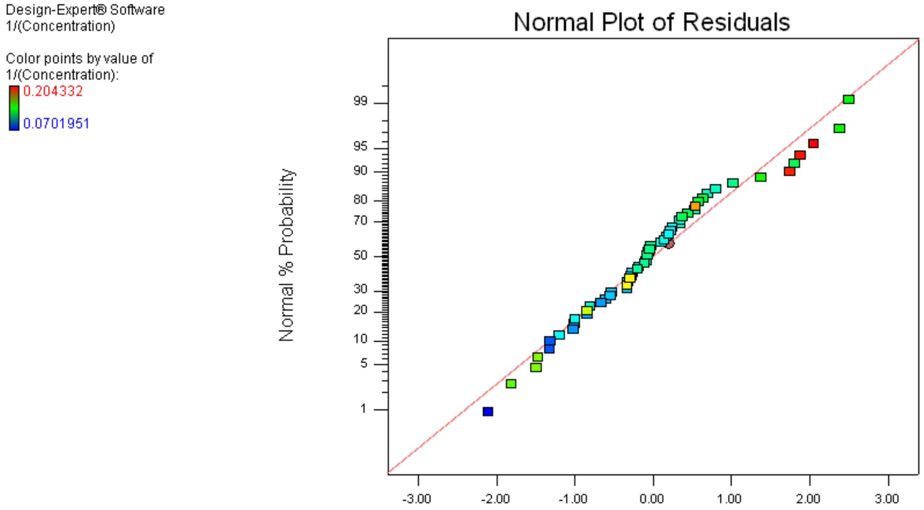


Figure 6: Normal Plot of Residuals for Concentration Levels of Mist

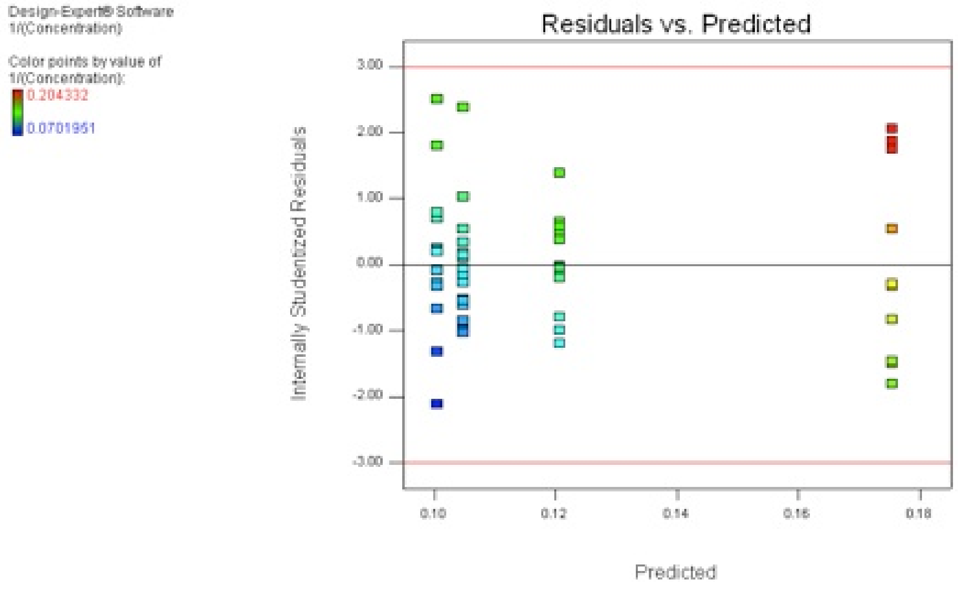


Figure 7: Constant Variance Plot of Residuals versus Predicted for Concentration Levels

A normal probability plot is used to inspect the distribution of data for the particle diameter. This is shown in Figure 8. The normal probability plot indicates a reasonable linear pattern for the center of data. However, there are a few points that are scattered around the centerline. These points are viewed as reasonable data since they are not a far departure from the centerline or follow a specific curve.

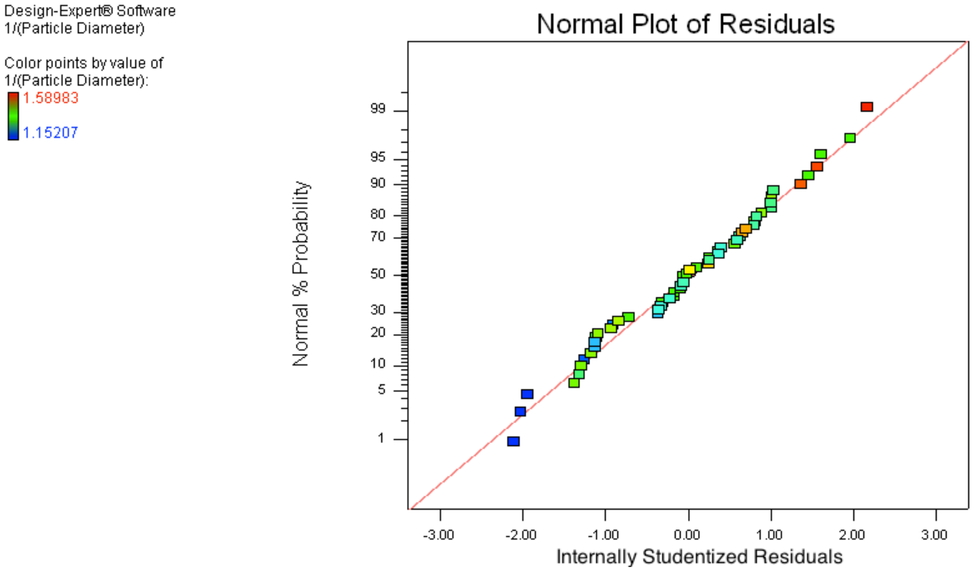


Figure 8: Normal Plot of Residuals for Particle Diameter of Mist

Plots from Design Expert are used to show the constant variance for the particle diameter. Figure 9 shows there is constant variance for the residuals versus the predicted. The plot shows that the data does not follow a particular trend, thus indicating constant variance.

