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THEORETICAL STUDY ON THE EFFECTS OF VELOCITY AND EVAPORATION RATE OF CUTTING FLUID IN MINIMAL FLUID APPLICATION

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Abstract-Cutting fluid plays an important role in hard turning with minimal fluid application as it influences the cutting performance. Fine tuning of fluid application parameters such as pressure, quantity of cutting fluid, frequency of pulsing of cutting fluid are critical for the efficiently applying of cutting fluid in the form of pulsing jet during minimal fluid application. In this paper a theoretical study was made on the characteristics of pulsing jet of cutting fluid in terms of velocity and evaporation rate of pulsing jet of cutting fluid. This study also attempts to optimize these parameters in order to efficiently applying cutting fluid in minimal fluid application using Genetic Algorithms. Theoretical investigation showed that the velocity of the cutting fluid increases when the pressure and the quantity of the cutting fluid increases and whereas velocity decreases when the frequency of pulses decreases. Study also revealed that the total evaporation rate of the cutting fluid increases when the frequency of pulses of the cutting fluid decreases.

Keywords - Minimal fluid application, pulsing jet, velocity, evaporation rate, genetic algorithm.

I. Introduction

To meet the high production requiremnt, it is usual practice for the machining industries to use high material removal rate by incorporating high cutting velocity, depth of cut and tool feed. This leads to the development of high temperature and pressure at the cutting zones resulting in high rate of tool wear and dimensional inaccuracy. If efficient cooling methods are not employed, it would adversely affect the efficiency of the cutting process.

In the recent past, there has been a large research exploration towards minimal fluid application (MFA) technique. In MFA, extremely small quantity of cutting fluid is injected with the help of fluid injector in the form of ultra fine droplets at very high velocity that tend to penetrate deep into the critical zones rather that float in the air as in most of the MQL applications.

The main aim of Minimal fluid application (MFA) is to reap the benefits of cutting fluids without getting affected with the harmful effects of the cutting fluids. Minimal fluid application technique is widely used nowadays in different machining operations such as turning, drilling, milling, grinding etc.

Minimal fluid application is characterized by fluid application parameters such as pressure, quantity of cutting fluid and frequency of pulsing of cutting fluid. These parameters are to be fine-tuned for the efficient application of cutting fluid during metal machining operations for improving cutting performance.

II. Literature Survey

Reduction of tool wear, improvement of surface finish, minimizing cutting force, removal of chip and workpiece cooling are the important functions of cutting fluids in metal machining process. However, usage of cutting fluids in machining are accompanied with many drawbacks. Cost associated with procurement and disposal of cutting fluid as well as health hazard to the human operator had made the metal cutting industries to move towards dry machining.

The most common method of application of cutting fluid is flood cooling which involves copious use of cutting fluid in the cutting zone. This method not only increases the cost of production but also creates serious environmental and health hazards. To overcome these adverse effect of cutting fluid many alternate cooling method are innovated.

Minimal fluid application is one such technique, which can alleviate all problems associated with cutting fluids. In this method extremely low quantity cutting fluid was applied as a high velocity pulsing jet at the immediate cutting zones. The cutting performance produced by this method is found to be superior to that of conventional hard turning in wet and dry conditions [1].Specially developed minimal fluid applicator can apply the pulsed jet of cutting fluid through nozzle at a specified injection pressure, frequency of pulsing and rate of cutting fluid. These controlling parameters of pulsing jets are varied independanty by the minmal fluid applicator.

Study on the optimisation of these fluid application parameters along with the cutting parameters while turningwith minimal cutting fluid application revealed that

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there was a substantial improvemnt in cutting performance in minimal cutting fluid application due to better rake face lubrication [2-3].

Machining ofhigh-speed milling of hardened steel with pulsed-jet application was studied and compared with dry and flood application of cutting fluid. Result showed that machining with pulsed-jet application lowered cutting forces, and improved surface roughness while machining was done at high speed. [4].

High speed turning of bearing steel GCr15 under different cooling environments was studied by He et al. [5].It was interesting to know that MQL scheme both internal and external resulted in high speed spray that could penetrate in to the the rake and flank faces. This lead to the reduction in cutting force than other cooling environment.

Investigation of MQL using vegetable oil during the machining of AISI D2 steel was made by Sharma et al. [6]. The results of the investigation showed that machining with MQL at all cutting conditions reduced the cutting temperature.

Attanasio et al. [7] carried out a study on the machining of normalized 100Cr6 steel with MQL. It was observed that MQL method gave better rake face lubraiction which reduced tool wear and improved tool life.

