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RECENT TRENDS IN THE EFFECTIVE UTILIZATION OF MINIMUM QUANTITY LUBRICATION (MQL) IN TURNING LOW CARBON STEELS

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Abstract

Researchers have identified machining as the most versatile manufacturing process as compared to metal forming process due to its ability to get close dimensional control, better surface finish and higher production rate. Minimum Quantity Lubrication (MQL) has been a replacement to conventional flood and dry machining due to optimal coolant usage, good heat dissipation at the cutting zone and ecological safety concerns. C15 steels which are low carbon steels find major applications in production from small pins to large axles and shafts. It has advantage over other materials due to its good strength, low cost, ease of heat treatment and machinability. Many researchers have discussed the economical, environmental and health effects of dry, flood and MQL machining during turning steels. This paper reviews the selection of optimum cutting parameters in turning of steels with dry, flood and MQL cooling with or without nano-material. Critical responses analyzed by some researchers during these studies were tool life, surface roughness, material removal rate, energy utilization, cutting forces and tool-work-piece interface temperature, effects of mist generated during machining, chip morphology, mist concentration analysis and improper disposal of cutting fluids. This paper also reviews tool-work interface temperature and cutting force measurement by computational fluid dynamics (CFD) techniques and finite element analysis (FEA) respectively. Finally, an overview of optimization tools such as response surface methodology (RSM), particle swarm optimization (PSO), Design of Experiments and Taguchi method are put forth to establish proper inter-relationship of factors, levels and responses to solve problems in machining especially, mist pollution, surface improvements and tool life enhancement.

Keywords – Minimum Quantity Lubrication(MQL), Nano-Material, Optimization, Steels, Turning

INTRODUCTION

Metal machining processes such as turning, milling and drilling are very versatile and economical. These machining processes give shape to work-piece by removing the materials by the action of shear from the work piece surface using a hardened sharp edged tool and also establishes a relative motion between the workpiece and the cutting tool. The metal machining (i.e. chip forming) process is preferred over metal forming process due to its ability to achieve high precision in workpiece tolerances of up to 50 microns and a workpiece surface finish of up to 1 microns. The metal machining process is considered versatile to other manufacturing processes due to the fact that the machines are flexible to part-program for different free-form shapes, different size ranges and can be automated. Moreover, machining process requires least use of dies or moulds as compared to metal forming processes. Also, with the advancement of newer tool coating materials, better machinability, reduction of lead time and fast delivery of manufactured parts are at par with industry requirements in today's demanding customer-driven environment [1].

As far as machining operations are concerned, steel (eg. free machining steel – C15 steel) is majorly been a work material due to the large availability of iron ore deposits in the earth's crust. It has excellent mechanical properties such as strength, toughness and good machinability and it is easy to fabricate into different shapes. C15 steels find its applications majorly in the manufacture of large quantities of screwed components, shafts and different components of automobiles.

Among the different machining operations, turning operation has been successful since 1960's for carrying out several operations on cylindrical objects with accuracy and speed. In this process, various experiments were conducted by researchers on improving the machining quality of work and improvement of cutting tools. It was found that major issues existed with this process especially in the area of health and safety of the workers and environmental impacts. Different research works have proved that machining using flood cooling is injurious to health and used coolant if not treated properly and disposed off in sewage harms the environment biotic things to a large scale. Avoiding flood cooling altogether (i.e. dry machining) also has many disadvantages, in terms of low tool life and bad surface quality of work.

In this case, the use of cutting fluid which is inevitable and prime need for any machining has led to minimal use of coolant technology in machining called as "Minimum Quantity Lubrication – MQL" or also called as "Near – Dry Lubrication – NDL". This technology has been advantageous to the machining sector due to the fact that chips after machining are almost dry and need no further drying and can be recycled again at economy. Lubricant in MQL system is forced into the cutting zone with compressed air up to 5 bar pressure with lubricant concentration of 0.2 to 500 ml/hr. The lubricant molecules evaporate quickly after leaving the machining zone leaving nothing to recycle back to the MQL system. This avoids disposal problems to a large extent. It is found by researchers that MQL system produces very less mist (aerosol) in atmosphere (permissible exposure level –PEL) of up to 5 mg/m^3 and 0.5 mg/m^3 which are within the standards of air quality prescribed by OSHA (U.S.- Occupational Safety and Health Administration) and NIOSH (U.S.- National Institute for Occupational Safety and Health). Compared to this, flood lubrication produces around 20 mg/m^3 mist which is injurious to health of workers as in case of automotive industries. MQL maintains a comfortably lower temperature zone than dry machining where chips burn and there are possibilities of BUE – built-up edge of tool and early tool failures. Abrupt temperature variations in short time intervals of machining such as at high feeds or depth of cuts in machining is prevented in MQL, hence thermal shocks are drastically reduced and work surface integrity is maintained [3].