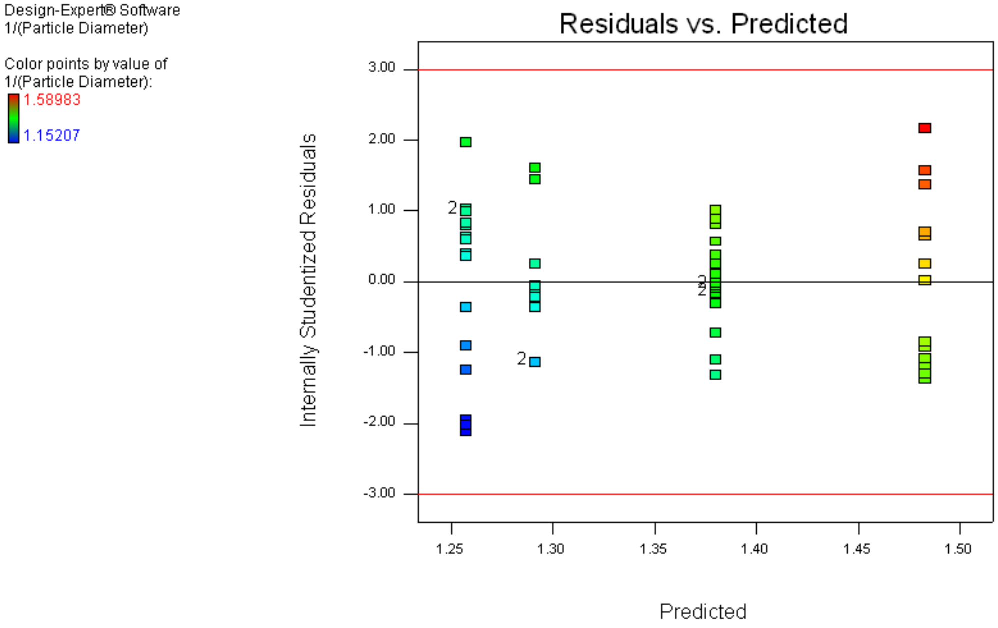
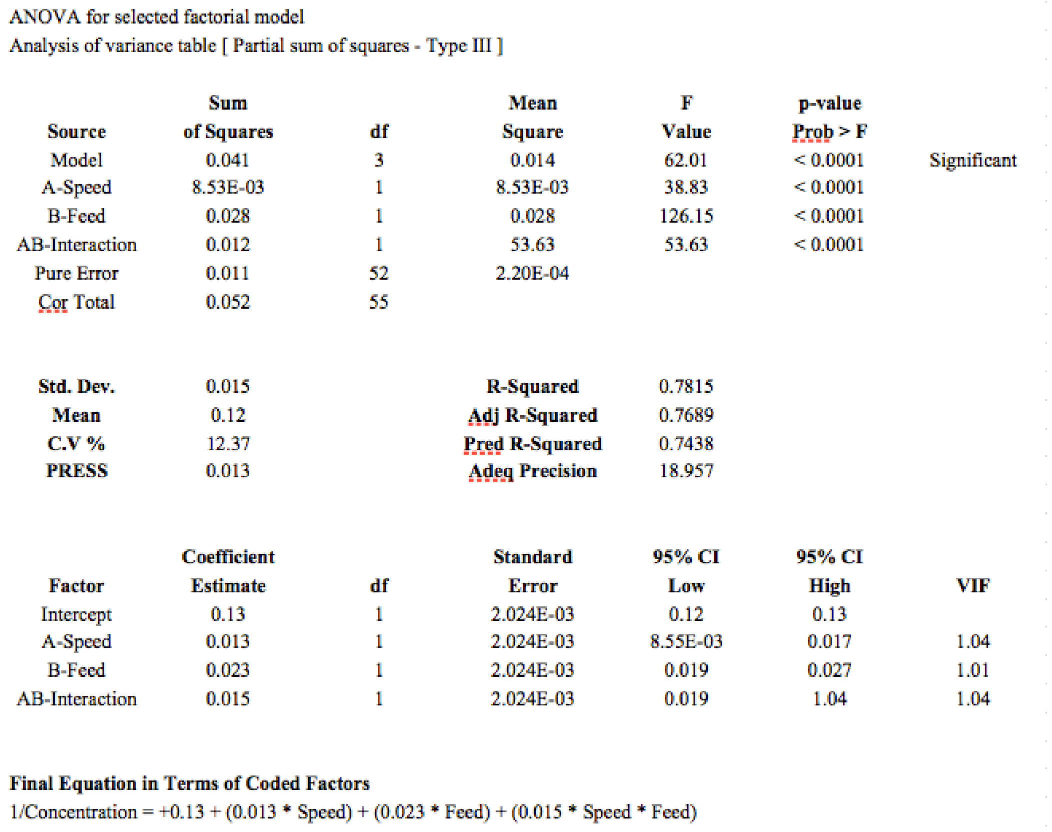


Figure 9: Constant Variance of Residuals versus Predicted for Particle Diameter

ANOVA Results for Concentration Level

Table 5 shows the analysis of variance for the concentration levels of mist produced while drilling. This is a general factorial model for a two-factor design. Within Table 5, the factors are labeled as A-speed, B-feed and AB-interactions. Summary of the analysis of variance includes the factor's sum of squares, degrees of freedom (df), the mean square, *F* value and prob > F. Within the prob > F column, all values are < 0.0001. Any values less than 0.0001 are automatically defaulted to < 0.0001. The model itself has an *F* value of 62.01. This value implies that the model is statistically significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of prob > F less than 0.0500 indicate models terms are significant. In this case, A, B and AB are significant model terms. Values greater than 0.100 indicate the model terms are not significant.

Table 5: Analysis of Variance for Concentration Level



ANOVA for selected factorial model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.041	3	0.014	62.01	< 0.0001	Significant
A-Speed	8.53E-03	1	8.53E-03	38.83	< 0.0001	
B-Feed	0.028	1	0.028	126.15	< 0.0001	
AB-Interaction	0.012	1	53.63	53.63	< 0.0001	
Pure Error	0.011	52	2.20E-04			
Cor Total	0.052	55				

Std. Dev.	0.015	**R-Squared**	0.7815
Mean	0.12	**Adj R-Squared**	0.7689
C.V %	12.37	**Pred R-Squared**	0.7438
PRESS	0.013	**Adeq Precision**	18.957

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.13	1	2.024E-03	0.12	0.13	
A-Speed	0.013	1	2.024E-03	8.55E-03	0.017	1.04
B-Feed	0.023	1	2.024E-03	0.019	0.027	1.01
AB-Interaction	0.015	1	2.024E-03	0.019	1.04	1.04

Final Equation in Terms of Coded Factors
1/Concentration = +0.13 + (0.013 * Speed) + (0.023 * Feed) + (0.015 * Speed * Feed)

Included in table 5 are the R-squared, adj R-squared, pred R-squared and adeq precision. The R-squared value is an indicator to whether the regression model is a good predictor. For the concentration's model, the R-squared value is 0.7815 or 78.15%. This percentage can predict 78.15% of the variation of data whereas there is 21.85% of variance that cannot be explained. Much larger values of R-squared are preferred as it predicts less variability of the data. The pred R-squared of 0.7438 is in reasonable agreement with the adj R-aquared of 0.7689. Finally, the adeq precision measures the signal to noise to ratio. A ratio greater than 4 is desirable. The ratio of 18.957 indicates an adequate signal. The final equation in terms of coded factors is:

