EFFECTS OF MINIMUM QUANTITY LUBRICATION IN DRILLING 1018 STEEL

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A common goal for industrial manufacturers is to create a safer working environment and reduce production costs. One common method to achieve this goal is to drastically reduce cutting fluid use in machining. Recent advances in machining technologies have made it possible to perform machining with minimum-quantity lubrication (MQL). Drilling takes a key position in the realization of MQL machining. In this study the effects of using MQL in drilling AISI 1018 steel with HSS tools using a vegetable based lubricant were investigated. A full factorial experiment was conducted and regression models were generated for both surface finish and hole size. Lower surface roughness and higher tool life were observed in the lowest speed and feed rate combination.

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I

INTRODUCTION

Minimum quantity lubrication (MQL) technique consists of misting or atomizing a very small quantity of lubricant, typically of a flow rate of 50 to 500 ml/hour, in an air flow directed towards the cutting zone (Autret & Liang, 2003). The lubricant is sprayed by means of an external supply system which can be one or more nozzles. The amount of coolant used in MQL is about 3-4 order magnitude lower than the amount commonly used in flood cooling condition. For example, in flood cooling up to 10 liters of fluid can be dispensed per minute.

MQL is also known as “microlubrication” (MaClure, Adams, Gugger & Gressel, 2007), “near-dry machining” (Klocke & Eisenblatter, 1997) or “spatter lubrication”. MQL is the latest technique of delivering metal cutting fluid to the point of cut or tool and workpiece interaction. This technique may be a continuation of the old flood cooling method of applying the lubricant on work and tool interface. But in this technology a little fluid, when properly selected and applied, can make a substantial difference in how effectively a tool performs.

In regular machining operations that use a flood coolant supply, cutting fluids have been selected mainly on the basis of their characteristics, i.e., their cutting performance. In MQL however, secondary characteristics of a lubricant are important, such as their safety properties, (environment pollution and human contact), biodegrability, oxidation and storage stability. This is important because the lubricant must be compatible with the environment and resistant to long term usage caused by low consumption (Wakabayashi, Inasaki & Suda, 2006). In MQL, lubrication is obtained via the lubricant, while a minimum cooling action is achieved by the pressurized air that reaches the cutting surface. When MQL is applied to the tool rake, tool life is generally no different from a dry condition, but MQL applied to the tool flank can increase tool life (Attanasio, Gelfi, Giardini & Remino, 2006). In machining, excessive heat is generated; using flood coolant will induce thermal shock causing tool failure. Hence, MQL will promote tool life as induced thermal shock will be less as compared to flood coolant. MQL helps to increase the workpiece surface integrity in situations of high tool pressure (Attanasio, Gelfi, Giardini & Remino, 2006).

Types of MQL Systems

Hardware systems for MQL mist application have been developed. In mass production manufacturing, the mist is usually delivered through the spindle and tool, rather than through an external mode (Filipovic & Stephenson, 2006).

There are two basic types of MQL systems: external spray MQL and through-tool MQL. The external spray MQL system consists of a coolant tank or reservoir which is connected with tubes fitted with one or more nozzles.

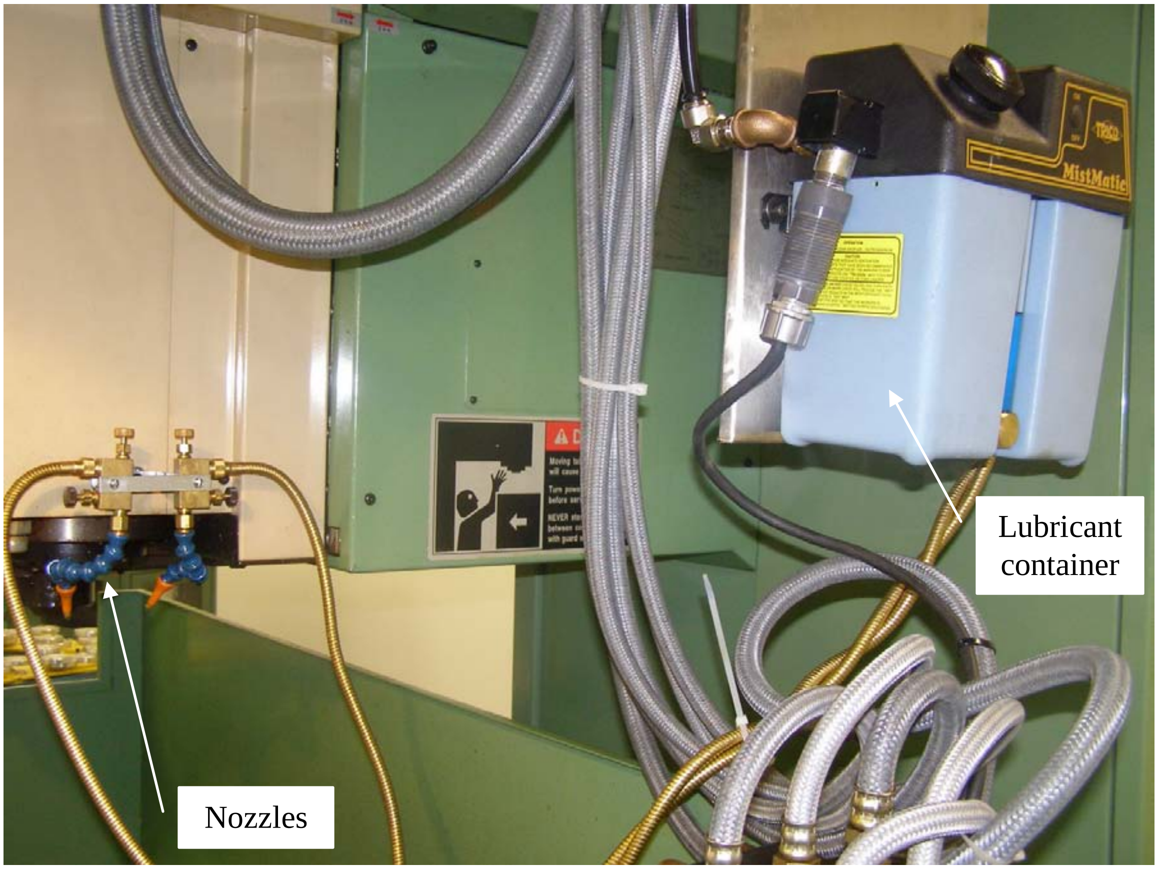

Figure 1: External Spray MQL System

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Figure 1 shows an external spray MQL system. This MQL system can be assembled near the machine or on the machine as per the operator's convenience. It is a pump operated system which allows the user a wide range of coolant delivery. The system has independently adjustable air and coolant flow which help for balancing coolant delivery. The system is inexpensive, portable and is suited for almost all machining operations.

There are two basic types of through-tool MQL systems, based on a method of creating an air-oil mist. The first is the external mixing or one-channel systems. In this type the oil and air are mixed externally, and piped through the spindle and tool to the cutting zone.

The advantages of such systems are they are simple and inexpensive; they are suited to retrofitting to the existing machine with high-pressure through the tool coolant capability. They are easy to service since no critical parts are located inside the spindle. The disadvantage is the oil-mist is subjected to dispersion and separation during its travel from the nozzle. To minimize oil drop outs, a mist of relatively fine particles is used, which often limits the amount of lubrication that can be supplied to the cutting zone and consequently affects the performance of the cutting process.

The second technique is the internal mixing or two channel systems. Most commonly in a two channel system, two parallel tubes are routed through the spindle to bring oil and air to an external mixing device near the tool holder where the mist is created.

This approach requires a specially designed spindle. The standard high pressure coolant spindle can be modified by adding a separate tube external to the spindle to deliver oil to the spindle nose. Such systems have less dispersion and dropouts and can deliver mist with larger droplet sizes than external mixing devices. Such systems have less lag time when changing tools between cuts or oil delivery rate during a cut. However, the systems are more difficult to repair since critical parts are located inside the spindle (Filipovic & Stephenson, 2006).

Lubricant composition in MQL varies between 0.2 and 500 ml/hr. Chips produced are nearly dry. In MQL, the fluid does not recirculate through the lubrication system. But in a flood coolant lubrication system, same coolant is recirculated through the system, filtered and used again. Hence, in MQL there is no filtering cost. Since very good lubrication properties are required in MQL, vegetable oil or synthetic easter oil are used instead of mineral oil. Air pressure is roughly 5 bars. Pressure should be monitored consistently, so a regulating device is incorporated in the setup (Filipovic & Stephenson, 2006). MQL is a type of consumption lubrication. The lubrication applied is almost evaporated at the point of application. Because of this evaporation and through compressed air streams, the workpiece is additionally cooled. The remaining heat is dissipated via the tool and metal chip (www.schunk-usa.com, Topic of the Month, 2007). The chips, workpiece and tool stay almost dry if the system is ideally adjusted. The MQL concept can be used where friction needs to be minimized by using lubricants. MQL is ideal for drilling, deep hole drilling, tapping, milling and turning. Lubricant consumption and value differentiate depending on the cutting performance, material, tool design and/or volume of chips. The average consumption of coolant in MQL was found to be approximately 5 to 30 ml/hr. Depending on environmental condition MQL can lead to minimum up to far-reaching changes of the machine and tool. It is important to ensure a proper removal of metal chips from the machine as well as an efficient extradition of air-oil mixture (aerosol) steams. For high performance cutting, specially designed machines, tools and tool holding systems for applications with MQL are used (www.schunk-usa.com, Topic of the Month, 2007).

CHAPTER II

LITERATURE REVIEW

The concept of minimum quantity lubrication (MQL) was suggested a decade ago as a mean for addressing the issues of environmental intrusiveness and occupational hazard associated with airborne cutting fluid particles on the shop floor. The minimization of cutting fluid leads to economical benefits by saving lubricant costs. The work piece, tool and machine cleaning time are reduced (Autret & Liang, 2003).

According to a survey conducted by the European Automobile Industry, the cost incurred on lubricants comprises nearly 20% of the total manufacturing cost (Brockhoff & Walter, 1998). The cost of the cutting tool is only 7.5% of the total cost. Hence, the cooling cost is significantly higher (Autret & Liang, 2003). As a result, the need to decrease cutting fluid consumption is strong. Considering the adverse effects caused by the emission of fumes and aerosol particles to the environment due to lubrication, a number of programs have been launched relating to the destruction of the ozone layer and global warming. For example, in Japan, new regulations include an environmental impact assessment law, a pollutant release and transfer register (PRTR), and special measures against dioxins.

According to the U.S. Occupational Safety and Health Administration (OSHA) (Aronson, 1995) and the U.S. National Institute for Occupational Safety and Health (NIOSH) the permissible exposure level (PEL) for metal working fluid aerosol concentration is 5 mg/m^3 and 0.5 mg/m^3 respectively (NIOSH Publication, 1998). The oil mist level in U.S. automotive parts manufacturing facilities has been estimated to be 20-90 mg/m^3 with the use of conventional lubrication by flood coolant (Bennett & Bennett, 1985). The exposure of such amounts of metal working fluid can cause adverse health effects and safety issues, including toxicity, dermatitis, respiratory disorders and cancer. When considering large system quality, the recirculating coolant in cleanliness and concentration overtime results in variation of tool wear and affects part finish and dimensions. In flood coolant, the trenches and hard piping for a recirculating coolant system hinders the rapid reconfiguration of equipment. In conventional flood coolant, wet chips are produced, that have to be dried before remelting, which incurs cost. But MQL produces dry chips, so the cost of drying chips is reduced (Filipovic & Stephenson, 2006).

In 1992, Horkos Corporation developed the semi dry machining of cast iron parts by combining the outside method and the outside nozzle. Research was carried out for the application to difficult machining. Problems were overcome by improving equipment. Semi dry machining was developed for minimum quantity lubrication (www.horkos.co.jp). Apart from considering different areas and processes for MQL, holes processing has a more significant impact from MQL. Initially, hole processing of aluminum had problems of adhesion and had been considered difficult for dry machining. A number of hole processing processes were realized by MQL: drilling, deep drilling, tapping, fluteless tapping, burnishing drilling, gun drilling and gun reaming (www.horkos.co.jp). Achievements of the Horkos Corporation were praised. They received the Onizuka Invention Service Award in the 23rd Invention Award, and the

Secretary's Award from the Science and Technology Agency in the 19th Science and Technology Promotion Service Award in Japan (Horkos Corp, 2008).

When MQL was developed in 1992, only cast iron parts were made with external mixing and an outside nozzle (www.horkos.co.jp) & (JIMTOF & IMTS). In 1993, aluminum parts were being worked by application of MQL (www.horkos.co.jp) & (EMO, 2007). In 1994, aluminum and cast iron parts with vacuum systems were introduced. The first application of MQL mixing inside the spindle with a vacuum system in a mass production plant of machining aluminum was in 1996 (www.horkos.co.jp) & (JIMTOF & IMTS). In 1998, various chip removal systems for MQL were developed such as the combination of the gravity drop method and the vacuum method (suction method) (www.horkos.co.jp) & (EMO). MQL generally uses vegetable oil or ester oil as the cutting fluid. These high- performing oils have excellent lubrication and natural dissolving properties. Furthermore, they are environmentally friendly (www.horkos.co.jp).

In the initial stages of MQL development low quantities (such as 200 – 300 ml/hr) of lubricants were used in machining (Machado & Wallbank, 1997). These low quantities were applied in fast flowing air streams. It was proved that MQL was more efficient when low cutting speeds and high feed rates are used (i.e. cutting speed of 200 m/min and feed rate of 0.15 mm/rev) (Machado & Wallbank, 1997). Cutting and feed force are reduced when machining a medium carbon steel under low cutting speed and high feed rates. The mixture of air-water or air-soluble oil reduces the amplitude of oscillation of the force component. For producing these two mixtures a venturi was designed to mix compressed air with small quantities of a liquid lubricant (water and soluble oil). This venturi ends with a nozzle that directs the mixture onto the rake face of the tool. A pressure regulator and valve were placed between the air compressor and venturi. With the valve shut the air pressure was set to 2.3 bars (34 psi). With the valve fully open the pressure dropped to 2 bars (29 psi). For water, the mean flow rate was 293.98 ml h-1 and for soluble oil (Cimstar MB603, manufactured by Cimcool, at the concentration of 5%) the mean flow rate was 195.76 ml h-1 (Machado & Wallbank, 1997). A P40 uncoated steel cutting grade cemented carbide insert (S6) having SNMG 120404 ISO specification and a CSSNR 3225 M12 tool holder, manufactured by Sandvik were used in all tests. AISI 1040 normalized forged steel bars were used as work materials. The machine tool was a Torshalla S250 CNC lathe with 30 kW of power. Due to the application of mist, an effective exhaust extraction system was required. Cutting and feed force are reduced when a lubricant is applied when machining a medium carbon steel under low cutting speed and high feed rates. Mixtures of air + water or air + soluble oil reduce the amplitude of oscillation of the forced component. The influence of the lubrication is noticeable for low cutting speed and high feed rates, with mixtures of air + water and air + soluble oil outperforming other lubricant conditions tested. The results with air + water combinations were found to be encouraging. This result avoids pollution of the environment and related problems of health and safety, and drastically reduces lubricant costs, although it may cause problems of corrosion (Machado & Wallbank, 1997).

Experiments of MQL were conducted using diamond-coated and uncoated tools (Braga, Diniz & Miranda, 2002). The coating improvement of carbide tools and the chemical and mechanical properties of the tool material has caused an increase in tool working life in machining processes. When a diamond coated tool was used, the result was an irregular surface wear of the drill and a decrease in hole quality, compared with the uncoated K10 drill (Braga, Diniz & Miranda, 2002). The experiments were carried out in a rigid CNC machining center with 22 kW of power and maximum rotation of 12,000 rpm. Drills used in the experiments were made of uncoated ISO K10 carbide (NS kind), according to DIN 338 and diamond coated carbide. The K10 carbide drills had an average diameter of 9.986 mm and the diamond drills had an average diameter of 9.992 mm (both with tolerance ISO h8). The workpieces were made of aluminum–silicon alloy with 7% silicon (SAE 323) (Braga, Diniz & Miranda, 2002). The conclusion is the process performance (in terms of forces, tool wear and quality of holes), when using MQL, was similar to that obtained when using a high amount of soluble oil, with both, coated and uncoated K10 drills. These conclusions prove the potential of using this technique in the drilling process for aluminum-silicon alloys. In this experiment two cooling systems were used. The first was a mixture of air and oil (MQL): 10 ml/h of mineral oil was pulverized in an air flow of 72 m^3/h and 4.5 bar of pressure. The second system was a flood of soluble oil (1 part oil to 25 parts water) with a flow rate of 2.4 m^3/h. For both systems, the condition and tools, a cutting speed of 300 m/min and feed of 0.1 mm/rev were used (Braga, Diniz & Miranda, 2002). It was observed that the value of flank was similar when using an uncoated K10 drill, (after 612 holes the difference in flank wear was less than 0.050mm). The values of power consumed for the two drill materials, when using MQL were similar at 0.81 and 0.79 Kw for diamond coated and uncoated tools respectively at 20 m feed length. Feed force represented almost the same rate of increase with feed length for all experiments regardless of the cutting condition and tool material. The uncoated K10 drill presented the best results related to the average diameter of the hole. For the diamond coated drill, results are better when MQL was used. For uncoated drills results are similar for both cooling systems (Braga, Diniz & Miranda, 2002).

A study in 2006 analyzed the temperature during drilling of the titanium alloy Ti6Al4V, employing class K10 carbide drills with and without hard coating (TiAlN, CrCN or TiCN) (Zeilman & Weingaertner, 2006). Plates of alpha–beta Ti6Al4V alloy (Tensile Strength $R_m = 970$ N/mm^2 and Hardness 300 BHN) with dimensions of 200mm×150mm×20mm were prepared for these drilling experiments. Holes were drilled with 8.5mm diameter drills using a vertical machining center. Cutting fluids were applied with a pressure of 3.5 bars. Two types of drills (Type 125 and Type 105) were used in these experiments, all were of carbide class type K10, micro grains, containing 9.5% of cobalt, with a clearance angle of 6°, diameter of 8.5mm and three edges (Type 125 drill had internal cooling hole and Type 105 drill for cooling with external nozzle). To verify piece temperature at particular depths, special plates were made for insertion of type K thermocouple. In the experiments cutting speeds of 10–50 m/min and feed of 0.1–0.2 mm were used (Zeilman & Weingaertner, 2006). The lubrication was applied either with an external nozzle or internally through the drill. It was concluded that the measured temperature with application of MQL internally through the tool were 50% smaller than those obtained with MQL applied with an external nozzle. When MQL was applied with an external nozzle the greatest temperature was measured in a piece drilled with an uncoated drill. For different coatings there was no significant variation in temperature (Zeilman & Weingaertner, 2006).

Deep hole drilling with a depth of ten times the hole diameter is used in the automobile industry. In the initial development of deep hole drilling using MQL, a depth of 5 times the diameter showed that vibration drilling is effective to a depth of 5 times the diameter (Hidetaka and Hideyo, 1996). In this study, drilling a depth of 10 times the diameter was done. A drill of 3mm diameter was used with an overall length of 71mm and point angle of 118°. The cutting condition for both the vibration drilling and conventional drilling were the same. Work material used was SS400. Cutting speed was based on 1700 rev/min. Feed rate was 0.008, 0.16, 0.20 and 0.24 mm/rev. Cutting fluid used was Neat oil type: JIS (2-1) (Hidetaka and Hideyo, 1996). When deep holes were drilled the contact resistance between the chip edges and hole walls increases and produces chip congestion. Increase of feed speed helps to prevent this congestion. Vibration drilling disposes of chips at a fast speed because it accelerates the penetration of oil and produces a large variation of chip thickness. Disposal in vibration drilling extends drill life in comparison with conventional drilling (Hidetaka & Hideyo, 1996).

A study was conducted at Georgia Institute of Technology to compare the mechanical performance of minimum quantity lubrication over completely dry lubrication for the turning of hardened bearing-grade steel materials with low content CBN cutters (Autret & Liang, 2003). Process attributes analyzed were surface roughness, cutting temperature, cutting forces, and tool life. A range of feeds from 0.002

to 0.014 inch/rev, cutting speeds of 450 sfpm and depth of cut of 0.012 inch were tested with a triglyceride and propylene glycol ester solution vegetable based cutting fluid at a constant flow rate of 50 ml/hour and a nozzle pressure of 20 psi. The cutting tool used was a low content CBN tool (Kennametal KD5625) with a rake angle of -6◦ chamfer length of 0.12 mm, horn radius of 0.03 mm, and nose radius of 0.8 mm. A slant bed horizontal lathe (Hardinge T42SP) was used (Autret & Liang, 2003). In the context of resulting surface roughness, no noticeable difference was concluded with the use of a near-dry over completely dry condition. However, an improvement of surface finish was felt by near-dry machining under greater depths of cut and feeds such as 0.012 inch and 0.006 in/rev respectively. In the context of a steady-state cutting temperature, a 10% to 30% reduction was consistently observed when a minimum quantity lubrication condition was applied as opposed to completely dry. This result was expected due to an increase in the evaporative heat transfer at the cutting zone. In the contest of cutting forces, there was no significant difference with or without the use of minimum quantity lubrication. The cutting force was approximately 250 N at a feed of 0.012 in/rev. In the context of tool life, the study showed a significant increase from 35% to 50% by minimum quantity lubrication over a wide range of cutting conditions (Autret & Liang, 2003).