There are wide varieties of cutting / lubricating oils used in MQL with additives to enhance cooling capabilities and cutting abilities such as the use of nano-materials mixed in lubricating oils. Also, research on optimization of cutting parameters under different coolant conditions and temperature/forces analysis is reviewed in the following sections.

LITERATURE REVIEWS

Camposeco Negrete [2], enlisted the concepts of sustainable manufacturing in turning process through a reduction in energy consumption during machining, which is a function of machine tool and cutting operation itself. Consumed energy was calculated as the average power taken by the cutting process and the total time taken for the operation. Material removal rate (MRR) was kept constant (1333.33 mm^3/sec) for all runs. The experiment design consisted of inner array of three factors – viz. cutting speed, feed and depth of cut at three levels and outer array of two factors – viz. coolant and type of machine used, both at two levels. The work material was AISI 1018 steel of 150 mm length and 50 mm in diameter and Sandvik inserted-carbide tools were used in the operation. Through ANOVA calculations, it was found that energy consumed was lower for low values of depth of cut and lower cutting velocities and for higher feed rates. This is because, cutting feed reduces the machining time, hence less energy is needed. High cutting speeds imply more power to drive spindle to the required rpm. Incremental values of depth of cut imply extra force required for cutting, so energy requirements increase. It was concluded that feed of 0.2 mm/rev, depth of cut of 1.14 mm and cutting speed of 350 m/min lead to minimal energy consumption which helps in reduction of overall production cost.

A study was conducted by Boubekri and Shaikh [3] to explain the benefits of vegetable oils and synthetic polyol esters as potential metal cutting oils. Vegetable oils are high in biodegradability and are selected due to better contributions to cutting performance which is the primary characteristics. Synthetic oils show wide ranges of bio-degradability index and in conjunction to its viscosities they can be identified for the replacement of vegetable oils. One good example was reviewed in this paper of use of thin perfluoropolyether (PFPE) lubricant film surface treated on tool gives improved surface finish of machined parts and better tool life. In another example, use of rapeseed oil, and synthetic ester mixed in water which was forced through MQL system had better lubricating effects in intermittent turning of aluminium alloy on CNC lathe. It was concluded to use vegetable or synthetic oils instead of mineral oils for health and safety concerns with improvement in lubrication in machining.

An experiment in turning of AISI 1018 steel material in dry condition (without using lubricating oil) was conducted for diameter 25 mm workpiece, cutting parameters at 224 spindle rpm, the tool edge temperatures are lesser with good surface finish and lower cutting force on the tool. Recommended feed rates of 0.08 – 0.12 mm/rev and depth of cut of 0.5 – 1.0 mm is defined through experimental results. Dhiman *et al.* [4] suggested to use annealing and normalizing AISI 1018 steel to improve machinability characteristics. This heat treatment coarsens pearlite in the microstructure of steel. More the amount of pearlite and cementite in steel, more is the abrasive action on the cutting tool. Heat treatment before machining steels can help better machining and long tool life feasibility.

Milling experimentation of AISI 1018 steel was carried out with MQL – Accu-Lube LB 2000 as a lubricant. Shaikh *et al.* [5] and Shaikh and Boubekri [6] explained that vegetable oil, because of its ability of a molecules to carry polar charges sticks on the work when applied through lubrication system. This prevents ease to wipe off from the work. Mineral oils do not carry such characteristic features, hence are not efficient. The experiment consisted of six cutting speed and feed rate combinations using a randomized factorial design (Full Factorial) and analysis of results of flank wear of tool was done by Analysis of Variance (ANOVA) using Design Expert 8.0 software. Experiments proved that lower speeds (24 m/min) and feed rate (0.15 m/rev) of tool has better tool life up to five times and material removal rates doubled since micro-lubricant particles can access the cutting zone better at lower speeds and feeds which were hypothesized. This access of lubricant forms boundary layer of solid film lubricant that contributes to increase in tool life and high material removal rates.

