



International Journal of **Manufacturing Systems**

ISSN 2152-1913



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An Environment Friendly Twin-jet Minimal Fluid Application Scheme for Surface Milling of Hardened AISI4340 Steel

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ABSTRACT

Surface milling of hardened steel is usually carried out with copious supply of cutting fluid and is obviously associated with problems related to procurement and storage of cutting fluid. The disposal of cutting fluid has to comply with environmental legislation such as OSHA regulations. The present investigation aims at establishing an environment friendly minimal pulsed jet cutting fluid application scheme for surface milling of AISI4340 steel with a hardness of 45 HRC using commercially available carbide tools. A special minimal fluid applicator was developed which facilitated the independent variation of fluid application parameters such as pressure at the fluid injector, frequency of pulsing, rate of fluid application and mode of fluid application. A set of operating parameters for optimum performance was determined using Response Table Methodology. Accordingly, an 8 run experiment was designed based on Taguchi's techniques. The new fluid application system offered a reduction in surface roughness (Ra) from 1.177 microns to 0.631 microns, reduction in flank wear from 0.051 to 0.018 mm and reduction in cutting force from 228.25 to 105.79 N when compared to conventional wet milling under the same cutting conditions which requires very large quantity of cutting fluid. The scheme can be implemented as such on the shop floor with out the need for any major alternations on the existing facilities and it was observed that the new scheme is not only environment friendly but also provided better cutting performance.

Key words: Environment friendly, hard milling, high velocity pulsed jet, minimal cutting fluid application, surface milling

INTRODUCTION

Conventional surface milling of hardened steel needs application of large quantities of cutting fluid. Procurement, storage and disposal of cutting fluid incur expenses and large scale use of cutting fluid causes serious environmental and health hazards on the shop floor. Apart from the fact that it gives a foul smell, disposal of cutting fluid is a problem and one has to comply with environmental legislation.

In this context, dry milling is a logical alternative which is totally free from the problems associated with storage and disposal of cutting fluid. But it is difficult to implement on the existing shop floor as it needs ultra hard cutting tools and extremely rigid machine tools. Ultra hard cutting tools may be introduced but the existing machine tools may not be rigid enough to support dry hard milling. In this context the best alternative is to introduce pseudo dry milling or milling with

Table 1: Chemical composition of work material

Element	Percentage
C	0.38-0.43
Cr	0.7-0.9
Mn	0.6-0.8
Mo	0.2-0.3
Ni	1.65-2.0
P	0.035 max
Si	0.15-0.3
S	0.04 max
Fe	Balance

minimal fluid application. In this method, extremely small quantity of cutting fluid is introduced at high velocity (70 m sec^{-1}) in the form of tiny droplets at critical zones so that for all practical purposes it resembles dry machining (Varadarajan *et al.*, 1998, 1999, 2001; Attansio *et al.*, 2006).

It is reported that minimal cutting fluid application can improve cutting performance during turning (Varadarajan *et al.*, 2000). Some fundamental work is reported in the field of fluid minimization during turning. But very less work is reported in the area of fluid minimization during milling (Anil Raj *et al.*, 2008; Thepsonthi *et al.*, 2009; Rahman *et al.*, 2002). The present work aims at a systematic investigation on the viability of cutting fluid minimization during surface milling of AISI4340 steel with a hardness of 45 HRC by developing a fluid application system that can deliver a high velocity narrow pulsed jet of cutting fluid through fluid application nozzles that can be located with the help of fixtures so that cutting fluid particles can reach critical zones and offer better cooling and lubrication. The most important aspect of this scheme is that it can be easily implemented on the shop floor and offers better cutting performance when compared to conventional wet milling while using very small quantities of cutting fluid (about $5\text{-}15 \text{ mL min}^{-1}$).

Selection of work material: A through hardenable AISI4340 steel was selected as work material. It was hardened to 45 HRC by heat treatment. It is a general purpose steel having a wide range of applications in automobile and allied industries by virtue of its good hardenability. Plates of 125 mm length, 75 mm breadth and 20 mm thickness were used for the present investigation. The composition of the work material is shown in Table 1.

Selection of cutting tool: Carbide inserts with the specification AXMT 0903 PER-EML TT8020 of TaeguTec was used in the investigation along with a tool holder with the specification TE90AX 220-09-L.

Formulation of cutting fluid: Since, the quantity of cutting fluid used is extremely small, a specially formulated cutting fluid was employed in this investigation. The base was a commercially available mineral oil and the formulation contained other ingredients (Varadarajan *et al.*, 2002). It acted as an oil in water emulsion.

Fluid application system: A special fluid application system was developed for this purpose (Varadarajan *et al.*, 2001). It consists of a P-4 fuel pump (Bosch make) coupled to an infinitely variable electric drive. An injector nozzle of single hole type with a specification DN0SD151 with a spray angle of 0° was used in the investigation. The fluid application system facilitated

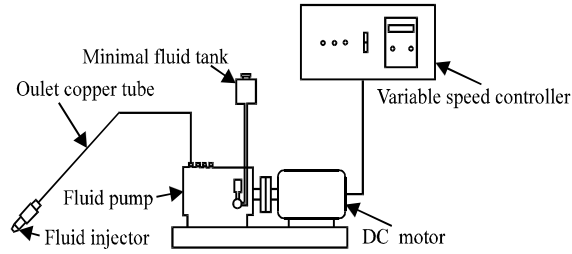


Fig. 1: Schematic view of the minimal fluid applicator



Fig. 2: Fixtures for locating the fluid injector

independent variation of pressure at fluid injector (P), frequency of pulsing (F) and the rate of fluid application (Q). The system can deliver cutting fluid through four outlets simultaneously so that cutting fluid could be applied to more than one location or more than one machine tool at the same time. By selecting proper settings the rate of fluid application could be made as small as 0.25 mL min^{-1} . The frequency of pulsing is determined by the speed of rotation of the DC variable speed motor that drives the fluid pump.