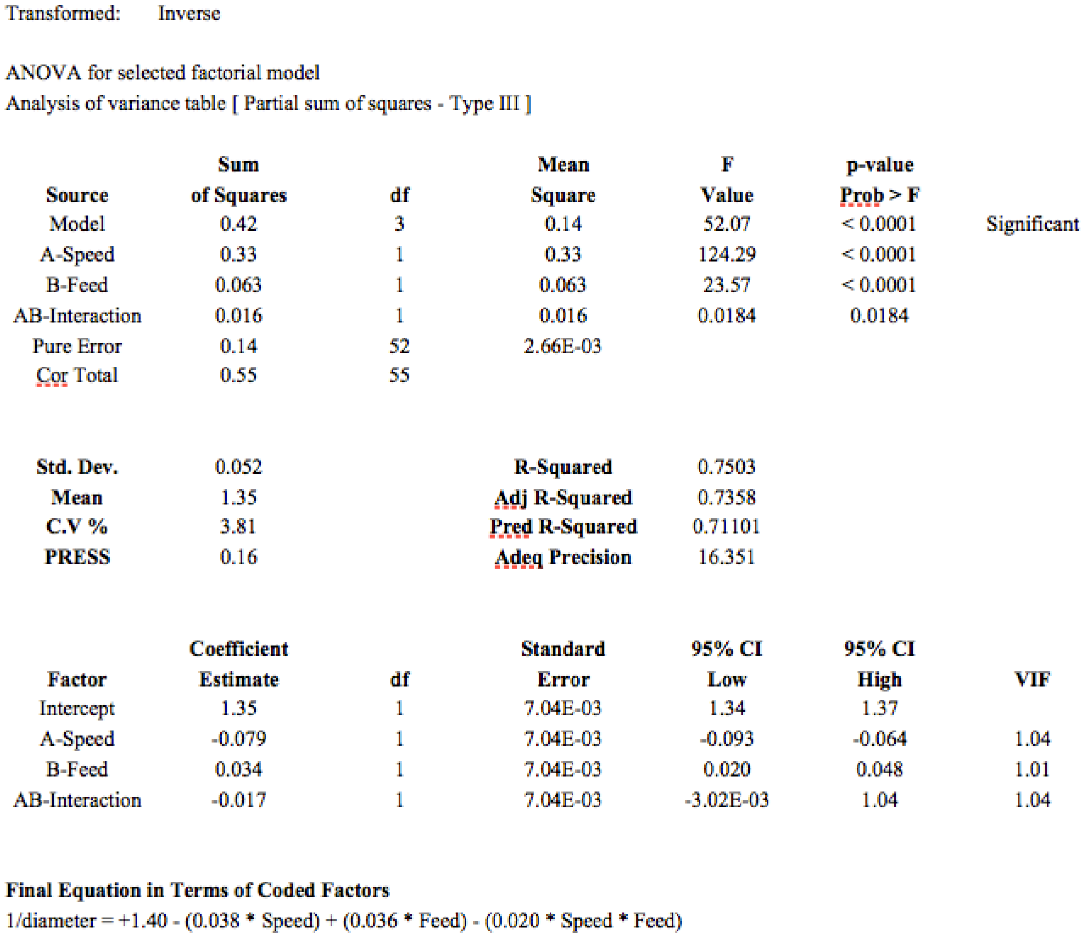
$$1/(concentration) = 0.13 + (0.013 \times Speed) + (0.023 \times Feed) + (0.015 \times Speed \times Feed)$$

The R-squared for this analysis is 78.15% leaving 28.15% of variance unaccountable. Reasons for this can be contributed to the excessive chip formation produced during some combinations. Under the individual sections of combinations, the chip formation is described. A second explanation can be due to the cleaning of the tool. After three holes were drilled, the machining program allowed for the tool to be cleaned of debris. When the door was opened, mist escaped, thus not creating a consistent concentration. The length of time to clean the tool depended on the chip formation produced. Finally, the non-electrostatic tubing could contribute to this variance. Figure 4 shows a setup of the tubing and DataRAM4. There is a noticeable curve required to access the CNC. Mist could have easily built up in the curvature creating a capillary effect. Since the tubing was not cleaned during the runs, particles could have been lodged in the curvature and not give an accurate assessment of the concentration levels.

ANOVA Results for Particle Diameter

Table 6 shows the analysis of variance for the particle diameters of mist produced while drilling. This is a general factorial model for a two-factor design. Within Table 6, the factors are labeled as A-speed, B-feed and AB-Interactions. Summary of the analysis of variance includes the factors sum of squares, degrees of freedom (df), the mean square, *F* value and prob > F. Within the prob > F column, all values are < 0.0001 except for the AB-interaction. Any values less than 0.0001 are automatically defaulted to < 0.0001. The model itself has an *F* value of 52.07. This value implies that the model is statistically significant. There is only a 0.01% chance that a model F-value this large could occur due to noise. Values of prob > F" less than 0.0500 indicate models terms are significant. In this case, A and B are significant model terms while the AB interaction is not a significant factor. Values greater than 0.1000 indicate the model terms are not significant.

Table 6: Analysis of Variance for Particle Diameter



Transformed: Inverse

ANOVA for selected factorial model
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.42	3	0.14	52.07	< 0.0001	Significant
A-Speed	0.33	1	0.33	124.29	< 0.0001	
B-Feed	0.063	1	0.063	23.57	< 0.0001	
AB-Interaction	0.016	1	0.016	0.0184	0.0184	
Pure Error	0.14	52	2.66E-03			
Cor Total	0.55	55				

Std. Dev.	0.052	**R-Squared**	0.7503
Mean	1.35	**Adj R-Squared**	0.7358
C.V %	3.81	**Pred R-Squared**	0.71101
PRESS	0.16	**Adeq Precision**	16.351

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	1.35	1	7.04E-03	1.34	1.37	
A-Speed	-0.079	1	7.04E-03	-0.093	-0.064	1.04
B-Feed	0.034	1	7.04E-03	0.020	0.048	1.01
AB-Interaction	-0.017	1	7.04E-03	-3.02E-03	1.04	1.04

Final Equation in Terms of Coded Factors
1/diameter = +1.40 - (0.038 * Speed) + (0.036 * Feed) - (0.020 * Speed * Feed)

Included in table 6 are the R-Squared, adj R-Squared, pred R-squared and adeq precision. The R-squared value is an indicator to whether the regression model is a good predictor. For the concentration's model, the R-squared value is 0.7503 or 75.03%. This percentage can predict 75.03% of the variation of data whereas there is 24.97% of variance that cannot be explained. Much larger values of R-squared are preferred as it predicts less variability of the data. The pred R-squared of 0.7101 is in reasonable agreement with the adj R-squared of 0.7358. Finally, the adeq precision measures the signal to noise to ratio. A ratio greater than 4 is desirable. The ratio of 16.351 indicates an adequate signal. The final equation in terms of coded factors is:

$$1/(diameter) = 1.35 - (0.079 \times Speed) + (0.034 \times Feed) - (0.017 \times Speed \times Feed)$$

The R-squared for this analysis is 75.03% leaving 24.97% of variance unaccountable. The reasons for this variance can be accounted towards the same reasons for the variance in concentration's ANOVA results.

Frequency Distribution

Histogram graphs were used to show the frequency of the concentration levels and particle diameter. Figure 10 displays the histogram for the concentration levels. The frequency is grouped between 4-7, 7-8, 8-9, 9-10 and greater than 10 mg/m³. Ten data points grouped between 4-7 mg/m³ accounting for 17.86% of the data. Eight data points are each grouped in the 7-8 and 8-9 mg/m³ range and allotting for 14.29% in both bins. Fifteen data points are in the 9-10 mg/m³ range and comprising 26.79% of the data. Finally, 15 points are greater than 10 mg/m³. This also accounted for 26.79% of the data points.