In May 2007, an article was published by Tech Solve, based on a comparison between flood and microlubrication (MaClure, Adams, Gugger & Gressel, 2007). The lubricant used was Experimental vegetable oil based soluble oil (10%). The flow rates used for flood and mist conditions were 1.7 gpm and 0.0029 gpm respectively. Experiments were conducted for drilling and milling operations. For the drilling operation the material used was AISI 4340 Steel (32-34 HRC). Speed, feed rate and depth of cut were 55 sfpm, 0.007 ipr and 0.006 inch respectively. The drill used was 0.5 inch heavy duty, oxide coated, high speed steel with a 135° split point. Analysis showed no significant differences in tool life (number of holes to reach end of life criteria) between mist and flood cooling. They were 60 and 61 holes for flood and mist conditions respectively. The average thrust forces were 570 lbs and 447 lbs for flood and mist cooling respectively (MaClure, Adams, Gugger & Gressel, 2007). For the milling operation the material used was AISI 4140 Steel (24-26 HRC). Speed, feed rate and depth of cut were 400 sfpm, 0.005 ipr and 0.5 inch respectively. The cutter body was RA2 15.44-25 MN25 – 15 C (1 inch diameter) and the cutter insert was R215.44-15T308AAM (grade SM-30 uncoated carbide). Analysis showed little differences in tool life (number of holes to reach end of life criteria) between mist and flood cooling. There were 66 and 80 holes for flood and mist conditions respectively. The average resultant forces observed were 46 lbs and 36 lbs for flood and mist cooling respectively (MaClure, Adams, Gugger & Gressel, 2007).

In 2003, a study was conducted in Japan to investigate the tribological behavior of lubricants for semi-dry application in connection with cutting performance (Wakabayashi, Inasaki, Suda & Yokota, 2003). Two kinds of synthetic biodegradable esters and a rapeseed vegetable oil were used. One is a fully synthetic polyol ester the other is a vegetable based synthetic ester. For comparison, a neat type cutting oil is used for conventional flood supply. Cemented carbide or cermet was used as the cutting tool and the workpiece material was JIS (Japan Industrial Standards) S45C carbon steel. A cutting speed of 200 m/min was used with a feed of 0.1 mm/rev and a depth of cut of 1 mm. MQL was supplied with a pressure of 0.3 mpa and flow rate of 25 ml/h through an external nozzle. The experiments were conducted in a vacuum chamber. When the chamber pressure was 1.0×10^{-4} Pa, a two gas component was introduced into the chamber. After the chamber flow was constant by inlet and outlet gas, machining was carried out (Wakabayashi, Inasaki, Suda & Yokota, 2003). The result indicated cutting performance in MQL machining in ester is superior to that in dry machining. MQL machining with vegetable oil with viscosity of 35.6 mm^2/s was not preferred. The surface roughness by MQL machining with ester oil was just below 1 Ra, µm as compared to vegetable oil which was 1.25 Ra, µm. The coefficient of friction for ester oil was approximately 1.48 and for vegetable oil 1.52. For tool rake surface analysis, an electron probe microanalysis (EPMA) was done which provided detailed information about surface elements. According to this analysis carbon was significantly observed on the tool face in MQL machining with synthetic ester oil. This analysis implied the possibility of strong absorption of polyol ester on to the tool surface. Such carbon does not exist in MQL using vegetable oil. This lack is probably the reason why the cutting performance of synthetic ester was better than vegetable oil (Wakabayashi, Inasaki, Suda & Yokota, 2003).

In 2006, a paper published in Machining Science and Technology Journal introduced synthetic polyol esters and described their capacity as a potential MQL fluid, particularly compared with vegetable-based MQL oils, from the viewpoint of optimal secondary performance for MQL operations (Wakabayashi, Inasaki & Suda, 2006). For this study, the base stocks of cutting fluids were mineral oil or polyalkylene glycol (PAG) that do not have high biodegradability. In contrast, vegetable oils have high biodegradability, and synthetic esters provide a wide range of biodegradability depending on their combined molecular structures of acids and alcohols. Since most synthetic polyol esters can be regarded as biodegradable and have suitable viscosity for MQL machining, several polyol esters were chosen as lubricants for examination. The tapping test done is recognized as a standard screening method to evaluate the cutting performance of fluids and the tapping energy efficiency provides a sensitive and accurate measure of performance. The workpiece material used for this test was JIS (Japan Industrial Standards) S25C steel and the tool was an M8 nut tap. MQL was used with an air pressure of 0.3 mpa and flow rate of 25 ml/hr. Results showed the performance of MQL cutting with polyol ester is almost equal to that of conventional cutting. We can conclude that a very small amount of this lubricant can provide highly effective action at the cutting point (Wakabayashi, Inasaki & Suda, 2006). A turning test was also done to evaluate the cutting performance of fluids. The evaluation of cutting performance was done by the coefficient of friction on the tool rake face. This process used cutting force dynamometry during turning, and workpiece surface finish roughness after the test. These results indicate the cutting performance in MQL machining with both esters is superior to that in dry machining (Wakabayashi, Inasaki & Suda, 2006). Compared with the conventional flood supply of neat type oil, the fully synthetic polyol ester indicates excellent performance for both cemented carbide and cermet tools. The workpiece material used for this test was JIS (Japan Industrial Standards) S45C carbon steel and the tool was cemented carbide or cermet. MQL was used with an air pressure of 0.3 mpa and flow rate of 25 ml/hr. A cutting speed of 200 m/min was used with a feed rate of 0.1 mm/rev. Physical properties and biodegradability of polycol esters were compared with a vegetable oil. The viscosity, total acid number, pour point and biodegradability for polycol ester oil were 19.1 mm^2/s, 0.02 mgKOH/g, 45˚ C and 100% respectively. The viscosity, total acid number, pour point and biodegradability for vegetable oil were 35.6 mm^2/s, 0.04 mgKOH/g, 20˚ C and 98% respectively. The molecular weights of polycol ester oil and vegetable oil were also compared. The molecular weight of the oil film increased by more than 10%, and feels sticky to the touch. The molecular weight of vegetable oil increased by 65%, and also felt sticky. In contrast, there was no significant change in the molecular weights of polyol esters (Wakabayashi, Inasaki & Suda, 2006). Most vegetable oils consist of a number of ester compounds mainly derived from a combination of glycerin and fatty acids. These vegetable oils are usually liquids at room temperature because the fatty acid structures of their molecules normally involve unsaturated bonds. Unfortunately, an unsaturated bond structure is chemically unstable and may easily lead to oxidation polymerization. For this reason, vegetable oil exhibited a considerable increase upto 65% in its molecular weight. A detailed investigation of this degradation behavior was carried out by the GPC analysis. The results of the analysis indicate that some of the molecules in vegetable oil have changed into chemical compounds having higher molecular weights. Results of the UV analysis, which can selectively detect changes in unsaturated double bonds, indicate the unsaturated structure decreased significantly. This result also supports the hypothesis that the unsaturated bond structure of vegetable oil molecules is the main cause of their easy degradation by oxidation polymerization. The polyol esters chosen as preferable biodegradable lubricants in this investigation are synthesized from a specific polyhydric alcohol rather than glycerin. Their molecules can greatly improve oxidation stability because they are free from unsaturated bonds in their fatty acid structure. Though they contain no unsaturated bonds, they can be liquid at room temperature. Compared with vegetable oils, the synthetic polyol esters used here are optimal lubricants for MQL machining from the standpoint of maintaining a clean working environment (Wakabayashi, Inasaki & Suda, 2006).

Lubricant containers are often stored outside, and the temperature in the containers can rise as high as 70˚C. Since an MQL system consumes very little lubricant, the lubricant must remain stable under such conditions. In order to simulate this storage situation, an oxidation test was conducted at 70˚C for 4 weeks. Then 50 ml of lubricant was placed in a 100 ml glass bottle, and the bottle capped. After the test, changes in viscosity, total acid number (TAN) and odor were measured. The change in viscosity for polyol ester oil and vegetable oil after the storage stability test were 0.01% and 1.5% and the change in total acid number (TAN) were 0.01% and 0.18% respectively. While the viscosity and TAN of polyol ester were almost constant, the values for vegetable oil increased considerably. In the case of vegetable oil, a gluey material was found near the bottle cap and a peculiar odor noticed (Wakabayashi, Inasaki & Suda, 2006). These result confirm the stability of the molecular structure of the synthetic esters against oxidative degradation and promotes their stability in storage. The results indicate the cutting performance in MQL machining with polyol ester and vegetable based synthetic ester is superior to that in dry machining. Even compared with conventional flood supply of neat type oil, the fully synthetic polyol ester indicates excellent performance for both cemented carbide and cermet tools. On the other hand, MQL machining with vegetable oil is not always preferable. A similar evaluation of cutting performance was obtained in surface roughness after turning, where the surface finish quality for MQL using polyol ester is better than vegetable oil. Significant carbon concentrations was observed on the tool face in MQL machining with synthetic ester polyol ester, implying the possibility of strong adsorption of polyol ester on to the tool surface. Such carbon does not exist in the case of MQL using vegetable oil. This result may be the reason why the cutting performance of synthetic polyol ester was better than that of rapeseed vegetable oil (Wakabayashi, Inasaki & Suda, 2006).

A series of MQL drilling tests were conducted to determine if a high penetration rate could be achieved (Filipovic & Stephenson, 2006). Tests were performed on a Horkos HFN-P40H machining center with internal mixing (2-channel) through-the-tool MQL capability. A vegetable oil lubricant was used (Bluebe LB-20/Acculube 6000). The oil delivery rate was 50 ml/hr. Air pressure for all tests was 4.96 bars, and air consumption was approx 31 l/min. Cylindrical workpiece samples were drilled axially. Pilot holes of 6.1mm in dia and 10mm deep were drilled, followed by 6mm blind holes 100mm deep. Approximately 140 holes were drilled in each sample. Initial tests were conducted on 1038 steel samples (Rc 26 hardness). The cutting conditions for these tests were spindle speed= 4130 rpm, cutting speed= 80 m/min, feed rate= 0.13 mm/rev and penetration rate= 537 mm/min. In these tests, two identical solid carbide TiAlN-coated drills were used to drill 730 holes. These drills were then sent to separate sources for stripping, regrinding, and recoating. One additional drill, which had not been used, was sent to each of the sources for recoating and regrinding as well. Summary of the results of the initial tests is given below in Table 1.

Table 1: Summary of initial test on 1038 steel.

Tool	**Number of holes drilled**
New Drill 1	730
New Drill 2	730
Drill 1 reground at source A	460
Drill 2 reground at source B	560
New drill reground at source B	560

The new drills, as noted above, were used to drill 730 holes without incident. The drill reground and recoated at source A failed due to chatter after 463 holes. Both drills reground at source B (one used, one new) were used to drill 560 holes before testing was stopped due to lack of material. Source A was the original drill supplier and recoated with the initial drill coating, while source B used an alternative coating after regrinding. Drills #1 and #2 we observed before and after drilling 730 holes. There was minimal margin and flank wear. The maximum flank wear was 0.13mm at the outer corner. There was some minimal buildup of material on the margins and near the chisel edge (Filipovic & Stephenson, 2006). The spindle power trace was observed for the 500th hole drilled with Drill 1. The power remained constant with hole depth, in contrast to through-tool applications, which require increasing power with hole depth to overcome coolant back pressure. The reground drills exhibited flank and margin buildup after use. Drill 2, was reground and recoated at source B, after 560 holes. These drills did not show excessive margin wear. However, buildup may have been due to less effective polishing of the coating following reconditioning (Filipovic & Stephenson, 2006).

A second series of tests on 1038 steel was run at a penetration rate of 974 mm/min. The cutting conditions for these tests were: spindle speed= 4870 rpm, cutting speed= 90 m/min, feed rate= 0.2 mm/rev and penetration rate= 974 mm/min. Four new drills were tested, and one was reground and retested. The results are summarized in Table 2.

Table 2: Summary of second test on 1038 steel.

Tool	**Number of holes drilled**
Drill 3 (new)	0
Drill 4 (new)	15 @ half-depth
Drill 5 (new)	905
Drill 5 (reground)	966
Drill 6 (new)	950

Test Drills 3 and 4, which came from the same manufacturer, did not perform well. Drill 3 broke on the first hole and Drill 4 produced sparks and excessive noise after 15 holes at half depth (50 mm). Later examination showed that it had chipped at the outer corner. Test Drills 5 and 6, which also came from the same source but a different source from Drills 3 and 4, completed over 900 holes each without incident, although chip form and consistency deteriorated after 700 holes with Drill 5. After the use neither of these two tools showed excessive flank or margin wear, although Drill 6 exhibited a noticeable buildup of material behind the margin. Drill 5 was reground and recoated; the reconditioned drill successfully drilled 966 holes before the test was stopped due to chatter and sparking. Since the target production application for the process was a nodular iron crankshaft, Drills 5 and 6 were also tested in a primarily pearlitic nodular cast iron with a yield stress of 357 mpa and UTS of 552 mpa (Filipovic & Stephenson, 2006). The test conditions were identical to those used in the second series of tests. The results for the two drills were that Drill 5 drilled 788 holes before being stopped for excessive noise and Drill 6 produced 985 holes without incident. Although both drills performed well, they exhibited significant chisel edge and margin wear, due to the abrasive nature of the work material. The margin wear in particular was of concern as it might limit the number of regrinds that can be performed before a drill must be discarded. The chip forms produced by both drills were acceptable; neither produced significant quantities of undesirable needle-type chips, which are often obtained from this material (Filipovic & Stephenson, 2006).

In summary, MQL drills can be run at much higher penetration rates than gun drills. MQL drills tend to exhibit buildup on the flanks and margins, perhaps due to excessive hole temperatures. Buildup is more common on reground than new drills and may depend on coating properties such as finish. Nodular cast iron showed the same results as steel, when drilled with MQL under similar cutting conditions. Nodular cast iron produces more margin wear than steel, which may be a concern if it limits the number of regrinds for a given tool (Filipovic & Stephenson, 2006).

In 2006, a study was conducted on tool life of small twist drills in deep hole drilling (Heinemann, Hinduja, Barrow, Petuelli, 2006). Table 3 shows the specifications of the twist drills.

Table 3: Specifications of the twist drills used.

Tool Type	**Manufacturer -- tool code**	**Substrate**	**Coating**
A	Titex-A1222	HSS	Uncoated
B	Titex-A1249	Co-HSS	Uncoated
C	Titex-A1249	Co-HSS	TiN
D	Titex-A1249	Co-HSS	TiAlN multilayer

The drilling experiments were carried out on a high speed three-axis CNC milling machine of the portal frame type; the machine spindle had power of 2.6 kW and a maximum speed of 40,000 rpm. The workpiece material was plain carbon steel (carbon content 0.45%); the workpiece billets, all of which were from one batch, were cut and pre-milled into plates of 65×75×15 mm. A plate held in a vice was mounted on top of a Kistler two component dynamometer (9271A) which measured the thrust force and torque. The twist drills tested, all had a diameter of 1.5 mm and a straight shank. The drills were provided with wide chip flutes in combination with a parallel web, a helix angle of 40°, an enlarged point angle of 130° and a split point web thinning (Heinemann, Hinduja, Barrow, Petuelli, 2006). These geometric features were recommended for twist drills involved in deep hole drilling. A cutting speed of 26 m/min and a feed rate of 0.26 mm/rev were used. Except for the uncoated drills, these cutting parameters were within ± 10% of the values recommended by the drill manufacturers. The MQL-supply in the first series of tests was stopped once the drill reached a depth of 5 mm, equivalent to approximately 3 times its diameter. In the second series of tests, two other lubricants, details of which are shown in Table 4 were used. The first of these was SETOL ST-SHAD, which had the same chemical composition as the lubricant used in the first series, except that it did not contain any alcohol. Hence, SETOL ST-SHAD had almost no cooling but an improved lubrication capability. The second lubricant, SETOL SOE, was an oil-free synthetic lubricant with a water-content of 40%. In the third test series, drilling was carried out under dry conditions.

Table 4: Properties of minimum quantity lubricants.

Feature	**SETOL ST-SHAD**	**SETOL ST-SHAD 20A**	**SETOL SOE**
Main ingredients	Synthetic ester + additives	Synthetic ester + additives + alcohol (20%)	Oil-free synthetic lubricant + water (40%)
Viscosity (mm2/s)	85 (at 40 8C)	80 (at 40 8C)	40 (at 40 8C)
Density (g/cm3)	913	895	1033
Effect(s) on the cutting process	Lubricating	Lubricating (primary) and cooling (secondary)	Cooling (primary) and lubricating (secondary)

It was observed that the interruption of the MQL-supply caused a drop in tool life from 536 to 13 bore holes for the uncoated Co-HSS drills of type B, which is a dramatic drop of 98%. In the case of the TiN- and TiAlN coated twist drills, the tool life decreased, by 42% (from 709 to 411) and 27% (from 966 to 709) respectively. A series of tests was carried out with three different types of minimum quantity lubricant, the lubricant being supplied continuously at a rate of 18 ml/h. All tests, were performed with uncoated type A HSS drills. Using alcohol-free SETOL ST-SHAD lubricant resulted in a tool life of 689 boreholes, which is an increase of 23% when compared to the tool life (558 boreholes) obtained with the alcohol-blended SETOL ST-SHAD 20A lubricant. When using the SETOL SOE lubricant, the tool life increased by a 100% to 1117 boreholes (Heinemann, Hinduja, Barrow, Petuelli, 2006). A continuous MQL supply is beneficial in terms of tool life, whereas interrupting the MQL supply leads to a substantial drop in tool life, especially in the case of heat-sensitive drills. With respect to the type of MQL lubricant, a low viscous type with high cooling capability gives rise to a notably prolonged tool life (Heinemann, Hinduja, Barrow, Petuelli, 2006).

One of the first projects for evaluating effectiveness of MQL machining for aluminum parts was performed under the management of the National Center for Manufacturing Sciences (NCMS) (Filipovic & Stephenson, 2006). Work was performed by a coalition member of consisting of automotive and defense end users and tooling and machine tool manufacturers. Comparisons were done between MQL and through the tool cooling machining. Parts were processed by the standard wet process, MQL, and MQL with vacuum chips collection. It was concluded that MQL process costs were approximately 10% lower than the traditional machining process. Dry chips were produced and could have been sold to a recycling facility without additional processing. Air quality for MQL was better than conventional machining, with a significant reduction in aerosol particle concentration (Filipovic & Stephenson, 2006).

A study was carried out on aluminum turning. In this study an intermittent turning process on a CNC lathe was employed (Itoigawa, Childs, Nakamura & Belluco 2006). There were two test conditions. The first had a cutting speed of 200 m/min, feed rate of 0.05 mm/rev and axial travelling length of 3 mm. The second condition had a cutting speed of 800 m/min, feed rate of 0.2 mm/rev and axial travelling length of 10 mm. In both MQL methods, the oil supply rate was fixed at 30 ml/h and air flow rate at 70 l/min (normal). For MQL with water droplets, tap water was used at a rate of 3000 ml/h. Rapeseed oil and synthetic esters (mono carboxylic acid with polyalcohol) were employed as lubricants. Cutting tests using emulsion type coolant (Rocol A208A plus) and dry machining, were performed in the same conditions. When using lubricant, a nozzle was set at about 50mm above the rake face of the tool. Two kinds of tools were used. One was a sintered diamond tool with 0° rake angle. Another was a K10 grade carbide tool with 5° rake angle (Itoigawa, Childs, Nakamura & Belluco 2006). MQL with rapeseed oil has a small lubricating effect in light loaded machining conditions. The boundary film developed with rapeseed on a tool surface is not strong enough to sustain low friction and avoid adhesion of work material. Results showed MQL with water droplets, namely oil film on water droplet, gives good lubrication performance if appropriate lubricant such as synthetic ester is used. When MQL with synthetic ester without water was used, it showed a lubrication effect. However, tool damage and adhesion of material onto the tool surface cannot be suppressed (Itoigawa, Childs, Nakamura & Belluco 2006).