The fluid applicator delivers cutting fluid in the form of pulsed spray at the rate of one pulse per revolution. This facility enables application of less amount of cutting fluid per pulse. The quantity per pulse is adjusted by a plunger with helical groove arrangement which is present in the fluid pump which can be rotated about its axis and the angle through which the plunger is rotated determines the quantity of fluid delivered per stroke. In this system, it is possible to deliver cutting fluid at the same rate of fluid application with different frequencies of pulsing. For example, if Q is the rate of fluid application in mL min^{-1} and F is the frequency of pulsing in pulses min^{-1} , fluid applied per pulse is given by Q/F . Pulsing jet aids in fluid minimization without compromising the velocity of individual particles as the pressure at the fluid injector remains constant. By varying the frequency, the rate of fluid delivered per pulse can be controlled. For example if Q is 1 mL min^{-1} and F is $1000 \text{ pulses min}^{-1}$ and the pressure at the fluid injector is set at 100 bar, then fluid delivered per pulse is equal to $1/1000 = 0.001 \text{ mL}$ while the velocity of the individual fluid particles will be approximately equal to 70 m sec^{-1} (Philip *et al.*, 2001; Heywood, 1996).

A schematic view of the fluid applicator is shown in Fig. 1. Special fixtures were designed as in Fig. 2 so that the injector nozzle could be located in any desired position without interfering the tool or work during actual cutting.

MATERIALS AND METHODS

The Minimal Pulsed Jet Fluid Applicator (MPFA) for carrying out this research work was characterized by the following fluid application parameters which can be varied independently.

Table 2: Input parameters and their levels

Pressure at fluid injector (Bar)		Frequency of pulsing (pulses min ⁻¹)		Rate of fluid application (mL min ⁻¹)		Mode of fluid application		Composition of cutting fluid	
Level 1 (P1)	Level 2 (P2)	Level 1 (F1)	Level 2 (F2)	Level 1 (Q1)	Level 2 (Q2)	Level 1 (N1)	Level 2 (N2)	Level 1 (C1)	Level 2 (C2)
50	100	500	750	5	15	Single jet	Twin jet	10% oil in water	20% oil in water

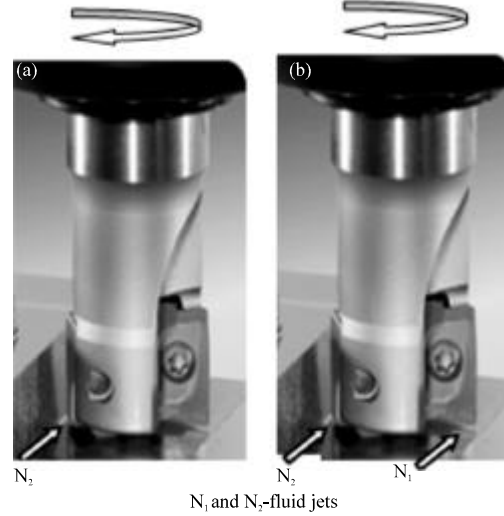


Fig. 3: Mode of cutting fluid application (a) single jet configuration and (b) twin jet configuration

- Pressure at the fluid injector (P) in bar
- Frequency of pulsing (F) in pulses min⁻¹
- Rate of fluid application (Q) in mL min⁻¹
- Mode of fluid application (N)

It was decided to explore the relative significance of these fluid application parameters along with one cutting fluid parameter namely the composition of the cutting fluid on the cutting performance. The fluid application and fluid composition parameters were varied at two levels as summarized in Table 2.

In order to ensure better penetration of cutting fluid in to the rake face, an attempt was made to make use of more than one fluid jet. Accordingly a single jet configuration as in Fig. 3a that corresponds to level-1 and a twin jet configuration as in Fig. 3b which corresponds to level-2 were used in this investigation.

Two compositions of cutting fluid were considered in this investigation. The first composition contained 10% oil and the rest water (level-1) and the second contained 20% oil and the rest water (level-2).

Mode of analysis: Selection of the operating parameters for optimum performance was planned using Response Table Methodology (Lochner and Matar, 1990). A set of levels of operating parameters are to be determined to obtain minimum surface roughness, minimum flank wear and

Table 3: Parameters kept constant and their values

Parameters	Values
Speed of the milling cutter	45 m min ⁻¹
Feed	0.14 mm tooth ⁻¹
Depth of cut	0.4 mm

Table 4: Basic design matrix for eight-run two-level experiments with five factors

Run No.	Factor columns				
	1	2	3	4	5
1	1	1	1	2	2
2	1	1	2	2	1
3	1	2	1	1	2
4	1	2	2	1	1
5	2	1	1	1	1
6	2	1	2	1	2
7	2	2	1	2	1
8	2	2	2	2	2

minimum cutting force. These operating parameters are to be used to compare the relative advantage of this method with respect to conventional wet milling and dry milling for the same tool work machine tool system with constant cutting parameters such as cutting speed, feed and depth of cut which are shown in Table 3.

An 8 run experiment was designed based on Taguchi's techniques (Lochner and Matar, 1990) and the design matrix is shown in Table 4. The experiments were conducted with two replications. Surface finish, flank wear and main cutting force were considered as the performance parameters. With optimum cutting performance as the basis, it was sought to determine (1) the level of the rate of fluid application (2) the level of frequency of pulsing (3) the level of pressure at the fluid injector (4) the level of composition of the cutting fluid and (5) the level of number of fluid jets to be employed.

