Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 6 Issue 12, December - 2017

Investigations on Hard Turning with Minimum Quantity Lubrication and its Automation Thereof

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Abstract*— Minimal quantity lubrication (MQL) is a recent technique introduced in machining (in particular, in drilling) to obtain safe, environmental and economic benefits, reducing the use of coolant lubricant fluids in metal cutting. In MQL a very small lubricant flow (ml/h instead of l/min) is used. In this case, the lubricant is directly sprayed on the cutting area. It guarantees a good level of lubrication. The cost of coolant is approximately from 7 to 17% of the total machining cost. This cost continues to rise. So coolant in wet machining operations is a crucial economic issue. An alternative, machining with "minimum quantity lubricant," or MQL, is gaining acceptance as a cost-saving and environmentally friendly option in place of some wet machining processes. In the present work a specially formulated cutting fluid was applied as a high velocity, thin pulsed jet at the immediate cutting zones at an extremely low rate of 2 ml/min using a fluid application system developed for this purpose during turning of hardened steel. The performance of HTMF (Hard Turning – Minimum Fluid) is studied in comparison with that of conventional hard turning in wet and dry form in terms of cutting force, cutting temperature, surface roughness, average flank wear, etc.

Keywords*— *Minimal quantity lubrication (MQL); coolant lubricant fluids; hard turning;

INTRODUCTION

Minimum quantity lubrication (MQL) offers a compromise between coolant-based machining and machining dry. The process provides significantly reduced coolant consumption, without sacrificing lubrication and temperature control. Minimal quantity lubrication is a recent technique introduced in machining (in particular, in drilling) to obtain safe, environmental and economic benefits, reducing the use of coolant lubricant fluids in metal cutting. In MQL a very small lubricant flow (ml/h instead of l/min) is used. In this case, the lubricant is directly sprayed on the cutting area. It guarantees a good level of lubrication.

Turning of hardened steel components may be carried out by adopting suitable machining strategies. Hard dry turning is one such strategy. During hard, dry turning, the work can be turned to its final dimension in the hardened state. This is accomplished by selecting suitable cutting tools such as CBN or ceramic tools and machine tools of high rigidity. This method eliminates the conventional process cycle consisting of initial turning, subsequent hardening by heat treatment and final finish grinding. Hard turning can save time, improve surface quality, reduce operations and decrease rejections. But hard, dry turning involves heat dissipation without coolants and hence demands costly high performance cutting tools and extremely rigid machine tools. In many instances this cannot be implemented directly on the shop floor, as the existing machine tools lack the requisite rigidity. Hard turning in accompaniment with a copious supply of cutting fluid is the normal practice on the shop floor, which is supposed to exploit the cooling, lubrication and chip removal action of cutting fluids. However recent concepts and awareness of sustainable manufacture are often on a collision course with the use of cutting fluids. Used in large quantities they pose problems of procurement, storage, disposal and maintenance. In other words, apart from the cost, flood application is not environment or people friendly. This factor assumes considerable significance in the recent climate of strict work safety and environmental protection. According to the Occupational Safety and Health Administration (OSHA) regulations, the permissible exposure Level for mist within the plant (PEL) is 5 mg/m3 and is likely to be reduced to 0.5 mg/m3. A plausible solution to overcome these issues is an approach, which is intermediate between pure dry and conventional wet turning. The concept of pseudo dry turning or turning with minimal cutting fluid is very much relevant in this context. In this method extremely small quantity of cutting fluid is used and it almost resembles dry turning.

There are reports of attempts to introduce cutting fluid at the tool–chip interface through specially designed cutting tools with the objective of achieving better cutting performance. Such attempts brought forth better tool life better surface finish, low cutting force and better chip forms. Research work carried out in the laboratory has indicated that good cutting performance could be achieved in terms of surface finish, tool wear and cutting force when a specially formulated cutting fluid was applied on critical locations such as tool–work interface or the tool–chip interface using a cutting fluid application system in the form of a high velocity, thin pulsed jet during turning of round bars of through hardened AISI 4340 steel of 46HRC using multicoated hard metal inserts with sculptured rake face. No modifications need be done on the cutting holder or inserts. The fluid application system developed is relatively simple and can supply cutting fluid to six machine tools without necessitating any modifications on the existing system setup. The parameters of fluid application viz. composition of cutting fluid, pressure of injection, rate of delivery, the frequency of pulsing, the mode of delivery and direction of delivery were optimized using Response Table methodology. In the present work, HTMF in its optimized mode is compared with conventional wet turning and dry turning under identical cutting conditions.

