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Review Article

Review on Hard Machining with Minimal Cutting Fluid Application

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Abstract

In the manufacturing industry there is always a concern for reducing the production cost. The process of producing hard components requires different stages of machining, heat treatment, finish grinding etc. Hard machining is opted to reduce processing time and to improve the production efficiency. Hard machining involves machining of work parts in their hardened state to the required near net size, hence it requires tough machine tools as well as ultra-hard cutting tools. To reduce the cutting forces and cutting temperature during machining, cutting fluids are used. The use of cutting fluids in large quantities affect the shop floor environment and health of workers associated with the machining process. So there is always an urge to reduce the use of cutting fluids during machining. Techniques like mist cooling, minimal cutting fluid application and minimal quantity lubrication systems came into existence since last 3 decades. Serious research is going on in the area of cutting fluid minimization for the past few years. This review paper deals with machining with minimal cutting fluid application (MCFA), which involves application of high velocity cutting fluid in the form of pulsed jet at the critical cutting zone. The heat generated in the critical zone is carried away by the high velocity cutting fluid and it also provides sufficient lubrication to reduce the cutting force. The former studies proved that this process is much efficient compared to dry and wet machining. This review is based on the research works carried out by various researchers in the field of minimal cutting fluid application.

Keywords: *Hard turning, Minimal quantity lubrication, Minimal cutting fluid application*

1. Introduction

Manufacturing industries now a days are concerned about reducing the cost of production and optimizing the production process. Optimization involves finding out best possible machining conditions which will give maximum possible tool life, minimum cutting force, maximum surface finish etc. Components require high hardness are normally machined to their near net shape under soft condition. Then they are heat treated to obtain their required hardness. Finally they are ground to get the required final size. All these processes are time consuming and increase the cost of the product. Hard machining consumes a lot of cutting fluid. Storage, maintenance and disposal of cutting fluid causes financial burden to the industries. According to a study conducted by Attanasio et. al, (2006) 7% to 17% of total production cost is spent on cutting fluids. This calls for the reduction in the use of cutting fluids. There is also a health concern when large quantities of cutting fluids are used in the industry. The permissible exposure level (PEL) in a manufacturing industry for cutting fluid aerosol concentration is 5 mg/m^3 as per the Occupational Safety and Health Administration (OSHA) and is 0.5 mg/m^3 according to the U.S. National Institute for Occupational Safety and Health (NIOSH) by Aronsin (1995). The higher exposure of oil mist in the shop floor can result in serious health problems to the operator. Workers exposed to cutting fluids in large quantities develop dermatitis, respiratory diseases like asthma and even cancer. Bacteria and fungi growth, odour, smoke, pH, concentration and contamination of cutting fluids need to be monitored and controlled. So there should be an active cutting fluid processing system for the maintenance of cutting fluids as suggested by Machado *et al.*, (1997). So to reduce the harmful effects of cutting fluids and their financial burden on the industry, studies were conducted in dry machining.

Dry machining as the name states will not use any cutting fluid during machining process. But hard dry machining requires very hard cutting tools and rigid machine tools. Some of the studies conducted by various researchers proved that dry machining increases tool wear rate, cutting force, cutting temperatures which will lead to reduction in surface finish and surface accuracy (Varadarajan *et al.*, 2002, Dhar *et al*,. 2007). The vibrations produced in the tool holder are immense. Without providing a proper damper, vibrations will affect the product quality as well as tool life. Premature tool failure may occur due to vibration in hard turning (Sampaul *et al.*, 2013). So

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hard dry machining is not always feasible for machining hard materials above 45 HRC. The cutting fluid when used for machining provides cooling and lubrication effect which will also allow the easy flow of chips. Minimal quantity lubrication (MQL) and minimal cutting fluid application were studied by various researchers. In these techniques, cutting fluids are used in very small quantities in the order of 5 - 50 ml/min. In MQL, cutting fluid is mixed with a high pressure stream of air which will atomise the cutting fluid in to smaller molecules which is directed to the cutting zone at high velocity through a nozzle (Itoigawa *et al*., 2006, Vasu *et al*., 2011).