Figure 11 displays the histogram for the distribution of the particle diameter size. The frequency is grouped between 0.6 - 0.65, 0.65 - 0.70, 0.70 - 0.75, 0.75 - 0.8 and greater than 0.8

µm. Three data points are grouped between 0.6 - 0.65 µm accounting for 5% of the data. Eight data points are each grouped in the 0.65 - 0.70 µm range and allotting for 14% of the bins. Thirty-one data points are in the 0.70 – 0.75 µm range and comprising 36% of the data. Seventeen points are in the 0.75 – 0.80 range and making up 30% of the data. Finally, 8 points were greater than 0.80 µm. This also accounted for 14% of the data points.

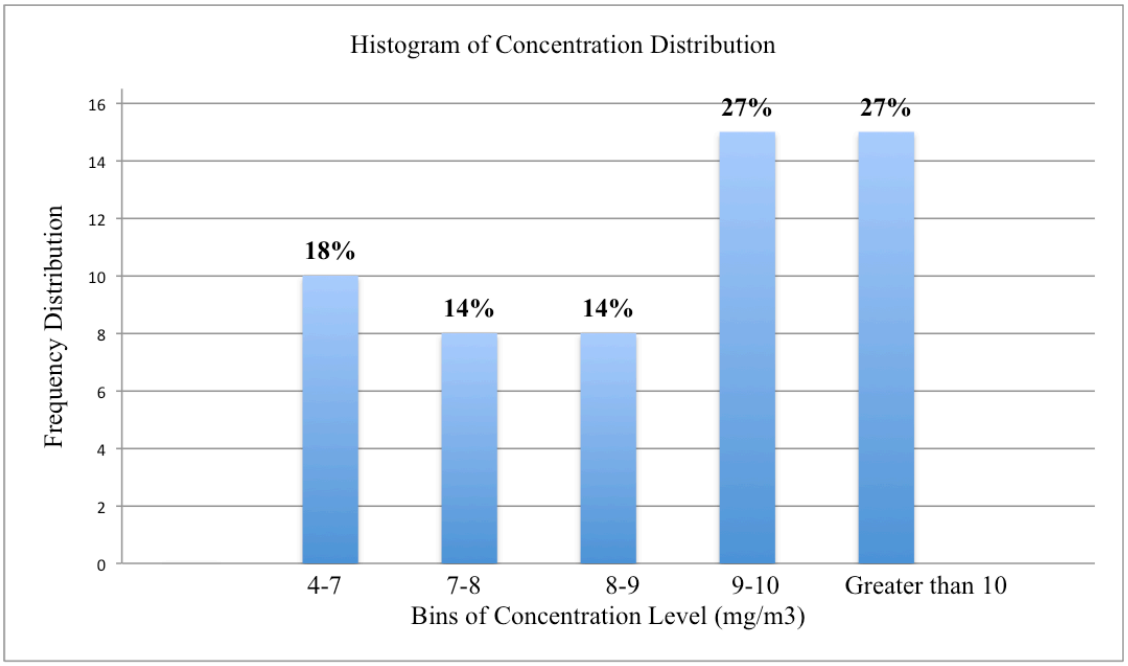


Figure 10: Frequency Distribution of Concentration Levels

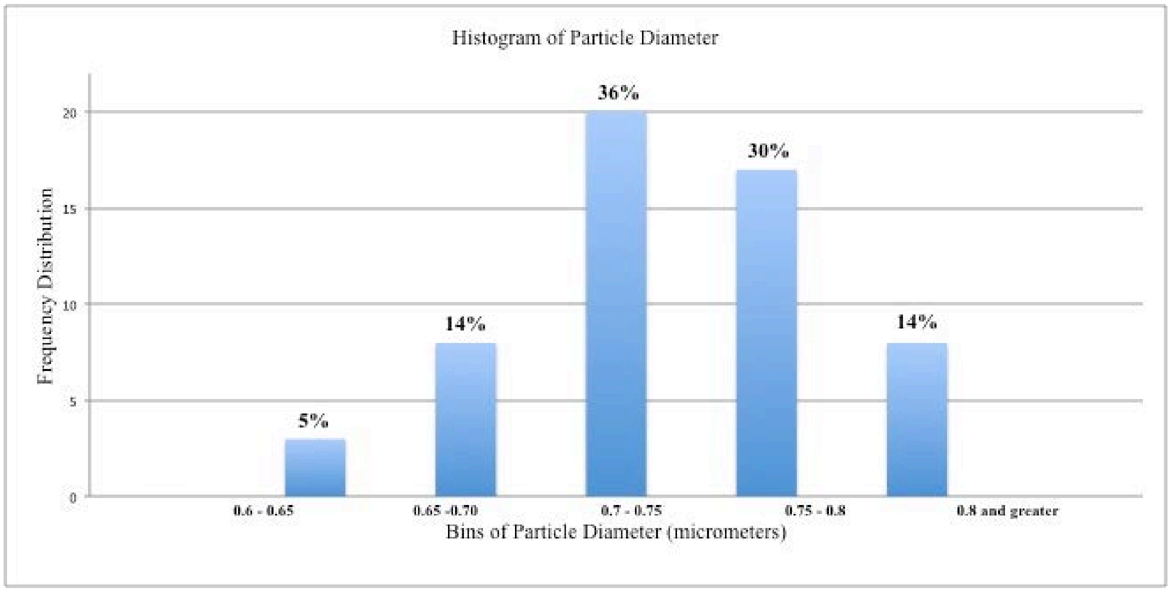


Figure 11: Frequency Distribution of Particle Diameter

Correlation Analysis

Correlation analysis is used to evaluate the strength between two variables. The correlation, r, can range from -1 to +1. A value of -1 shows a negative correlation. When one variable increases the other variable decreases. A value of zero means that there is not a correlation between the variable, and a +1 value shows a strong positive correlation. When one variable increases the other variable also increases. Figure 12 shows the correlation of concentration levels and particle diameters throughout all four combinations. The r-value associated with this plot is 0.08. This indicates there is not a strong correlation among the variables. This low value can be contributed to the chip formation that was found on three of the four combinations. More thorough explanations for this result are found in chapter V, Conclusions and Results. Correlation analysis is computed for each individual combination in the following sections. The chip formation for each treatment is also described in those sections.