Lubrication – Methods, Purpose and Properties

Hand Application: This type of application is used only in small batch production, because, using this lubrication method, it is not easy continuously to apply the cutting fluids and sufficiently to cool the work piece. It guarantees a low level of lubrication, cooling and chip removal.

Flooding: This application is the most common one. It guarantees a very good level of lubrication, cooling and chip removing. Applying this method of lubrication, it is also possible to orientate the nozzle to the clearance tool surface, reducing the flank wear, especially when the cutting speed is slow.

Minimal Quantity Lubrication (MQL): In MQL a very small lubricant flow (ml/h instead of l/min) is used. In this case, the lubricant is directly sprayed on the cutting area. It guarantees a good level of lubrication, but the cooling action is very small and the chip removal mechanism is obtained by the air flow used to spread the lubricant.

MINIMUM QUANTITY LUBRICATION AND CLASSIFICATIONS

Background

Minimum Quantity Lubrication is a new machining method that delivers the required minimum quantity of lubricant mixed with air and performs machining through a continuous supply of this oil/air mixture to the tool tip. This method is also called semi dry machining, near dry machining (NDM), and MMKS. This method for machining and the mixture are called MQL. MQL makes it possible to reduce the amount of lubricant to nearly zero. In conventional manufacturing of mass-produced parts that typify automotive parts (engine, transmission, brake, etc.), a large volume of cutting fluid (coolant) is used to improve productivity and machining accuracy. Recently, the negative effects of cutting fluid upon people and the environment have become a serious problem so the reduction of coolant is strongly required.

Fig 1 Conventional machining (flooded)

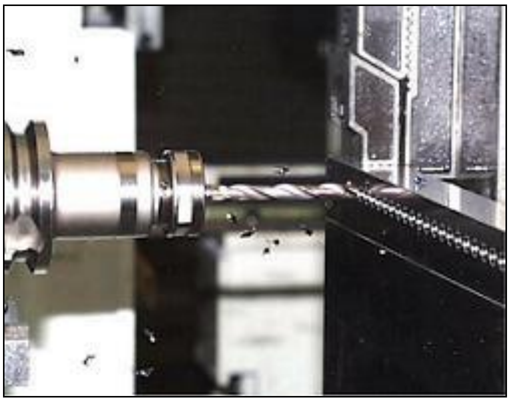

Fig 2 MQL machining

Advantages Of MQL Over Using Coolant

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. Many advantages are realized through the use of MQL and the reduction of cutting oil consumption. These include improvement of the plant environment; improvements in chip recycling, reduction of electricity consumption, increased tool life, a "greener" environment, and a decrease of machine maintenance due to contamination by coolant.

MQL Equipment-Classifications

Two different mixing methods can be used: mixing inside nozzle and mixing outside nozzle. Using the mixing inside nozzle equipment, pressurized air and lubricant are mixed into the nozzle by a mixing device. The lubrication is obtained by the lubricant, while a minimal cooling action is achieved by the pressurized air that reaches the cutting surface. Several advantages derive applying this method. Mist and dangerous vapors are reduced and the mixture setting is very easy to control. In the mixing outside nozzle method the mixture is obtained in a mixing device positioned in a specific tank. Also, in this case lubrication between work piece and tools can be achieved.