Experimental details: Experiments were carried out on a HMT (model: FN1U) milling machine. A Kistler dynamometer was used for measuring cutting force. Surface finish was measured using a stylus type Perthometer (Mahr make), flank wear measurement was done using a tool maker's microscope. The cutting speed, feed and depth of cut were set in the semi finish milling range for the tool-work combinations.

RESULTS AND DISCUSSION

Figure 4 presents the relative significance of the operating parameters (fluid application as well as the cutting fluid parameter) on attainable surface finish. The relative significance of operating parameters on flank wear is shown in Fig. 5 and the relative significance of the operating parameters on cutting force is presented in Fig. 6. ANOVA analysis was also carried out using Qualitek-4 software to find out the percentage influence of individual parameters on surface roughness, flank wear and cutting force. From the ANOVA results, it was evident that pressure at the fluid injector forms the most significant parameter influencing the output parameters. It was also found that the interaction effects were not significant. The percentage of significance of pressure at the fluid injector on surface roughness, flank wear and cutting force were 54.203,

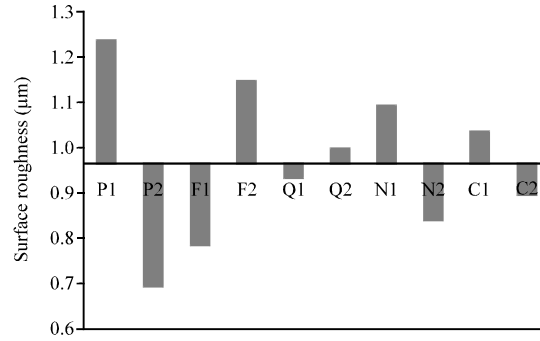


Fig. 4: Relative significance of levels of operating parameters on surface roughness

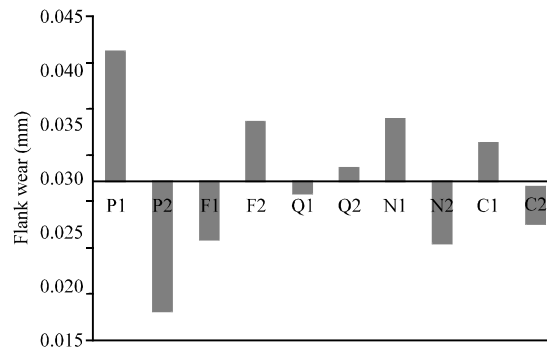


Fig. 5: Relative significance of levels of operating parameters on flank wear

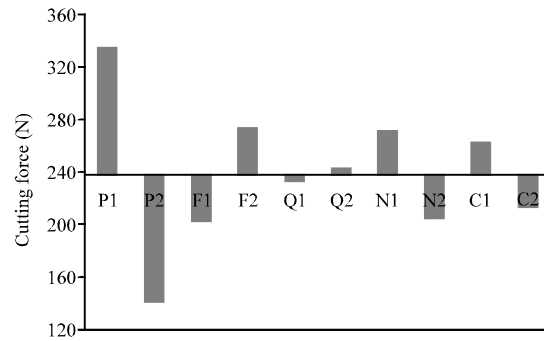


Fig. 6: Relative significance of levels of operating parameters on cutting force. (P: Pressure at fluid injector, F: Frequency of pulsing, Q: Rate of fluid application, N: Mode of fluid application and C: Composition of cutting fluid)

58.962 and 72.99, respectively. The results of the analysis which led to a set of levels of fluid application as well as cutting fluid parameter to minimize surface roughness, flank wear and cutting force are summarized in Table 5.

Pressure at the fluid injector: The pressure at the fluid injector kept at level -2 (100 bar) favored lower flank wear and better surface finish. The penetration power of the fluid droplet is directly proportional to the exit velocity (approximately 70 m sec^{-1}) (Philip *et al.*, 2001). The velocity

Table 5: Summary of operating parameters for optimum performance

Output parameters	Objective	Pressure (bar)	Frequency (pulses min ⁻¹)	Quantity (mL min ⁻¹)	No. of jets	% of oil in water
Surface roughness (μm)	To minimize surface roughness	100	500	5	Twin jet	20
Flank wear (mm)	To minimize flank wear	100	500	5	Twin jet	20
Cutting force (N)	To minimize cutting force	100	500	5	Twin jet	20

