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Numerical analysis of the effect of air pressure and oil flow rate on droplet size and tool temperature in MQL machining

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ABSTRACT

Dry machining is undesirable for machining of good surface quality products, because the thermal properties of a material may contribute to a reduction of tool life when machining difficult to cut materials. Likewise, the conventional lubrication through a jet or flood cooling is not economical or eco-friendly and increases the environmental burden. Owing to the above facts it becomes necessary to implement Minimum Quantity Lubrication (MQL) in end milling process. In this study, a numerical analysis has been carried out to investigate the impact of compressed air pressure and the oil flow rate on Sauter mean diameter of MQL spray and on tool temperature. Sauter Mean Diameter (SMD) of MQL spray and temperature distribution in the end milling tool are calculated for three different air pressure (2, 3, and 4 bar) and oil flow rate (100, 150, and 200 ml/hr). ANSYS Fluent software is used for the analysis with discrete phase model (DPM) for predicting the spray particle size. From the analysis, SMD and tool temperature are found to decrease with increase in air pressure for constant oil flow rate whereas there is no considerable change in SMD as the flow rate of oil is changed beyond 150 ml/h. This study has been used for selecting the optimum air pressure and flow rate of the oil for efficient lubrication and cooling in MQL aided machining.

1. Introduction

Cutting fluid has a significant effect on the quality of machining. Conventional cooling techniques are not effective in providing lubrication between tool-chip interfaces efficiently. Also, the machine operator has a risk of getting exposed to skin and respiratory problems due to flood cooling. In recent years, the stringent application of new health regulations and standards has raised the price of conventional flood cooling system. Such demands make researchers to evolve more environment friendly techniques of lubrication [1]. While machining by turning, milling or drilling processes, the tool-work contact and the resulting friction causes conversion of mechanical energy into thermal energy. Further energy is expended with chip formation and noise produced from the impact of vibration or chatter. Thus high temperature is produced in machining process and it affects the surface quality as well as the tool life. This is why manufacturing industry introduced the cooling techniques to lower the temperature generated at the tool and work piece, thereby enhancing the energy efficiency of the system. Dry, compressed cold air and Minimum Quantity Lubrication (MQL) have been studied and considered as ecologically friendly machining techniques. MQL gives better performance over flood cooling as it reduces fluid consumption, reduces pollution and is less expensive. Oil from MQL forms thin layer of coating on the cutting tool and work piece which results in minimization of the frictional coefficient during machining. Different studies have reported that MQL technique reduces surface roughness as compared to dry machining method. MQL is a highly effective lubricant supply technique, which delivers micro scale aerosol particles through eco-friendly lubricants mixed with compressed air and sprayed to the cutting zone accurately [2]. The performance of MQL can be improved with well-suited lubricants, and atomization parameters. Considering external minimum quantity lubrication, nozzle arrangement plays a key role in the effectiveness of the lubrication.