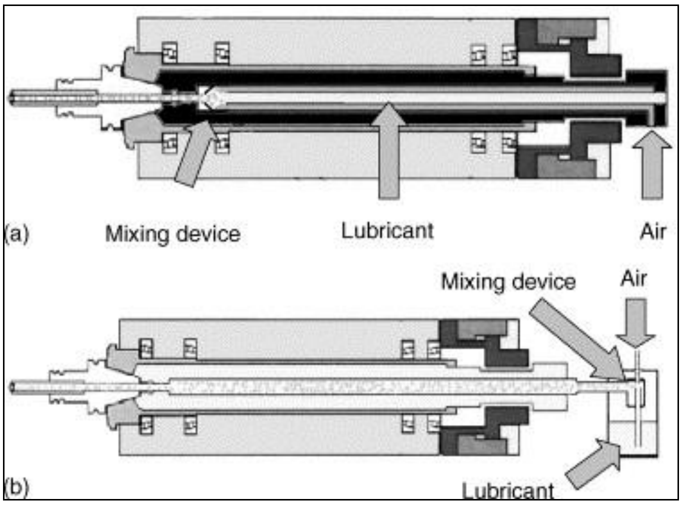

Fig 3 Mixing inside nozzle and Mixing outside nozzle

Cost Merit

The cost of cutting fluid (coolant) is 3 to 4 times higher than tool cost in production cost of parts for automobile. The below bar chart shows a calculated cost comparison when considering fluid consumption, personnel expenses, cost of waste liquid treatment, electricity consumption for compressed air and coolant pump, and depreciation of equipment. When compared with processes that require medium to high coolant pressures, MQL promises sharp cost reductions.

Chip Removal

The countermeasure of chip treatment is one of the problems that should be mostly considered in the construction of mass production. A large quantity of coolant is conventionally used for discharging chips outside machine. In order to adopt MQL in mass production, it is necessary to be surely done chip treatment with another method instead of much coolant. Horkos Corp has solved problems to use the combination of the gravity drop method and the vacuum method (suction method). The followings are examples of chip treatment.

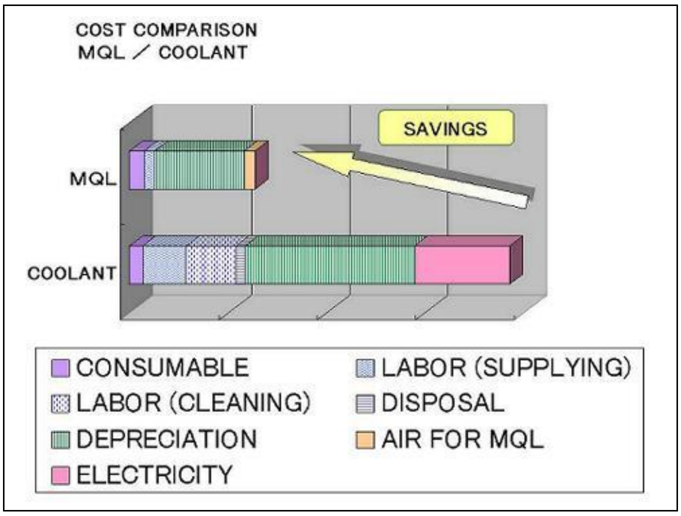

Fig 4 Cost Merit

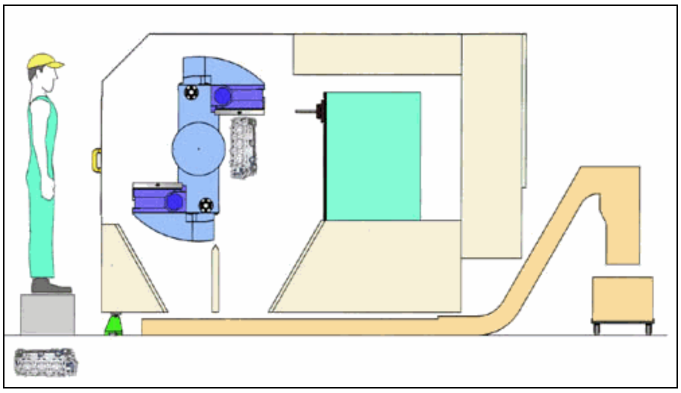

Fig 5 Gravity drop method (with vertical inversion jig)

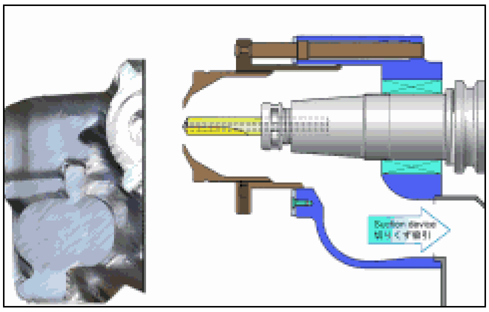

Fig 6 Vacuum hood for hole process (patented)

INVESTIGATIONS ON HARD TURNING WITH MINIMAL CUTTING FLUID APPLICATION (MQL) AND IT'S COMPARISON WITH DRY AND WET TURNING

Selection of Work Material

The work material was a through hardened steel (AISI 4340) which was hardened to 46 HRC (460 HV) by heat treatment. It is general-purpose steel having a wide range of application in automobile and allied industries by virtue of its good harden ability enabling it to be used in fairly large sections. Bars of 75 mm diameter and 320 mm length were used in the present investigation. The composition of the work material is given below

C	Ni	Cr	Mo	Mn	Si	Fe
0.44	1.91	1.25	0.34	0.68	0.38	Rest

Selection of Cutting Tool

Based on their easy availability and widespread use multicoated hard metal inserts with sculptured rake face geometry with the general specification, SNMG 120408 with a P30 or equivalent substrate with TiC, TiN and TiCN coatings from SANDVIK, Sweden were used in the present study. The tool holder used from the same source had the specification PSBNR 2525 M12.