Applications of temperature field measurements in orthogonal cutting of AISI 1055 steel using coated carbide tools to measure mechanical and thermal effects of cutting process was listed by Artozoul *et al.* [7] in their research paper and emphasizes that high temperatures during cutting soften the tool material, it accelerates flank wear mechanism and also induces plastic deformation on machined surface by inducing high tensile residual stresses and phase transformations. Infrared Camera (FLIR SC7000) was adopted into CNC machine tool to obtain thermal maps of cutting tool and chip for temperature ranges of 0 – 300ºC and 300 to 1500ºC. For better temperature measurements, coolant is avoided in the system. One-factor-at-a-time (OFAT) using cutting speed, feed and depth of cut was employed. Kistler piezo-electric dynamometer was coupled to the system to measure tool forces in relation to the temperature recordings. Results showed that at low cutting speeds, images showed chips were continuous. At higher speeds, however, localized shear bands were evident. Shear angles increased with increase in cutting speeds, feeds, and width of cut. Tool chip contact length which consists of sticking and sliding regions shows an increase in values if feed increases, and is independent of the width of cut. Cutting speeds increase temperature gradients along the flank face which has a direct effect on flank wear. The location of peak temperatures moves away from the cutting edge and mean temperature of the tool increases as steady state is reached.

Application of Computational Fluid Dynamics software for numerical analysis and modeling of cooling system – Flood, Dry and Cooling Air with MQL was presented by Chowdhury *et al.* [8] in his paper. Results indicate that chip tool interface temperatures are found to be lowest when flood cooling is used at 24 lit/min. It was found that temperature difference in tool chip interface by flood and Cooling Air with MQL was not enormous and amounts to 10 %. However, the detrimental effects of use of flood cooling systems on the health and environment were not presented in this paper.

Micro-lubrication effects during end milling AISI 1018 steel with the application of vegetable based cutting fluid aerosol was explained by Shaikh *et al.* [9] in their paper. Along with flank wear measurements, a particulate monitor for aerosol was used to record real time data of aerosol concentration in air and mean diameter particle size of aerosol. ANOVA analysis using Minitab software was made use for calculations. Results indicate parameter optimization of mass concentration and particulate size to be 5.91mg/m^3 and 5.92 mg/m^3 for higher cutting speeds of 36 m/min and higher feeds of 0.25 mm/rev. High heat generation at high speeds and feeds is transferred to the lubricant which evaporates the mist resulting in low mass concentration aerosol particle size.

Boubekri and Shaikh [10] and Boubekri *et al.*[11] listed the advantages of MQL which are experimentally conducted by various researchers for different machining conditions and notable key points were drawn regarding the use of MQL in machining. It is emphasized to use synthetic polyol esters than vegetable oils due to the stability of molecular structure oxidation degradation thus promoting their stability in storage. In drilling, it is suggested that interrupted MQL is not advisable since it leads to a significant drop in tool life. Use of internal MQL through tool has 50% lower measured temperature than that with external coolant nozzle. Emulsions based MQL in drilling indicate highest wear rates. The operation cost of MQL was found to be 15% lesser than flood cooling. At lower feeds and depth of cuts, surface finish shows very feeble noticeable differences, but at a higher depth of cuts and feeds, an improvement of surface roughness was indicated. In grinding, MQL was found to be better than flood lubrication because it gave the functionality of cooling with extremely low consumption of lubricant.

Srikant *et al.* [12] indicated the use of nano-particles in MQL cooling system in AISI 1040 steel turning for effective temperature removal from the tool-chip contact. Heat transfer principles are estimated by the analogy of flow over flat plates in all lubricating conditions. ANSYS 5.4 software was used to draw temperature profiles of the tool inserts for ordinary cutting fluids, cutting fluids with different percentage of nano-particles ranging from 0.5% to 8%. Temperature gradients were lowest with the used of nano-particle inclusions up to 1% in cutting fluids thereby depicting that thermal conductivity of fluids are greatly affected by the addition of nano-materials in them. However, higher percentages of nano-materials from 1% to 6% resulted in a decrease in thermal efficiencies of fluids. It was concluded that coolant with 1% nano-particles is advantageous and also it avoids more usage of this costly nano-materials thereby reducing overall cost. In this paper, the cutting fluid type and nano-material used were not listed.