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Many researchers have worked experimentally and numerically on the MQL technique and their effect on the machining performance. Najiha et al. [3] used Computational Fluid Dynamics (CFD) to carry out 2-D steady-state incompressible analysis to evaluate minimum amount of lubricant flow needed in milling operations. Four-teeth milling cutter operation was considered for the analysis of flow and heat transfer. Results obtained from the CFD analysis show that flow velocity and the number of nozzles are the factors that affect the flow penetration into the cutting zone. The study also reported that MQL with single nozzle was not effective in high-speed milling because it can not reach to inner zones of tool teeth. Najiha and Rahman [4] carried out a three-dimensional CFD analysis of the effect of nozzle position in relation to feed direction and suggested using more than one MQL nozzle for proper lubrication of milling cutter. Catherine et al. [5] calculated the efficiency of cooling the cutter with nozzles using CFD analysis, in Ti alloy milling. From the study they observed that turbulence has been created at the edge of the cutter with one or two nozzles. High velocity was recorded near to the cutting tool as compared to away from the tool. Tool life increased when two nozzles are used for cooling. Rohit et al. [6] conducted an experimental and numerical analysis to investigate effect of droplet size on MQL milling performance of SS304. They reported that mass flow rate of oil and pressure of air affect the mist particle size and velocity. Simulation result indicates that increase in flow rate and atomization pressure decreases the droplet size. Effectiveness of lubrication of tool chip interface is dependent on the medium-sized droplet with higher pressure. Oil mass flow rate is said to have more effect on cutting forces and surface roughness than air pressure. El-Bouri et al. [7] carried out a numerical and experimental analysis of turbulent flow and heat transfer in MQL turning process, using discrete phase model. The temperature profile and the oil droplet performance at cutting zone were determined by using CFD. Results show that cooling effect produced by aerosol water is more than MQL because of the fact that flow rate of aerosol water was much higher than MQL oil flow rate. Zhu et al. [8] investigated the impact of interaction of oil and air flow rate, spindle speed and nozzle standoff distance, experimentally and numerically, on the droplet size and penetration to optimize the MQL milling process. Critical nozzle standoff distance value has been found to be increasing with droplet diameter and air flow rate. Ishak et al. [9] carried out a numerical analysis to investigate nozzle flow and spray characteristics from different nozzles using diesel and biofuel blends in IC engines. Results obtained from the simulation shows that the cavitation area depends on spray shape of nozzle and no massive effect of type of fuel on cavitation area is reported. The elliptical nozzle has a higher spray width than those of circular spray. The droplet size of the elliptical shape was smaller than those of circular shape nozzle. Diesel fuel has slightly higher spray tip penetration compared to hybrid biofuel blends. Vazquez et al. [10] carried out a CFD analysis to determine efficient cooling and lubrication conditions in micro-milling of Ti6Al4V alloy. The aim of the work was to evaluate the efficiency of MQL in micro milling of the Ti alloy against dry machining and jet application. The experiments were also carried out to analyse cooling and lubrication effect on accuracy, burr formation, and geometric shape. It was found that there is a reduction in tool wear rate with MQL as compared to jet application. Benjamin et al. [11] carried out a mechanistic investigation on end milling of Ti-6Al-4V alloy to study the inclusion of sub-zero air in MQL systems. It was found that, minimum quantity cooling lubrication (MQCL) was beneficial for improving lubricity of cutting fluid at lower temperatures and ease of separating chips from the rake face. Rahim and Dorairaju [12] investigated the behaviour of MQL method with various combinations of spray and machining parameters. The Phase Doppler Anemometry was used to measure the droplet size. The nozzle with larger diameter was found to reduce cutting force and temperature more efficiently by providing more fluid at the cutting zone. Saberi et al. [13] presented a MQL method with compressed cold air jet from vortex tube to enhance the performance in surface grinding process of CK45 soft steel. From the results it was reported that the air pressure is a more significant factor in the cooling process at high machining power. Efficient lubrication in the contact zone reduces power consumption by lowering the tangential grinding force and the friction coefficient. Salaam et al. [14] conducted an investigation of Ranque Hilsch Vortex Tube used in MQL machining. The study reported that MQL along with the Vortex Tube can produce higher pressure than a normal MQL method. Also, this system improves the surface finish, while cutting force and power are also found to be reduced under vortex cooling. Mia et al. [15] presented an investigation that was conducted to study performance of nitrogen gas cooling, nitrogen gas-assisted MQL and Ranque-Hilsch vortex tube on surface roughness and tool life. Results from the research work showed that nitrogen gas assisted MQL was better than dry or nitrogen gas assisted cooling technique for reducing tool flank wear. A combination of the above two cooling-lubrication methods were showing better surface finish and minimum tool flank wear.

Several numerical models have been used to simulate oil spray characteristics thus far. It is important to select the optimum values of pressure and flow rate of the coolant for getting a better work surface quality and tool life. By this we can ensure that the tool wear, cutting force and tool chip interface temperature are at the minimum level. This research work mainly focuses on the effect of change of air pressure and flow rate of the coolant on the performance of MQL. A discrete phase model (DPM) is used to find the droplet Sauter mean diameter and the motion of oil. CFD analysis is carried out to determine the coolant spray particle size, velocity and the temperature of tool in end milling of Ti6Al4V. Three different pressure (2, 3, and 4 bar) along with three different flow rates (100, 150, and 200 ml/hr) of the oil were used to investigate the performance of the nozzle spray. The numerical results are comparable to the results available in the literature.