Studies were also conducted on turning steel using MQL. In a similar study, AISI-1040 steel rod of initial diameter 110mm and length 620mm was plain turned in a BMTF Lathe, bangladesh, 4 hp by uncoated carbide insert of integrated chip breaker geometry at different speed-feed combinations under dry and MQL conditions to study the role of MQL on machinability characteristics of that work material mainly in cutting temperature, chip reduction coefficient and dimensional deviation (Dhar, Islam, Islam & Mithu, 2006). Cutting speeds used were 64, 80, 110 and 130 m/min and feed rates used were 0.10, 0.13, 0.16 and 0.20 mm/rev. The depth of cut was 1 mm. Flow rate used was 60 ml/hr through an external nozzle. The cutting performance of MQL was better than conventional machining with flood coolant. MQL reduced the cutting temperatures, which improved chip tool interaction and maintained sharpness of the cutting edges. This was concluded by the observation of chips produced which were more or less half turn and their back surface appeared much brighter and smoother. Dimensional accuracy was also improved mainly due to reduction of wear and damage at the tool tip (Dhar, Islam, Islam & Mithu, 2006).

Experiments have been completed by plain turning a 125 mm diameter and 760 mm long rod of AISI-4340 steel in a rigid lathe (Lehmann Machine Company, USA, 15 hp) at an industrial speed-feed combination under dry, wet and MQL conditions to study the role of MQL on the machinability characteristics in respect to tool wear and surface roughness (Dhar, Kamruzzaman & Ahmed, 2006). Cutting speeds used were 110 m/min and feed rate was 0.16 mm/rev. The depth of cut was 1.5 mm. Flow rate was 60 ml/hr through an external nozzle. The MQL jet provided reduced tool wear and cutting temperature, improved tool life and surface finish as compared to the dry and wet machining of steel. During machining of the ductile material heat was generated in the primary deformation zone, chip-tool interface and work-tool interface. These factors influenced the chip formation mode, cutting forces and tool life. The MQL jet in its application enabled reduction of the average cutting temperature by 5%-10% depending on the levels of processing parameters, cutting speed and feed rate (Dhar, Kamruzzaman & Ahmed, 2006).

MQL can also be applied to the grinding process. An experiment was carried out to determine the effectiveness of MQL in the grinding process. The material used in this test was tempered and annealed ABNT 4340 steel 60 HRC classified as tempering steel, and was employed in the manufacture of pieces that require mechanical strength and toughness (Da Silva, Bianchi, Fusse, Catai, Franca & Aguiar, 2007). The tests were carried out with aluminum oxide (Al2O3) grinding wheels (355.6 × 25.4 × 127mm - FE 38A60KV). Lubricant used was LB 1000. The main input parameters i.e. grinding wheel speed = 30 m/s, infeed rate = 1 mm/min, workpiece speed = 20 m/min, depth of cut = 0.1 mm and spark-out time = 10 sec, were selected based on preliminary testing. These parameters were kept constant throughout the tests. A synthetic emulsion in a 5% concentration was used in the conventional cooling condition. The maximum flow rate supplied by the pump and by the machine's original nozzle was 8.4 l/min (Da Silva, Bianchi, Fusse, Catai, Franca & Aguiar, 2007). The roughness values were decreased due to the excellent properties of lubricity. No significant clogging of the grinding wheel pores was found with the MQL technique. The use of MQL did not negatively affect surface integrity. No significant subsurface alterations in the microstructure were detected under conventional cooling and with MQL (Da Silva, Bianchi, Fusse, Catai, Franca & Aguiar, 2007).

MQL was carried out in high speed grooving. The MQL technique reduces the tangential cutting force to a certain extent as compared with conventional cooling. MQL reduces both corner and flank wear (Obikawa, Kamata & Shinozuka, 2006). The performance of MQL in high-speed cutting was evaluated in grooving 0.45% C carbon steel with a carbide tool coated with TiC/TiCN/TiN triple coating layers. MQL with vegetable oil (100% fatty acids) at a small and constant rate of 7 ml/h reduced corner and flank wear more effectively than a solution type of cutting fluid at high cutting speeds of 4 and 5 m/s and feed rate of 0.12 mm/rev (Obikawa, Kamata & Shinozuka, 2006). The experiment was carried out on a CNC lathe. In MQL grooving, it was also observed that wears decreased drastically with increasing the pressure of air supply. This suggested that the air supply plays an important role in transporting oil mist to the interface between the flank wear land and machined surface. A controlled oil mist direction (COD) tool was devised and its performance proved to be high at a reduced rate of oil supply (Obikawa, Kamata & Shinozuka, 2006). After considering the above points, information is lacking which requires further development to increase MQL implementation in high volume machining operation.

Air Quality

MQL greatly reduces total mist generation compared to high-pressure through-tool coolant applications, but also reduces the average mist particle size. Mist collection or filtering equipment may still be required to manage this fine mist. In ferrous machining sparking and smoking is sometimes observed with MQL. Hence, some filters may be required to manage smoke if it cannot be eliminated through process or tooling design.

Capability and Robustness

MQL works well in short term tests in many applications, but long term capability and robustness issues may still arise. These issues may be sorted out when MQL can be accumulated for production experience. More material specific issues may require additional testing. For example aluminum machining includes the sensitivity of surface finish (or the tendency for tool build-up) to expected variations in tool geometry or coating conditions. Hence, for capability and robustness additional experiments need to be conducted.

Cost

Production experience to date has indicated higher costs in some areas than expected for MQL, based on early laboratory studies. For example in crank shaft hole drilling tool cost is significantly increased by the high initial cost of drills, the necessity to strip and recoats drills during the grinding process, and the limited numbers of regrinds that can be performed before a tool is discarded. Standardization of drill diameters, changes in drill geometries, and coating innovations may be effective in reducing these costs.

MQL is mainly applied to drilling process. Other processes such as deep drilling, tapping, fluteless tapping, burnishing drilling, gun drilling and gun reaming should be considered using MQL. MQL should be used in the machining of different materials, rather than selective materials such as aluminum or cast iron. Different combinations for the MQL lubricant should be considered apart from air and water. A detailed study is required in relation to the use of coated and uncoated tools for MQL with specific materials. A detailed study of the temperature analysis in MQL should be completed for coated drills. A study related to the discontinuous use of MQL during machining should be completed to help in the minimization of lubricant use. MQL has been mainly applied to the hole manufacturing process. Hence, further study is required in areas such as grinding, grooving, turning and boring. Research is required on different lubricants properties (oil based versus vegetable based).

Summary

Previous studies stated vegetable based oils were not recommended to be used as minimum quantity lubricants. Because, of many factors such as low penetration rate, unclean working environment due to smoke and particles generated (specially in case of machining cast iron with ceramics) (Bryne & Scholta, 1993) and unstable molecular structure consisting of acids and alcohol. Vegetable based oils are chemically unstable and consist of a number of ester compounds mainly derived from a combination of glycerin and fatty acids. Vegetable oils are usually liquids at room temperature because the fatty acid structures of their molecules normally involve unsaturated bonds. Unfortunately, an unsaturated bond structure is chemically unstable and may easily lead to oxidation polymerization. Hence, there were mixed results obtained pertaining to the use of vegetable based oil as minimum quantity lubricants. One study showed that drilling under MQL with vegetable oil (Bluebe LB-20/Acculube 6000) had higher penetration rate upto 974 mm/min. The study was conducted on 1038 steel with solid carbide TiAlN-coated drills. The cutting conditions for these tests were spindle speed= 4130 rpm, cutting speed= 80 m/min, feed rate= 0.13 mm/rev. There was minimum margin and flank wear until 730 holes were drilled. A second series of tests was conducted in the same study with the cutting conditions as follows: spindle speed= 4870 rpm, cutting speed= 90 m/min, feed rate= 0.2 mm/rev. It was observed that two drills completed over 900 holes each without incident, although chip form and consistency deteriorated after 700 holes. Again, these tools were reground and recoated; the reconditioned drill successfully drilled 966 holes. The test was also conducted for pearlitic nodular cast iron with a yield stress of 357 mpa and UTS of 552 mpa. The tests conditions were identical to those used in the second series of tests. The results for the two drills were that reground tool drilled 788 holes and new tool produced 985 holes without incident. The characteristics of this lubricant used for this study is shown in Table 5.

Table 5: Characteristics of lubricant Acculube 6000.

Characteristics	**Units**
Appearance	Medium blue viscous oil
Density	7.74 lbs / gallon
Active sulfur content	0.0%
Silicones	None
Flash Point	418°F (214°C)
Mineral Oil Content	0.0%
Specific gravity	0.93
Viscosity	8.85 centistokes (40°C)
Total chlorine	0.0%
VOC level	0.8 ppm
Pour Point	-40°F (- 40°C)
Water Solubility	Insoluble

Conclusion

More studies should be done to investigate the effects of vegetable based oil. The objective of this study is to evaluate the performance of regular high speed steel tools when drilling AISI 1018 steel under three different cutting speeds and two different feed rates. The lubricant will be Acculube 6000 as described in Table 5. A total of six different treatments will be applied to evaluate the effects of the cutting speeds and feed rates on the resulting inner diameter and surface finish of one-inch deep peck-drilled holes in 1018 steel.

CHAPTER III

EXPERIMENTAL METHOD AND PROCEDURES

This chapter includes the experimental methods and procedures used in this study. The objective of the study, the drilling tool and its composition, the drilling equipment, the procedure for drilling and the data collecting method are also described. The method adopted to analyze the data was the design of experiments. Design Expert 7.1 analytical software was used to perform the ANOVA analyses.

Objectives

The specific objective of this study is:

- To evaluate the performance of regular high speed steel (HSS) tool when drilling AISI 1018 steel at (Cutting speeds = 120, 100 and 80 SFM, Feed rates = 0.004 and 0.003 IPR) using Acculube 6000 vegetable based lubricant. The measures of performance are tool life (number of holes drilled) and surface finish of the resulting hole.

Design of Experiment

The study was conducted using a randomized factorial design. Table 6 shows the factorial experiment layout. The two independent variables considered were cutting speed and feed rate. The depth of the hole was 1 inch for all drilling operations. The two dependent variables were surface finish and hole size (inner diameter, I.D.). The speed and feed are expressed in feet per minute, (SFM) and inch per revolution (IPR) respectively.

Table 6: Factorial Experiment Layout of Cutting Speed and Feed Rate Combination.

HSS Drill		**Cutting Speeds (SFM)**		
		120	**100**	**80**
Feed Rates (IPR)	**0.004**	120, 0.004	100, 0.004	80, 0.004
	0.003	120, 0.003	100, 0.003	80, 0.003

The experiment was fully randomized. The process of randomization of data involves randomly allocating the experimental units across the treatment groups. As shown in Table 6, there are six combinations of cutting speed and feed rate. Hence, six experiments were performed each consisting of one of the six combinations. At the start of every experiment, one combination of cutting speed and feed rate was selected at random and manually inserted into the CNC program. After tool failure, one combination was again selected at random and inserted into the CNC program replacing the earlier combination. This procedure of randomly selecting the cutting speed and feed rate combination was followed until all six experiments were completed.

There were 200 samples available for drilling holes; each sample was cut from a 10 foot long bar having a 4 inch diameter. One sample could include 30 holes. All 200 samples were kept on a wooden pallet. Each sample was selected at random and loaded in the pneumatic chuck of CNC milling machine. After 30 holes were drilled, the samples were unloaded and the hole size for every 10^{th} hole was measured to check the possible failure of the tool. If the tool did not fail, one sample was again selected at random from the pallet and loaded in the chuck. This procedure of randomly selecting the sample was followed until tool failure.

Randomization reduces bias by equalizing other factors that have not been explicitly accounted for in the experimental design. Randomization of data is necessary because the output result should not be affected by the sequence of input data. If a particular sequence is followed, the results will not be randomized data and the treatment will be assigned by choice not by chance which is against the principle of randomization. For conducting a randomized factorial experiment a fair and equal chance must be given to all combinations to be selected for the experiment. Bias weakens the study results and consists of human choices, belief or any other factors besides those being studied that can affect the trials results.

Cutting Tool

The tool used for this experiment was a regular high-speed steel (HSS) drill bit as shown in Figure 2. The tools were ordered in a batch of 10, assuming that all tools used in the experiments were of the same make without any differences. The tools were manufactured by Guhring Inc. with the following specifications/dimensions (www.guhring.com).

- (Part Specification # 205)

1. Regular high-speed steel (general purpose)
2. Cutting angle = 118°

3. Diameter = 0.500”
4. Jobber length, 5 × D
5. Straight shank
6. Bright oxide finish

Figure 2: High Speed Steel Drill Bit

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Sample Preparation

Sample preparation was completed before the actual drilling process was carried out. The material was supplied in the form of three barstocks of AISI 1018 steel from a local vendor. The barstocks were 10 feet in length and 4 inches in diameter as shown in Figure 3.

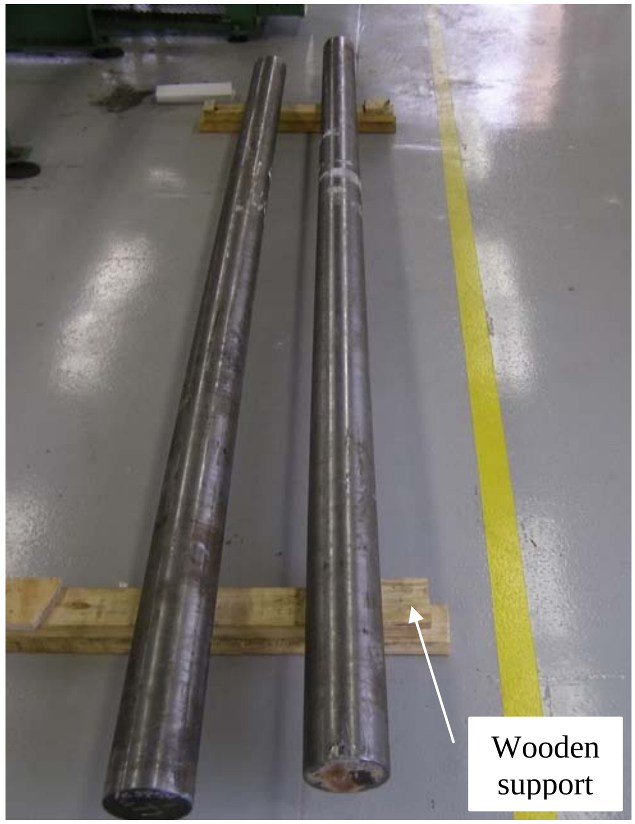

Figure 3: Barstock

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Due to the limitation of the CNC drilling machine work holding device, where the final sample had to be drilled, the diameter of the sample was restricted to 4 inches. The vendor unloaded the material, the material was transferred to the University of North Texas Manufacturing Engineering Laboratory on a pallet jack. From the pallet jack the barstocks were transferred to two wooden supports as shown in Figure 3. The barstocks were kept near the bandsaw machine where they were cut into rough samples. Four helpers were required to lift the barstock and keep it on the roller guideways of the bandsaw machine. Figure 4 shows the bandsaw machine, two barstocks kept idle on a wooden support and one barstock on the roller guideways to be clamped for cutting.

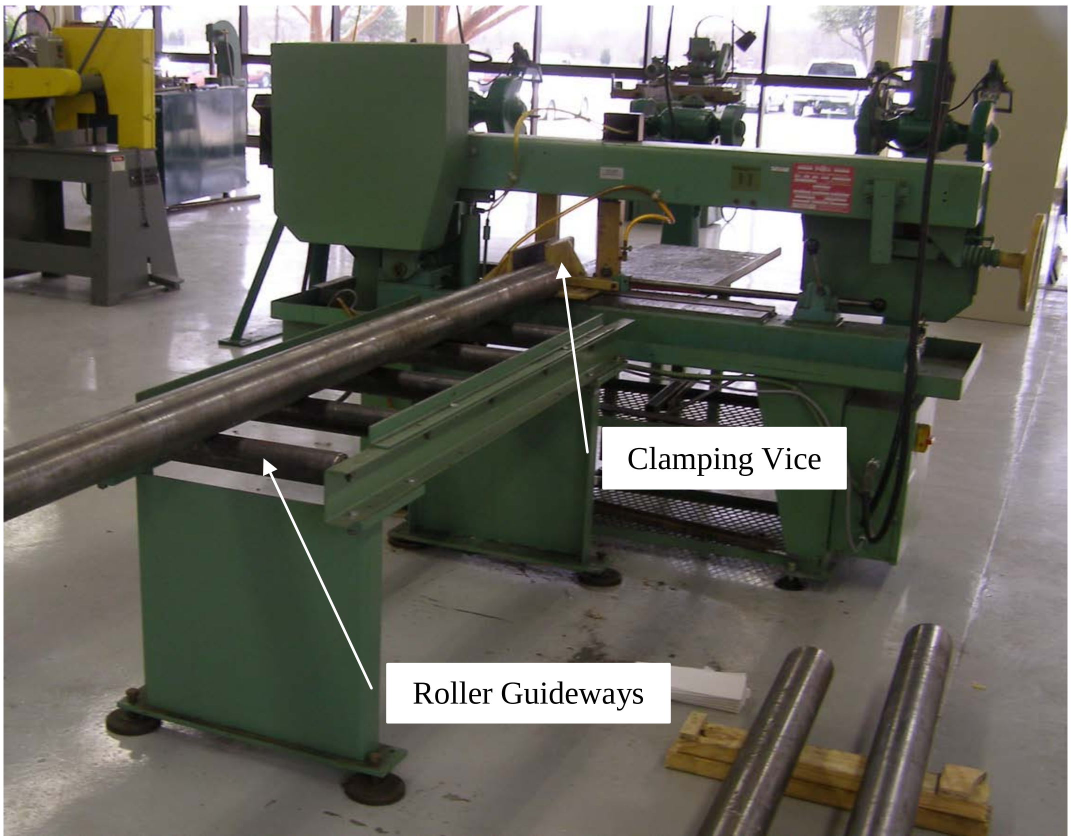

Figure 4: Bandsaw

(Source: University of North Texas, Manufacturing Engineering Laboratory)

After the barstocks were loaded on the roller guideways, the length to be cut was measured manually with a steel ruler. The barstocks were than clamped in the vice. The bandsaw machine was automatically operated by pressing the “ON” button. As soon as the machine is “ON” the coolant is automatically directed on the area of cutting and the saw starts cutting the barstock into a rough sample. Rough samples were made of 1.75 inch thickness because the bandsaw machine cannot produce exact perpendicular samples. The final size of the samples was 1.5 inches thickness. The extra material was removed by precision facing on the CNC lathe. The CNC lathe is shown in Figure 5.

Figure 5: CNC Lathe

(Source: University of North Texas, Manufacturing Engineering Laboratory)

The rough samples were kept on a pallet. The remaining barstocks were loaded and cut into rough samples. The rough samples were transferred near the CNC lathe via a pallet jack. Care was taken that the samples did not fall while transferring. Before the samples were faced on the lathe, a CNC lathe program was written and inserted. Dry runs were conducted to test the program. The program was written to face both side of the samples so an exact thickness of 1.5 inches could be maintained and to turn the sample to a diameter of 3.975 inches and upto 0.75 inches length with a small radius of 0.125 inches at the edge. The turning of the rough samples was done so the smooth sample can slide through and be easily located in the three jaw pneumatic chuck of the CNC drilling machine. Each sample was loaded on the CNC lathe. A pneumatically operated chuck was used to clamp the workpiece for machining. Before starting the machining cycle, the machine door was closed so the coolant would not dispense. After the machining cycle the final samples were kept on the pallet. The samples were faced, turned and chamfered. The final samples were ready for drilling. Before drilling, different layouts were considered so that a maximum numbers of holes could be made on every sample via one program. The best layout included 30 holes in each sample. This layout was opted for programming for the experiments. A final sample ready for drilling holes is shown in Figure 6.