Application of Al_2O_3nanofluids and nanodiamond fluids to micro grinding process was studied by Lee et al.[8] It was found that nano diamond particles were found to be more effective in reducing grinding forces and enhancing the surface quality whereas nano Al_2O_3 particles improved surfacefinish.

Sam Paul et al. [9] experimentally optimised fluid application parameters and tool vibration. It was found from the results that minimal fluid application at the optimised condition produced low vibration levels and brought forth better cutting performance.

The pusling jet produed in injection nozzle canform a cone shaped spray at a nozzle exit.This phenomenon is called atomisation breakup which produces droplets with sizes very much less than the nozzle exit diameter.The atomisation of cutting fluid spary is characterised by sauter mean diameter, liquid penetration length, velocity of cutting fluid droplets and evaporation rate. It is inferred from literature that for better atomization to occur, the diameter of droplet should be less and liquid penetration and spray evaporation rate should be higher in a pulsed jet nozzle [10]

The effects of sauter mean diameter and liquid penetration were studied by the authors [11] and found that sauter mean diameter decreased when the pressure and frequency of pulsing jet increased. At the same time, it increased when the quantity of pulsing jet increased. The reaseach further revealed that the liquid penetration length found to be increased with the increase of pressure and quantity of pulsing and with the decrease of frequency of pulsing jet increases.

The time required for complete evaporation of the atomized liquid spray was completely studied and analyzed and it was inferred that evaporation rate was independent of pressure but decreased rapidly as the droplet radius increased. Hence the effect of reduction of pressure increased the initial diameter of the droplet and decreased the evaporation rate. In the second regime, the effect of increasing radius of the droplet was offset by the increase in the diffusion rate.

In this research work, characteristics of pulsing jet of cutting fluid in terms of velocity and evaporation rate of cutting fluid was analyzed theoretically. An attempts was also made to optimize these parameters in order to efficiently applying cutting fluid in minimal fluid application using Genetic algorithms.

III. Theoretical Investigation

This research work theortically investigates the effect of veocilty of cutting fluid particles in pulsing jet and cutting fluid evaporation rate on the efficient application of cutting fluid during minimal fluid application. For this purpose, use of pindle nozzle having the specification DN OSD 151 was used in this study. The photograph of the pintle nozzle is shown in Figure 1. It consists of stem, pin or pintle and nozzle body. The pindle of the nozzle is available in different size and shape. The nozzle used in this study has spherical shaped pindle which produces spary with zero degree cone angle.

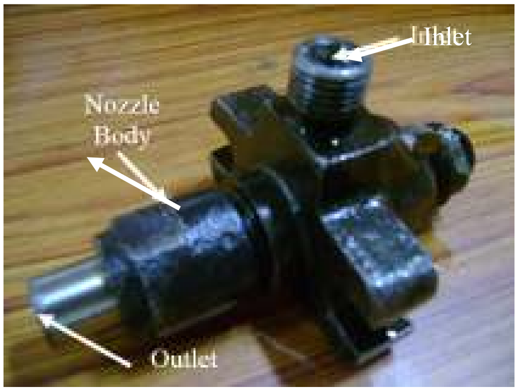

Fig. 1Photograph of DN OSD 151pintle nozzle

Minimal fluid application has a pulsing jet of cutting fluid which is produced by the pintle nozzle characterized by sauter mean diameter, liquid penetration length, velocity, total evaporation rate as shown in Figure 2. These parameters are controlled by minimal fluid application parameters such as quantity of cutting fluid application, pressure and frequency of pulsing. Among the jet charateristics, in this paper, the velocity and eveopration rate of the cutting fluid particle are considered and analysed. Before analyzing the effect of minimal fluid application parameter on pulsing jet characteristics it is necessary to find the mathematical expression of these pulsing jet characteristics in terms of minimal fluid application parameters such as pressure, frequency of pulsing and quantity of cutting fluid.

Velocity of the cutting fluid

Nozzle is a device that is used to increase the velocity of the fluid. The output parameter can be found from pressure, quantity of cutting fluid, frequency of pulsing and the variation in velocity can be obtained from these input parameters. If pressure upstream of the nozzle is obtained and assuming the flow through nozzle is quasi steady, in compressible and one dimensional, the mass flow rate of the cutting fluid through the nozzle is given by equation (1).

$$\dot{\mathrm{m}} = \mathrm{C_d} * \mathrm{A} * \sqrt{2 * \rho_f * \Delta P}(1)$$