Formulation of Cutting Fluid

Since the quantity of cutting fluid used is extremely low in this new method, specially formulated cutting fluids with appropriate ingredients and properties were used in the present investigation. The base was a commercially available mineral oil. The formulation contained, in addition to coolant and lubricant, additives such as surfactant, evaporator, emulsifier, stabilizer, biocide and a deodorizing agent.

Fluid Injection System

An overall view of the special test rig developed for injecting the cutting fluid is presented in Fig. 7. It consisted of a P-6 Bosch fuel pump generally used for diesel fuel injection in truck engines coupled to a variable electric drive. A high-speed electrical mixing chamber facilitated thorough emulsification. The test rig facilitated the independent variation of the injection pressure (p) the frequency of injection (N) and the rate of injection (Q). The system can deliver fluids through six outlets simultaneously, so that cutting fluid could be injected to more than one location or more than one machine tool at the same time. By selecting proper settings, the rate of injection could be made as small as 0.5 ml/min. Special fixtures were designed, so that the injection nozzle could be located in any desired position without interfering with the tool or work during actual cutting.

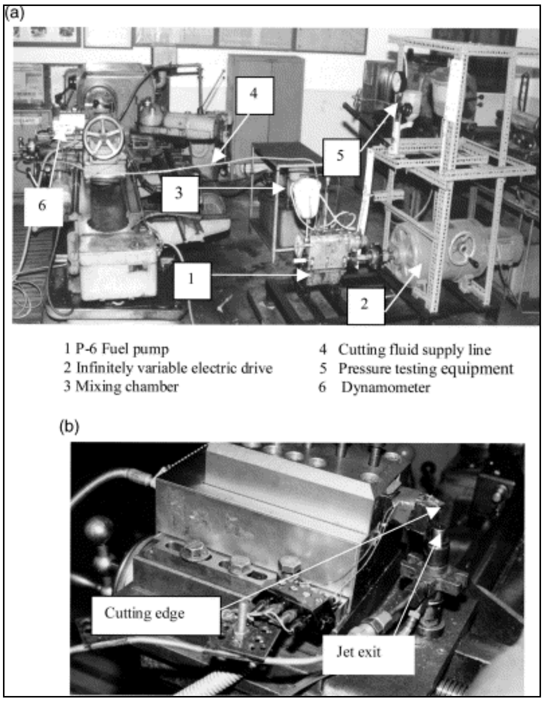

Fig 7 Overall view of the fluid application system

Electronic Control System for Fluid Application

Controlling the flow of lubricant and air is critical for the automation of milling, drilling & turning machines to further save the quantity of lubricant. For this purpose a microcontroller based electronic system can be used. Two solenoid valves can be used for independently controlling the flow of coolants and air to the mixing chamber. The feedback of rotating speed of the machine/tool is to be provided to the microcontroller. Microcontroller can be programmed in such a way that the opening of the solenoid valves is proportional to the speed of rotation. That means when the rotation speed increases the flow of coolants and air also increases. The exact required flow discharge of the coolant and air for various rotation speeds can be programmed in the microcontroller. Advantage of this automation is that the quantity of coolants can be precisely adjusted in accordance with its requirements instead of continuously pumping the coolants and air corresponding to the maximum speed. Another advantage is that the flow of coolants and air can be independently controlled so that a optimum combination of coolants and air can be configured in the microcontroller for each particular applications.

EXPERIMENTAL PROCEDURE ANALYSED

Selection of Levels of Parameters of Fluid Application

The optimization procedure carried out during the earlier work lead to the identification of the parameters of fluid delivery and fluid composition. The investigation revealed that a coolant-rich (60%) lubricant fluid with minimal additives is the ideal formulation for HTMF. The effect of fluid delivery parameters on cutting performance was evaluated and on that basis their optimum levels were identified. Within the practical range investigated these were a low (2 ml/min) delivery rate, high (20 MPa) injection pressure, high (600 pulses/min) pulsing rate and a collimated slug.