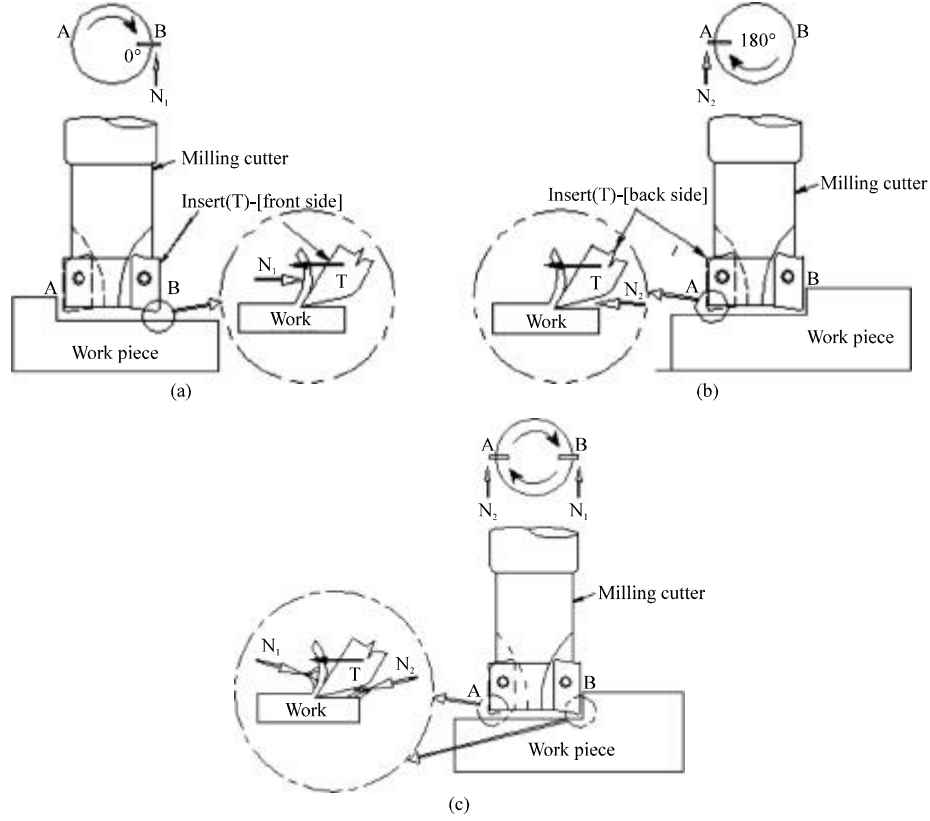


Fig. 7: (a) Location of fluid jet in single jet configuration (N_1), (b) Location of fluid jet in single jet configuration (N_2) and (c) location of fluid jets (N_1 and N_2 in the twin jet configuration)

varies as a function of the square root of the injection pressure (Heywood, 1996) where as the size of the individual droplets is inversely proportional to the exit velocity (Hiroyasu and Kadota, 1974). The cutting force is directly related to the chip friction on the rake face. Any attempt to reduce friction on the rake face can bring forth lower cutting force, lower energy consumption, better surface finish and lower flank wear. When the pressure at the fluid injector is high, better penetration will be facilitated leading to better lubrication at the contact surfaces.

Mode of fluid application: When the tool insert T is in location B as shown in Fig. 7a, the direction of impingement of the fluid droplets from nozzle N_1 is opposite to the direction of movement of the tool insert T and the fluid drops fall on the back side of the chip. When the cutter rotates through 180° and assumes the location A, the scenario is as indicated in the Fig. 7b. In this case, the direction of impingement of fluid droplets from the nozzle N_2 is in the same direction as the direction of movement of tool insert T and the fluid droplets fall on the tool-work interface.

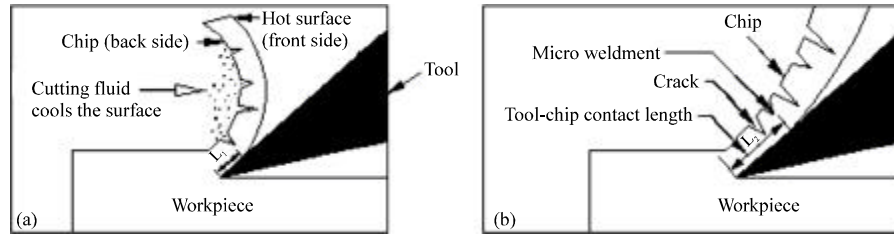


Fig. 8: Effect of cooling the back side of the chip (a) cooling of the back side of the chip leads to bending of the chip away from the rake face and (b) no supply of cutting fluid at the back side of the chip. L_1 and L_2 : Tool chip contact length ($L_2 > L_1$)

In the present investigation two configurations were used. The configuration as shown in Fig. 7b forms level-1 and that in Fig. 7c forms level-2 for the mode of fluid application as presented in Table 2. It was observed that the twin jet configuration as shown in Fig. 7c gave better cutting performance when compared to the single jet configuration.

The single jet configuration was selected as level-1 based on earlier work and results (Philip *et al.*, 2001) in which mention is made about the advantages of minimal fluid application on the tool-work interface during hard turning.

When a configuration as in Fig. 7c is selected, fluid droplets are applied both on the back side of the chip (Fig. 7a) and on the tool-work interface (Fig. 7b). When cutting fluid is applied on the back side of the chip, the fluid particles owing to their high velocity tend to adhere to the back side of the chip. These droplets evaporate taking the latent heat of vaporization from the chip. The cooling of the back side of the chip (Fig. 8) leads to its contraction where as the chip surface in contact with the rake face is hot and tends to elongate. This leads to the curling of the chip away from the tool rake face resulting in the reduction of tool chip contact length. Reduction in tool-chip contact length brings forth lower cutting force; lower flank wear and hence improved surface finish (Philip *et al.*, 2001; De Chiffre, 1988).

A chemical phenomenon can also occur at the tip of the micro cracks that formed on the back side of the chip. High velocity fluid droplets can penetrate on the back side of the chip and reach the tip of the micro cracks and stick on the surface owing to their high velocity. In the absence of cutting fluid, the nascent surface at the crack tip can coalesce due to the formation of micro weldments. The micro weldments can strengthen the back side of the chip thereby reducing the tendency of the chip to bend away from the rake face. But when a fluid droplet is present at the crack tip, it dopes the nascent surface and acts as a dielectric preventing the formation of micro weldments. This leads to the weakening of the back side of the chip and the chip tends to bend backwards, i.e., away from the rake face resulting in lower tool chip contact length and hence lower cutting force (Ball, 1997). Weakening of the back side also leads to its ultimate fracture resulting in the formation of fragmented chips that can be handled easily.

When cutting fluid is applied through the nozzle N_2 , the high velocity fluid droplets can enter the tool work interface (Fig. 7b) and finally can make their way to the tool chip interface as shown in Fig. 9.