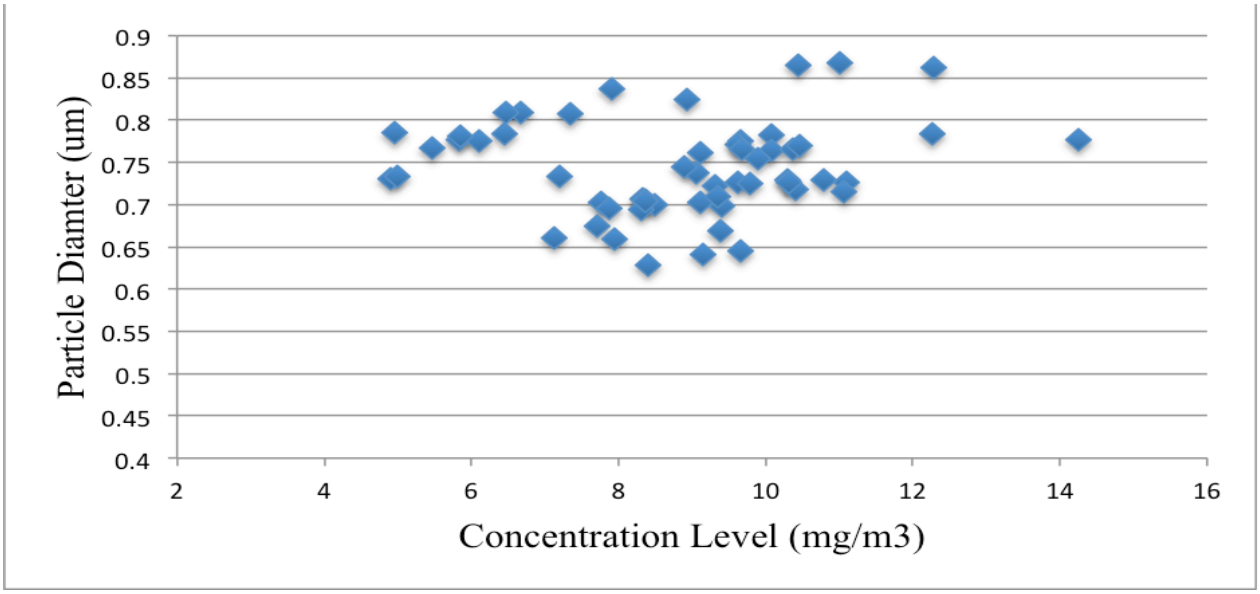


Figure 12: Correlation Analysis of Concentration Levels and Particle Diameter

Individual Speed and Feed Rate Analysis

The following sections group the four combinations of speed and feed rates into individual subcategories. Within those categories, graphs displaying the data points for averages of every thirty holes (one workpiece) of concentration levels and particle diameters are displayed. The plots show the data's trend throughout the drilling cycle. The lowest and high points recorded as well as the average concentrations or particle diameters are discussed. Additionally, correlation analysis is computed for the combinations.

Speed: 120 SFM Feed: 0.004 IPR

Figure 13 (a) shows the data trend of concentration levels collected at 120 SFM and 0.004 IPR. Each data point represents 30 drilled holes or one work piece. Tool failure occurred on the 280th hole. The average concentration was 5.77 mg/m³. The smallest data point was 4.89 mg/m³ while the largest point recorded was 6.67 mg/m³. Figure 13 (b) shows the data trend of particle diameter. The average particle diameter was 0.775 µm. The smallest data point was 0.73 µm and the largest point recorded was 0.81 µm. During the drilling of this combination, there was not any chip formation attached to the drill. This was the cleanest drilling of all four combinations.

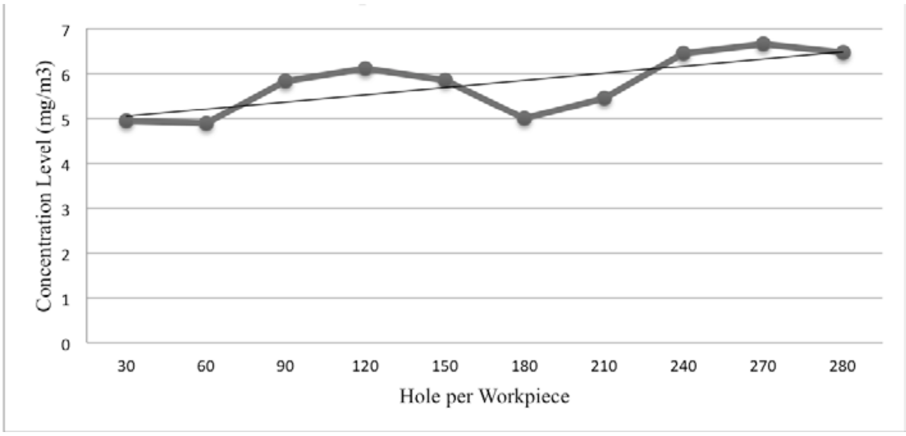


Figure 13 (a): Concentration levels at Speed 120 SFM and Feed 0.004 IPR

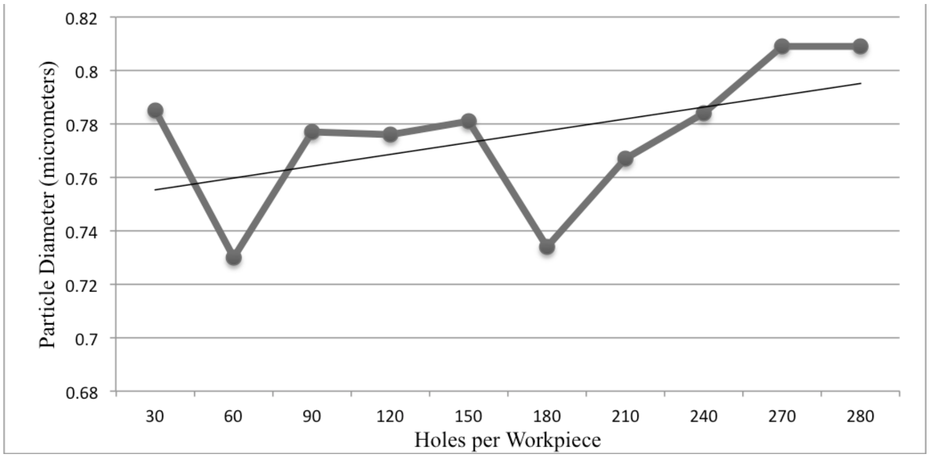


Figure 13 (b): Particle Diameter at Speed 120 SFM and Feed 0.004 IPR

A correlation analysis was also performed on this combination. The r-value associated with this data is 0.79. This represents a strong correlation between the variables. Figure 13 (c) shows the scatter plot of the correlation.

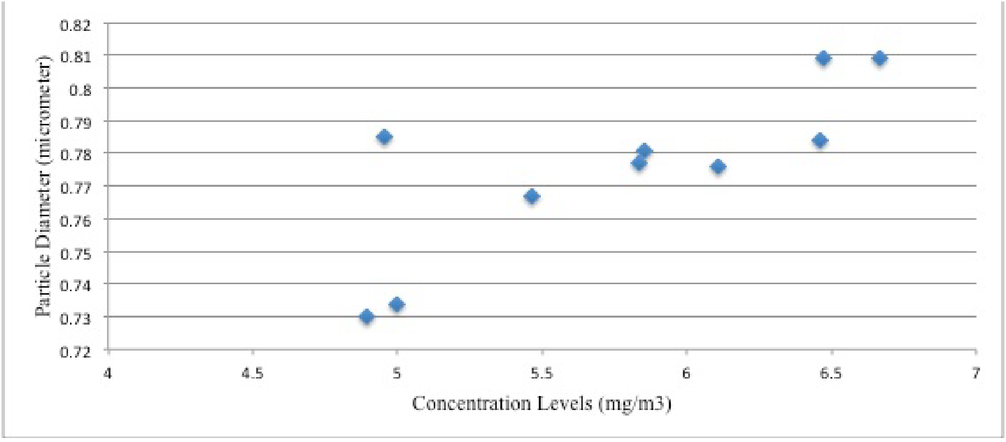


Figure 13: Correlation Analysis of Speed 120 SFM and Feed of 0.004 IPR

Speed: 120 SFM Feed: 0.003 IPR

A total of 470 points are depicted in Figure 14 (a). The tool originally failed after the 560th hole. 90 holes were removed because the DataRam 4 malfunctioned during this run. The non-electrostatic tubing disconnected from the machine three times and produced false readings. The readings were identified because of their extremely low concentration and particle diameter values. Figure 14 (a) shows the concentration levels at a speed of 120 SFM and a reed rate of 0.003 IPR. The lowest point of the graph is at 7.34 mg/m³ and the highest point is at 14.27 mg/m³. The average concentration is 10.21 mg/m³.