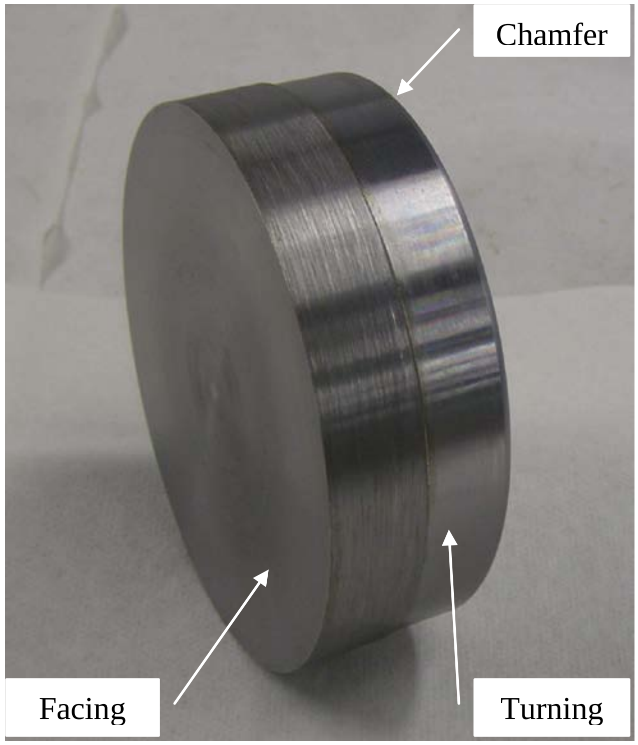

Figure 6: Final Sample

(Source: University of North Texas, Manufacturing Engineering Laboratory)

A CNC drilling program was written and inserted into the CNC milling machine. Dry runs were conducted to test the program. The program was written to make 30 centre drilled holes, 30 holes of 1 inch depth and 0.5 inches diameter and face milling on the edge which would serve the purpose of component locating for taking surface roughness readings. During the sample preparation the mister was assembled on the CNC milling machine. The mister was initially fastened to a wooden plate which was covered with a tin sheet. The wooden plate was fastened to the side of the CNC milling machine. The mister was filled with the required coolant of Acculube 6000 and was kept in working condition. Figure 7 shows the assembled mister on the CNC milling machine. The nozzles of the misters were fastened to the vertical column of the machine. As the vertical column moved up and down so did the nozzles of the mister. This ensured that the nozzles were always spraying the coolant at the drill.

Figure 7: Mister Assembled on CNC Milling Machine

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Drilling quipment

A computer numerical control (CNC) Mori Seiki vertical milling machine was used to perform the drilling operation for this study. Figure 8 shows the machine in idle condition. The machine has a Fanuc 10 M Numerical Controlled (NC) unit that has a pneumatically operated three jaw chuck which is foot pedal operated. To start the machining cycle the green button on the NC controller was pushed. A pneumatic door prevented chips from coming out during the machining process. The machine was covered by a plastic sheet during the drilling process so the mist would not come out of machine. All three tools were loaded in the tool magazine. The setting for all tools tool length compensation was inserted manually through the NC controller.

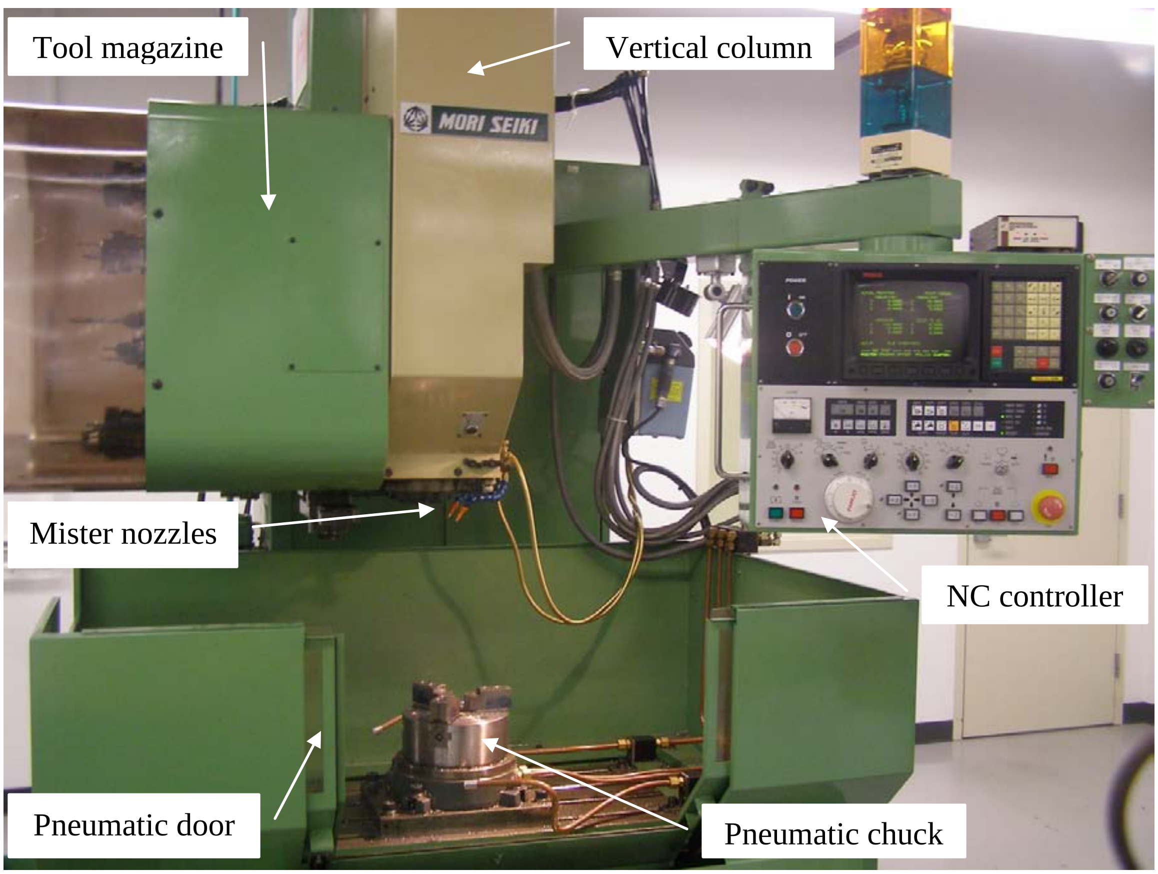

Figure 8: Mori Seiki Vertical Milling Machine

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Workpiece Material

The workpiece material used was 1018 steel and is among the most commonly available grades. It is widely available in cold finished rounds, squares, flat bar and hexagons. Despite its unimpressive mechanical properties, the alloy is easily formed, machined, welded and fabricated. Due to its higher Mn content, it can, in thin sections, be hardened to Rc 42. The alloy is a free machining grade that is often employed in high volume screw machine parts applications and is commonly employed in shafts, spindles, pins, rods, sprocket assemblies and an incredibly wide variety of component parts (ThyssenKrupp Materials, 2008). Table 7 shows chemical composition of 1018 steel.

Table 7: Chemical composition of 1018 steel.

Element	**Weight %**
C	0.15-0.20
Mn	0.60-0.90
P	0.04 (max)
S	0.05 (max)

Drilling Procedure

Before drilling it was ensured the component was tightly held in the CNC milling machine three jaw pneumatic chuck and the machine sliding door was closed. The components to be drilled were kept randomly on the pallet so that when any sample was selected for the experiments that sample would be a random sample. There should not be any bias in the experiment.

The drilling procedure followed was as follows:

1) Select at random a combination of cutting speed and feed rate from Table 6.

2) Turn on the three-axis CNC vertical milling machine (Mori Seiki, MV Junior)

3) Insert the selected speed and feed rate into the machine through the NC controller.

4) Select a work piece at random from the batch.

5) Place the workpiece manually in the three jaw pneumatic chuck.

6) Close the chuck by operating the foot pedal.

7) Ensure the workpiece is properly tightened in the chuck.

8) Adjust the mister to 6” away from drill bit at a 45˚ angle and aim it on lower ¼ portion of the drill bit cutting end.

9) Close the pneumatic door.

10) Cover the entire machine with the plastic sheet.

11) Press the green controller button on the machine.

12) After the spot drilling is completed, turn “ON” the misters.

13) Again, press the green controller button on the machine.

14) After making three holes the machine will stop automatically because of the optional stop in the program to ensure that chips do not get tangled over the drill bit.

15) Remove any chips from the drill bit.

16) Again, press the green controller button on the machine.

17) Complete the process by following steps 13, 14, 15 and 16.

18) Stop the mister when the machining is over.

19) Remove the plastic sheet covering the machine.

20) Open the pneumatic door.

21) Remove the component from the chuck by pressing the foot operated pedal.

22) Clean the component of chips and coolant.

23) Measure every 10^{th} hole of the component with a digital vernier caliper according to the data collection procedure.

24) Note the reading of the holes.

25) If the tool does not fail repeat the procedure from step 4, on all remaining components until the tool fails.

If the tool fails, load the next tool in the tool magazine. Do the tool length compensation for the drill and follow the same procedure of drilling. Before loading the next component in the chuck, ensure that the chuck is thoroughly cleaned of chips and coolant. At the end of each day measure the surface finish roughness of all components and note the readings of surface finish and hole diameter. All data collected should be saved on a spreadsheet.

Figure 9 shows the components after the drilling was completed.

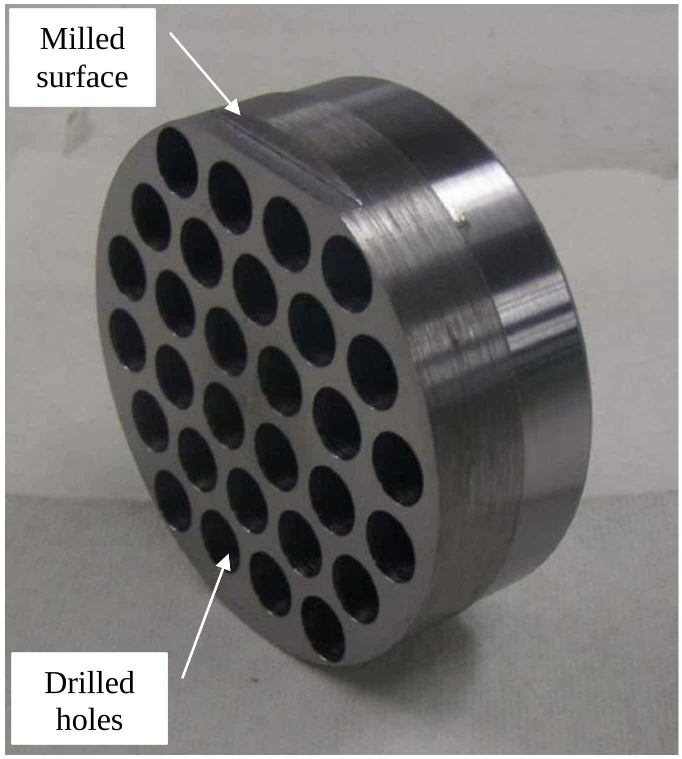

Figure 9: Drilled Workpiece

(Source: University of North Texas, Manufacturing Engineering Laboratory).

Data Collection Method

Each treatment was repeated until the tool failed. The tool was declared failed if:

- Three consecutive inner diameter readings were greater or equal to 0.51”.

or

- The hole diameter became less than the first hole. The criterion was determined feasible by the die and mold industry tool makers.

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Inner Diameter Measuring Procedure

1. Using a standard digital caliper, measure the inside diameter of the first and every 10th hole and record on a spreadsheet.
2. If the inner diameter hole size is greater than 0.510”, measure the previous two holes. If three consecutive readings are greater or equal to 0.510”, the tool is declared failed.
3. If the previous two holes do not depict the same failure result of greater than or equal to 0.510”, the drilling process is repeated for another sequence of thirty holes.

Measuring Surface Finish

1. Measure the surface finish of all the holes drilled at the end of every day.
2. Use the Mitutoyo surface finish profilometer, model no. SJ-201, for measuring surface finish.
3. Set the work piece on a fixture for surface finish measurement.
4. Set the cut off length for the measurement at 0.1”.
5. Insert the stylus and push the startup button to take the [Ra] reading. Record two readings of surface finish for every 10th hole of each row of drilled holes.

   Figure 10 shows the profilometer in use measuring the surface roughness.

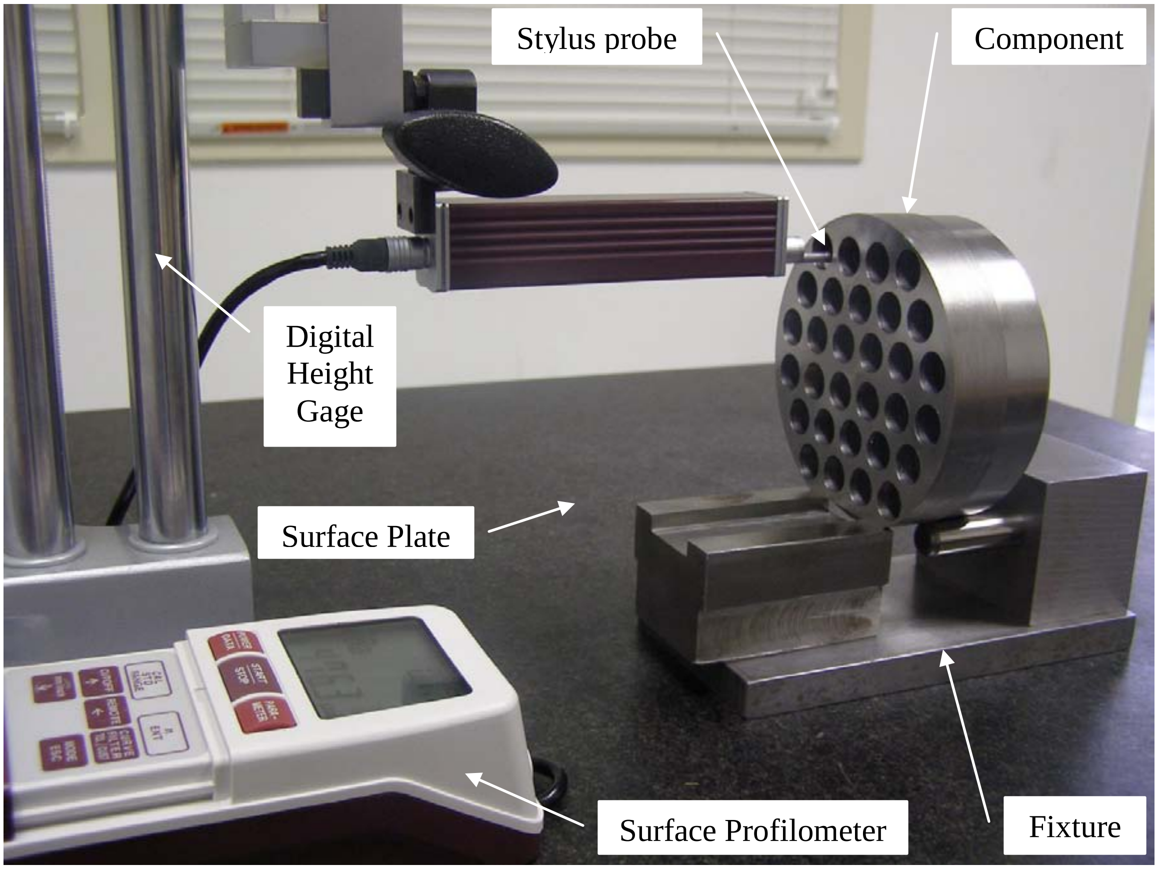

Figure 10: Measurement of Surface Roughness

(Source: University of North Texas, Manufacturing Engineering Laboratory)

Data Analysis

Analyses of variance were conducted for both surface finish and hole size and for all treatments. The purpose was to investigate the significant effects of each response variable and develop predicting models for both surface finish and inner diameter of each drilled hole.

The following steps were performed in the analysis:

1. Organize and input the resulting experimental data.

2. Check the F-value to determine if the resulting models are significant.
3. Perform significance tests for interaction and main effects for the independent variables.
4. Check the R-square and Adj. R-square values for the resulting regression models. If necessary perform any transformation of the resulting models.
5. Plot graphs to aid in analyses.

Assumptions of Study

1. Spot drilling had negligible impact on tool life.
2. Surface roughness and hole diameter were appropriate indicators of tool life.
3. ANOVA was appropriate statistical technique used for the analysis.
4. Use of digital vernier caliper was uniform throughout the study.
5. Any lack of rigidity in machine tool and set up did not affect the data in the study.
6. Position of the mister and flow rate was consistently same throughout the study.

Limitations of Study

The study was limited to:

1. AISI 1018 steel.
2. Acculube 6000.
3. 0.5 inch diameter HSS drills manufactured by Guhring Inc.

CHAPTER IV

ANALYSES

All collected data was recorded using Microsoft Excel and transferred to Design Expert 7.1 analytical software for the ANOVA analysis.

ANOVA Assumptions

1. Individual differences and errors of measurement are normally distributed within each group.
2. Size of the variance and distribution of individual differences and random errors are identical in each group.
3. Individual differences and errors of measurement are independent from group to group.

Hypothesis

1. Null Hypothesis:

   There is no significant difference between the responses obtained by varying the individual input variables (i.e. speed and feed).

2. Alternate Hypothesis:

   There is a significant difference between the responses obtained by varying the individual input variables (i.e. speed and feed).

Plots from Design Expert were used to inspect the data for normality for inside diameter readings. A normal probability plot was used to determine if the distribution of data approximates a normal distribution. In the analysis of variance, the normal probability plot is usually more effective and straightforward when it is done with residuals. The residual is the difference between the actual and predicted response values. The normal plot of residuals for the inside diameter is shown in Figure 11. The normal probability plot indicates that the residuals follow a normal distribution because the plot follows a straight line. There are some points which are slightly scattered but are acceptable as they do not follow any curve or a specific pattern. In general, these are moderate departures from normality which are of little concern in an analysis of variance. As the normal plot of residuals for the inside diameter response indicate the data is normalized, the analysis of variance can be said to be robust to the normality assumption.

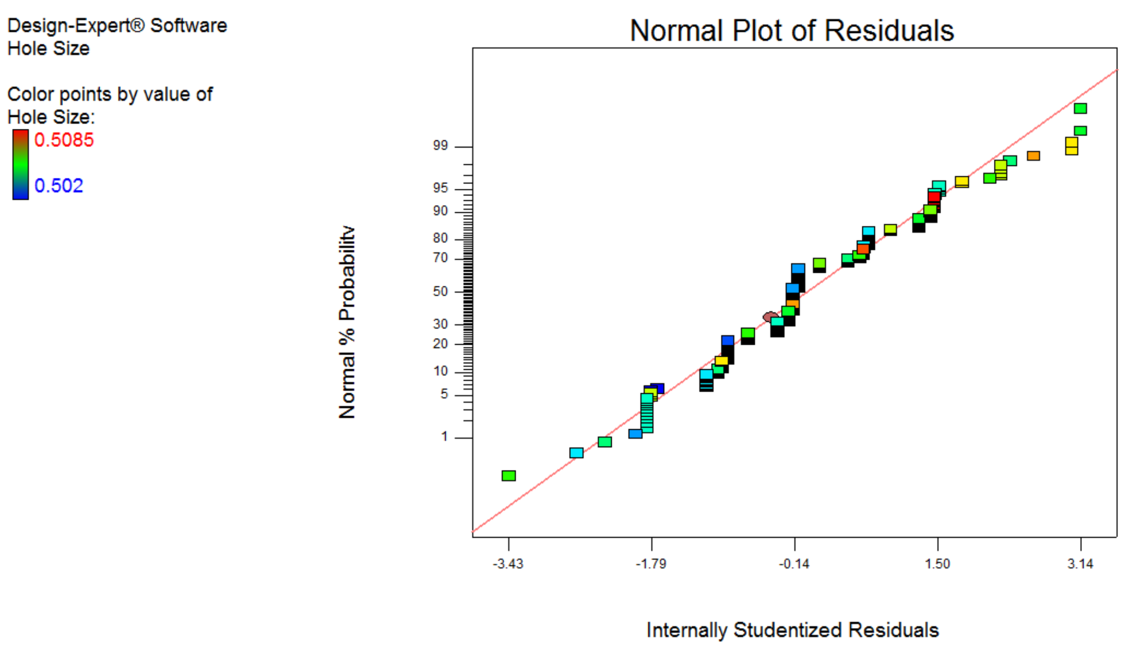

Figure 11: Normal Plots of Residual in Data for Inner Diameter Deviation

Furthermore, plots from Design Expert were also used to test the assumption of constant variance for inside diameter readings. To fulfill the test, these plot should be a random scatter (i.e. constant range of residual across the graph). The plots of residual vs. predicted for the given response in the inside diameter readings is shown in Figure 12. The constant variance in the data demonstrates the data does not follow a particular pattern, indicating constant variance.

