Machining Using Minimum Quantity Lubrication: A Technology for Sustainability

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Abstract

The purpose of this article is to review the relevant literature in machining using minimum quantity lubrication particularly as it pertains to environmental, and health issues , and outline future potential research in this technology. The results indicate that the process of mist particles generation and their physical characteristics are yet to be determined for a whole class of machining processes and machining conditions. The resulting impact of the findings as related to machine and work place design is yet to be determined.

Keywords- Minimum Quantity Lubrication, Sustainable Machining

Introduction

The necessity to machine using less harmful cutting fluids has prompted many researchers to investigate the use of minimum quantity lubrication (MQL). Chalmers(1999) reported that more than 100 million gallons of metalworking fluids are used in the U.S. each year and that 1.2 million employees are exposed to them and to their potential health hazards. The U.S. Occupational Safety and Health Administration (OSHA) (Aronson, 1995) and the U.S. National Institute for Occupational Safety and Health (NIOSH) reported that the permissible exposure level (PEL) for metal working fluid aerosol concentration is 5 mg/m³ and 0.5 mg/m³ respectively (U. S. Department of Health and Human Services, 1998). However, the oilmist level in the U.S. automotive parts manufacturing facilities has been estimated to be 20 – 90 mg/m³ with the use of conventional lubrication by flood coolant (Bennett and Bennett, 1985). The exposure to such amounts of metal working fluid may contribute to adverse health effects and safety issues, including toxicity, dermatitis, respiratory disorders and cancer. The mechanical infrastructure that sustains a flood coolant system is of such complexity that it hinders the rapid reconfiguration of equipment. In the conventional application of flood coolant, the chips produced are wet. They have to be dried before recycling, which incurs additional cost. Minimum quantity lubrication (MQL), on the other hand, produces essentially dry chips, so the cost of drying chips is reduced (Filipovicand Stephenson, 2006). The savings in cutting fluid and related costs could be significant if minimum quantity lubrication was adopted.

Minimum Quantity Lubrication

MQL, also known as "Microlubrication", (MaClure, Adams, GuggerandGressel, 2007) and "Near-Dry Machining" (KlockeandEisenblatter, 1997),is the latest technique of delivering metal cutting fluid to the tool/work interface. Using this technology, a little fluid, when properly selected and applied, can make a substantial difference in how effectively a tool performs. In conventional operations utilizing flood coolant, cutting fluids are selected mainly on the basis of their contributions to cutting performance. In MQL however, secondary characteristics are important. These include their safety properties, (environment pollution and human contact), biodegradability, 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, InasakiandSuda, 2006). In MQL, lubrication is obtained via the lubricant, while a minimum cooling action is achieved by the pressurized air that reaches the tool/work interface. Further, MQLreduces induced thermal shock andhelps to increase the workpiece surface integrity in situations of high tool pressure (Attanasio, Gelfi, GiardiniandRemino, 2006).

Types of MQL Systems

There are two basic types of MQL delivery systems: external spray and through-tool. The external spray system consists of a coolant tank or reservoir which is connected with tubes fitted with one or more nozzles. The system can be assembled near or on the machine and has independently adjustable air and coolant flow for balancing coolant delivery. It is inexpensive, portable, and suited for almost all machining operations. Through-tool MQL systems are available in two configurations; based on the method of creating the air-oil mist. The first is the external mixing or one-channel system. Here, the oil and air are mixed externally, and piped through the spindle and tool to the cutting zone.

The advantages of such systems are simplicity and low cost; they are suited to be retrofitted to existing machines with high-pressure, through the tool coolant capability. They are easy to service; no critical parts are located inside the spindle. The disadvantage is that 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 configuration 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. Such systems have less dispersion and dropouts and can deliver mist with larger droplet sizes than external mixing devices. They also have less lag time when changing tools between cuts or oil delivery rate during a cut. However, the systems are more difficult to maintain; critical parts are located inside the spindle (Filipovicand Stephenson, 2006).

Selected Research on MQL

MQL Applied to Drilling, Milling and Turning Operations

In May 2007, an article was published by Tech Solve, based on a comparison between flood and MQL (MaClure, Adams, GuggerandGressel, 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. The drilling operation used 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 oxide coated HSS with a 135° split point. Sixty holes were drilled using flood coolant and 61 were drilled utilizing MQL. Analysis showed no significant differences in tool life (number of holes to reach end of life criteria) between MQL and flood cooling. Average thrust forces were 570 lbs and 447 lbs for flood and MQL cooling respectively.