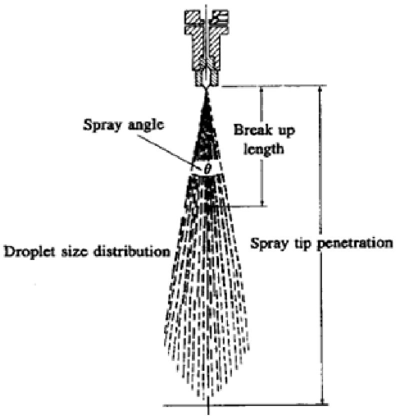

Fig. 2 Spray parameters of a pintle nozzle

We know that mass flow rate $\dot{\mathrm{m}}$ can be written as

$$\rho_f * A * v = C_d * A * \sqrt{2 * \rho_f * \Delta P}(2)$$

Where ρ_f - Density of the cutting fluid in Kg/ml

A – Area at the exit of the nozzle in m^2

v – Velocity of the cutting fluid in m/min

C_d – Coefficient of Discharge of cutting fluid

ΔP - Pressure drop across the nozzle in Mpa

Therefore equation (2) can be modified and rewritten as in equation (3) that shows the effect of velocity with the variation in pressure.

$$v = C_d * \sqrt{\frac{2 * \Delta P}{\rho_f}} \qquad (3)$$

Volume of the cutting fluid $v_f$injected at the nozzle exit is given by

$$v_f = \frac{Q}{N} \qquad (4)$$

Where, Q - Total quantity of cutting fluid in ml/min

N - Number of Frequency of pulse in pulses/min

The effect of velocity with the variation of total volume (quantity)of the cutting fluid and frequency of pulsing can be obtained by

$$V_f = A * v \qquad (5)$$

By substituting the formula forV_f and A, we get the final equation (6) for the variation in quantity of the cutting fluid, frequency of pulsing

$$v = \frac{4Q}{\pi N {d_n}^2} \qquad (6)$$

Where d_n - Nozzle diameter in m

Q – Total quantity of the cutting fluid in ml/min

N – Frequency of pulsing in pulses/min

1.1 Evaporation rate

When the cutting fluid comes in contact with the hot machining surface it evaporates. The rate at which the droplet of the cutting fluid evaporates when it touches the hot surface during hard turning is called evaporation rate. At the exit of the nozzle atomization takes place, hence the droplet size distribution varies. When cutting fluid breaks in to smaller diameter, when the smaller droplet hits the hot machining surface evaporation will be faster, therefore evaporation rate mainly depends on the droplet size distribution.

There are two types of heat transfer takes place, they are

1. Convective heat transfer
2. Evaporative heat transfer

Evaporation rate is independent of pressure but will decrease rapidly as the drop radius increases. Hence the reduction in pressure increases the initial diameter of the droplets and to decreases the evaporation rate.

$$Q = m * C_p * \Delta T\ (\text{Convective heat transfer}) + m * L\ (\text{Evaporative heat transfer})(7)$$

Where, Q – Total heat transfer in kJ

m – Mass of evaporative fluid in Kg

ΔT – Temperature difference between the hot surface and the cutting fluid in K

L -Vaporative enthalpy in kJ/Kg

C_p- Specific heat capacity in kJ/Kg K

The above equation (7) is suitably modified for finding the total evaporation rate for the variation in particle size of the cutting fluid and frequency of pulses of the cutting fluid and given in equation (8)

$$Q1 = \frac{Q}{t_e} = \frac{Q * C_p * \Delta T * \rho_v * d}{\left(\frac{D}{2}\right)^2 * N} + \frac{Q * L * \rho_v * d}{\left(\frac{D}{2}\right)^2 * N} \quad (8)$$

Where D – Diameter of the droplet (Sauter mean diameter) in m

Q1 – Total heat transfer rate in kJ/min

IV Results and Discussions

IV.I. Velocity of the cutting fluid

Effect of pressure of pulsing jet of cutting fluid on the velocity of cutting fluid particle is shown in Figure 3. It shows that velocity of the cutting fluid increases with the increase in pressure of cutting fluid application because for a nozzle pressure and velocity is directly proportional to each other.

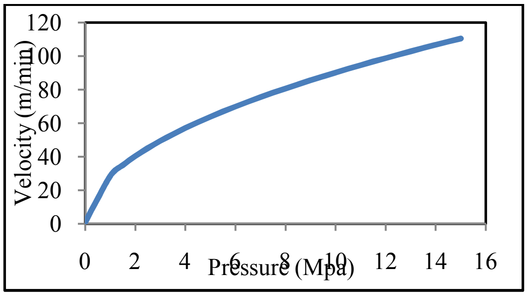

Fig. 3 Effect of pressure on velocity of cutting fluid particle

Effect of quantity of cutting fluid per pulse and the frequency of pulsing on the velocity of cutting fluid particle is shown in Figure 4. It was found that by increasing the quantity of the cutting fluid the velocity of the cutting fluid also increased. It was evident that when the frequency of pulsing of the cutting fluid was less the velocity of the cutting fluid was high because nozzle pressure and velocity are directly proportional to each other with less number of pulses.