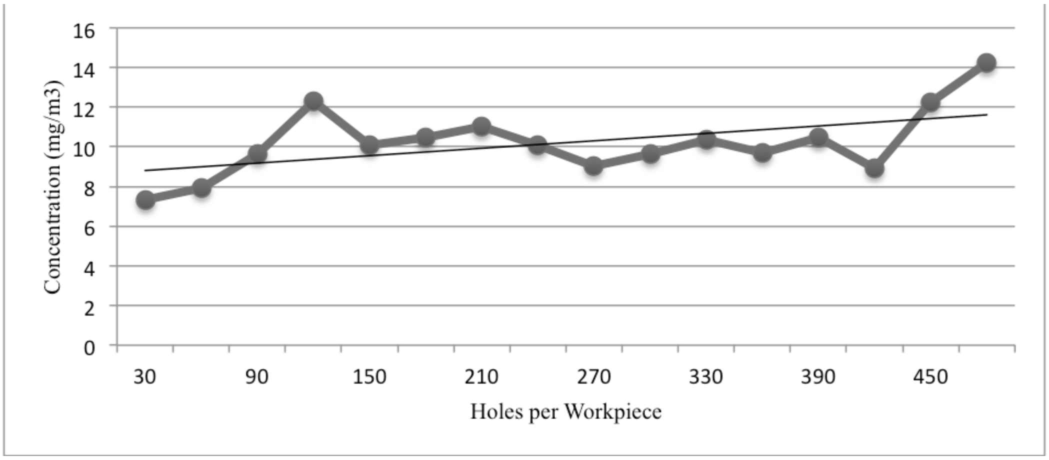


Figure 14 (a): Concentration Levels at 120 SFM and Feed of 0.003 IPR

Figure 14 (b) shows the particle diameter collected during this run. The same amount of holes are removed for the particle diameter analysis. The lowest value within the graph is at 0.764 µm while the highest point recorded is at 0.868 µm. The particle diameter's average is 0.797 µm. This combination produced excessive chip formation on the tool during the entire run of the combination.

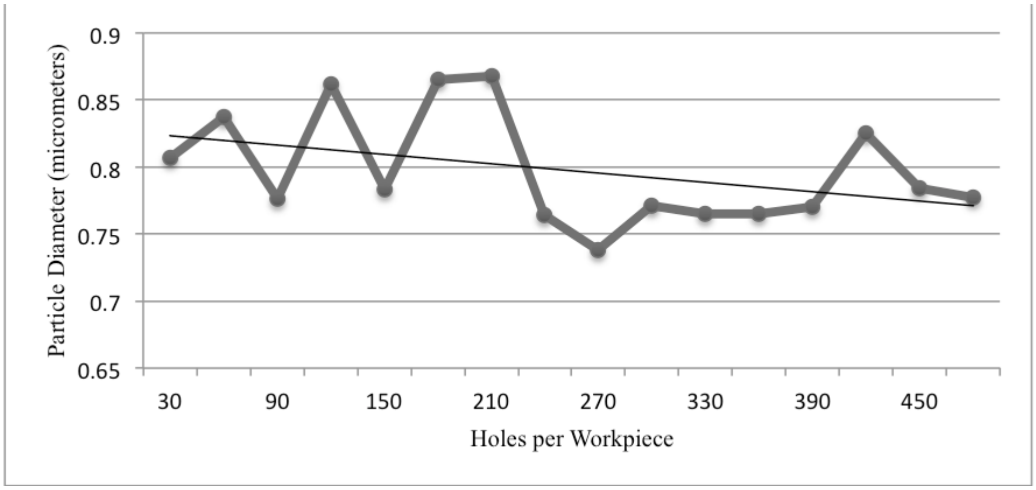


Figure 14 (b): Particle Diameter at Speed 120 SFM and Feed 0.003 IPR

The correlation analysis plot for this combination is shown in figure 14 (c). The r-value is 0.05. This indicates that the variables do not show a correlation between one another.

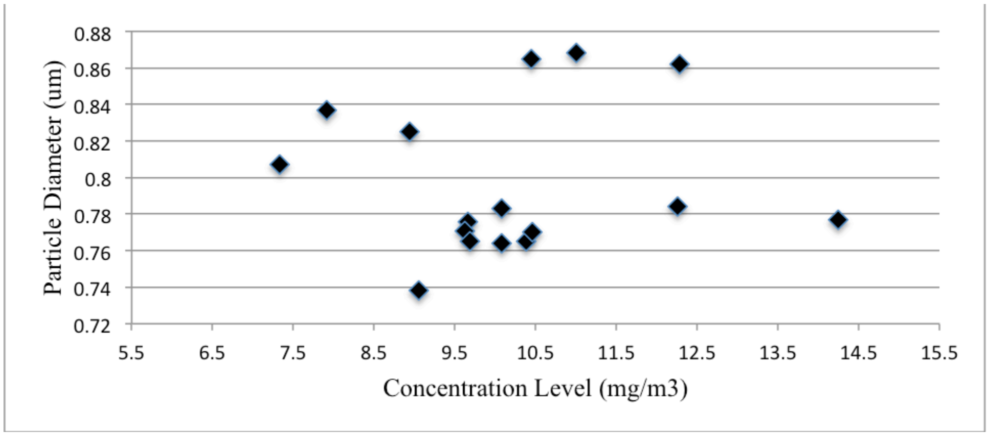


Figure 14 (c): Correlation Analysis at Speed 120 SFM and Feed 0.003 IPR

Speed: 100 SFM Feed: 0.004 IPR

Figure 15 (a) displays the graph obtained for concentration levels under a speed of 100 SFM and a feed rate of 0.004 IPR. The tool failed on the 390th hole. The lowest point recorded is 7.13 mg/m³ while the highest point recorded is 9.65 mg/m³. The average concentration is 8.34 mg/m³. Figure 15 (b) plots the particle diameter during the drilling. The lowest point recorded is 0.629 µm. The highest point recorded was 0.707 µm. The average particle diameter is 0.676 µm. During the drilling for this combination, the chip formation was intermitant. The greatest amount of formation was found at the begining of the run. The chip formation tended to decrease towards the end of the tool's life.

Figure 15 (c) displays the correlation plot for this combination. The r-value for the analysis is -0.32. This value establishes that there is not a correlation between the two variables.