The milling operation used AISI 4140 Steel (24-26 R_C). Speed, feed rate and depth of cut were 400 sfpm, 0.005 ipr and 0.5 inch respectively. The cutter insert was grade SM-30 uncoated carbide.Analysis showed little differences in tool life between flood and MQL cooling. Sixty-six holes were milled for the flood tests and 80 were milled for the MQL tests. The average resultant forces observed were 46 lbs for flood and 36 lbs forMQL cooling (MaClure, Adams, GuggerandGressel, 2007). Yan et al (2009) investigated the cutting performance of MQL and compared it to dry and wet cutting using cemented carbide tools in Milling High strength steel. The results indicated that MQL reduced tool wear and surface roughness as compared to dry and wet cutting. Similarily, Sharif et al (2009), evaluated the performance of vegetable oil as an alternative cutting lubricant when end milling stainless steel using TiAlN coated carbide tools. The results indicated that vegetable oil using MQL outperformed dry cutting and flood cooling when tool life and surface roughness are the response variables. Sanz et al.(2008) reported on the advances in the ecological machining of magnesium and magnesium based hybrid parts . A study involving the intermittent turning of aluminum alloy on a CNC lathe was undertaken by Itoigawa, Childs, Nakamura andBelluco(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, the MQL oil supply rate was fixed at 30 ml/h and air flow rate at 70 l/min. 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 and dry machining, were performed in the same conditions. Two tools were used; a sintered diamond tool with 0° rake angle and a K10 grade carbide tool with 5° rake angle. 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 chip welding. Results showed MQL with water droplets, specifically an oil film on a water droplet, provided good lubrication performance if an appropriate lubricant, such as synthetic ester, was used. When MQL with synthetic ester but without water was used, it showed a lubrication effect. However, tool damage was evident as waschip welding (Itoigawa, Childs, Nakamura andBelluco 2006)

MQL performance using coated and uncoated HSS and Cobalt HSS drills, in a high aspect ratio operation, was examined by Heinemann, Hinduja, Barrow andPetuelli (2006).The workpiece material was AISI 1045. The workpiece was mounted on top of a two component dynamometer which measured thrust force and torque. The twist drills tested had a diameter of 1.5 mm and an included angle of 130°. Drills were of uncoated HSS, uncoated Cobalt HSS, and Cobalt HSS with various coatings. A cutting speed of 26 m/min and a feed rate of 0.26 mm/rev were used. Three series of tests were performed. MQL-supply in the first series of tests was stopped once the drill reached a depth of 5 mm. In the second series of tests, two other lubricants were used; one with the same chemical composition as the lubricant used in the first series but without alcohol, and one composed of an oil-free synthetic lubricant with a water content of 40%. In the third test series, drilling was carried out under dry conditions.

In the first series of tests, it was observedthat the interruption of the MQL-supply caused a dramatic drop of 98% in tool life for the uncoated cobalt HSS drills. In the case of the TiN- and TiAlN coated twist drills, the tool life also decreased, but by 42% and 27%, respectively. The second series of tests, carried out with three different types of MQL, hadthe lubricant being supplied continuously at a rate of 18 ml/h. All tests, were performed with uncoated HSS drills. The alcohol-free lubricant resulted in an increase of 23% in tool life over that achieved with the alcohol-blended lubricant. When using the oil-free synthetic lubricant plus 40% water, the tool life increased by a 100%. 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 andPetuelli, 2006).

MQL Lubricant Characteristics

Lubricant concentration in MQL varies between 0.2 and 500 ml/hr., and does not recirculate through the coolant delivery system. 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 (Filipovicand Stephenson, 2006). MQL is consumption lubrication, that is, the bulk of the lubrication applied is evaporated at the point of application. This evaporation,in concert with the compressed air stream, cools the workpiece. The remaining heat is dissipated through the tool and the chips (www.schunk-usa.com, Topic of the Month, 2007). The chips, workpiece and tool remain nearly dry in an ideally adjusted MQL system. Wakabayashi, InasakiandSuda(2006) introduced synthetic polyol esters and described their capabilities as MQL fluids. These represent a potential replacementfor vegetable-based MQL oils,particularly with regard to their optimal secondary performance characteristics.All vegetable oils display high biodegradability. Synthetic esters, however, provide a wide range of biodegradability depending on their combined molecular structures of acids and alcohols. This characteristic, in conjunction with their suitable viscosities, promptedWakabayashi, et al., to identify these lubricants for further examination.