Cutting Experiments

Experiments were seen carried out on a heavy-duty VDF S500 lathe of Heidenreich and Harbeck, Hamburg, Germany. The cutting velocity was varied from 40 to 120 m/min at five levels while the feed was kept at 0.1 mm/rev and the depth of cut at 1.25 mm. The performance parameters such as surface roughness, main cutting force, cutting temperature and the average flank wear were measured during dry turning, wet turning and during minimal application in the optimized mode. A stylus type perthometer was used for measuring surface roughness. The cutting force was measured using a Kistler dynamometer. The cutting temperature was measured using tool–work thermocouple technique and the average flank wear was measured using a tool maker's microscope.

To evaluate the performance during the variation of feed, experiments were conducted with the feed ranging from 0.05 to 0.14 mm/rev at five levels with the cutting velocity maintained at 80 m/min and depth of cut at 1.25 mm during dry, wet and optimized minimal application. Tool life tests were carried out in the three modes at a constant feed of 0.1 mm/rev.

RESULTS AND DISCUSSIONS

Main Cutting Force

Fig. 8 shows the variation of cutting force with feed and cutting velocity respectively under specified conditions. It is observed that cutting force is lower during minimal application when compared to dry turning and conventional wet turning. Presumably minute capillaries exist at the tool–chip interface especially if the seizure and sub layer plastic flow at the tool–chip contact zone are not total, as was found in this case by an examination of the chip underside. So capillaries can also exist in the body of the chip as extensions of outer surface serrations. Penetration of the cutting fluid with EP additives in to the interface can reduce the frictional contribution to cutting force. So also penetration of the fluid through the mass of the chip can influence chip curl and the primary deformation process. Through high-pressure injection the fluid is fragmented into tiny droplets the size of which is inversely proportional to the pressure of injection. The velocity varies as a function of the square root of the injection pressure. This high velocity (of the order of 100 m/s for a pressure of 20 MPa) facilitates better penetration of the cutting fluid on impact to the root as well as the underside of the chip facilitating its passage to the tool–chip interface resulting in the reduction of friction. Such a condition is not possible in conventional wet turning where no such fragmentation is taking place and the kinetic energy of the fluid jet is in no way comparable to that during fluid injection.

Tool–Chip Contact Length

Reduced contact length and improved cutting ratio are indicative of favorable frictional conditions at the tool–chip interface. A quantitative analysis of the former is given in. Reduction of tool–chip contact length is expected to occur due to the following.

1. Contamination of tool rake face,

2. Promotion of plastic flow at the backside of the chip due to Rebinder effect and

3. Overall reduction of cutting temperature.

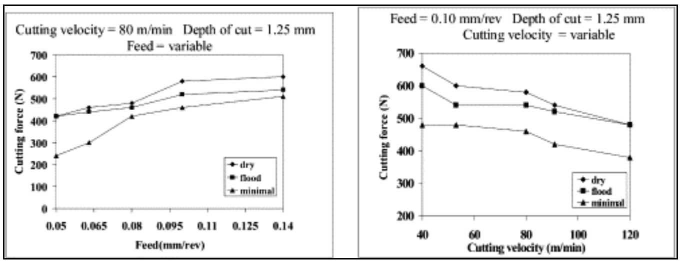

Fig 8 Variation of cutting force during dry, wet and during minimal application in optimized condition.

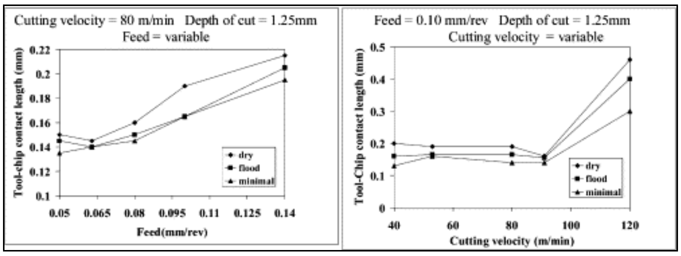

Fig 9 Variation of tool–chip contact length during dry, wet and during minimal application in optimized condition.