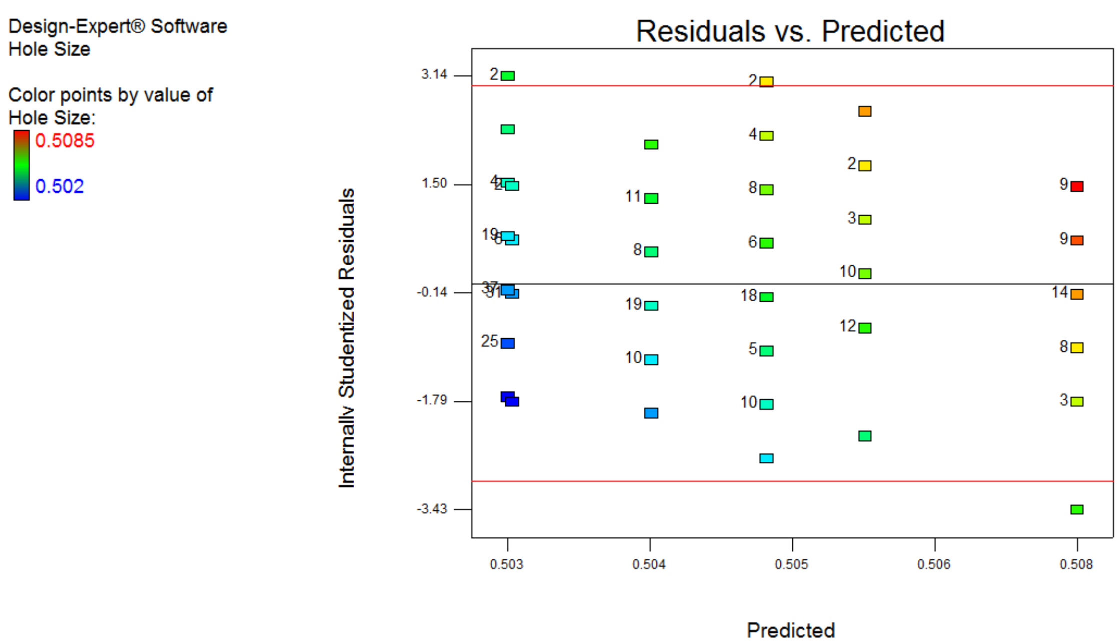

Figure 12: Constant Variance in Data for Inner Diameter Deviation

Plots from Design Expert were used to inspect the data for normality for surface finish readings. A normal probability plot was used to determine if the distribution of data approximates a normal distribution. The normal plot of residuals for the surface finish is shown in Figure 13. The plots did fall on a straight line except for a few scattered points which were acceptable as they did not resemble any curve or specific pattern. In visualizing the straight line, more emphasis was given on the central values of the plots than on the extremes. The error distribution was normal indicating that the data is normally distributed; hence we can say that the analysis of variance is robust to the normality assumption.

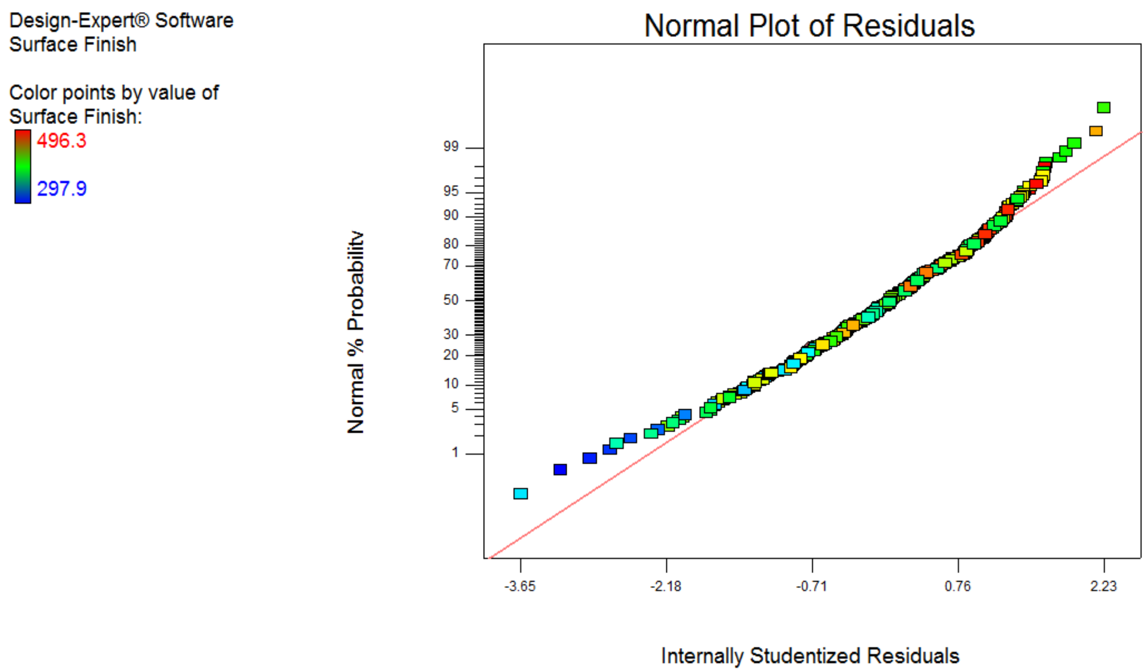

Figure 13: Normal Plots of Residual in Data for Surface Finish

Plots from Design Expert were used to test the assumption of constant variance for surface finish readings. The plot of residual vs. predicted for the given response in surface finish is shown in Figure 14. The constant variance in data demonstrates the data does not follow a particular pattern, indicating constant variance.

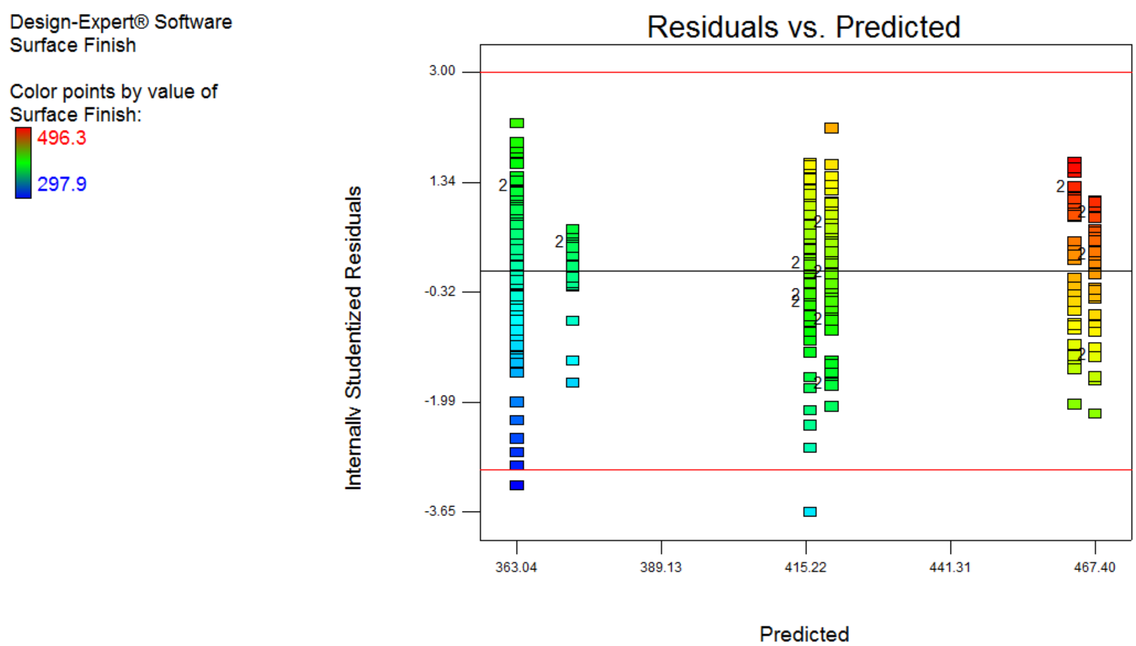

Figure 14: Constant Variance in Data for Surface Finish

Inside Diameter Analysis of Variance Results

Table 8 shows the inside diameter analysis of variance results. The model used for analysis of variance is a general factorial model for a two-factor design. The model source is further identified as A which is cutting speed, B which is the feed rate and AB which is the interaction term of cutting speed and feed rate. The analysis of variance summary at the top of the table contains the sum of squares, degrees of freedom (df), mean squares, and test statistic F_o. The column “Prob > F” is the *p* value (actually, the upper bound on the *p* value, because probabilities less than 0.0001 are defaulted to 0.0001). The model *F* value of 399.56 shown in Table 8 implies that the model is statistically significant based on a 95% confidence level. The *F* value is the ratio of the model sum of squares divided by the residual sum of squares and shows the relative

Table 8: Inner diameter analysis of variance.

	Term	SumSqr	% Contribtn
Model	A-Speed	1.230E-004	13.9055
Model	B-Feed	2.174E-004	24.5748
Model	AB	4.286E-004	48.4638
Error	Lack of Fit	0	0
Error	Pure Error	1.155E-004	13.0558

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	7.690E-004	5	1.538E-004	399.56	< 0.0001	significant
A-Speed	1.883E-004	2	9.417E-005	244.67	< 0.0001	
B-Feed	1.346E-004	1	1.346E-004	349.71	< 0.0001	
AB	4.286E-004	2	2.143E-004	556.81	< 0.0001	
Pure Error	1.155E-004	300	3.849E-007			
Cor Total	8.844E-004	305				

Std. Dev.	6.204E-004	R-Squared	0.8694
Mean	0.50	Adj R-Squared	0.8673
C.V. %	0.12	Pred R-Squared	0.8642
PRESS	1.201E-004	Adeq Precision	52.265

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	0.50	1	3.756E-005	0.50	0.50	
A	9.484E-005	1	4.574E-005	4.828E-006	1.848E-004	
A^2	5.906E-004	1	2.671E-005	5.381E-004	6.432E-004	
B-Feed	7.024E-004	1	3.756E-005	6.285E-004	7.764E-004	1.05
AB	-9.391E-004	1	4.574E-005	-1.029E-003	-8.491E-004	
A^2B	6.287E-004	1	2.671E-005	5.762E-004	6.813E-004	

Final Equation in Terms of Coded Factors:

Hole Size = +0.50 + (9.484E-005 * Speed) + (5.906E-004 * Speed^2) + (7.024E-004 * Feed) – (9.391E-004 * Speed * Feed) + (6.287E-004 * Speed^2 * Feed) contribution of the model variance to the residual variance. In this model there is only a 0.01 % chance that a model F value this large could occur due to noise. The term of “Prob > F” is the probability value which is associated with the F value for this term and is the probability of getting an F value of this size if the term did not have an effect on the response. In this model the values of “Prob > F” less than 0.0500 indicate model terms are significant. Significant model terms are A, B, and AB. If the values are greater than 0.1000 the model terms are non-significant.

In addition to the basic analysis of variance, the program also displays additional useful information. The quantity R-squared is loosely interpreted as the proportion of variability in the data explained by the analysis of variance model. Variations can occur due to vibrations in the machine, human error in measurements or excessive heating of the tools. Thus, for the selected factorial model of the hole size, the R-squared value is 86.94 percent. This explains that the model is able to predict 86.94 percent of the variation in the data. The 13.06 percent is due to the uncontrollable factors such as tool wear and vibrations. Larger values of R-square are more desirable as they indicate less variability. The predicted R-square is a measure of how good the model predicts a response value and the adjusted R-square is the amount of variation about the mean. Here, the Pred R-Squared value of 0.8642 is in reasonable agreement with the Adj R-Squared of 0.8673.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 52.265 indicates an adequate signal. Hence, the model can be used to navigate the design space.

The resulting regression model is shown below:

$$\text{Hole Size} = 0.50 + (9.484E - 005 \ \times Speed) + \ (5.906E - 004 \ \times Speed^2) + \ (7.024\text{E} - 004 \ \times \ \text{Feed}) - \ (9.391\text{E} - 004 \ \times \ \text{Speed} \ \times \ \text{Feed}) + \ (6.287\text{E} - 004 \ \times Speed^2 \ \times \ \text{Feed})$$

This model is the predictor of the inside hole diameter as a result of changing the cutting speed and feed rate.

Surface Finish Analysis of Variance Results

Table 9 shows the surface finish analysis of variance results. The model used for analysis of variance is a general factorial model for a two-factor design. The model source is further identified as A which is speed, B which is feed and AB which is interaction of speed and feed. The analysis of variance summary at the top of the table contains the sum of squares, degrees of freedom (df), mean squares, and test statistic F_o.

The model F value of 246.69 shown in Table 9 implies the model is statistically significant based on 95% confidence level. In this model there is only a 0.01 % chance that a model F value this large could occur due to noise. In this model the values of Prob > F less than 0.0500 indicate model terms are significant. Significant model terms are A, B and AB. If the values are greater than 0.1000 the model terms are non-significant.

The quantity R-squared is loosely interpreted as the proportion of variability in the data explained by the analysis of variance model. Thus, for the selected factorial model of the surface finish, the R-squared value is 80.44 %. This explains that the

Table 9: Surface finish analysis of variance.

	Term	SumSqr	% Contribtn
Model	A-Speed	117940	18.9346
Model	B-Feed	146196	23.471
Model	AB	291.585	38.0304
Error	Lack of Fit	0	0
Error	Pure Error	121860	19.564

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	5.010E+005	5	1.002E+005	246.69	< 0.0001	significant
A-Speed	1.025E+005	2	51262.94	126.20	< 0.0001	
B-Feed	84066.33	1	84066.33	206.96	< 0.0001	
AB	2.369E+005	2	1.184E+005	291.58	< 0.0001	
Pure Error	1.219E+005	300	406.20			
Cor Total	6.229E+005	305				

Std. Dev.	20.15	R-Squared	0.8044
Mean	410.74	Adj R-Squared	0.8011
C.V. %	4.91	Pred R-Squared	0.7973
PRESS	1.263E+005	Adeq Precision	36.980

Term	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	417.19	1	1.22	414.79	419.59	
A	-9.41	1	1.49	-12.33	-6.49	
A^2	-13.23	1	0.87	-14.94	-11.52	
B-Feed	17.55	1	1.22	15.15	19.96	1.05
AB	-35.87	1	1.49	-38.80	-32.95	
A^2B	-3.10	1	0.87	-4.81	-1.39	

Final Equation in Terms of Coded Factors:

$$\text{Surface Finish} = +\,417.19 - (9.41 * \text{Speed}) - (13.23 * \text{Speed}^2) + (17.55 * \text{Feed}) - (35.87 * \text{Speed} * \text{Feed}) - (3.10 * \text{Speed}^2 * \text{Feed})$$

model can predict 80.44 % variation in the data. There is about 19.56 % noise in the data due to uncontrollable factors such as human error in aligning the component with fixture and surface profilometer, measuring the surface roughness, vibrations in the machine, excessive heating of the tools and tool wear. Here, the Pred R-Squared value of 0.7973 is in reasonable agreement with the Adj R-Squared value of 0.8011.

Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 36.980 indicates an adequate signal. This model can be used to navigate the design space.

The resulting regression model is shown below:

$$\text{Surface Finish} = 417.19 - (9.41 \times Speed) - (13.23 \times Speed^2) + (17.55 \times Feed) - (35.87 \times Speed \times Feed) - (3.10 \times Speed^2 \times Feed)$$

This model is the predictor of surface finish as a result of changing the cutting speed and feed rate.

The correlation analysis of inside diameter for treatment having 80 SFM and 0.003 IPR is shown in Figure 15 (a). From the figure we can observe a trend at the initial stage and at the end. These trends are highlighted in Figure 15 (b) and (c). Figure 15 (b) shows there is an initial increase in the hole diameter from 0.5025 inches up to 0.5050 inches at the 40^{th} hole. There is a decrease in hole size from the 40^{th} hole to the 100^{th} hole where the hole diameter becomes 0.5030 inches. A similar trend in hole diameter is observed when the machine is started again for drilling holes the next day and is highlighted in Figure 15 (c) where the hole size increases from the 730th to the 770th hole from 0.5025 to 0.5050 inches and then decreases to 0.5025 inches at the 820th hole. Both observations of Figure 15 (b) and (c) signify that when the machine was initially started it drilled holes with gradually increasing diameter and after a few holes the hole size decreased and remained constant. The holes drilled in between do not show any particular pattern. At the 880th hole the tool fails because the hole size becomes 0.5020 inches which is less than the first hole size. Out of the six combinations, the combination of 80 SFM and 0.003 IPR had the maximum number of holes drilled. The reason for this might be the lowest speed and feed rate used.

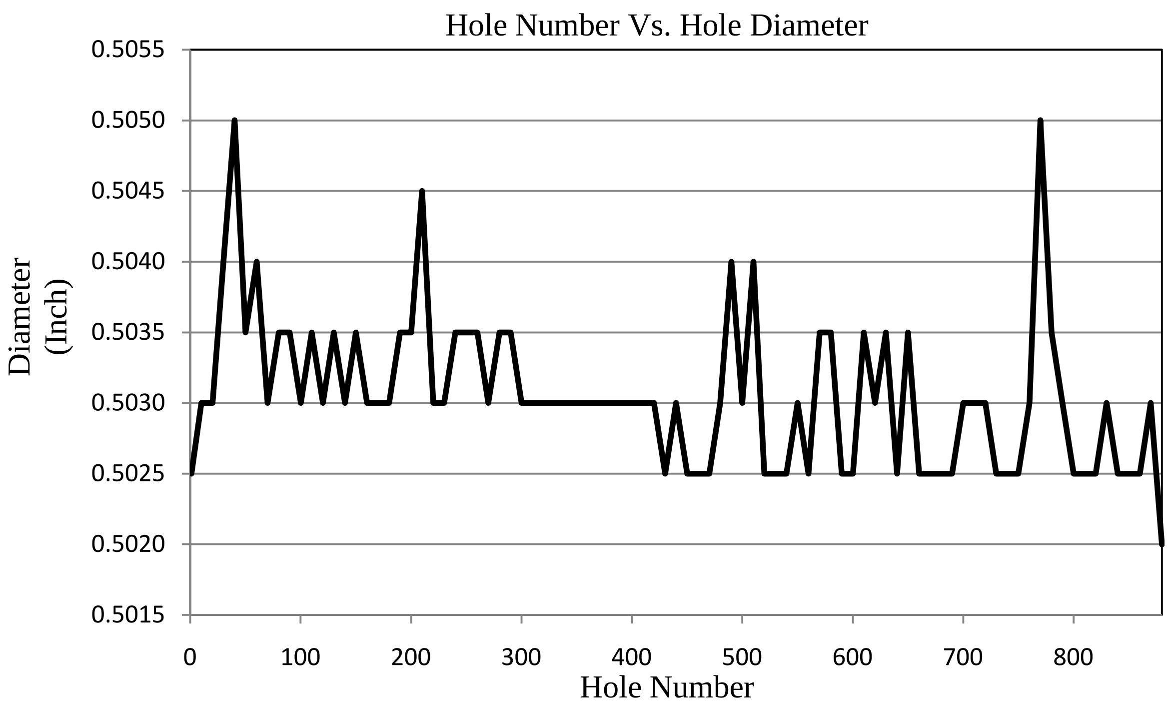

Figure 15 (a): Correlation Analysis of Inside Diameter (1st to 880th hole)

(Treatment 80 SFM & 0.003 IPR)

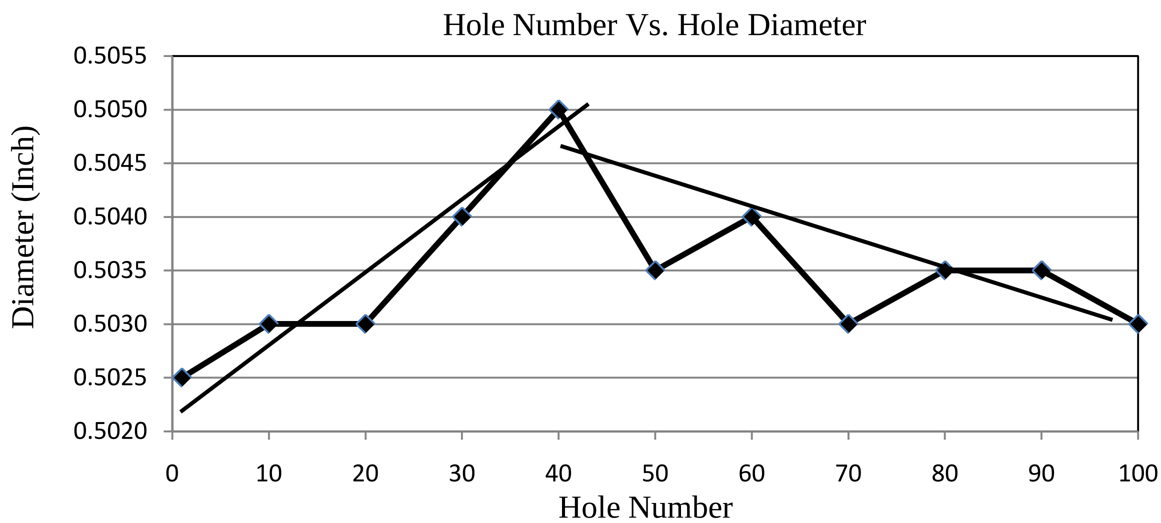

Figure 15 (b): Correlation Analysis of Inside Diameter (1st to 100th hole)

(Treatment 80 SFM & 0.003 IPR)

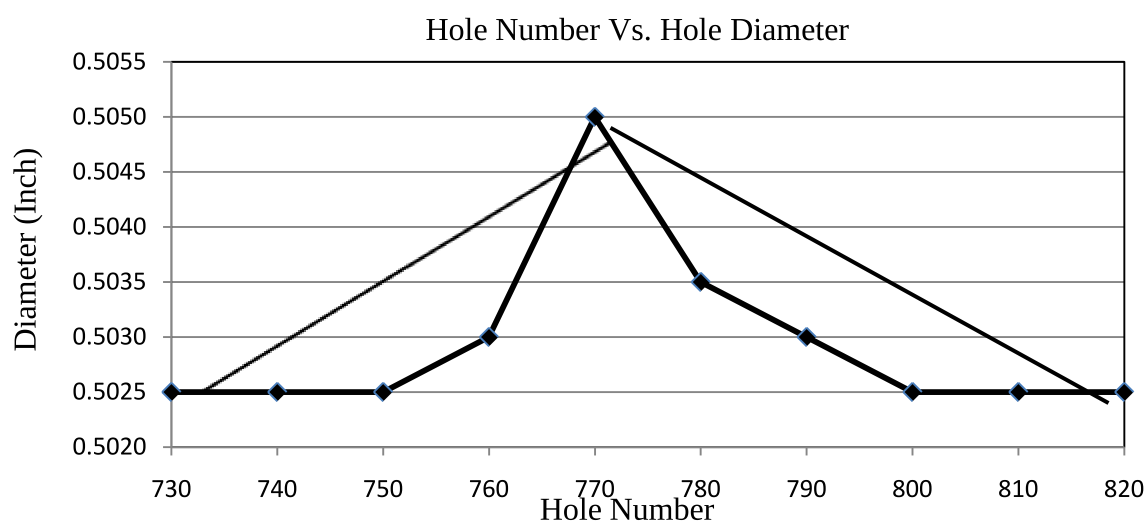

Figure 15 (c): Correlation Analysis of Inside Diameter (730th to 820th hole)

(Treatment 80 SFM & 0.003 IPR)

The correlation analysis of inside diameter for treatment having 120 SFM and 0.003 IPR is shown in Figure 16 (a). The first hole drilled is 0.5040 inches. An increasing trend of hole size is observed from the initial to the 340th hole is shown in Figure 16 (b), where the hole size becomes maximum at 0.5070 inches. This is a general trend observed during drilling of holes, where initially the hole size is less and as the drilling progresses the hole size increases due to heating of the tool. There is no specific trend seen in the figures. The tool failed at the 530th hole where the hole diameter became 0.5035 inches which is less than the first hole drilled. For the feed rate of 0.003 IPR, 120 SFM was the maximum speed used for the study. Eventhough after using maximum speed we got less number of drilled hole when we compare it with the earlier combination. Hence we can say that by increasing the speed of the tool we cannot increase tool life.