2. Sauter mean diameter (SMD or d_{32}) and its significance

The Sauter mean diameter is the diameter of droplets that have the same volume to surface area ratio in a given mist ensemble under study. The mist flow generated in MQL system contains droplets ranging from minimum to maximum size, therefore there is need of a single number that will characterize the droplet size, and this purpose is served by SMD. Active surface area of droplets plays an important role in reducing the tool work piece interface temperature and increasing lubrication in MQL assisted machining. SMD is advised in calculations where active surface area is involved and is given by [16] as

$$d_{32} = \frac{\sum_{i=1}^{n} n_i d_i^3}{\sum_{i=1}^{n} n_i d_i^2} \quad (1)$$

Thus SMD expresses mean diameter of droplet considering volume to surface area ratio. Very small value of SMD results in poor penetration in cutting zone whereas particles with very large SMD are difficult to carry upto cutting zone. A.S.S. Balan et al [17] conducted a study on MQL mist parameters and found that medium size droplets ranging from 6 μm to 15 μm resulted in efficient machining. Similar study was conducted by Rohit J.N et al [6] for milling process and found that medium size droplets ranging from 7 μm to 12.9 μm with higher velocity results in effective penetration in cutting zone during milling operation. However, droplet size also depends upon viscosity of oil and nozzle standoff distance, therefore further investigation becomes necessary.

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3. Numerical modelling

In MQL, mixing of small quantity of coolant with compressed air takes place in the nozzle and the resultant mist is then directed to the machining zone. Computational fluid dynamics (CFD) technique has been used to investigate the flow characteristics by varying air pressure and coolant flow rate. Flow simulations inside the mixing zone of the nozzle and in air domain is carried out using the finite volume based ANSYS Fluent software. A pressure based transient solver is used for the analysis of MQL spray. Numerical investigation is done with the objective of selecting optimum values of mass flow rate of oil and air pressure based on Sauter mean diameter and particle velocity. CFD study of flow through nozzle and spray analysis is based on following equations for incompressible flow,

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (2)$$

Momentum equation

$$\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho u v)}{\partial y}=\frac{\partial}{\partial x}\left(\mu_e\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial u}{\partial y}\right)-\frac{\partial P}{\partial x}+X \quad (3)$$

$$\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho u v)}{\partial x}=\frac{\partial}{\partial x}\left(\mu_e\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_e\frac{\partial v}{\partial y}\right)-\frac{\partial P}{\partial y}+Y \quad (4)$$

Energy equation

$$(\rho c_p u)\frac{\partial T}{\partial x}+(\rho c_p v)\frac{\partial T}{\partial y}=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\dot{S} \quad (5)$$

The Navier Stokes equation for flow modelling is represented in Eqs. (3) and (4). In order to incorporate turbulence model, the Reynolds Averaged Navier Stokes (RANS) equation is employed, which includes additional terms for Reynolds mean stress and eddy viscosity. For the high speed and high pressure flow simulations, a realizable k-ε model is considered, which takes into account of the turbulent kinetic energy (k) and the turbulent dissipation rate (ε). This model can predict a more accurate rate of spreading of spherical particles. As the oil is dispersed in the air as a discrete phase, the simulation of oil mist spray has been carried out using discrete phase modelling (DPM). The validation of model is done with existing literature [6].

4. Governing equations for discrete phase model (DPM)

Integration of force balance on the particle is used for predicting the trajectory of the droplet, stated in a Lagrangian reference frame. The equation of force balance in the x-direction is,

$$\frac{\partial u_{drop}}{\partial t}=F_D(u-u_{drop})+\frac{gx\left(\rho_{drop}-\rho\right)}{\rho_{drop}}+F_x \quad (6)$$

where Fx = additional acceleration or (force per unit particle mass), F_D (u - u_{drop}) = drag force/unit particle mass.