In MQL system, the cutting fluid used is mainly emulsions of water and oil or neat oils. The system uses high pressure air which is directed to a chamber where cutting fluid is supplied in low quantities. The mixture of air and cutting fluid is pumped through the nozzle which on the outlet forms a spray or mist. So it is also called as mist cooling. The cutting fluid mist is directed to the cutting zones (tool - work interface, tool - chip interface or back side of the chip). Most of the studies revealed that maximum heat is generated at the cutting zones and cooling these locations will reduce tool wear, cutting force and cutting temperature. The cutting fluid takes away heat by vaporisation and it also provides ample amount of lubrication (Dhar *et al*., 2007). The cutting fluid injected at the back side of the chip provides rebinder effect which helps in the breakage of chips which will in turn reduce the flank wear. The MQL system was found to be efficient in most of the cases. The discerning factors of this system which were considered are direction of application, velocity/pressure of mist and quantity of cutting fluid used. Most researchers have done experiments to optimise these parameters so as to improve the system of cooling and lubrication in machining. The mist formation in MQL system is to be limited so that it will not affect the machine operator. The minimal cutting fluid application (MCFA) is a new area of research which regulates the formation of mist during cutting fluid application. In this system the cutting fluids, basically emulsions are not mixed with air. The emulsions are directly pumped using a minimal cutting fluid applicator at desired pressure and quantity. In MCFA, a positive displacement pump which pumps the cutting fluid in the form of pulses. This system was developed by Varadarajan *et al*, (2002). This system is capable of providing six outlets at the same time.

The MCFA system delivers cutting fluid emulsion at a pressure in the order of 50 - 200 bar and a pulsing rate of 500 - 1000 pulses/minute. The quantity of application of cutting fluid can also be varied from less than 1 ml/minute to more than 30 ml/minute. The system proved to be efficient when cutting fluid emulsion is pumped directly at high velocities to the cutting zone. The cutting fluid reaches the cutting zone at high velocity and it directly vaporises which will lead to reduction of heat at the cutting zone. Specially formulated cutting fluids and vegetable oil based cutting fluids were also used in different studies to prove the efficiency of the system (Leo *et al*., 2010, Robinson *et al*., 2012). A detailed literature survey was conducted to assess the performance of MCFA where different materials, machining processes and cutting fluids were used.

2. Hard Turning Minimal Cutting Fluid Application

Varadarajan *et al*., (2002) performed experimentation on hard turning with minimal cutting fluid application (HTMF) of hardened steel. In this work, a specially formulated cutting fluid was applied at tool - work and tool - chip interface. The workpiece selected was AISI 4340 of 46 HRC and cutting tool was multicoated hard metal inserts with sculptured rake face (SNMG 120408 MT TT 5100) from SANDVIK. The developed cutting fluid application system supplied cutting fluid at high pressure and velocity in the form of pulsing jet. When cutting fluid was applied at high pressure and velocity into the cutting zone it provided ample amount of cooling as well as lubrication. The cutting fluid was applied at a maximum velocity of 100 m/s and at a pressure of 20 MPa. In this work, the quantity of cutting fluid was reduced to 2 ml/min and was found to be efficient than that of turning with flood cooing and dry turning. The cutting force and cutting temperature developed during hard turning were found to be much less. The author explained a chemo - mechanical effect called as rebinder effect, which helped in promoting the chip curl and reducing tool - chip contact length.

A study conducted by Vikram Kumar *et al*., (2007) to find out the performance of coated tools during hard turning with MCFA. In this study two different nitride coated hard metal inserts (TiCN coated and ZrM coated) were used. Both the inserts with general specification of SNMG 120408 MT TT 5100 were used for turning AISI 4340 steel of 35 HRC. The study was conducted by designing Taguchi's 8 run orthogonal array, which had 7 operating parameters and were varied in two levels. The parameters namely type of tool coating, pressure of cutting fluid, quantity of application, frequency of pulsing, cutting speed, feed rate and depth of cut were considered. The MCFA technique was proved to be efficient in reducing the cutting force, cutting temperature and improving the surface finish of the machined components. The pulsating jet of cutting fluid transferred heat efficiently than conventional wet turning because of both convective and evaporative heat transfer. ANOVA analysis was conducted in this study to find the influence of operating parameters.

Vikram Kumar *et al*., (2008) performed a variable speed, feed and flank wear test during hard turning with MCFA. In his study TiCN and TiAlN coated inserts were used and their performance was studied. The workpiece selected for the study was AISI 4340 steel of 44 HRC and they used a cutting fluid pumping set up which can deliver cutting fluids upto 30 MPa pressure with varying frequency of maximum 1000 pulses/min. The study used taguchi's L18 orthogonal array, in which 7 operating parameters were varied at 3 levels. During this study both the inserts performed well with MCFA technique compared to dry and wet turning. The TiAlN coated tool's performance was observed to be better compared to TiCN coated. The operating parameters such as pressure of cutting fluid, frequency of pulsing and quantity of application influenced much on the machining performance.