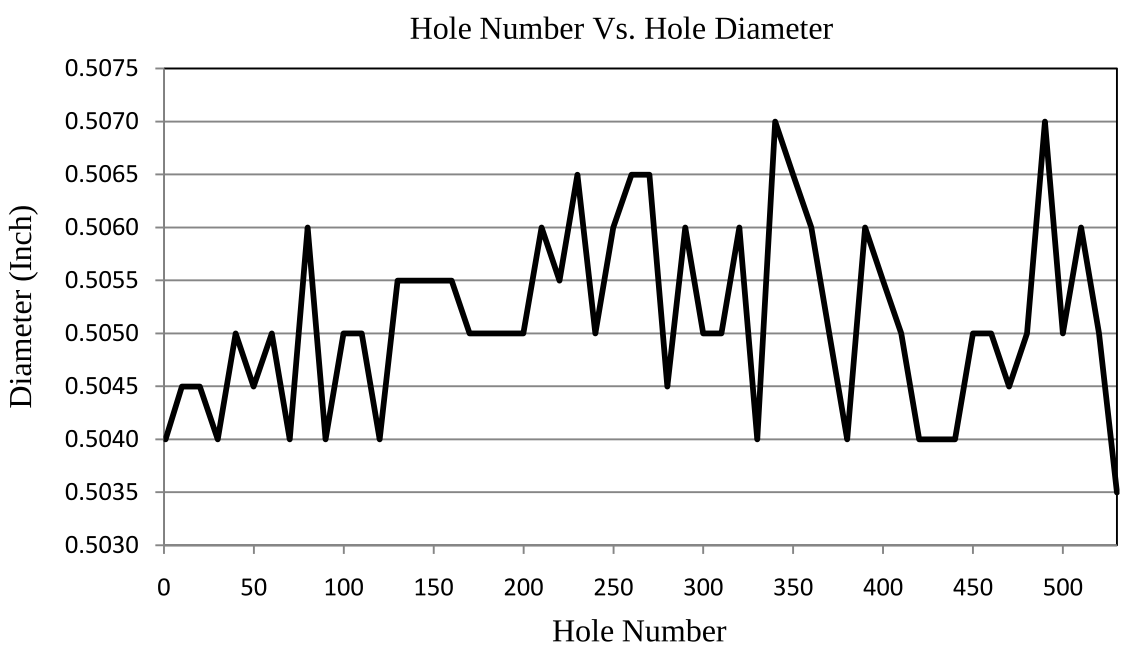

Figure 16 (a): Correlation Analysis of Inside Diameter (1st to 530th hole)

(Treatment 120 SFM & 0.003 IPR)

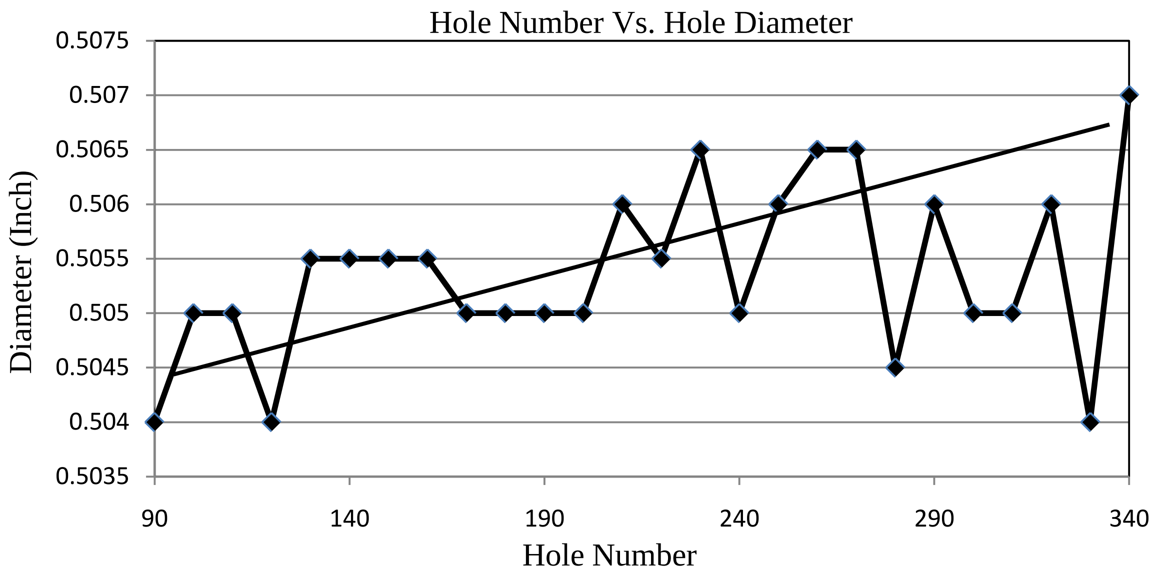

Figure 16 (b): Correlation Analysis of Inside Diameter (90th to 340th hole)

(Treatment 120 SFM & 0.003 IPR)

The correlation analysis of inside diameter for a treatment having 100 SFM and 0.003 IPR is shown in Figure 17. The first hole drilled is 0.5035 inches. The figure does not depict any trend. After the initial hole, the hole size varies in the range of 0.5035 to 0.5050 inches up to the 390th hole. The hole size becomes maximum at 0.5055 inches at the 390th hole and finally the tool fails at the 490th hole where the hole diameter becomes 0.5030 inches which is less than the initial hole size. For the feed rate of 0.003 IPR we observed that when the cutting speed was minimum the tool drilled maximum hole and vice versa. The speed of 100 SFM was the intermediate speed used between 80 SFM and 120 SFM. This speed of 100 SFM when used along with 0.003 IPR, gave a tool life of 490 holes which is lower that the tool life given by the highest speed of 120 SFM. The highest speed (i.e. 120 SFM) had a tool life of 530 holes and the lowest speed (i.e. 80 SFM) had a tool life of 880 holes.

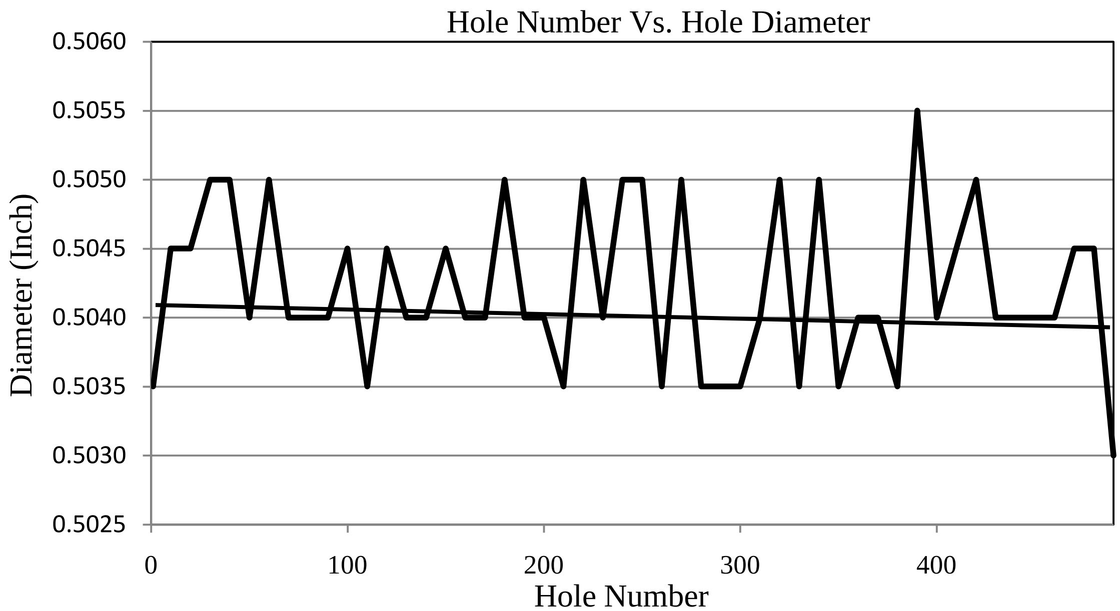

Figure 17: Correlation Analysis of Inside Diameter (1st to 490th hole)
(Treatment 100 SFM & 0.003 IPR)

The correlation analysis of inside diameter for a treatment having 80 SFM and 0.004 IPR is shown in Figure 18 (a). The first hole drilled is 0.5065 inches. From Figure 18 (b), we can observe the hole size follows a particular trend from the initial hole size to the 350th hole where the hole size becomes 0.5085 inches. After the 350th hole there is a decreasing trend of hole size as shown in Figure 18 (c). The tool fails at the 430th hole where the hole size becomes 0.5055 inches which is less than the first hole drilled. The increasing trend of the hole size until the 350th hole, can be a result of tool expansion caused by excessive heat generated at the point of cutting. The trend followed by hole size after the 350th hole is a general pattern observed in drilling. After drilling a particular number of holes there is wear and tear of the tool. The tool drills holes which are lesser in size than previously drilled holes. The tool wear and tear can be due to the higher feed rate of 0.004 IPR and becomes the main source of tool failure. Even though the speed used was minimum at 80 SFM; the tool could not drill more holes because of a higher feed rate of 0.004 IPR. The tool life for this combination of 80 SFM and 0.004 IPR was 430 holes.

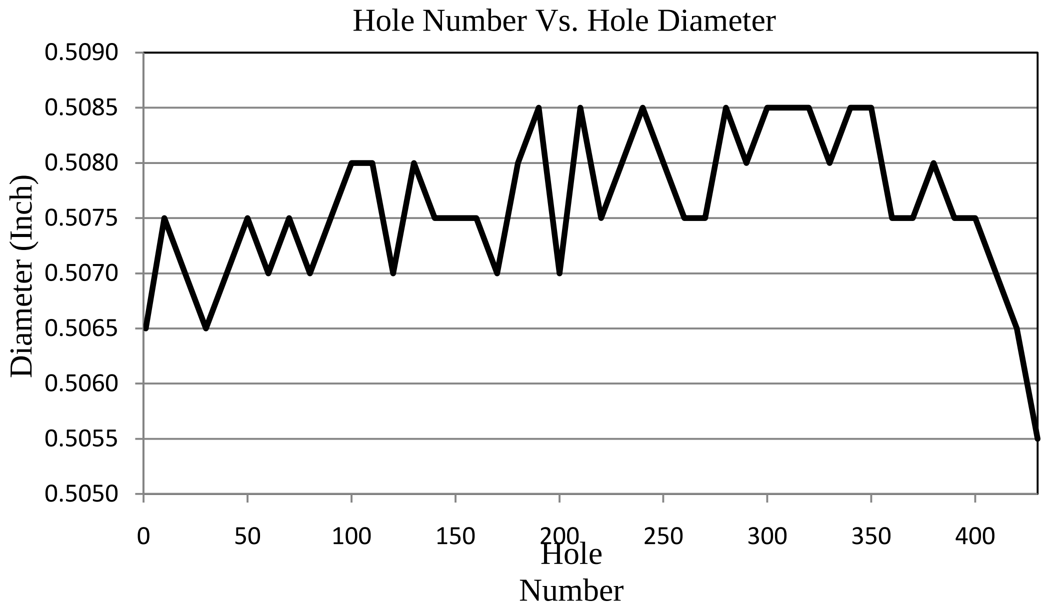

Figure 18 (a): Correlation Analysis of Inside Diameter (1st to 430th hole)

(Treatment 80 SFM & 0.004 IPR)

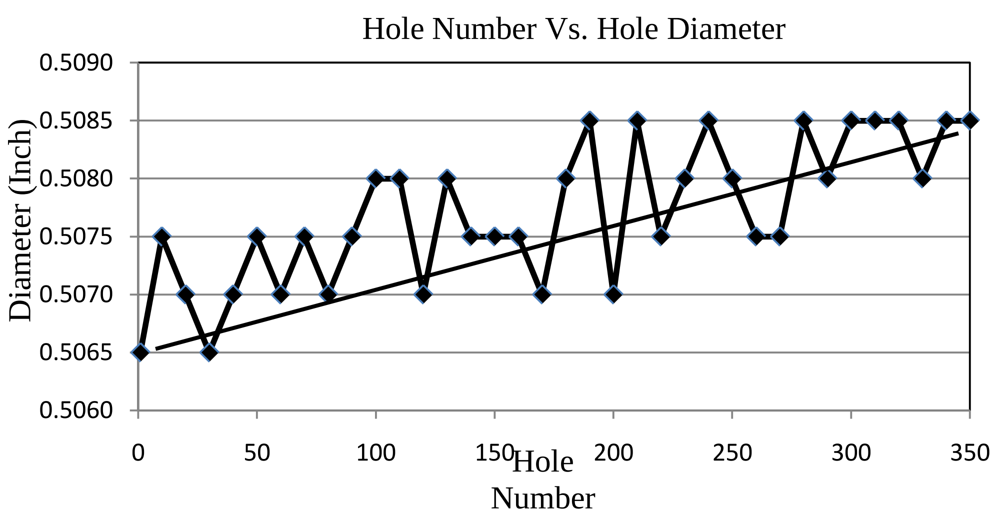

Figure 18 (b): Correlation Analysis of Inside Diameter (1st to 350th hole)

(Treatment 80 SFM & 0.004 IPR)

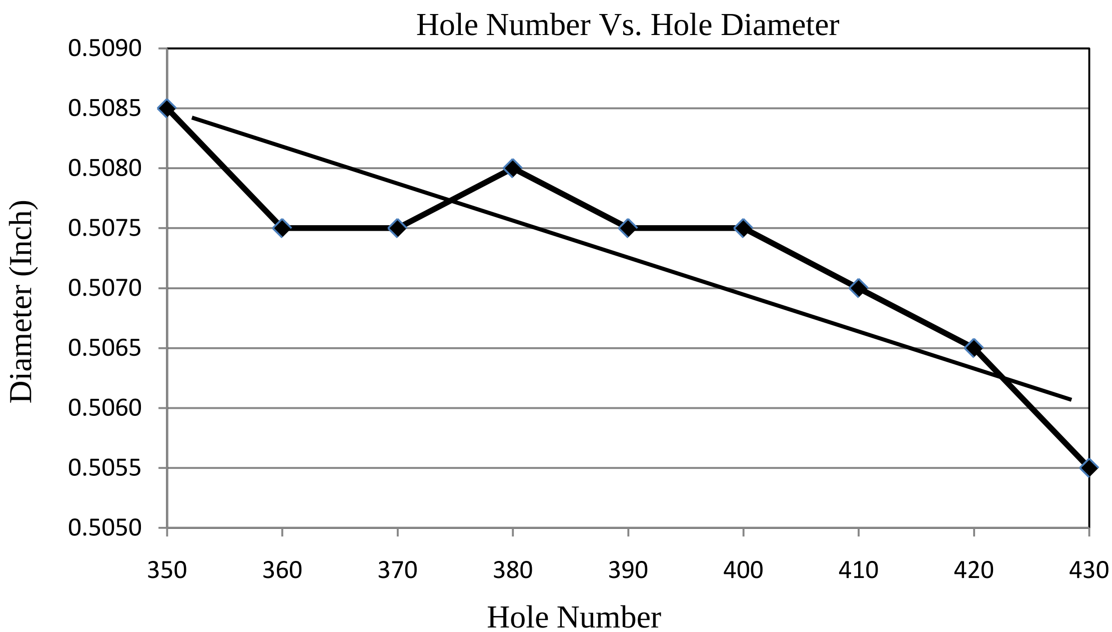

Figure 18 (c): Correlation Analysis of Inside Diameter (350th to 430th hole)

(Treatment 80 SFM & 0.004 IPR)

The correlation analysis of inside diameter for a treatment having 120 SFM and 0.004 IPR is shown in Figure 19 (a). The first hole drilled is 0.5055 inches. Figure 19 (a) shows a decreasing trend of hole size from the 250th to the 280th hole before the tool fails. This trend is highlighted in Figure 19 (b). The hole size decreases from a maximum of 0.5075 inches at the 250th hole to a minimum of 0.5045 inches at the 280th hole where the tool fails. This trend might have occurred due to wear and tear of the tool. Among the six combinations used for these experiments, this particular combination had the maximum speed and feed rate and produced the minimum number of holes. Hence we can say that just by increasing the speed and feed of the drill we cannot increase the tool life.

