Comparative Investigation of Different Types of Cutting Fluid in Minimum Quantity Lubrication Machining Using CFD

Payal Chauhan, Anjali Gupta, Amit Kumar Thakur, and Rajesh Kumar

Abstract Minimum quantity lubrication (MQL) is a method where cutting fluid is supplied to the machining zone in the form of droplets (10–500 ml/h). The performance of MQL machining depends on the quality of spray generated by the MQL system. The spray quality is defined by droplet diameter, velocity and the number of droplets. In the present work, computer simulations were performed to study the characteristics of spray generated with internal mixing nozzle using three different types of cutting fluids, namely vegetable oil (VO), synthetic oil (SO) and mineral oil (MO). Effects of air pressure and mass flow rate of these cutting fluids on spray formation were also studied using ANSYS FLUENT. The results showed that with increase in air pressure and mass flow rate of cutting fluids, diameter of droplets decreased, whereas velocity and number of droplets increased. It was observed that not only the spray quality generated using vegetable oil is better than other two cutting fluids, but also the surface heat transfer coefficient (HTC) improved using vegetable oil. Surface heat transfer coefficient (HTC) using vegetable oil (VO) increased by 16.28% over synthetic oil (SO) and 32.16% over mineral oil (MO).

Keywords Minimum quantity lubrication · Computational fluid dynamics · Internal mix nozzle · Cutting fluids

1 Introduction

Machining is the most common practice carried out in manufacturing industries to produce component of desired size and shape by removal of material. The plastic deformation of workpiece and friction at workpiece–tool interface generates large amount of heat in the cutting region. This stimulates the need for use of cutting fluids during machining process. Cutting fluids are required for cooling and lubricating the cutting zone. They not only reduce the temperature of the cutting region by carrying away the heat generated during machining but also reduce friction at workpiece–tool

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interface [1]. This results in improving the surface quality and dimensional accuracy of the workpiece and reduction in cutting forces. Along with these benefits, there are some disadvantages accompanied with the cutting fluids. The disposal of cutting fluids into environment can cause soil and air pollution. Their use has been reported to cause serious health problems to the operators such as respiratory problems, lung cancer, genetic and dermatological diseases [2, 3]. Moreover, it has been reported that use of cutting oils results in an additional 7−17% cost of the total machining cost [4]. Looking at these concerns, efforts are being made to limit their use. Dry cutting (DC) and minimum quantity lubrication (MQL) machining are the suggested alternatives. On one hand, where DC exterminates the ill effects of cutting fluids by completely eliminating the use of cutting fluids, on the other hand, it requires special tooling and coated tools to overcome its limitations such as overheating of tool, poor dimensional accuracy and adhering of chips to rake face of tool. The second method is minimum quantity lubrication (MQL), where cutting fluids are supplied in the form of tiny droplets which are formed as a result of atomization of the cutting fluid with the help of pressurized air [5]. The flow rate of the cutting fluids while machining is very low in MQL (nearly 10−500 ml/h) as compared to wet cutting (WC) where the flow rate is of the order of 60 l/h [6]. Also, the major part of the cutting fluid that is being used in MQL is evaporated. Thus, the cost related to disposal and treatment of cutting fluid after machining, cleaning of workplace and machinery is minimized. Tawakoli et al. [7] obtained better surface finish with MQL machining in comparison with WC and DC during grinding. Coefficient of friction, tangential forces and specific grinding energy were found to be lower with MQL grinding due to better penetration of lubricant. Recently, many experimental investigations have been carried out to show the suitability of using eco-friendly vegetable oil (VO) over petroleum-based mineral oil (MO) in MQL machining. Agrawal et al. [8] performed MQL turning of steel to compare the performance of mineral oil (MO) and aloe vera (VO) at different feeds, depth of cut and speed. It was observed that VO reduced surface roughness (6.7% lower), tool wear (0.14% lower) and environmental pollution as compared to MO. Wang et al. [9] studied the effect of MQL machining and WC on grinding performance using different VOs and MOs. MQL grinding with castor oil (VO) provided better surface finish, low coefficient of friction and low specific grinding energy than MO. Further, MQL grinding resulted in better performance than WC due to better lubrication. Singh et al. [10] performed MQL turning using soyabean oil (VO) and MO. The MQL turning using VO resulted in better surface finish at high speed and reduced pollution (because of its biodegradability) over MO. It can be concluded from the literature survey that MQL results in an improved machining performance over the DC and almost the comparable performance as WC due to better penetration of tiny droplets of cutting fluid into the cutting region. Also, the use of VOs as cutting fluid results in an improved performance over MOs in MQL machining. From the above experimental studies, it can be inferred that VO can be considered as a good substitute over conventional petroleum-based oils. Apart from experimental study, computer-based simulation is a good approach to understand any process well. Simulation saves time as repetitive calculations can be performed in computer to find the optimum value of critical parameters. Computational fluid dynamics (CFD) is one such approach which is used to study the true characteristics of fluid interactions in internal and external flows [11]. CFD can also be used to simulate the behavior of cutting fluid in MQL machining. The objective of this paper is to develop a CFD-based model for studying the effect of different factors that affect the spray quality in MQL machining. The study also carries out the comparative investigation of the performance of different types of cutting oils by studying their spray characteristics.