The minimal cutting fluid application technique was experimented by Ramkumar *et al*., (2008). They studied the effect of multiple jet of cutting fluid application on hard turning with MCFA. They experimented on AISI 4340 steel of 43 HRC with SNMG 120408 MT TT 5100 inserts with sculptured rake face. This study investigated the effect of additional pulsing jet of cutting fluid on the back side of the chip. The study intended to find out the promotion of chip curl by rebinder effect which would reduce the tool - chip contact length and in turn reduce tool wear and cutting force. They designed a taguchi's L8 orthogonal array with four operating parameters varied in two levels. The study used mineral oil emulsion as cutting fluid. The parameters selected for the study were quantity of cutting fluid, frequency of pulsing, composition of emulsion and direction of application. The study revealed that the quantity of cutting fluid at 5 ml/min, frequency of pulsing at 300 pulses/min, composition of 10% emulsion of cutting fluid with 90% of water provided good results. The provision of additional jet on back side of chip enhanced better surface finish. The tool wear, cutting temperature and cutting force were found to be less with a very low tool chip contact length. The study also compared dry and wet turning, which proved that MCFA is a better alternative to hard dry turning.

The effect of auxiliary jet of cutting fluid in minimal cutting fluid application was reported by Robinson Ganadurai *et al*., (2012), where a deep study was conducted to prove its effect. In this work, AISI 4340 steel of 45 HRC was employed with SNMG 120408 MT TT 5100 insert with P30 or equivalent substrate provided by TaeguTec. The study justified the results mentioned by Ramkumar et. al. (2008), but in this study, emulsion of 20% concentration was proved to be effective. The author conducted variable feed, speed and tool life tests to prove the effectiveness of MCFA. The X Ray Diffraction test (XRD) and Electron spectroscopy for chemical analysis (ESCA) were performed at the back side of the chip to find out the effect of cutting fluid. Both the tests indicated that embrittlement of chip occurred which promoted the rebinder effect. Scanning Electron Microscope was used to analyse the tool wear happened during dry, wet, MCFA and MCFA with auxiliary jet. The results displayed that tool wear was comparatively less during hard turning with MCFA with auxiliary jet.

In the course of time, the research with MCFA entered into application of various types of cutting fluids and semi-solid lubricants. Study conducted by Varadarajan. *et al*., (2012) used environmental friendly coconut oil based cutting fluid. The green machining is getting lot of attention in the manufacturing industry. The cutting fluid was formulated with several additives which improve the properties of coconut oil then this oil was used in the form of emulsion for experimentation. The MCFA with mineral oil and coconut oil based cutting fluids were compared in this study. The study proved that the performance of coconut oil based cutting fluid can be a suitable alternative to mineral oil based cutting fluid.

The research work further extended by adding semi-solid lubricant along with MCFA. This method proved to be efficient than MCFA, but a separate setup is required to pump semi-solid lubricant in required quantity. Sampaul *et al*., (2013) studied the effect of hard turning of AISI 4340 steel of 46 HRC with the use of semi-solid lubricant. This research study was carried out with the presence of MCFA along with semi-solid lubricant (grease) in its pure form and with a 10% graphite addition. The semi-solid lubricant was applied at tool - chip interface, back side of the chip and at tool - work interface. The heat transfer by the application of semi-solid lubricant was by evaporative mode, which was more competent than conventional heat transfer during wet turning. The semi-solid lubricant was applied using a pneumatically actuated system that can deliver desired quantity in the required direction. The MCFA was set at 80 bar pressure, quantity of application at 5 ml/min, frequency of pulsing at 300 pulses/min and composition of cutting fluid at 10% mineral oil with 90% water. The semi-solid lubricant was applied at the rate of 8 g/min. Taguchi's L18 orthogonal array was selected with variables as cutting speed (80, 90 and 100 m/min), feed rate (0.08, 0.1 and 0.12 mm/rev), composition (MCFA, MCFA + grease and MCFA + grease + 10% graphite) and direction of application of semi-solid lubricant (tool - chip interface, tool - work interface and uncut portion of workpiece). The results were derived in the form of cutting force, surface roughness, tool vibration, tool wear and cutting temperature. The effectiveness of semi-solid lubricant was proved by comparing MCFA with dry and conventional wet turning. From the comparison of results, the turning with MCFA and semi-solid lubricants exhibited less tool vibration, less cutting force, better surface finish, reduced cutting temperature and less tool wear.