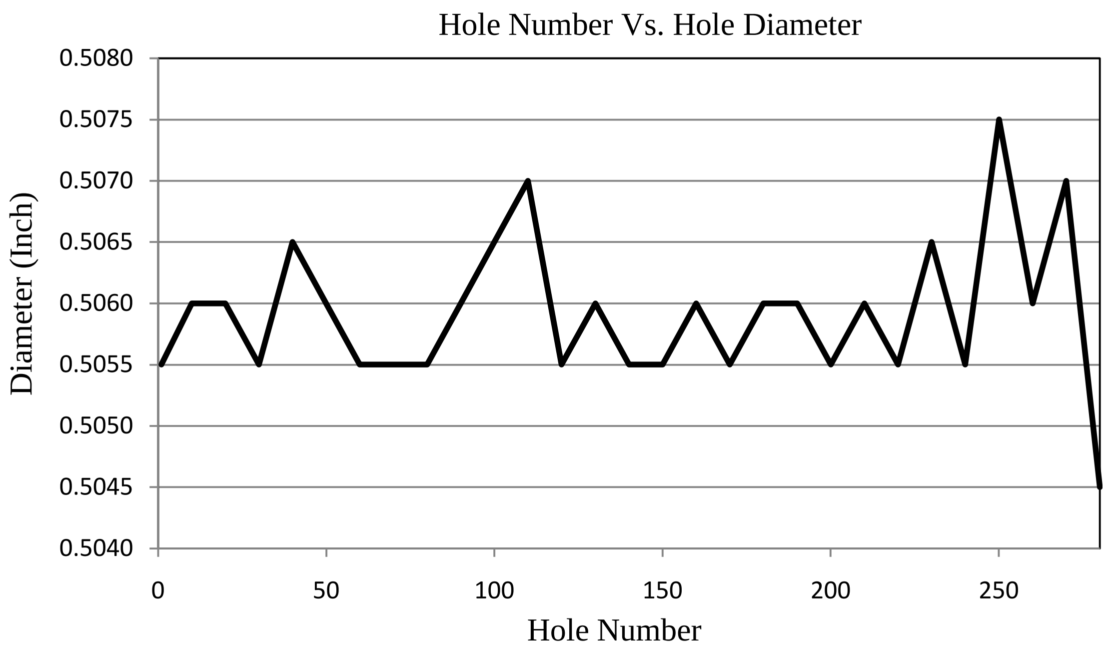

Figure 19 (a): Correlation Analysis of Inside Diameter (1st to 280th hole)

(Treatment 120 SFM & 0.004 IPR)

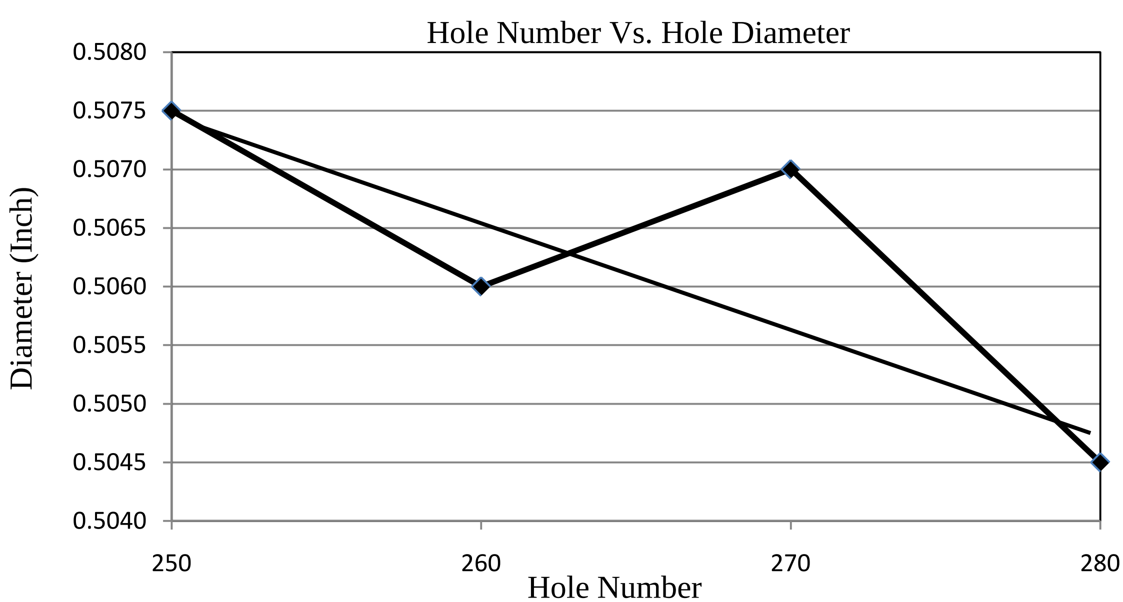

Figure 19 (b): Correlation Analysis of Inside Diameter (250th to 280th hole)

(Treatment 120 SFM & 0.004 IPR)

The correlation analysis of inside diameter for a treatment having 100 SFM and 0.004 IPR is shown in Figure 20. The first hole drilled is 0.5030 inches. Figure 20 shows a slight increase in hole diameter reading until the 60th hole, where the decreasing trend in hole diameter begins, until the tool failed when the hole diameter became 0.001 inch less than the first hole diameter at the 390th hole. The speed of 100 SFM was the intermediate speed used between 80 SFM and 120 SFM. This speed of 100 SFM when used along with 0.004 IPR, gave a tool life of 390 holes which is between the tool life given by the highest speed and lowest speed when used along with 0.004 IPR. The highest speed (i.e. 120 SFM) had a tool life of 280 holes and the lowest speed (i.e. 80 SFM) had a tool life of 430 holes.

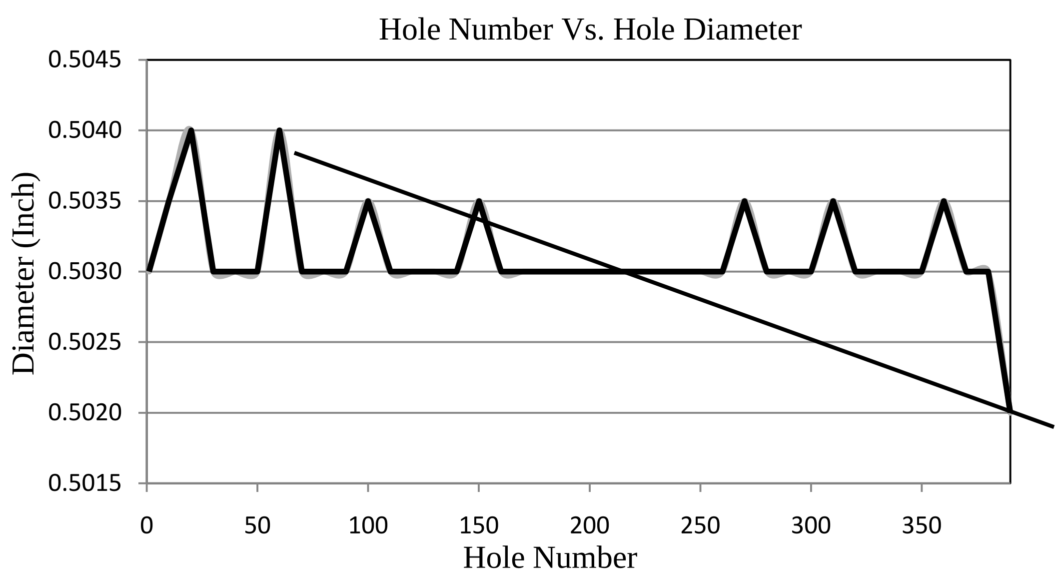

Figure 20: Correlation Analysis of Inside Diameter (1st to 390th hole)
(Treatment 100 SFM & 0.004 IPR)

The correlation analysis of surface roughness for a treatment having 80 SFM and 0.003 IPR is shown in Figure 21 (a). The first hole drilled has a surface roughness of

361.3 micro inches. No specific trend was observed in the initial set of data for the surface roughness. The data was scattered over a wide range. At the 360th hole, the surface roughness value reaches a maximum of 407.7 micro inches. At the end before tool failure we could observe a trend as shown in Figure 21 (b) where the surface roughness decreases to a minimum value of 297.9 micro inches. This was also the point where tool failure occurred. When the tool continues drilling holes the surface roughness of the holes increases. But in this case as the final drilled hole was approached the holes showed a smoother surface than any of the previously drilled holes. The reason for this smoother surface can be excessive heat generation at the end of the drilling cycle which makes the tool more blunt. Due to excessive heat generation there is more wear and tear of the tool and edges of the flute lose their sharpness. There is more friction rather than cutting action which makes the surface smoother.

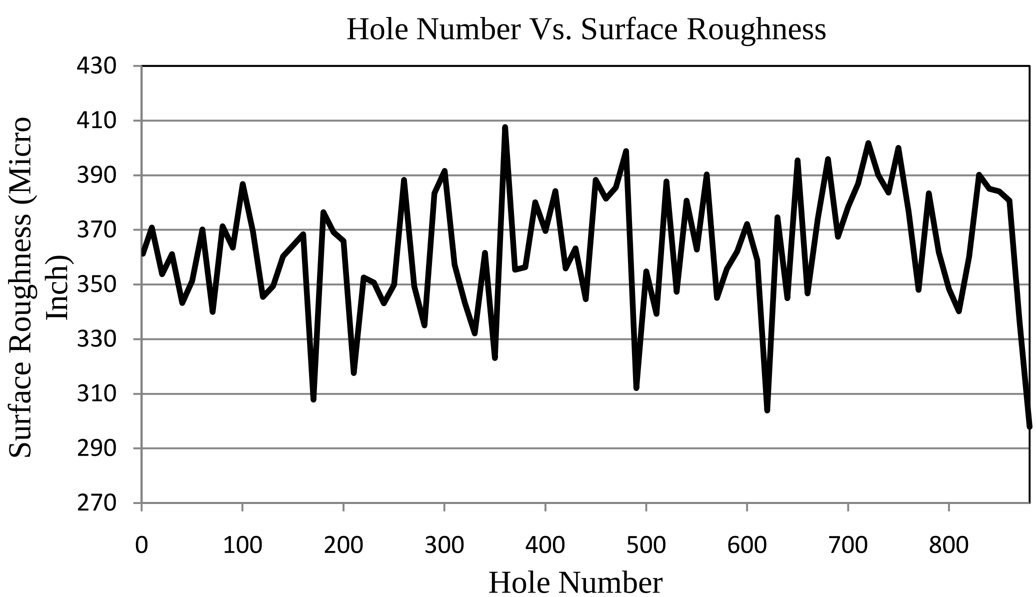

Figure 21 (a): Correlation Analysis of Surface Roughness (1st to 880th hole)
(Treatment 80 SFM & 0.003 IPR)

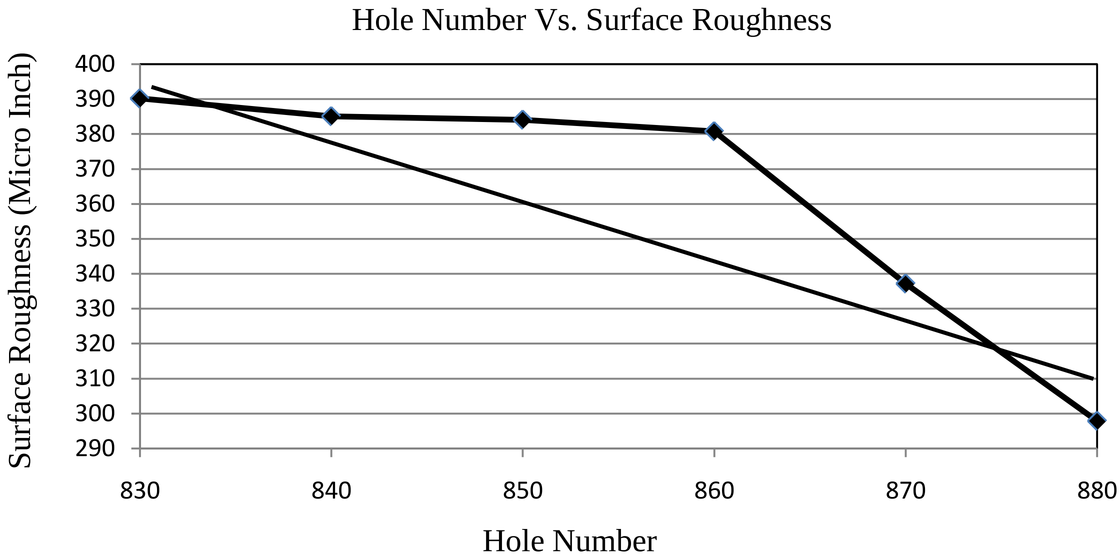

Figure 21 (b): Correlation Analysis of Surface Roughness (830th to 880th hole)

(Treatment 80 SFM & 0.003 IPR)

The correlation analysis of surface roughness for a treatment having 120 SFM and 0.003 IPR is shown in Figure 22 (a). The first hole drilled had a surface roughness of 445.6 micro inches. Figure 22 (a) depicts a trend of decreasing surface roughness throughout the drilling of holes for this combination. But the surface roughness drastically decreased before the tool failure as shown in Figure 22 (b). At the 250th hole, the surface roughness reading increased to a maximum value of 448.3 micro inches. After the 510th hole, the surface roughness decreased drastically until the 530th hole where the hole diameter became less than the initial hole with a minimum surface roughness of 343.1 micro inches. The range of surface roughness for the combination of 120 SFM and 0.003 IPR is approximately 410 micro inches which is more than the range of surface roughness for the combination of 80 SFM and 0.003 IPR which is approximately 350 micro inches. Hence we can say that increasing cutting speed does not produce a good surface finish.

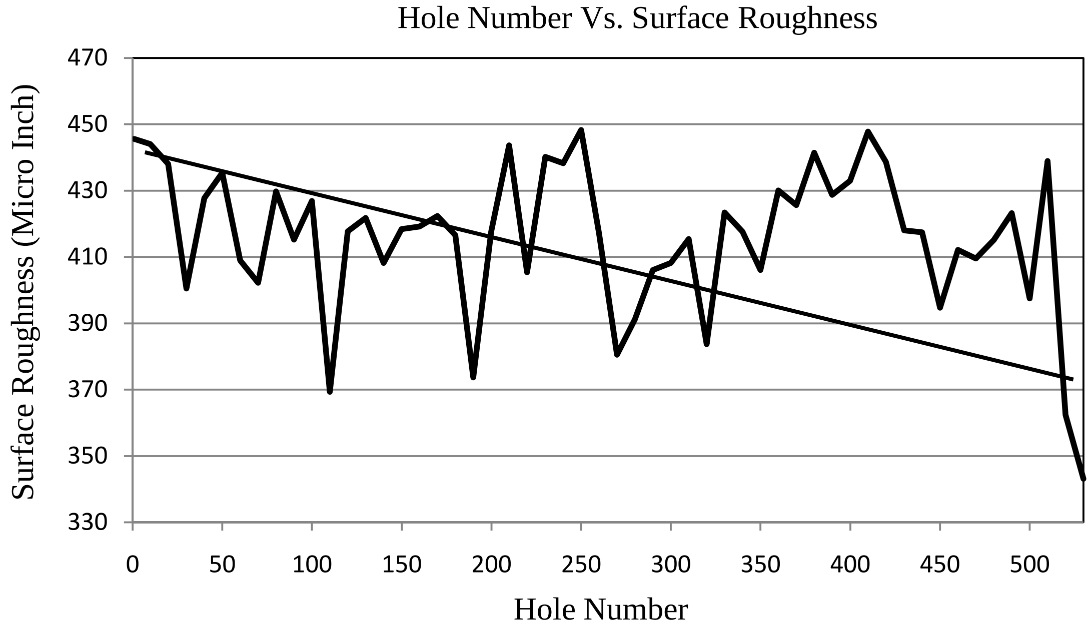

Figure 22 (a): Correlation Analysis of Surface Roughness (1^{st} to 530^{th} hole)

(Treatment 120 SFM & 0.003 IPR)

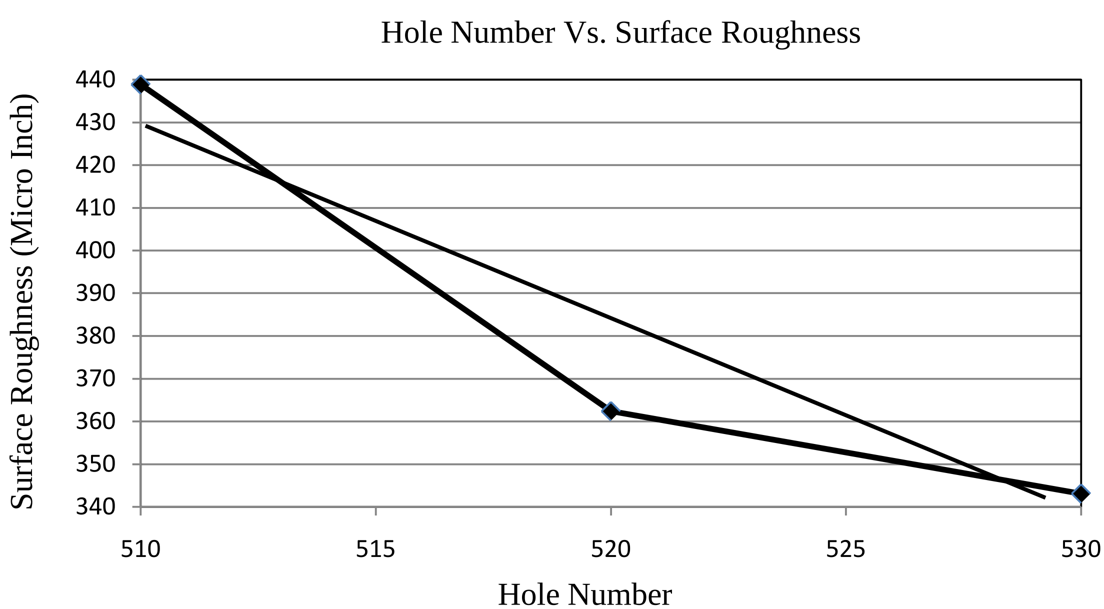

Figure 22 (b): Correlation Analysis of Surface Roughness (510^{th} to 530^{th} hole)

(Treatment 120 SFM & 0.003 IPR)

The correlation analysis of surface roughness for a treatment having 100 SFM and 0.003 IPR is shown in Figure 23 (a). The first hole drilled had a surface roughness of 462.8 micro inches. There is a specific decreasing trend in the surface roughness from the first hole to the 270th hole as observed in Figure 23 (a). This trend is highlighted in Figure 23(b). At the end of the experiment the data became fairly constant. This was a unique trend when compared with surface roughness readings of earlier experiments. The first hole had the maximum surface roughness value of 462.8 micro inches and the 40th hole had the minimum surface roughness value of 378.9 micro inches. The tools failed at the 490th hole, where the hole diameter became less than the initial hole with a surface roughness of 404.8 micro inches.

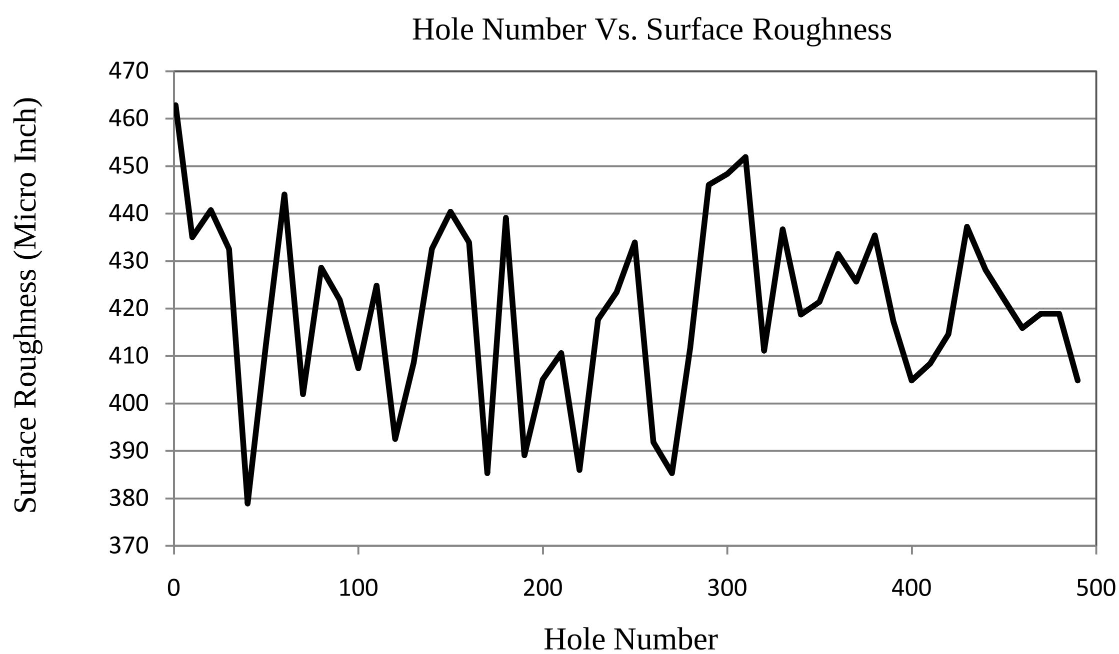

Figure 23 (a): Correlation Analysis of Surface Roughness (1st to 490th hole)

(Treatment 100 SFM & 0.003 IPR)

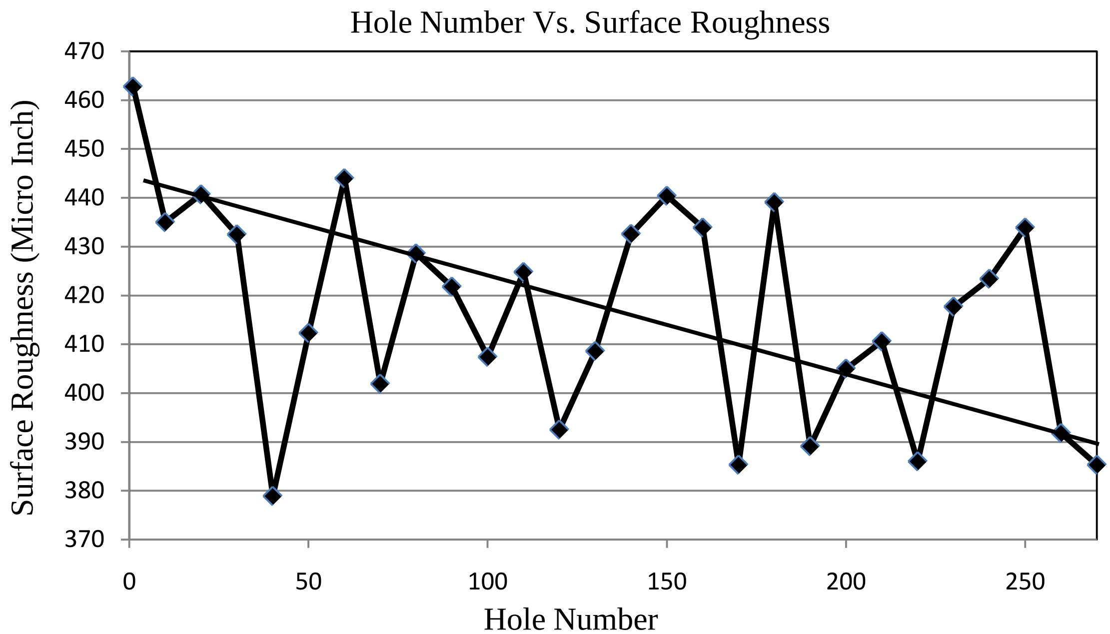

Figure 23 (b): Correlation Analysis of Surface Roughness (1st to 270th hole)

(Treatment 100 SFM & 0.003 IPR)

The correlation analysis of surface roughness for a treatment having 80 SFM and 0.004 IPR is shown in Figure 24 (a). The first hole drilled had a surface roughness of 496.3 micro inches. Figure 24 (a) does not show any particular trend of surface roughness readings in the initial stage of drilling holes where the 30th hole had the maximum surface roughness value of 496.3 micro inches and the 70th hole had the minimum surface roughness value of 423.5 micro inches. The data is scattered over a large range until the 350th hole. Just before tool failure a decreasing trend was observed in the surface roughness reading as shown in Figure 24 (b). The tools failed at the 430th hole, where the hole diameter became less than the initial hole with a surface roughness of 438.0 micro inches.