Figure 15 (a): Concentration Levels at 100 SFM and Feed of 0.004 IPR

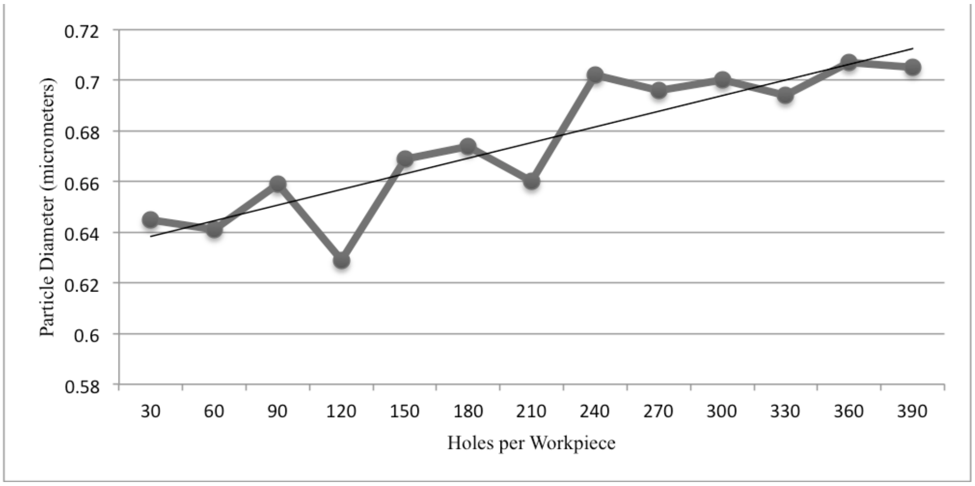


Figure 15 (b): Particle Diameter at Speed 100 SFM and Feed 0.004 IPR

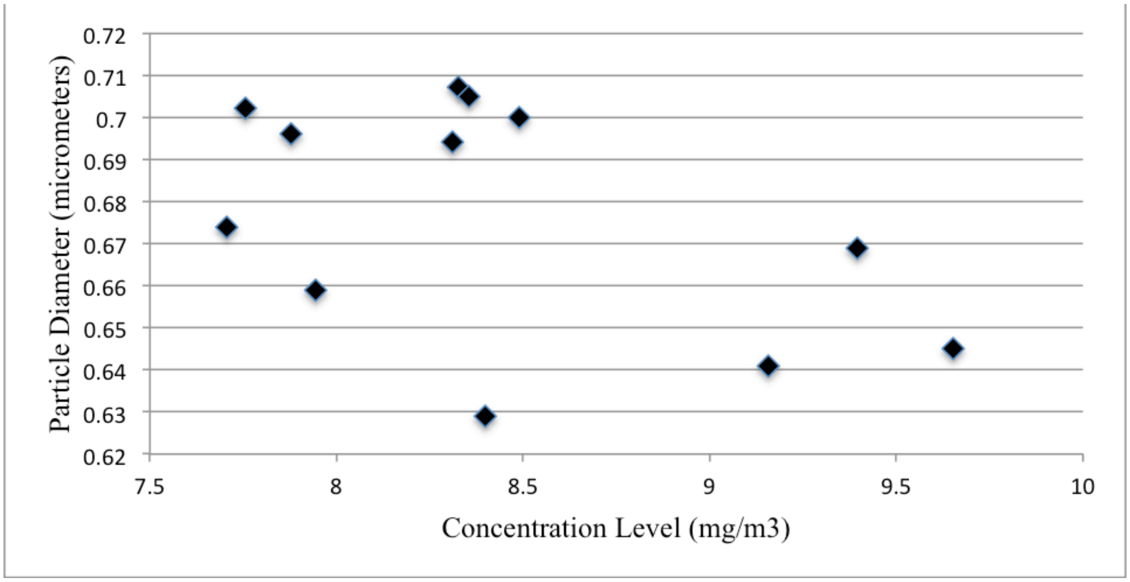


Figure 15 (c): Correlation Analysis at Speed 100 SFM and Feed 0.004 IPR

Speed: 100 SFM Feed: 0.003 IPR

Figure 16 (a) displays the concentration trend under a speed of 100 SFM and a feed rate of 0.003 IPR. On this combination, the tool failed on the 490th hole. The lowest point recorded is 7.19 mg/m³ while the highest point recorded is 11.09 mg/m³. The average concentration throughout the process is 9.64 mg/m³.

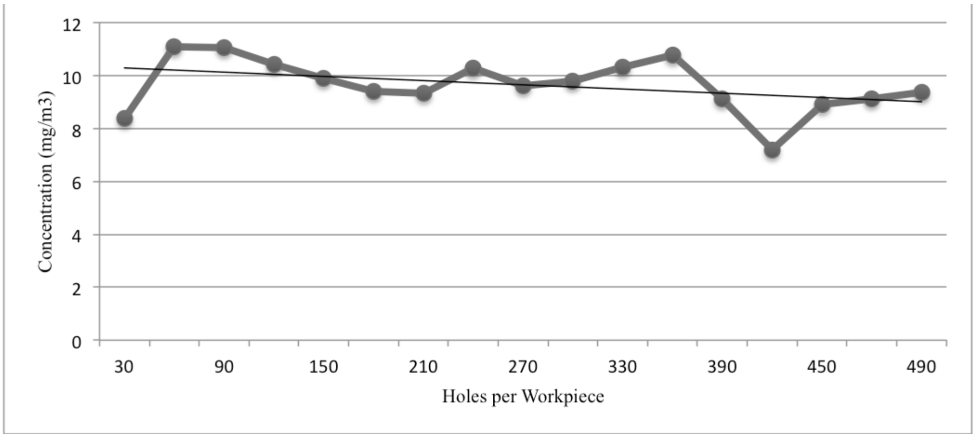


Figure 16 (a): Concentration Levels at 100 SFM and Feed of 0.003 IPR

Figure 16 (b) shows the particle diameter throughout the drilling process. Under these speed and feed rates, the lowest point recorded is 0.699 µm. The highest point recorded is 0.744 µm. The average particle diameter through this run is 0.725 µm. The chip formation for this combination was also excessive; however, not as high as the other combination with a low feed rate.

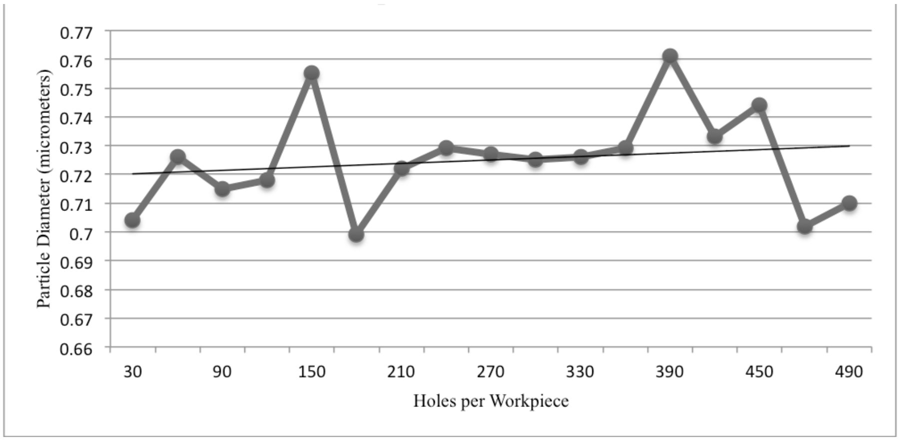


Figure 16 (b): Particle Diameter at Speed 100 SFM and Feed 0.003 IPR

The correlation analysis is shown in Figure 16 (c). The r-value for this analysis is -0.02. This value is very close to zero and does not show a correlation between the two variables.