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 mm2/s, 0.02 mgKOH/g, 45˚ C and 100% respectively. These characteristics for vegetable oil were 35.6 mm2/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%.The molecular weight of vegetable oil increased by 65%. In contrast, there was no significant change in the molecular weights of polyol esters. Most vegetable oils 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, due to their unsaturated bonds. Unfortunately, unsaturated bonds are chemically unstable and may cause vegetable oils' molecular weight to increase. A detailed investigation of this behavior was carried out using GPC analysis. The results indicated that some of the molecules in vegetable oil had changed into 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 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; they are free from unsaturated bonds.Regardless, they can be liquid at room temperature. Compared with vegetable oils, the synthetic polyol esters studied were optimal lubricants for MQL machining from the standpoint of maintaining a clean working environment.

Another secondary characteristic studied concerned the long-term storage potential of polyol esters and vegetable oils. 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. Changes in viscosity and total acid number (TAN) 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. These results confirm the stability of the molecular structure of the synthetic esters regarding oxidative degradation, thus promoting their stability in storage(Wakabayashi, InasakiandSuda, 2006).

Summary and Conclusions

Findings from the forgoing research indicate the following:

MQL does generate a significant amount of mist compared to flood cooling. Mist collection or filtering equipment is required to manage the resulting fine mist. With these technologies in place however, machining is safe for both operators and the environment, particularly if using vegetable based lubricants.

On the other hand,The processes of lubrication and cooling in MQL are yet to be well understood. Similarly the process of mist particles generation and their physical characteristics are yet to be determined for a whole class of machining processes and machining conditions.

References

R. B. Aronson. (1995), "Why Dry Machining", Manufacturing Engineering, pg 33-36.

A. Attanasio, M. Gelfi, C. Giardini, C. Remino. (2006), "Minimum Quantity Lubrication in Turning", Wear Vol. 260, pg 333-338.

E. O. Bennett and D. L. Bennett, (1985), " Occupational Airways Diseases in the Metal Working Industries", Tribology International, 18/3, pg. 169-176, 1985.

Chalmers, R.E. (1999), "Global Flavor Highlights NAMRC XXVII", Manufacturing Engineering, Vol. 123 No.1, pp. 80-88.

AleksandarFilipovic and David A. Stephenson (2006), "Minimum Quantity Lubrication (MQL): Applications in Automotive Power-Train Machining", Machining Science and Technology, Vol. 10, pp: 3-22.

R. Heinemann, S. Hinduja, G. Barrow, G. Petuelli. (2006), "Effect of MQL on the Tool Life of Small Twist Drills in Deep-Hole Drilling", International Journal of Machine Tool and Manufacture, Vol.46, pg. 1-6.

F. Itoigawa, T. H. C. Childs, T. Nakamura, W. Belluco. (2006), "Effects and Mechanisms in Minimal Quantity Lubrication Machining of an Aluminum Alloy", Wear, Vol. 260, pg. 339-344.

F. Klocke and G. Eisenblatter. (1997), "Dry Cutting", Annals of the CIRP, Vol.46 No.2, pp. 519-526.

T. F. MaClure, R. Adams and M.D. Gugger, M.G. Gressel. (2007), "Comparison of Flood vs. Microlubrication on Machining Performance", website: http://www.unist.com/pdfs/articles/AR_flood_v_micro.pdf.

Sanz, C.; Fuentes, E.; Gonzalo, O.; Bengoetxea, I.; Obermair, F. ; Eidenhammer, M., (2008),

"Advances in the ecological machining of magnesium and magnesium based hybrid parts", International Journal of Machining and Machinability of Materials,Vol: 4,

Issue: 4, pp: 302-319.

Sharif, S.; Hisyam, M.A.; Kurniawan, D.; Orady, E.A., (2009), "Performance evaluation of

vegetable oil as an alternative cutting lubricant when end milling stainless steel

using TiAlN coated carbide tools", Transactions of the North American Manufacturing Research

Institution of SME,Vol: 37, pp: 9-14.

Wakabayashi, T., Ichiro Inasaki and Satoshi Suda. (2006), "Tribological Action and Optimal Performance: Research Activities Regarding MQL Machining Fluids", Machining Science and Technology, Vol. 10, pp: 59-85.

Wakabayashi, T., Inasaki, I., Suda, S., and Yokota, H. (2003), "Tribologial Characteristics and Cutting Performance of Lubricant Esters for Semi-Dry Machining", CIRP Annals, Vol. 51 No.1 pp: 61–64.

Yan, L.T.; Yuan, S.M.; Liu, Q., (2009), "Effect of cutting parameters on minimum quantity

lubrication machining of high strength steel", Materials Science Forum,Vols: 626-627, pp: 387-392.

"For Minimum Costs and Maximum Protection of the Environment", (2007), Topic of the Month, website: www.schunk-usa.com.

U.S. Department of Health and Human Services. (1998), "Occupational Exposure to Metal

Working Fluid", NIOSH Publication No. 98-102.