It can be seen that all the three mechanisms are active during fluid injection. The penetration of fluid vapor as described earlier leads to the contamination of the rake face. This prevents adhesion of the virgin chip surface on to the tool surface and shifts the condition from seizure and sublayer plastic flow to one of sliding and as a consequence there is a considerable reduction in the contact length.

Environmental factors can affect the mobility of near surface dislocation on the chip surface and this chemomechanical effect is known as the Rebinder effect. During minimal application the cutting fluid is applied at the tool–work interface and there is a possibility of some tiny fluid particles penetrating the work surface near the cutting edge, which will form the top of the chip in the next revolution. These particles, owing to their high velocity and smaller physical size can penetrate and firmly adhere to the work surface resulting in the promotion of plastic flow on the backside of the chip due to Rebinder effect. This relieves a part of the compressive stress and promotes chip curl that reduces tool chip contact length.

In the present investigation the tool–chip contact length was the least during minimal application followed by wet turning and dry turning over the entire cutting range as observed in Fig. 9 respectively. In conventional wet turning rake face lubrication is not as effective as in fluid injection, as the fluid particles cannot have penetrant contact and consequently the chip curl due to Rebinder effect and the associated reduction in contact length is less pronounced.

Cutting Ratio

The cutting ratio (t/tc) is an index of the frictional conditions existing at the tool–chip interface. A higher cutting ratio implies better lubrication at the tool–chip interface and formation of chips of thinner sections. In Fig. 10 it is observed that higher cutting ratios are possible during minimal application than during dry turning and conventional wet turning. Chip section micrographs during dry turning, conventional wet turning and during minimal application are presented in Fig.11 respectively. It is observed that the chip thickness is a minimum during minimal application followed by wet turning and dry turning. It is also observed that the deformation on chips formed during minimal application is less when compared to the other two.

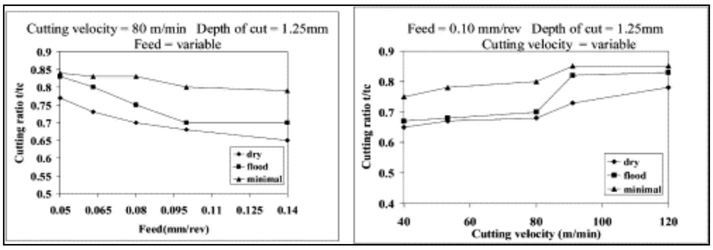

Fig 10 Variation of cutting ratio during dry, wet and during minimal application in optimized condition.

Cutting Temperature

Cutting temperature is a dominant factor in tool wear as all the wear mechanisms are temperature-dependant. Apart from reducing wear, low cutting temperature reduces adhesion tendency and promotes contact area restriction. During conventional wet turning the quantity of heat (Q) extracted by convective heat transfer is given by

$$Q = MCp\Delta T \qquad (1)$$

Where Q is heat quantity in kcal, M is the mass of cutting fluid, Cp is the specific heat capacity and ΔT is temperature reduction brought about.

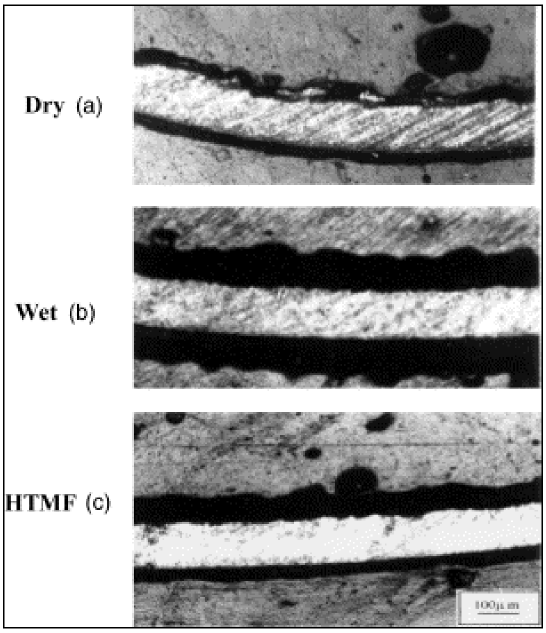

Fig 11 Chip section micrograph during dry turning wet turning and HTMF

However, during minimal application, cooling occurs due to both convective and evaporative heat transfer. The evaporative heat transfer is facilitated by the increase in surface area caused by atomization and the quantity of heat removed (Q1) is given by

$$Q1=MCp\Delta T+mL \quad (2)$$

Where M, Cp and ΔT have the same notation as before. m is the mass of the evaporation fluid and L is the evaporation enthalpy. In the case of water, the evaporation enthalpy is 2260 kJ/kg and in the case of mineral oil it is about 210 kJ/kg. The specific heat capacity Cp for water is 4.2 kJ/kg K and that for mineral oil is 1.9 kJ/kg K. Since the evaporation enthalpy of water is very high, evaporation of even a very small quantity of water is sufficient to create significant cooling.