An experiment on finding the effectiveness of nano-fluids –viz. coconut oil (CC) with solid lubricant – nano Boric Acid during turning of AISI 304 austenitic stainless steels to identify variations in flank wear, surface roughness of machined part and cutting tool temperature at different levels of speeds, feeds and depth of cut using Taguchi DOE optimization approach was made by Sodavadia and Makwana [13] in his paper. Here, temperature measurement was done by embedded K-type shielded thermocouple placed at the bottom of tool insert. Experiment on different percentages of nano-boric acid particle suspension in coconut oil viz. 0.25%, 0.5%, and 1% were been employed for different speeds, feeds and depth of cuts. In all cases, coconut oil with 0.5% nano Boric Acid suspensions showed good performances in terms of achieving low cutting temperatures, low flank wear rate and low surface roughness of work. In this paper, however, the exact number of runs and combinations of experimental design has not been listed and the effect of factors and its interactions were not explained.

Padmini *et al.* [14] depicted extensive experimentations in turning of AISI 1040 steels to compare effectiveness of coconut oil and sesame oil lubricant with nano-particle inclusions (npi) viz. nano-Boric Acid and nano-Molybdenum Disulphide to evaluate the cutting forces (Fz), cutting temperatures, surface roughness and tool flank wear. The npi percentage were from 0.25% to 1 % and cutting parameters were 60 m/min cutting velocity, at 0.14 mm/rev feed rate and depth of cut as 0.5 mm. Flow rate of nano-fluid was set to 10 mL/min and directed on tool-chip interface. With addition of nano-materials, the fire point, flash point, thermal conductivity of cutting fluids was found to increase considerably by 30 minute sonification mixing treatment process of nano-particles with the cutting fluid. Results showed that cutting forces, cutting temperatures, tool flank wear and surface roughness with respect to speed and feed reduced considerably when coconut oil mixed with nano-molybdenum disulphide at 0.5% and 0.25% npi was applied. 0.5% npi was found to be the best optimum mix in all the responses measured. Enhancement of npi more than 0.5% did not show good results.

An investigation of machining performance of turning 1040 steel using uncoated carbides with regards to tool temperature and surface roughness with the use of mixture of nano-crystalline graphite and mineral oil such as SAE40 as nano-lubricant was carried by Pavan Kumar *et al.* [15]. Cutting parameters were 78 m/min as cutting velocity, 1 mm as depth of cut and 0.1 mm/rev as the feed. Sample weight percentages from 0.25% to 10% in 60 ml of SAE40 oil was used for experimentation. Experiments were conducted dry, wet and MQL with nano-particles. MQL was dispensed to the cutting area at the rate of 10mL/min. Nano-particle sizes of 5-10 nm , 15-30 nm, 40-60 nm and 70-90 nm were used for experiment. Results indicate that good surface quality and lower temperature generation at tool tip was found with cutting fluids mixed with larger size of nano-particles of 70-90 nm. It was inferred that smaller particles stay on the workpieces causing more rubbing which causes rise in temperature and hence more tool wear. Tool chatter due to excessive tool wear is main cause for poor surface quality of work machined. 0.5% of nano-particle inclusions was found optimum for low temperature of tool chip interface and for lower surface roughness characteristics of work. Regarding cutting parameters, optimum levels of surface roughness was found to be at higher cutting speeds at constant feed rate and constant depth of cut.

CONCLUSIONS

From the following reviews, it can be concluded that:

1. MQL – Minimum Quantity Lubrication is the economical cooling method compared to flood cooling. Dry machining reduces tool life and has detrimental poor surface quality of work machined. So, it is clear that machining with coolant is inevitable, but heavy coolant usage such as in flood cooling not only increases cost of coolants, but has lots of health issues due to physical contact to skin and mist generated has serious effects such as respiratory disorders and other diseases. Mist generated is lower and safer with MQL.
2. Use of nano-materials such as nano-graphite, nano-molybdenum disulphide, nano-boric acid etc., improves the thermal conductivity of cutting fluids when added upto 1% by weight in cutting fluids. Fire and flash point of nano fluids are improved. Also, the size of nano-particles suggested in literature need not be too small in the order upto 5 nm, it need to be within 70 -90 nm so that it will not stick on the work surface and affect machining capabilities of cutting tools.
3. MQL systems are found to be better in performance when applied internally through the tool than external coolant applications. Better tool design incorporating internal cooling distribution channels for MQL with nano-particles may prove a viable solution for research.
4. Use of Infra-red Camera for real time temperature measurements and comparing with the computational prediction of temperatures by CFD software and ANSYS can validate the temperature of tool chip interface.
5. Vegetable oils and synthetic esters oils prove to be better cutting fluids due to its high oxidation capabilities and good biodegradability which breaks into simpler molecules when disposed into atmosphere. They are comparably safe to use and have better lubricity and when mixed with nano-fluids have better machinability performances compared to mineral oils.

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