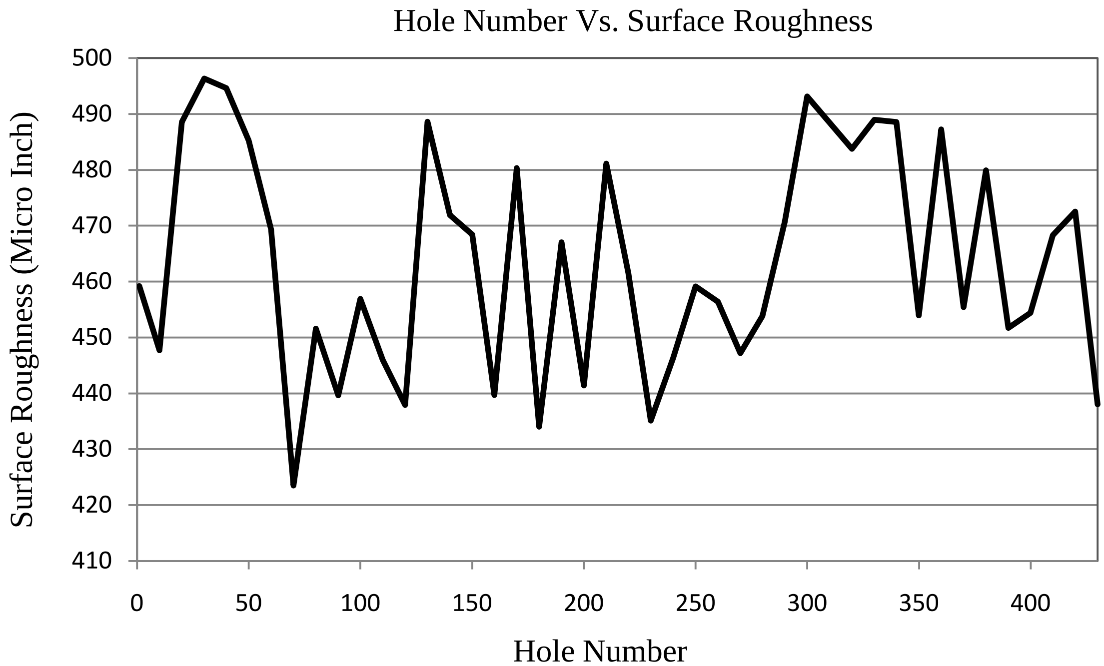

Figure 24 (a): Correlation Analysis of Surface Roughness (1st to 430th hole)

(Treatment 80 SFM & 0.004 IPR)

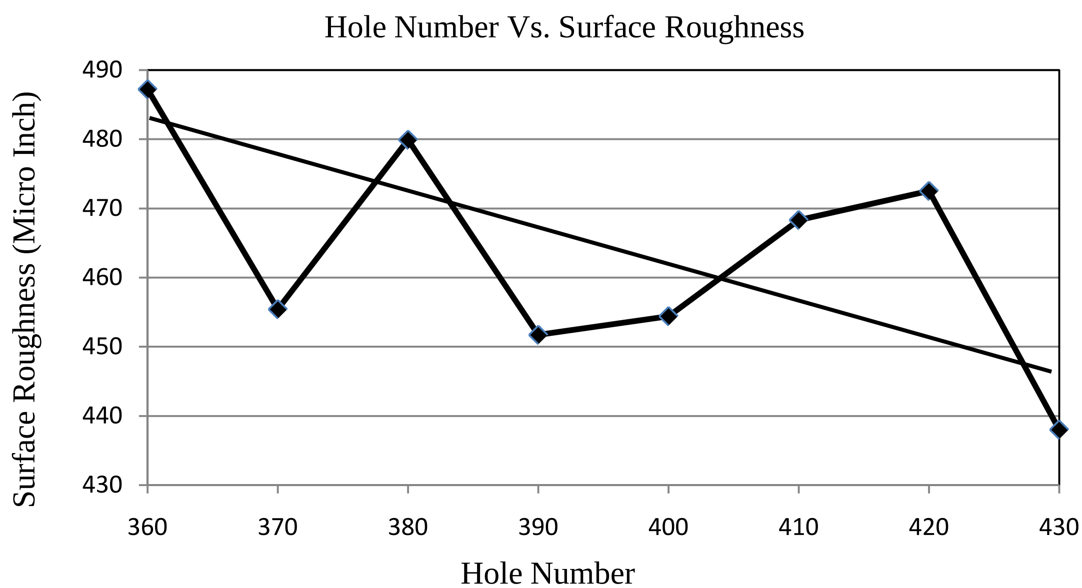

Figure 24 (b): Correlation Analysis of Surface Roughness (360th to 430th hole)

(Treatment 80 SFM & 0.004 IPR)

The correlation analysis of surface roughness for a treatment having 120 SFM and 0.004 IPR is shown in Figure 25 (a). The figure shows that the surface roughness value of the first hole drilled is 374.6 micro inches. The figure also shows an increasing trend of surface roughness from the initial hole to the 250th hole which is the general case of drilling holes and can be a result of expansion due to excessive heat generation at the point of cutting action. But after the 250th hole the surface roughness value decreases as shown in Figure 25 (b), until the tool failed at the 280th hole, where the hole diameter became less than the initial hole with a surface roughness of 339.6 micro inches. Such unusual trends were observed in all the drilling and the reason can be the bluntness of the tool and tool wear and tear due to chip tool interface.

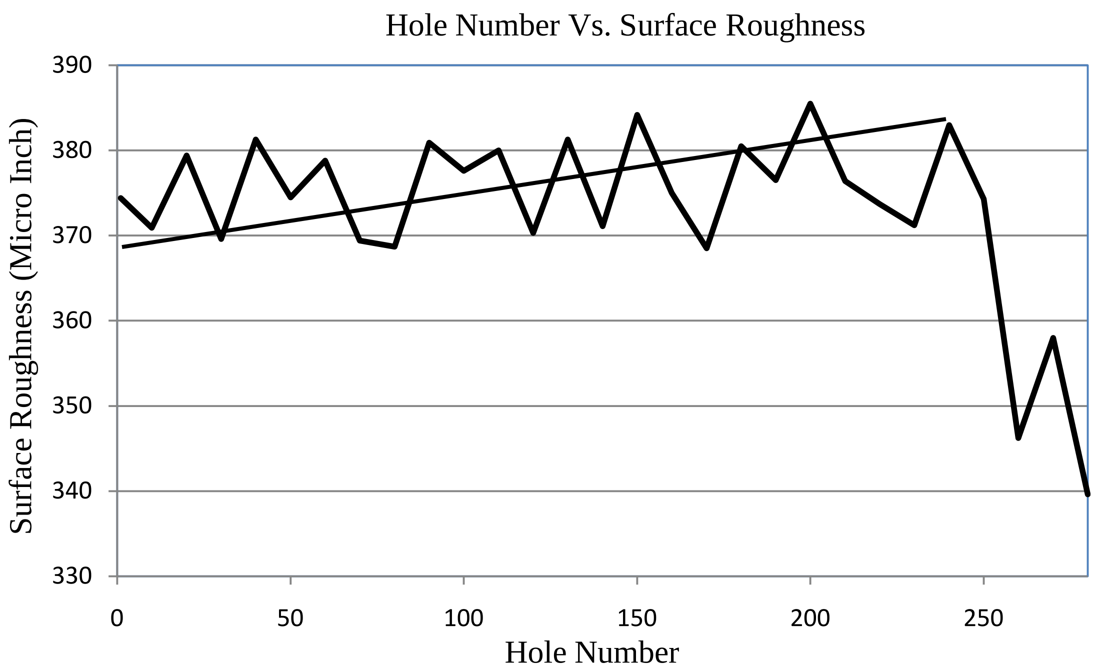

Figure 25 (a): Correlation Analysis of Surface Roughness (1st to 280th hole)

(Treatment 120 SFM & 0.004 IPR)

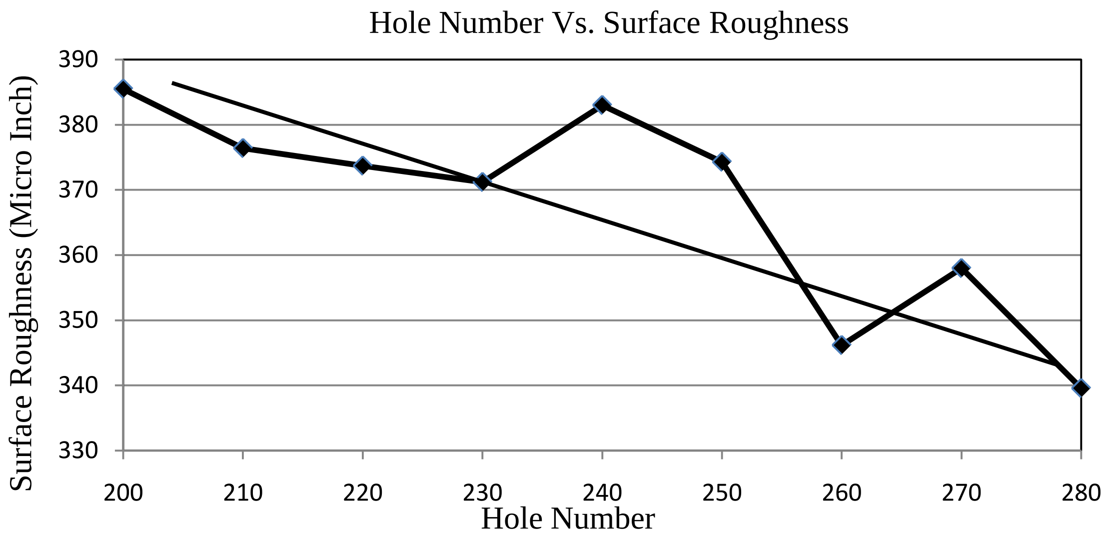

Figure 25 (b): Correlation Analysis of Surface Roughness (200th to 280th hole)

(Treatment 120 SFM & 0.004 IPR)

The correlation analysis of surface roughness for a treatment having 100 SFM and 0.004 IPR is shown in Figure 26. The figure shows that the surface finish of the first hole drilled is 458.9 micro inches. The figure does not show any pattern. The data is very widely scattered. Observed is that at 250th hole, the surface roughness value decreases to 424.3 micro inches. The tool failed at the 390th hole, where the hole diameter became less than the initial hole with a surface roughness of 471.9 micro inches. The range of surface roughness (i.e. around 490 micro inches) is greater as compared to the combination of 120 SFM and 0.004 IPR which has a surface roughness range of approximately 380 micro inches. The surface roughness range of a combination of 100 SFM and 0.004 IPR is somewhat similar to the range given by a combination of 80 SFM and 0.004 IPR. We can conclude that when feed rate is high, smoother surfaces are obtained when higher speeds are used.

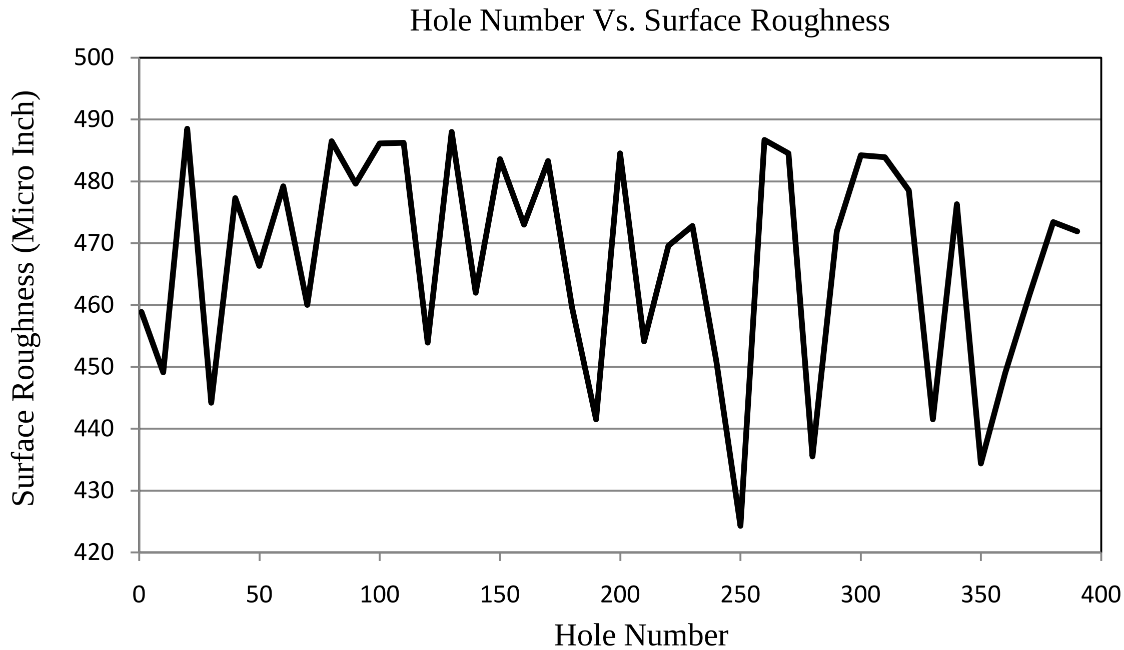

Figure 26: Correlation Analysis of Surface Roughness (1st to 390th hole)

(Treatment 100 SFM & 0.004 IPR)

Summary

The analysis was based on inside diameter deviation and surface roughness readings of holes drilled for a total of six combinations having speeds of 80, 100 and 120 SFM and feed rates of 0.003 and 0.004 IPR.

The treatment having 80 SFM and 0.003 IPR had a tool life of 880 holes. Two similar trends were observed in hole size deviation, one at the initial stage and the other before tool failure. Both trends showed an increase of hole size upto 0.5050 inches at the 40th and 770th hole respectively and a decreasing trend until 100th and 880th hole. The minimum hole size measured was at the 880th hole with 0.5020 inches. No specific trend was observed in surface roughness values. At the 360th hole, the surface roughness value reached the maximum of 407.7 micro inches. And at the 880th hole, the surface roughness value reached the minimum of 297.9 micro inches.

For the treatment having 120 SFM and 0.003 IPR the tool life was 530 holes. An increasing trend of hole size was observed from the initial to the 340th hole where the hole size reached the maximum of 0.5070 inches. The maximum hole size measured was 0.5070 inches at the 340th and 490th hole respectively. The minimum hole size measured was at the 530th hole with 0.5035 inches. A decreasing trend of surface roughness was observed throughout the drilling of holes for this combination. The 530th hole had the minimum surface roughness of 343.1 micro inches.

For the treatment having 100 SFM and 0.003 IPR the tool life was 490 holes. The measurement of hole size does not depict any trend. The hole size became maximum at 0.5055 inches at the 390th hole. The tool failed at the 490th hole where the hole diameter became 0.5030 inches which is less than the initial hole size. A decreasing trend in surface roughness from the first hole to the 270th hole was observed. The first hole had the maximum surface roughness of 404.8 micro inches.

Tool life for the treatment having 80 SFM and 0.004 IPR is 430 holes. The hole size followed a particular trend from the initial hole size to the 350th hole where the hole size became 0.5085 inches. After the 350th hole there was a decreasing trend of hole size until the 430th hole where the hole size became 0.5055 inches and the tool failed. The surface roughness reading does not depict any trend. The data is scattered over a large range until the 350th hole. Just before tool failure the surface roughness reading tended to decrease in a range of 40 micro inches.

Tool life for the treatment having 120 SFM and 0.004 IPR is 280 holes. Before the tool failed, a decreasing trend of hole size was observed. The hole size decreased from a maximum of 0.5075 inches at the 250^{th} hole to a minimum of 0.5045 inches at the 280^{th} hole. An increasing trend of surface roughness was observed from the initial hole up to the 250^{th} hole when the surface roughness decreased until the tool failed at the 280^{th} hole with a value of 339.6 micro inches.

Tool life for the treatment having 100 SFM and 0.004 IPR is 390 holes. There is a slight increase in the hole diameter reading until the 60^{th} hole, where the decreasing trend in the hole diameter begins, until the tool failed at the 390^{th} hole where the hole diameter became 0.001 inch less than the first hole diameter. The figure does not show any pattern. The data is widely scattered. Observed is that suddenly at 250^{th} hole, the surface roughness value decreased to 424.3 micro inches.

CHAPTER IV

CONCLUSIONS

This study is conducted to investigate the effects of drilling a 1-inch deep hole into a block of AISI 1018 steel using 0.5 inch high-speed steel drill bits. Two feed rates (0.003 and 0.004 IPR) and three speeds (80, 100 and 120 SFM) for a total of six combination treatments have been performed on a CNC Mori Seiki vertical milling machine; using a vegetable based mist coolant delivered through minimum quantity lubrication (MQL) external method. Conclusions drawn from the results are as follows:

The greatest number of holes was realized using treatment levels of 80 SFM and 0.003 IPR, 880 holes were realized at this treatment. The best surface finish (i.e. ≈ 363 micro inches) was realized using treatment levels of 80 SFM and 0.003 IPR, as compared to all the other treatments. This may be attributed to the lowest speed and feed rate combination used for this treatment. When using cutting speed levels of 100 and 120 SFM and 0.003 IPR feed rate, only 490 and 530 holes were drilled respectively. This may be attributed to the excessive heat generated at the point of cutting and the resulting wear and tear of the tool due to the higher speeds.

The lowest number of holes was realized using treatment levels of 120 SFM and 0.004 IPR. Only 280 holes were realized at this treatment. The reason may be the higher cutting speed and feed rate combination of 120 SFM and 0.004 IPR respectively; which caused bluntness of the tool resulting into friction between work-tool interface which in turn accelerated tool failure. An acceptable level of surface finish (i.e. ≈ 373 micro inches) was realized at this treatment. Cutting with lower speeds of 80 and 100 SFM and 0.004 IPR levels, resulted in more drilled holes when compared to the treatment of 120 SFM and 0.004 IPR. It was also observed that drilling at 80 and 100 SFM and 0.004 IPR combinations, resulted in a poor surface finish of (≈ 463 and 467 micro inches respectively) when compared with that obtained with 120 SFM and 0.004 IPR (i.e. ≈ 373 micro inches). When the feed rate level of 0.003 IPR was used with cutting speed levels of 80, 100 and 120 SFM; the results show that an increase in the cutting speed decreases the surface finish. The reason may be due to the smaller chip thickness produced due to the lower feed rate level of 0.003 IPR. At this level of feed, the chip thickness does not allow for rapid absorption of the heat generated at the work-tool interface as the cutting speed level is increased from 80 to 120 SFM. This results in rougher surfaces of drilled holes. At 0.004 IPR feed rate level, the results show that an increase in the cutting speed decreases the surface roughness. The resulting chip thickness at this level of feed is higher which allows more heat absorption through the chip. This results in the decrease of surface roughness.

The analysis of variance clearly indicates that both the cutting speed and feed rate are statistically significant factors based on 95% confidence level for both the inside diameter deviation and the surface finish analysis. Therefore the null hypothesis stating that, "There is no significant difference between the responses obtained by varying the individual input variables (i.e. speed and feed) is rejected.

Based on the analyses of results described in Chapter IV. It can be concluded that both the number of holes to be drilled (tool life) and the resulting surface finish can be predicted using the obtained regression models, under the conditions investigated in this study.

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