Tool vibration is one of the important factors during turning which affects both surface roughness and tool wear. Some research works have been carried out to subdue the tool vibrations during MCFA. One of the similar works conducted by Sampaul *et al*., (2014), with the help of a magnetorheological fluid damper which was used to reduce the tool vibration. The author conducted experiments on AISI 4340 steel of 46 HRC using taguchi's L18 orthogonal array. They developed a magnetorheological fluid damper which can be activated with the help of electrical power. In

MR damper, magnetic particles in the fluid got magnetised and provided damping capability to the plunger. In this work, the plunger was connected at the base of the cutting tool. The vibration developed at the tool was transmitted to the end of the plunger. In this experimentation procedure, minimal cutting fluid parameters were kept constant. The variable parameters used in this investigation were supply current to the damper, plunger shape, viscosity of the oil used and size of ferro - magnetic particles in the damper. The experimental results were analysed using Qualitek software to find out the effectiveness of this method. It was found that the damper managed to take up all the vibrations. This helped in reducing the tool wear and increasing surface finish of work part produced.

Hard turning with MCFA was studied by different researchers and the method was found to be very efficient, environment friendly, shop floor friendly and economically beneficial to the industry. The studies were mostly conducted on AISI 4340 steel with SNMG 120408 MT TT 5100 inserts with sculptured rake face. Some of the researchers investigated with TiCN and TiAlN coated tools. The researchers adopted various methods to design their experimentation and most of them followed taguchi's technique followed by ANOVA analysis, artificial neural network and regression methods to prove their work. The chip produced and tools were analysed using Scanning Electron microscope, X Ray Diffraction test and Electron spectroscopy for chemical analysis (ESCA) to prove the effectiveness of their study.

3. Hard Milling with MCFA

The researchers in metal cutting studied the effect of MCFA in hard milling because milling operation is widely used for machining hard work pieces. The quantity of cutting fluid used in conventional hard milling is about 10 to 100 litres/min. Anil Raj *et al*., (2008) investigated the effect of MCFA in hard milling. The work piece selected was AISI 4340 steel of 43 HRC. The cutting tool insert and the tool holder were selected based on the recommendations by TaeguTec India Pvt.Ltd. Accordingly, inserts with specification TE90AX 220-09-L and end mill cutter with specification AXMT 0903 PER-EML TT 8020 were used.

The study was conducted using L8 taguchi's orthogonal array with four input parameters varied at two levels and a replication of this experiment was also conducted. The effect of MCFA was compared with conventional wet and dry milling. The input parameters considered for the experimentation were pressure at the fluid injector, frequency of pulsing, quantity of cutting fluid applied and direction of application of cutting fluid. The spindle speed, feed rate and depth of cut were kept constant. During the experiment cutting force, flank wear and cutting temperature were found to be very less compared to dry and wet milling. The surface finish was found better during hard milling with MCFA. The optimum conditions derived out of this work were pressure at 100 bar, frequency at 500 pulses/min, quantity of application at 15 ml/min and the direction of cutting fluid application towards tool - work interface.

High cutting force during hard milling results in increased tool wear and high cutting temperature, which will in turn affect the surface quality of work part produced. According to Leo Dev Wins *et al*., (2010) the quantity of cutting fluid used in conventional hard milling can be reduced by using MCFA with improvement in surface finish and reduction in tool wear. In this work AISI 4340 of 45 HRC was used with a high velocity narrow pulsed jet of cutting fluid. The study followed Taguchi's L8 orthogonal array with five input parameters varied in two levels. The parameters selected were pressure at fluid injector, frequency of pulsing, rate of fluid application, mode of application and composition of cutting fluid emulsion. The results evolved out of the experimentation revealed that pressure at 100 bar, frequency at 500 pulses/min, quantity of fluid at 5 ml/min, composition of emulsion at 20% and twin jet application provided good output. ANOVA analysis was performed using Qualitek-4 software to find the percentage influence of input parameters on the output performance. Comparative study was also conducted by the author with wet and dry milling to find the effectiveness of MCFA for milling hard components. They also performed SEM analysis on tool inserts of dry, wet and MCFA techniques which revealed there was a drastic reduction in tool wear during MCFA.