The cutting fluid droplets by virtue of their high velocity can puncture the blanket of vapor formed and reach the hot interfaces facilitating more efficient heat transfer than is possible in conventional wet turning, where the adherent film of lubricant retards the heat transfer. The lower cutting temperatures recorded in a cutting velocity range of 40–120 m/min and that in a feed rate range of 0.05–0.14 mm/rev during minimal application. Fig. 12 is direct consequences of the above factors. Cutting fluid injection thus provides effective heat transfer leading to lower cutting temperatures than is possible during conventional wet turning.

Surface Finish

The reduction in cutting force, lowering of cutting temperature, shortening of tool–chip contact length and increase of shear angle during minimal application should bring forth better surface integrity and improved tool life than otherwise, as is seen from Fig. 13.

Tool Life

Fig. 14(a) represents a comparison of the variation of surface roughness as a function of time. It is observed that a surface roughness within Ra=1 μm could be maintained for 360 s during minimal application where as it is 150 s in dry turning and 210 s in wet turning. Fig. 14(b) represents the comparison of average flank wear with time. It is observed that during dry turning the average flank wear was 0.3 mm after 150 s when the surface roughness became Ra=1 μm. Photographs of flank wear after a cutting time of 120 s during dry turning wet turning and during minimal application are shown in Fig. 14(c). The results are self-explanatory

Comparison of Chip Forms

The form of chip produced is one of the major parameters influencing productivity in metal cutting industry. According to Kaldor et al., there are two groups of chip forms, (1) acceptable chips and (2) unacceptable chips, based on the convenience of handling. Acceptable chips do not interfere with the work or the machine tool and do not cause problems of disposal. Unacceptable chips interrupt regular manufacturing operation, as they tend to tangle around the tool and work piece and pose safety problems to operators. Entangling chips can harm the surface finish and even lead to unexpected tool failure.

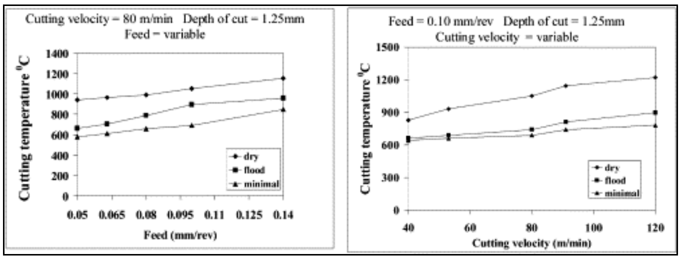

Fig 12 Variation of cutting temperature during dry, wet and during minimal application

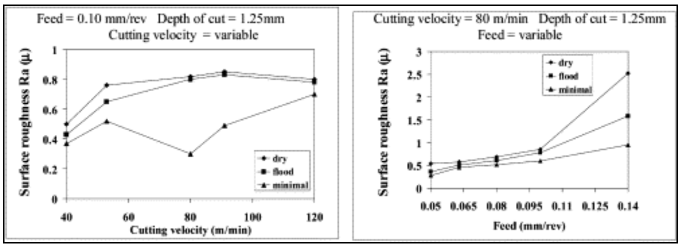

Fig 13 Variation of surface roughness during dry, wet and during minimal application