These fluid particles provide rake face lubrication by forming a film of lubricant that adheres strongly to the rake face of the tool which reduces friction and hence the cutting force. The extreme pressure that exists at the tool chip interface prevents the easy entry of cutting fluid particles into the tool-chip interface. But when cutting fluid is applied at the tool-work interface, some cutting

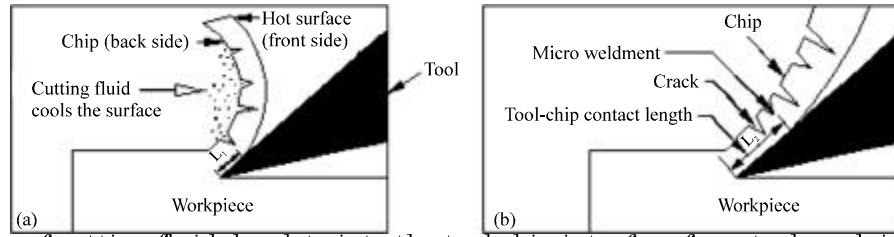


Fig. 9: Passage of cutting fluid droplets into the tool chip interface from tool work interface

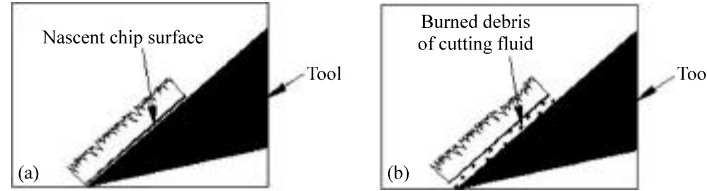


Fig. 10: Functioning of cutting fluid as a dielectric. (a) nascent chip surface tends to stick to the tool surface and (b) burned debris of cutting fluid act as dielectric and prevents surface interactions

fluid particles can enter the tool-chip interface through the small capillaries that exist at the root of the chip (Fig. 9) which can permit passage of cutting fluid particles of smaller size if they possess sufficient kinetic energy by virtue of their high velocities. There is also a possibility of formation of a complex compound on the tool chip interface which offers very low shear force and act as a lubricant owing to the extreme thermal conditions that exist in the rake face as proposed by Varadarajan *et al.* (2002). Moreover, the presence of cutting fluid at the tool-chip interface can act as a dielectric preventing the intensity of surface interaction between the chip and the tool thereby transforming the condition in the region OA in Fig. 9 from sticking to one of sliding, leading to reduction in cutting force.

There is of course the possibility of burning of cutting fluid droplets at the tool chip interface due to the severe thermal conditions that exist there. Even the burnt out fluid debris can act as a dielectric preventing inter molecular as well as inter atomic interaction between the tool and the chip (Fig. 10a, b) thereby preventing sticking of the chip on the rake face and this leads to reduction in cutting force. Moreover the fluid particles falling near the root of the chip can cause weakening of the cutting zone by creating zones of weakness on the work material and at the front side of the chip due to the embrittlement action of the cutting fluid. This action is based on Rebinder effect and involves micro cracks formation and healing (Astakhov, 2010). Adsorbed film/burned debris of cutting fluid prevents closing of micro cracks. Each micro crack near the root of the chip act as a stress concentrator and the energy needed for cutting gets reduced. In other words, penetration of foreign atoms from the cutting fluid decomposition produces an embrittlement effect near the root of the chip similar to hydrogen embrittlement which reduces the energy needed for cutting the material.

When cutting fluid is applied with two nozzles, performance improvement through reduction in cutting force is possible through two mechanisms namely reduction of tool chip contact length and better rake face lubrication whereas when a single jet is employed, only one mechanism namely better rake face lubrication is in operation.

Hence, a twin jet configuration can offer better cutting performance when compared to single jet configuration owing to the dual mechanisms of chip curl and rake face lubrication.

Rate of application: It is observed that the rate of fluid application at low level is advantageous in terms of better surface finish, lower flank wear and lower cutting force. According to the empirical relationship developed by Hiroyasu and Kadota (1974), the mean diameter D for a droplet size of cutting fluid injection is given by:

$$D = K(\Delta P)^{-0.135} \rho^{0.121} V^{0.131}$$

where, ΔP is the mean pressure drop, ρ is the density of the medium in which injection of fluid takes place, V is the quantity of fluid delivered per pulse and K is a constant. With lower delivery rates, the size of individual droplets decreases. As explained earlier, these tiny droplets provide better lubrication leading to lower cutting force, lower flank wear and better surface finish. Moreover, the rate of fluid application at lower level (5 mL min^{-1}) will also ensure efficient evaporative heat transfer, lower rates of fluid consumption and reduced mist formation that leads to a green environment on the shop floor.

During conventional wet turning, the quantity of heat extracted by convective heat transfer is given by:

$$Q = mC_p\Delta T$$

where, Q is the heat quantity in K cal, m is the mass of cutting fluid, C_p is the specific heat capacity and ΔT is the temperature reduction brought about.

During minimal fluid 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 is given by:

$$Q_1 = mC_p\Delta T + mL$$

where, m , C_p and ΔT have the same notation as mentioned before. m is the mass of the fluid evaporated and L is the evaporation enthalpy. In the case of water the evaporation enthalpy is 2260 kJ kg^{-1} and in the case of mineral oil is about 210 kJ kg^{-1} . The specific heat capacity C_p for water is $4.2 \text{ kJ kg}^{-1} \text{ K}^\circ$ and that for mineral oil is $1.9 \text{ kJ kg}^{-1} \text{ K}^\circ$. Since, the evaporation enthalpy of water is very high, evaporation of even a very small quantity of water is sufficient to create better cooling. Moreover, the cutting fluid droplets by virtue of their high velocity can puncture the blanket of vapor and reach the interfaces facilitating more efficient heat transfer which is not possible in conventional wet milling where the adherent film of lubricant retards the heat transfer.