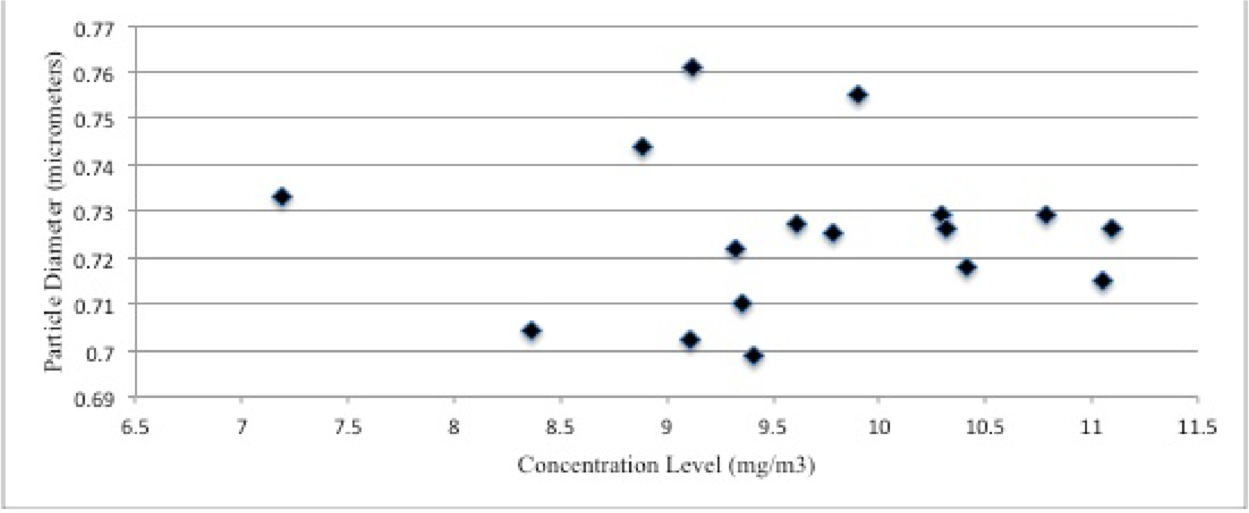


Figure 16 (c): Correlation Analysis at 100 SFM and Feed of 0.003 IPR

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This research is conducted to evaluate the mist produced while drilling 1018 steel under minimum quantity lubrication. Speed rates of (120 and 100 SFM) and feed rates of (0.004 and 0.003 IPR) were chosen as the drilling parameters creating four combinations. Vegetable based Accu-lube 6000 was supplied through an external nozzle under minimum quantity lubrication. The results were then compared to current OSHA and NIOSH standards. The results obtained may be applied to the same class of steels; however, this would have to be investigated. The parameters chosen for this study may or may not be applied to different materials. A summary for the results follows.

ANOVA results for concentration levels proved that the factors (speed, feed rate) and their interactions were significant. The model can predict 78.15% of the variation of data. ANOVA results for the particle diameter indicate that the speed and feed rates are significant factors whereas their interaction is not. This model can predict 75.03% of the data variance. These results rejects the null hypothesis, “Speed and feed rates do not have a significant effect on the particle size and concentration levels of mist produced during MQL drilling.”

OSHA and NIOSH recommended that mist concentrations produced should be regulated to 5 mg/m^3 or 0.5 mg/m^3, respectively, per 8 hour work day for a 40 hour work week. All four combinations produced concentration levels greater than the recommended levels. 18% of the data is between 5 to 7 mg/m^3. 14% of the data produced is in the 7 to 8 mg/m^3 range and 14% is also in the 8 to 9 mg/m^3 range. 27% of the data accounted for concentration levels between 9 to 10 mg/m^3, and 27% of the data comprised concentration levels greater than 10 mg/m^3.

Under 120 SFM and 0.004 IPR, the tool failed on hole 280th hole. The lowest concentration recorded is 4.89 mg/m³ while the largest point recorded is 6.67 mg/m³. The average concentration is 5.77 mg/m³. The data displayed an upward trend in concentration levels. For the particle diameter, the average diameter is 0.775 μm. The smallest data point is 0.73 μm and the largest point recorded is 0.81 μm. The data also displayed an upward trend in particle diameter. There is a strong correlation between the two variables.

The tool failed on the 560th hole for the combination of 120 SFM and 0.003 IPR. The lowest point for of the graph of concentration is at 7.34 mg/m³, and the highest point is at 14.27 mg/m³. The average concentration is 10.21 mg/m³. The concentraion has a downward trend during this run. For the particle diameter, the lowest point recorded is 0.699 μm and the highest point recorded is 0.744 μm. The average particle diameter through this run is 0.725 μm. The data displayed an upward trend in diameter. There is not a correlation between the variables for this combination.

The combination of 100 SFM and 0.004 IPR produced 390 holes before the tool failed. The lowest point recorded for concentration is 7.13 mg/m³ while the highest point recorded is 9.65 mg/m³. The average concentration is 8.34 mg/m³. The concentration displayed a downward trend. For particle size, lowest point recorded is 0.629 μm. The highest point recorded is 0.707 μm. The average particle diameter is 0.676 μm. The particle diameter exhibited an upward trend in particle size. Under this combination, there is not a correlation between the variables.

The last combiation was 100 SFM and 0.003 IPR. The tool failed on the 490th hole. The lowest point recorded was 7.19 mg/m³ while the highest point recorded was 11.09 mg/m³. The average concentration throughout the process was 9.64 mg/m³. The data for the concentration displayed a downward trend in levels. Under these speed and feed rates, the lowest point recorded is 0.699 µm. The highest point recorded is 0.744 µm. The average particle diameter through this run was 0.725 µm. The data diplayed an upward trend in particle size. Also, there is not a correlation between the two variables. The following conclusions can contribute to the results obtained from the experiement.

The lowest concentration levels produced were under the combination of 120 SFM and 0.004 IPR. There was a very clean run in regards to chip formation. The other three combinations had intermediate to excessive chip formation. This could result in the high concentration levels and varying particle size as well as the lack of a correlation relationship. The MQL was supplied externally six inches away from the drill bit. It is not understood how the particles react and disperse when they come into contact with the excessive chip formation. Additionally, mist easily escapes the drilling chamber when the door was opened to clean the drill, thus not keeping a consistent concentration level. The door remained closed on the 120 SFM and 0.004 IPR resulting in a more uniform concentration pattern.

It is recommended that future studies investigate the effects of faster speed and feeds rates. This could eliminate the excessive chip formation and the need to clean the tool. This would in turn enable the doors to remained closed the full run and keep a consistent mist level. Using a shorter collecting tube and eliminating its curvature could also improve the results. If possible, placing the DataRam 4 directly into an enclosure should yield better results.

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