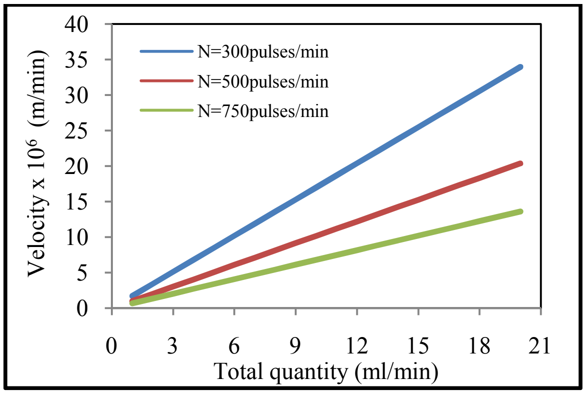

Fig 4 Effect of quantity and number of pulses of cutting fluid on velocity

IV.II. Evaporation rate

Figure 5 clearly shows that by decreasing the sauter mean diameter of the cutting fluid the convective heat transfer increases. And for less number of pulses, the convective heat transfer is high because evaporation rate is independent of pressure and the time required for complete evaporation is inversely proportional to the initial diameter of the droplet.

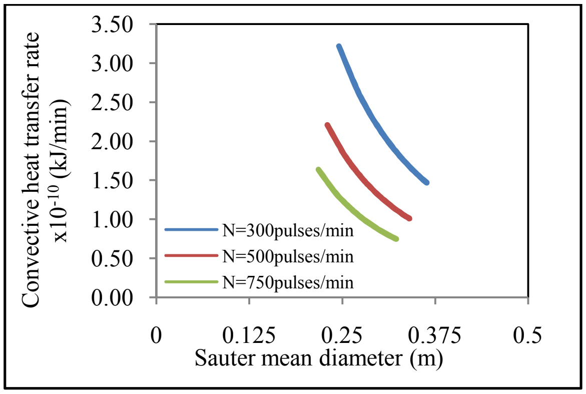

Fig 5 Effect of sauter mean diameter and frequency of pulsing on convective heat transfer rate

Figure 6 clearly shows that by decreasing the sauter mean diameter of the cutting fluid the evaporative heat transfer increases. This is because for less number of pulses of the cutting fluid the convective heat transfer is high because evaporation rate is independent of pressure and the time required for complete evaporation is inversely proportional to the initial diameter of the droplet.

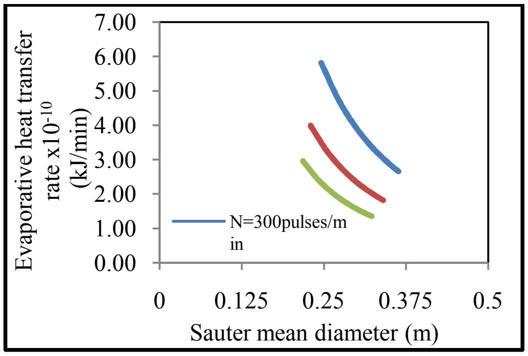

Fig 6 Effect of sauter mean diameter and frequency of pulsing on evaporative heat transfer rate

Figure 7 clearly shows that by decreasing the sauter mean diameter of the cutting fluid the evaporative heat transfer increases. It was infered that for less number of pulses of the cutting fluid the convective heat transfer is high. As convective and evaporative heat transfer are high, the total heat transfer was also higher for smaller droplet diameter.

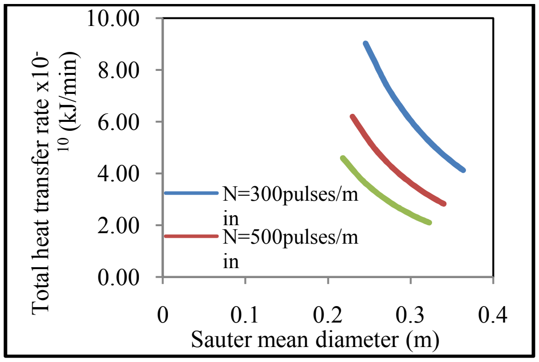

Fig 7 Effect of sauter mean diameter and frequency of pulsing on total evaporation rate.

IV.III. Optimization Using Genetic Algorithm

Genetic Algorithm has been very useful in determining the optimal parameters such as pressure, quantity of cutting and frequency of pulsing for improving velocity of cutting fluid particles and total evaporation. The settings that have been used for GA tool in MATLABis depicted in Table 1.