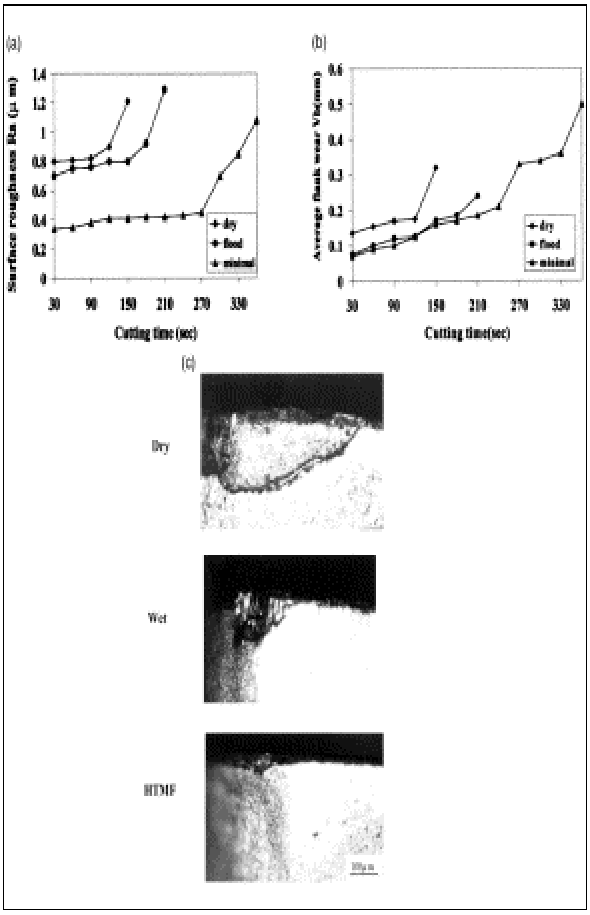

Fig 14 (a,b) Variation of surface roughness and average flank wear with time of cut during dry, wet and during minimal application. (c) Photograph showing flank wear during dry turning wet turning and HTMF respectively.

Fig 15(a) presents a comparison of chip forms obtained during dry, wet and minimal application at different feeds. The chip sampled shown in Fig. 15(b) correspond to various cutting velocities. It is observed that tightly coiled chips are formed during wet turning and during minimal application that could be handled easily where as long snarled chips are prevalent during dry turning. The chips formed during minimal application were similar to that during wet turning in spite of the rate of fluid application being only 0.05% of that used in wet turning. It is clear that HTMF promotes acceptable chips that can be handled easily.

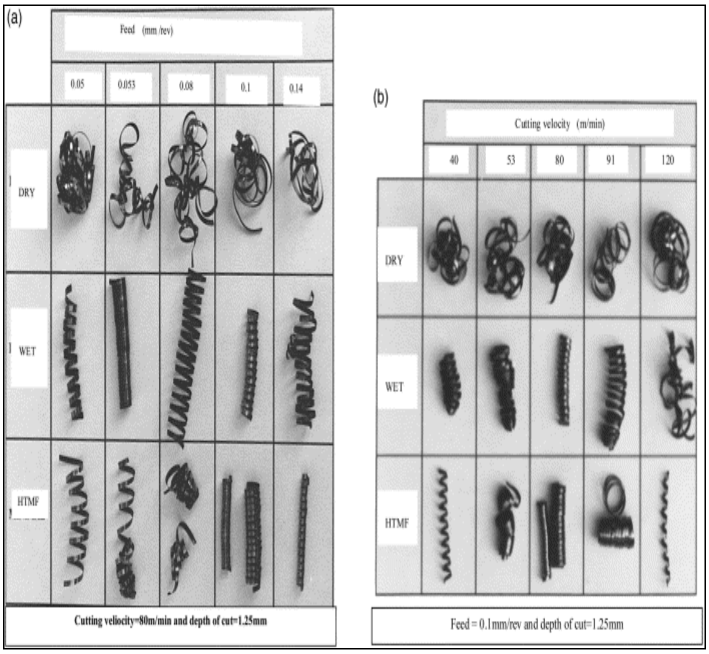

Fig15 Comparison of chip samples during dry turning, wet turning and during turning with minimal application for a feed range of 0.1–0.14 mm/rev. (b) Comparison of chip samples during dry turning, wet turning and during HTMF for the cutting velocity range of 80–120 m/min.

CONCLUSIONS

The overall performance during minimal cutting fluid application is found to be superior to that during dry turning and conventional wet turning on the basis of cutting force, tool life, surface finish, cutting ratio, cutting temperature and tool–chip contact length. This technique can form a viable alternative to conventional wet turning, as it can be implemented without drastic alterations in the existing facilities on the shop floor. As the minimal rate of application is as low as 2 ml/min a major portion of the fluid is evaporated. The remnants carried away by the work and chip is too low to cause contamination of the shop environment. The details presented in this paper can form a scientific basis for developing commercial minimal fluid application systems considering the backdrop of stringent environmental regulations on the shop floor.

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