Hence, when the rate of fluid application is low, smaller will be the droplet sizes, which leads to increased surface area to facilitate evaporative heat transfer and high individual droplet velocities facilitate better penetration of fluid particles into the tool-chip interface.

Composition: It is seen that composition of cutting fluid comprising of 20% oil and the rest water corresponding to level- 2 offered improved cutting performance when compared a composition with 10% oil. During machining, cutting fluid acts as a coolant and a lubricant. In case of oil in water emulsion as used in this investigation, water acts as a coolant and oil acts as a lubricant. During minimal fluid application, very small quantity of cutting fluid is expected to perform the dual functions of cooling and lubrication. It appears that a composition consisting of 10% oil is too lean

to provide effective rake face lubrication at the tool chip interface. A certain minimum quantity of lubrication must be present in the cutting fluid to compensate for the possible losses as the fluid reaches the tool chip interface through the tool work interface.

Frequency of pulsing: It is observed that frequency of pulsing of fluid application at low level favored better cutting performance. It is reported that the frictional forces between two sliding surfaces can be reduced considerably by rapidly fluctuating the width of the lubricant filled gap separating them (Landman, 1998).

When a pulsing jet is used, the width of the lubricant filled gap between the tool rake face and the chip fluctuates with a frequency equal to the frequency of pulsing of the fluid jet. The width will be maximum when the fluid slug falls at the gap and will be minimum when no particles fall on the gap during the pulsing cycle. This process continues as the fluid particles fall in the gap between the chip and the tool intermittently. When the frequency of pulsing (F) is $750 \text{ pulses min}^{-1}$, the quantity of fluid delivered per pulse is very less when compared with the frequency of pulsing of $500 \text{ pulses min}^{-1}$ for any fixed rate of fluid application. Hence, the fluctuation in the width of the liquid film between the tool and the chip is less appreciable when the frequency of pulsing is $750 \text{ pulses min}^{-1}$ when compared to that at a frequency of $500 \text{ pulses min}^{-1}$. A minimum quantity of cutting fluid should be delivered per pulse to get an appreciable fluctuation in the width. This leads to presence of fresh fluid droplets in the tool chip interface unlike in the case where a stagnant layer of cutting fluid will be present if a continuous jet is employed (Alexander *et al.*, 1998). The presence of fresh fluid droplets facilitates better filling of the gap on the tool-chip interface thereby providing better lubrication and enhanced cooling as the droplets evaporate.

Moreover, when the frequency of pulsing is very high, the individual particles will be small and may lack in kinetic energy to penetrate in to the tool chip interface. This leads to less fluid particles reaching the rake face and hence less efficient rake face lubrication. It is also to be noted that the pulsing nature of the fluid delivery vanishes when the frequency of pulsing is very high and the fluid delivery tends to resemble a continuous jet, devoid of all the aforesaid advantages claimed for a pulsing jet.

Chip characteristics: Figure 11a-c compares the types of chips formed during dry milling, wet milling and milling with minimal fluid application when the cutting speed was 45 m min^{-1} , feed was $0.14 \text{ mm tooth}^{-1}$, depth of cut was 0.4 mm and the fluid application parameters as in Table 5 to achieve minimum surface roughness, flank wear and cutting force for a cutting time of 60 sec.

It is seen that dark colored highly deformed chips were observed during dry milling (Fig. 11 a). Similar chips with slightly less traces of deformation were observed during conventional wet milling (Fig. 11b). Stubby type-2 chips (Boothroyd and Winston, 2006) which could be handled easily were observed while milling in the optimized condition (Fig. 11c). The chip produced during milling with minimal fluid application bore less traces of deformation when compared to that during wet milling even though the rate of fluid application was as low as 0.1% of that used in conventional wet milling.

Comparison of flank wear: Average flank wear was determined during dry, wet and minimal fluid application keeping the cutting speed, feed and depth of cut at 45 m min^{-1} , $0.14 \text{ mm tooth}^{-1}$ and 0.4 mm respectively. The flank wear was 0.127 mm during dry milling, 0.051 mm during



Fig. 11: Comparison of chip samples during dry milling, wet milling and during milling with minimal fluid application (a) dry milling, (b) wet milling and (c) milling with minimal fluid application. (Cutting speed: 45 m min^{-1} , Feed: $0.14 \text{ mm tooth}^{-1}$, Depth of cut: 0.4 mm)

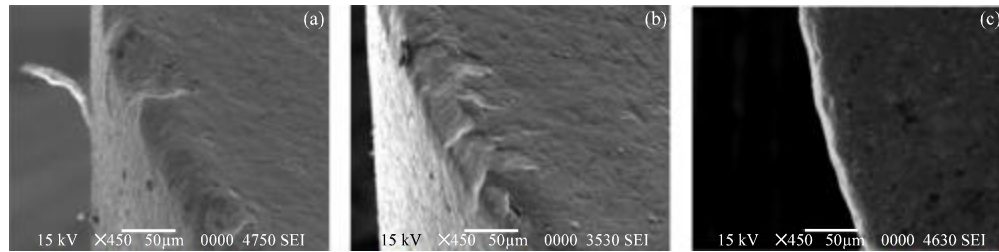


Fig. 12: SEM photographs on comparison of worn out insert edges during dry, wet and milling with minimal fluid application (a) dry milling, (b) wet milling and (c) milling with minimal fluid application. (Cutting speed: 45 m min^{-1} , Feed: $0.14 \text{ mm tooth}^{-1}$, Depth of cut: 0.4 mm)