2 Parameters Affecting the MQL Machining Performance

MQL machining performance depends on the quality of spray generated by MQL system. Spray quality depends on various parameters such as types of cutting fluid, pressure of inlet air, standoff distance, mass flow rate of cutting fluid, nozzle geometry, nozzle dimensions and nozzle angular position [12, 13]. The spray is characterized by droplets diameter, droplets velocity and the number of droplets. Velocity of droplets should be high enough to diminish the vorticities that may be produced due to aerodynamic interactions between spray and the surrounding atmosphere. Spray which is free of vorticities with uniform droplet size (neither too large nor too small) is considered as more effective in MQL. A small-sized droplet (<4 μm) becomes airborne when inhaled by workers and can cause acute respiratory disorders [14], and large-sized droplet may not penetrate effectively inside the cutting zone. Beside these factors, properties of gaseous medium into which cutting fluid is discharged also affect the spray quality. Density of air also plays important role in atomization of cutting fluid in MQL machining. In addition to this, properties of cutting fluids such as density, viscosity, surface tension, thermal conductivity and specific heat also affect the spray quality. Purpose of this paper is to study the effects of air pressure, mass flow rate and properties of different types of cutting fluid on the spray characteristics. Soyabean oil (VO), paraffin oil (MO) and ester oil (SO) are used for comparative performance. Operating conditions, properties of air and properties of cutting fluids that are being considered for simulations in present work are given in Tables 1, 2 and 3, respectively.

Table 1 Operating conditions

Air pressure (bar)	2, 3 and 4
Mass flow rate of cutting fluid (ml/h)	50, 100, 500

Table 2 Properties of air

Air density (kg/m^3)	1.1845
Air viscosity (kg/m-s)	1.86×10^{-5}
Specific heat (J/kg-k)	1005
Thermal conductivity (W/m-k)	0.02624

Table 3 Properties of cutting fluid

Cutting fluid	Density (kg/m^3)	Dynamic viscosity (kg/m-s)	Specific heat (c_p) (kJ/kg-k)	Surface tension (N/m)
Soybean oil (VO)	917	0.0418	1635	0.0309
Ester oil (SO)	964	0.0513	1905	0.0314
Paraffin oil (MO)	800	0.1181	2130	0.0230

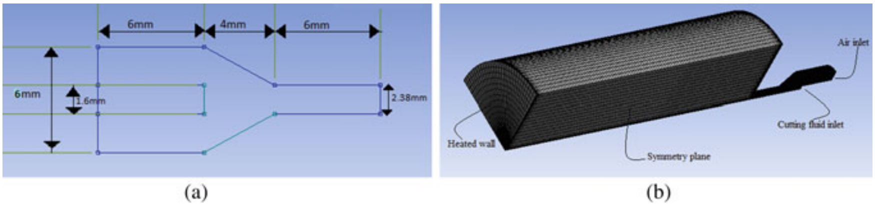


Fig. 1 **a** Geometry of nozzle with dimensions, **b** one-fourth model of internal mix nozzle [17]