A study presented by Leo Dev Wins *et al*., (2011), describes the effects of twin – jet minimal cutting fluid application system. The study followed Taguchi's L8 orthogonal array in which five input parameters were varied in 2 levels. The factors were pressure at the injector, frequency of pulsing, rate of fluid application, mode of application and composition of cutting fluid. The results obtained in the experiment strongly recommended twin jet configuration, pressure at 100 bar, frequency at 500 pulses/min, quantity at 5 ml/min and composition of cutting fluid as 20% oil in water emulsion. The author explained that the rebinder effect happened so effectively while using twin jet configuration. SEM analysis on chip and tool inserts were also performed with dry, wet and MCFA related experiments.

The direction of application of cutting fluid is one of the important parameters in MCFA technique, because a very little quantity of cutting fluid is used. Cutting fluid entering into the cutting zone removes heat and promotes rebinder effect. Leo Dev Wins *et al*., (2011) conducted a study on the influence of direction of application of cutting fluid. The workpiece selected was hardened AISI 4340 steel of 45 HRC. The tool inserts used in this study was carbide inserts of specification AXMT 0903 PER-EML TT 8020 of TaeguTec. Cutting fluid was formulated in this study by mixing friction modifiers, emulsifying agents, anti-corrosion agents and coupling agents with a commercially available mineral oil. In this study L9 orthogonal array was used with three parameters varied in three levels. The input parameters were frequency of pulsing, quantity of fluid applied and direction of fluid application. The frequency was varied in 250, 500 and 750 pulses/min, quantity was varied in 5, 10 and 15 ml/min and direction of application with two injectors were used and cutting fluid was injected by keeping both the jets radially, both tangentially and keeping one jet radially and another jet tangentially. From the experimental results, it was found that frequency at 500 pulses/min, quantity at 5 ml/min and direction of application while applying the cutting fluid by keeping both the jets tangentially proved to be efficient. ANOVA analysis was performed to find out the effect of individual parameters. Comparative study was also conducted with dry and conventional wet milling. The chip analysis was also performed using SEM to prove the effectiveness of MCFA technique. The chips formed in dry milling had severe deformations compared to wet and MCFA method. The chips derived from MCFA had fewer serrations.

While most of the researchers followed taguchi's technique to optimise the experiments, Leo Dev Wins *et al.*, (2011) used response surface methodology to fine tune the results. A 20 set design matrix was coded with a $2^3 = 8$ full factorial design plus six centre and six star points. Then experiments were carried out and a mathematical model was developed from the output. Surface roughness was considered as the output parameter in this experiment. The MINITAB software was used for this purpose. The accuracy of this mathematical model was tested. Then arrived results were compared with experimental results. During this experiment, quantity of cutting fluid applied was optimized at 6.706 ml/min, pressure at 100 bar and frequency at 500 pulses/min. The output value predicted by the developed mathematical model matched well with the experimental results.

Thepsonthi *et al.*, (2009) used MCFA with narrow pulsed jet of cutting fluid during high speed milling of hardened ASSAB DF3 steel of 51 HRC. In this research they used P20 grade titanium aluminium nitrite (TiAlN) coated inserts. The study compared dry, wet and MCFA techniques. Water miscible coolant ECOCOOL 6210 IT from FUCHS was used during wet cooling and applied at the rate of 7 liters/minute. During MCFA, cutting fluid was applied into cutting zone as pulsed jet at 200 MPa, 400 pulses/min and 2 ml/min. The cutting fluid was active sulphurized anti – mist neat cutting oil. In this experimentation procedure, pulsed jet was found to be effective by reducing surface roughness and tool wear rate. During most of the machining conditions, pulsed jet proved to be efficient. The cutting fluid used in the pulsed jet application at high pressure was able to lubricate the tool-work and tool-chip interface in an efficient manner.

In the process of research in milling with MCFA, Leo Dev Wins *et al.*, (2012) tried to simulate an Artificial Neural Network (ANN) system which would be helpful in predicting surface roughness during hard milling of AISI 4340 steel with MCFA. In this study author developed an ANN model with the help of MATLAB software. The networks with varying architecture were used for training the model. The Root mean square error (RMSE) was determined for each network. A network model of architecture 3-6-6-1 was found to give a minimum value of 0.01 as root mean square error. The input parameters selected for the experimentation were pressure at the fluid injector, frequency of pulsing and quantity of cutting fluid used. These parameters were varied in 3 levels. The model was then trained and tested with the input data. The predicted results were compared with the experimental results and found to be very much closer to the experimental results.

Conclusion

The study on machining with minimal cutting fluid application revealed that,

- The process of MCFA can generate a green environment in the shop floor and also reduces cutting fluid costs.
- The process proved itself to be efficient and useful in improving the health condition of workers in the industry.
- The study helped in understanding the effectiveness of MCFA process.

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