Table 1 Optimization settings using GA tool

Population type	Double vector
Population size	45
Reproduction, crossover fraction	0.8
Cross over ratio	1
Migration fraction	0.2
Plot function	Pareto
Evaluate fitness function	serial

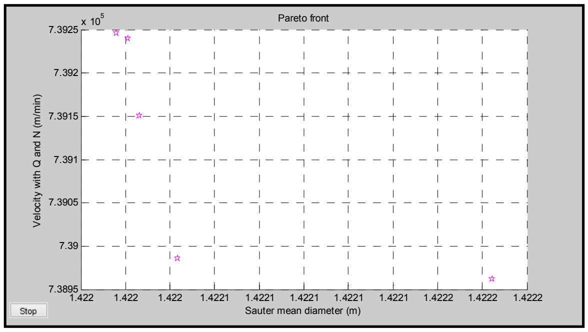

Fig. 8 Pareto plot between sauter mean diameter and velocity of the cutting fluid with varying quantity and frequency of pulsing of the cutting fluid

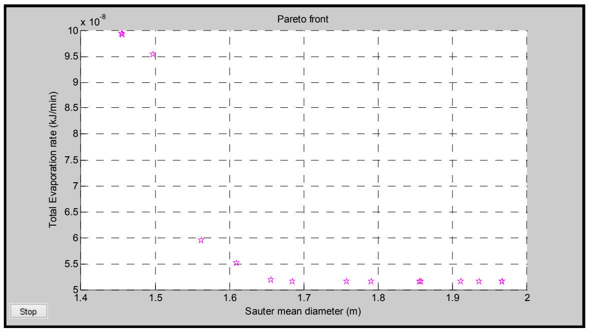

Fig 9 Pareto plot between sauter mean diameter and evaporation rate

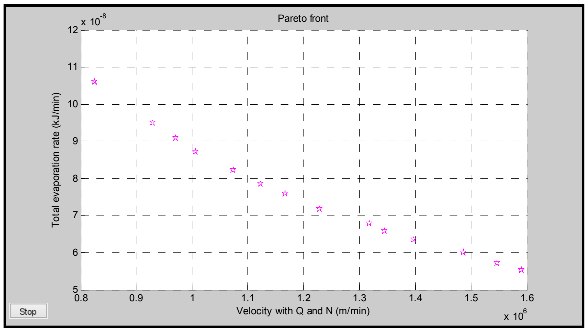

Fig.10 Pareto plot between velocity of the cutting fluid with varying quantity and frequency of pulses and total evaporation rate

Figure 8 shows the pareto front plot obtained between sauter mean diameter and velocity of the cutting fluid with varying quantity and frequency of pulsing. Figure 9 shows the pareto plot obtained between sauter mean diameter and total evaporation rate of the cutting fluid droplet.

Figure 10 shows the pareto plot between velocity of the cutting fluid by varying quantity and frequency of the cutting fluid. From these plots the optimized values can be obtained so that cutting performance can be improved.

Velocity of the cutting fluid increased when the pressure and the quantity of the cutting fluid increasd. On the other hand, velocity decreased with the decrease in frequency of pulsing. Total evaporation rate of the cutting fluid increased with the decrease in sauter mean diameter and the frequency of pulsing.

Table 2 Optimized values of cutting fluid parameters

Parameters	objective	Optimized value	Pressure (Mpa)	Quantity (ml/min)	Frequency of pulses (pulses/min)
Velocity (m/min)	max	1865341.30	2	1	309.805
Total evaporation rate (kJ/min)	max	0.003	15	1	521.854

The optimized values obtained using genetic algorithm are mentioned in Table 2. It is clear that pressure, frequency of pulsing jet should be higher and also quantity of the cutting fluid should be lesser. This can improve cutting performance by increasing velocity and evaporation rate of cutting fluid particles.

V. Conclusions

The above investigations evaluated the effect fluid application parametersbased on sauter mean diameter, liquid penetration length, velocity and total evaporation rate. Following are the findings of the theoretical investigation:

1. Velocity of the cutting fluid increased when there was an increase in the pressure and the quantity of the cutting fluid where as it decreased with the decrease in frequency of pulsing.
2. Total evaporation rate of the cutting fluid increased when the sauter mean diameter and the frequency of pulses of the cutting fluid decreased.
3. From the optimized parameters obtained using Genetic algorithm, it was infered that pressure, frequency of pulsing jet should be increase and quantity of the cutting fluid should be decreased for increasing velocity and evaporation rate of cutting fluid particles.

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