3 Physical Model of Internal Mix Nozzle

3.1 *Creating a 3D Model*

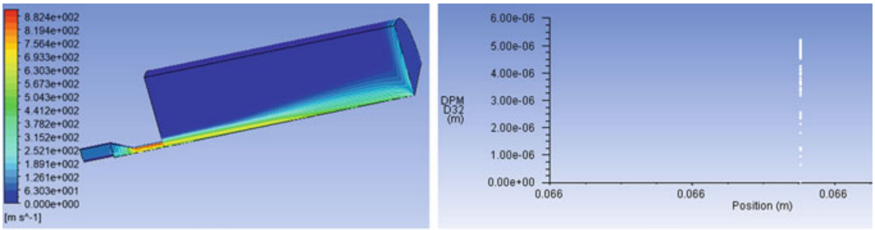
ANSYS FLUENT software was used to perform the CFD analysis of spray generated using internal mix nozzle. Nozzle geometry as shown in Fig. 1a consists of a concentric pipe where inner pipe carries cutting fluid and outer annular region carries air. Both air and cutting fluid were mixed in mixing chamber, and spray was produced by disintegration of cutting fluid by pressurized air energy and shearing action of the surrounding air. The dimensions of the nozzle considered were same as by Verma et al. [15] so that the model can be validated. Since the geometry is symmetric about x-axis, so one-fourth model of a nozzle (shown in Fig. 1b) is created to minimize the computational time.

3.2 *Meshing of 3D Model*

Accuracy of results depends on the quality of mesh. A good quality mesh is one with skewness below 0.3 and orthogonality above 0.7. A fine mesh was generated by taking these points into account.

3.3 Boundary Conditions, Governing Equations and Model Validation

Pressure-based solver was used to perform transient calculations by considering the gravity effect. Energy equation with K-ε realizable model was used to take into account the effect of turbulence. Surface injection through cutting fluid inlet surface was created at particular velocity and mass flow rate in discrete phase model (DPM), and simulation of discrete phase was done in Lagrangian frame of reference by Fluent. DPM has been chosen in this study as the amount of cutting fluid used in MQL is very small, and DPM model also requires very small volume fraction (less than 10%) of discrete phase. In DPM, air is taken as continuous (primary) phase and discrete (secondary) phase which comprises oil droplets. Pressure inlet and mass flow rate are given as boundary condition at air inlet surface and cutting fluid inlet surface, respectively. For simulating heat generation 0.5 MW/m^2, heat flux was given at wall. Pressure-based solver is used. ANSYS FLUENT uses mass, momentum and energy equations to solve the flow, and its working is based on three basic laws of fluid dynamics [16]. These laws are the law of mass conservation (continuity equation), the law of momentum conservation and the law of energy conservation. Simulations were first performed to validate the model using research work of Verma et al. [15]. For validation, water with mass flow rate 500 ml/h and air at 4 bar were used. Contours of air velocity obtained are shown in Fig. 2a, and value of Sauter mean diameter obtained is 5.3 μm (Fig. 2b) which are similar to as obtained by [15]. So, the model is validated, and it can be used for further studies.



(a) (b)

Fig. 2 **a** Air velocity contour, **b** Sauter mean diameter at 4 bar, 500 ml/h for model validation

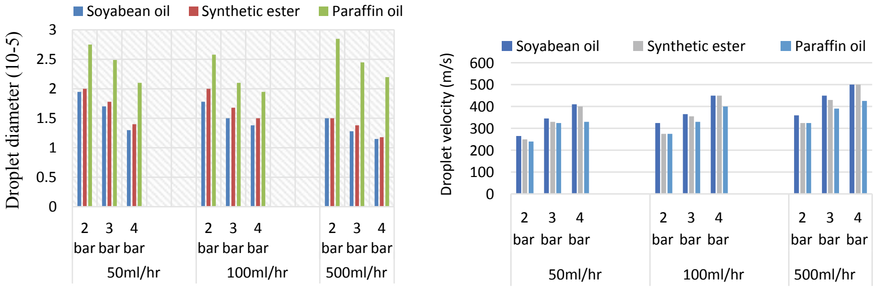
4 Results and Discussions

4.1 *Characteristics of Spray Formed Using Three Different Cutting Fluids (VO, SO and MO)*

Comparison of droplet diameter
Variation of droplet diameter with pressure of air, mass flow rate of cutting fluid and type of cutting fluids is shown in Fig. 3a. It can be seen that for VO, SO and MO droplet diameter decreases with increase in air pressure. This can be attributed to the fact that with increase in air pressure atomization process increases resulting in droplets with smaller diameter. This increased atomization leads to an increase in number of droplets. So diameter decreases and number of droplets increases with increase in air pressure. Further, diameter of droplets formed using VO was medium sized (7.5–16.3 μm) which in turn are more effective in providing better cooling and lubrication during machining operation [17].