Table 6: Comparison of output parameters during wet, dry and milling with minimal fluid application (Cutting time = 120 sec)

	Surface roughness Ra (μm)	Flank wear (mm)	Cutting force (N)
Dry milling	1.543	0.127	471.73
Wet milling	1.177	0.051	228.25
Minimal fluid application (Optimized condition)	0.631	0.018	105.79

conventional wet milling and 0.018 mm during optimized milling with minimal fluid application for a cutting time of 120 sec. SEM photographs of tool flank wear during dry milling, conventional wet milling and milling with minimal fluid application are presented in Fig. 12a-c, respectively. It is observed that flank wear is minimum during milling with minimal fluid application in the optimized mode. Lower flank wear during minimal fluid application is attributed to better rake face lubrication and lower tool chip contact length and better heat transfer due to evaporative cooling. The comparison of results of optimized milling with minimal fluid application with dry milling and conventional wet milling is presented in Table 6 from which it is clear that milling with minimal fluid application can offer improved surface finish, lower flank wear and lower cutting force when compared to dry milling and conventional wet milling.

Figure 13-15 present a comparison of surface roughness, flank wear and cutting force during dry milling, wet milling and milling with minimal fluid application.

Tool life test: A tool life test was performed in which the fluid application parameters were kept at levels as in Table 5 and keeping the machining parameters such as cutting speed, feed and depth

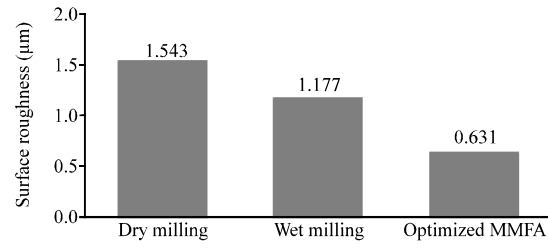


Fig. 13: Comparison of surface roughness (Ra)

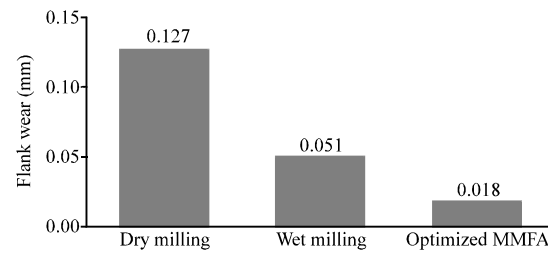


Fig. 14: Comparison of flank wear

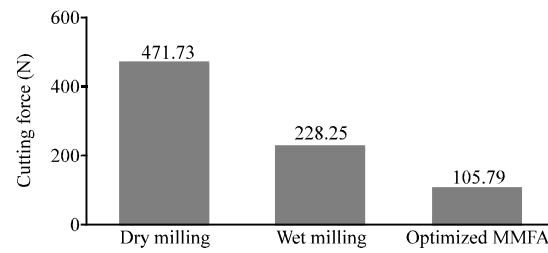


Fig. 15: Comparison of cutting force

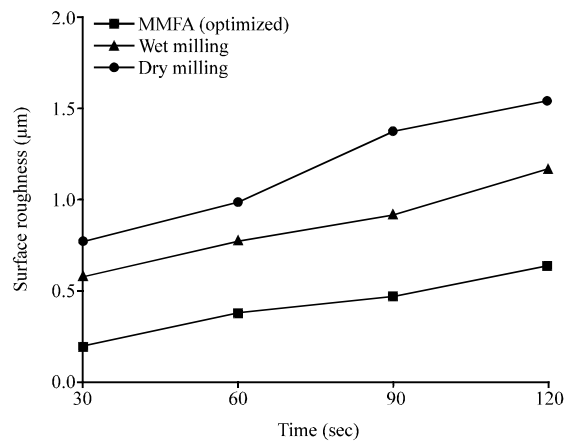


Fig. 16: Tool life test for comparison of surface roughness (Ra)

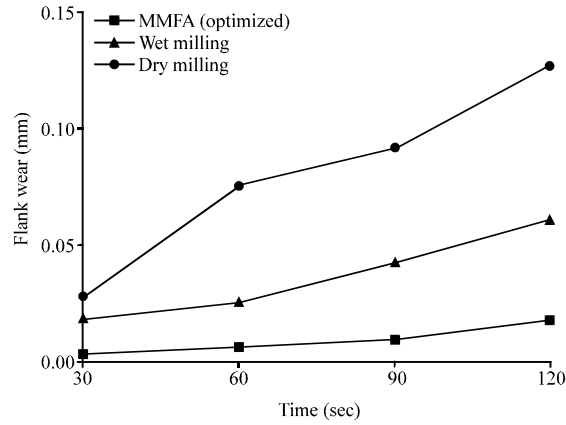


Fig. 17: Tool life test for comparison of flank wear

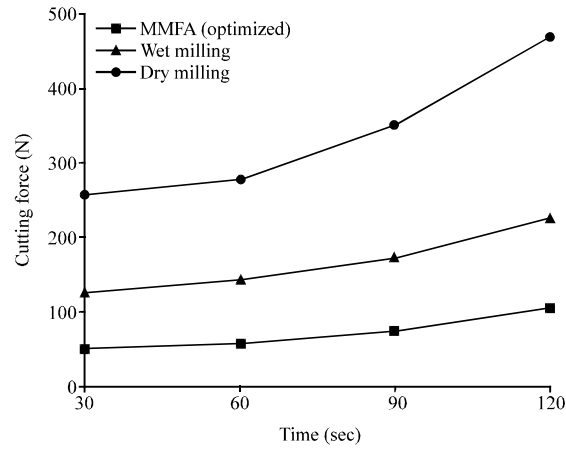


Fig. 18: Tool life test for comparison of cutting force

of cut at 45 m min^{-1} , $0.14 \text{ mm tooth}^{-1}$ and 0.4 mm , respectively. Measurement of surface roughness, flank wear and cutting force were done at the intervals of 30 sec from 30 to 120 sec.