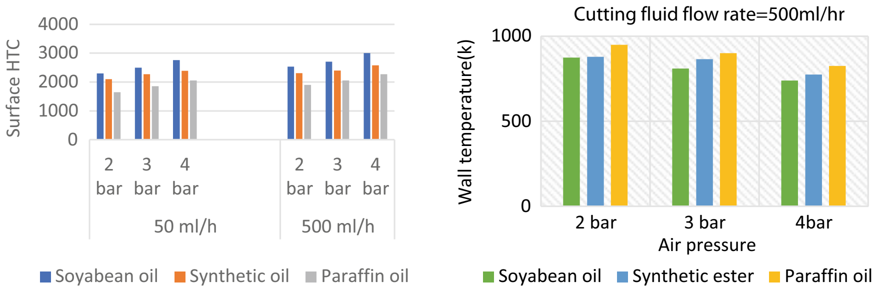
Comparison of droplet velocity
Variation of droplet velocity with pressure of air, mass flow rate of cutting fluid and type of cutting fluids is shown in Fig. 3b. Velocity of droplets increased with increase in air pressure because of greater momentum transfer to the droplets. The increase in velocity of cutting fluid droplets helps in droplet penetration into cutting region by overcoming the peripheral velocity of cutting tool. Highest velocity of droplets was obtained for VO in comparison with SO and MO, so better performance is expected from VO.

It can be concluded from the above simulation results that since the droplet diameter is minimum for VO and droplets velocity and number of droplets formed are maximum for VO, the machining performance will be better using VO as compared to SO and MO. These results are consistent with the experimental studies performed by various researchers [7–10].



(a) (b)

Fig. 3 **a** Variation of droplet diameter, **b** variation of droplet velocity with air pressure, flow rate of cutting fluid and type of cutting fluid



(a) (b)

Fig. 4 **a** Surface HTC at 500 ml/h flow rate of VO, SO and MO at different air pressures, **b** wall temperature at 500 ml/h flow rate of VO, SO and MO at different air pressures

4.2 Cooling Performance of Different Cutting Fluids

Comparison of surface HTC and wall temperature

Variation of surface heat transfer coefficient (HTC) and wall temperature at different air pressures and 500 ml/h flow rate for VO, SO and MO is shown in Fig. 4a, b, respectively. Surface HTC increased with increase in air pressure. This is because high air pressure results in high atomization resulting in large number of smaller diameter droplets that reach the cutting region easily and accelerate cooling by carrying away heat. An improvement of about 16.27% over SO and 32.16% over MO is obtained with VO in surface HTC. This results in better cooling with VO. Cooling performance of VO turns out to be best due to its low viscosity. The high viscosity decreases the Brownian movement that limits the heat exchange capacity of oils. Also, the high viscosity results in lower thermal conductivity. As boiling point and viscosity index of VO are higher (than SO and MO), so it can remove large amount of heat effectively. Increase in surface HTC with increase in pressure of air and flow rate of cutting oils decreased the wall temperature. VO have highest surface HTC and thus lowest wall temperature. Also, the high flash point and high molecular weight reduced loss of VO through evaporation and improved heat carrying capability of VO, therefore leading to lower wall temperature.

5 Conclusion

It is concluded from the above simulation studies that with increase in air pressure and mass flow rate of cutting fluid, droplet diameter decreased, whereas droplet velocity and number of droplets increased for same. Spray characteristics of VO favor better machining performance. VO results in medium-sized droplet, high velocity and large number of droplets in comparison with SO and MO and thus proved to be a better cutting fluid. VO provided highest value for surface HTC and lowest value for wall temperature.

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