It is observed from Fig. 16-18 that milling with minimal fluid application with twin jet configuration brought forth better surface finish, lower flank wear and lower cutting force when compared to that during conventional wet milling and dry milling. The findings during this research work were in line with the observations made during the preliminary investigations (Anil Raj *et al.*, 2008).

CONCLUSIONS

It is observed that the fluid application parameters influence cutting performance during surface milling of hardened steel based on pressure of fluid injection, frequency of pulsing, direction of fluid application, composition and rate of fluid application. The surface roughness (R_a) reduced from 1.177 to 0.631 microns, flank wear reduced from 0.051 to 0.018 mm and cutting force reduced from 228.25 to 105.79 N when compared to conventional wet milling under the same cutting conditions.

The study revealed that the following conditions could be recommended for this specific case to achieve improved performance: cutting fluid with 20% lubricant, the fluid is to be applied using the twin jet configuration at a rate of 5 mL min⁻¹ and the frequency of pulsing to be kept at 500 pulses min⁻¹ and the fluid pressure at the injector at 100 bar.

Therefore, results in this work indicate that milling with high velocity pulsed jet minimal fluid application holds promise for the development of a commercial environment friendly pulsed jet fluid application scheme with particular reference to surface milling of hardened steel.

REFERENCES

- Alexender, R., A.S. Varadarajan and P.K. Philip, 1998. Hard turning with minimum cutting fluid: A viable green alternative on the shop floor. *Proc. 18th AIMTDRC*, 1: 183-187.
- Anil Raj, K., L.D. Wins, R. Gnanadurai and A.S. Varadarajan, 2008. Investigations on hard milling with minimal fluid application. *Proceedings of the International Conference on Frontiers in Design and Manufacturing, (ICFDM'08)*, Karunya University, Coimbatore, pp: 183-187.
- Astakhov, V.P., 2010. Metal cutting theory foundations of near-dry (MQL) machining. *Int. J. Mach. Machinability Mater.*, 7: 1-16.
- Attansio, A., M. Gelfi, C. Giardimi and C. Remino, 2006. Minimal quantity lubrication in turning: Effect on tool wear. *Int. J. Wear*, 260: 333-338.
- Ball, A., 1997. A survey of metal working fluid mist in manufacturing plants. *Lubrication Eng.*, 53: 18-22.
- Boothroyd, G. and A.K. Winston, 2006. *Fundamentals of Machining and Machine Tools*. 3rd Edn., CRC Taylor and Francis, UK., pp: 69-100.
- De Chiffre, L., 1988. Function of cutting fluids in machining. *J. Soc. Tribol. Lubrication Eng.*, 44: 514-518.
- Heywood, J.B., 1996. *Internal Combustion Engine Fundamentals*. McGraw-Hill, New York.
- Hiroyasu, H. and T. Kadota, 1974. Fuel drop size distribution in diesel combustion chamber. *SAE Paper 740715 SAE Trans.*, 83: 715-721.
- Landman, U., 1998. FRUSTRATED lubricant molecules offer new strategy for reducing friction in mechanical devices. *Georgia Tech-Research news*.
- Lochner, R.H. and J.E. Matar, 1990. *Design for Quality*. Chapman and Hall, London, pp: 77-95.
- Philip, P.K., A.S. Varadarajan and B. Ramamoorthy, 2001. Influence of cutting fluid composition and delivery variables on performance in hard turning using minimal fluid in pulsed jet form. *J. Instit. Eng.*, 82: 12-19.
- Rahman, M., M.U. Salam and A. Senthil Kumar, 2002. Experimental evaluation on the effect of minimal quantities of lubricant in milling. *Int. J. Mach. Tools Manuf.*, 42: 539-547.
- Thepsonthi, T., M. Hamdi and K. Mitsui, 2009. Investigation into minimal-cutting fluid application in high-speed milling of hardened steel using carbide mills. *Int. J. Mach. Tools Manuf.*, 49: 156-162.
- Varadarajan, A.S., B. Ramamoorthy and P.K. Philip, 2002. Formulation of a cutting fluid for hard turning with minimal fluid application. *Proceedings of the 20th AIMTDR Conference at Birla Institute of Technology, (ACBIT'02)*, Ranchi, India, pp: 89-95.

- Varadarajan, A.S., P.K. Philip and B. Ramamoorthy, 1998. Neural network assisted performance prediction in hard turning with minimal quantities of cooling lubricants. Proceedings of the 14th International Conference, CAD/CAM, Robotics and Factories of the Future, (ICRFF'98), PSG College of Technology, Coimbatore, India, pp: 654-658.
- Varadarajan, A.S., P.K. Philip and B. Ramamoorthy, 1999. Investigations on hard turning with minimal pulsed jet of cutting fluid. Proceedings of the International Seminar on Manufacturing Technology Beyond, (ISMTB'00), Bangalore, India, pp: 173-179.
- Varadarajan, A.S., P.K. Philip and B. Ramamoorthy, 2000. Optimization of operating parameters for the cutting performance during hard turning with minimal cutting fluid. Proceedings of the International Conference on Intelligent, Flexible, Autonomous Manufacturing Systems, (ICIFAMS'00), Coimbatore, India, pp: 717-725.
- Varadarajan, A.S., P.K. Philip and B. Ramamoorthy, 2001. Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning. *Int. J. Mach. Tool Manuf.*, 42: 193-200.