4.1. Numerical analysis

The MQL nozzle used for numerical analysis has been modelled in Design modeler software. The nozzle dimensions and coolant properties are mentioned in Table 1. A 2D domain of the nozzle is selected for the analysis. The numerical domain of the nozzle is shown in Fig. 1. The nozzle is mounted with a stand-off distance of 85 mm to an open atmospheric section, towards the tool and work piece.

A virtual box of dimension 100 mm × 100 mm has been modelled connecting with the atmospheric domain for the analysis of the spray from nozzle and its spread over the tool and workpiece. A transient CFD simulation has been performed for 0.2 s, and unsteady particle tracking mode is kept on. The Simulation is performed with a residual convergence of 10^{-4} for momentum and 10^{-6} for energy. The turbulent realizable *k*-ε model is preferred for the more accurate results. A discrete phase model (DPM) is applied to exchange all conservation equations with droplet along with the air.

4.2. Computational domain

With the numerical domain set for the given Nozzle and Cutting tool conditions as in Fig. 2, the Boundary conditions are defined, as

Table 1
Dimensions of the nozzle and properties of the coolant.

Sr. No.	Parameters	Dimension
1	Diameter of orifice (Air)	2.3 mm
2	Diameter of orifice (Oil)	1.3 mm
MQL coolant Properties		
3	Oil Density	820 kg/m^3
4	Oil Viscosity	35 cst
5	Mist concentration (Air: Oil)	32,000: 1, 26,000: 1, 19,500: 1

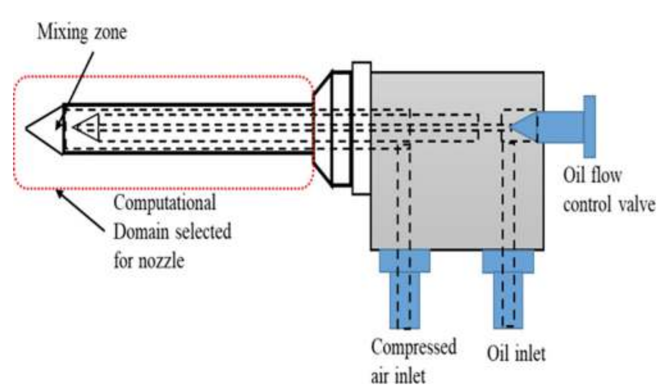

Fig 1. Schematic of nozzle used for the MQL.

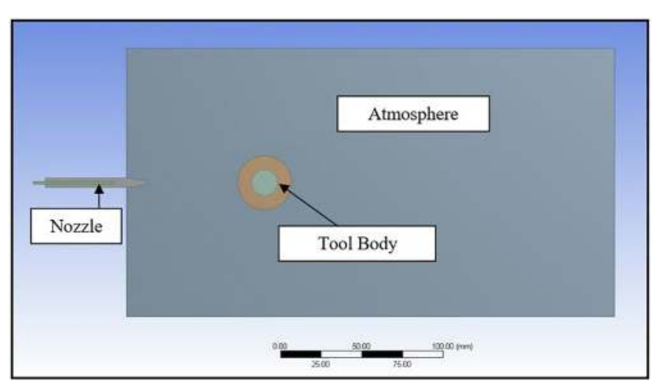

Fig. 2. 2D Computational domain used for the Numerical analysis.

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Table 2
Numerical analysis results for different air pressure and flow rate of the oil.

Pressure (bar)	Mass flow (ml/hr)	Average temperature of tool (K)	Sauter Mean Diameter (μm)	Droplet Maximum diameter (μm)	Droplet Minimum diameter (μm)	Temperature of tool after 0.2 sec (K)	Particle average velocity (m/s)
2	100	456	16.845	23.5	1.00	442.029	57.613
3	100	456	15.664	24.0	1.13	441.142	71.723
4	100	456	13.000	24.0	1.20	440.986	82.735
3	150	456	15.616	23.9	1.00	441.303	71.563
3	200	456	15.390	23.7	1.00	437.107	71.360

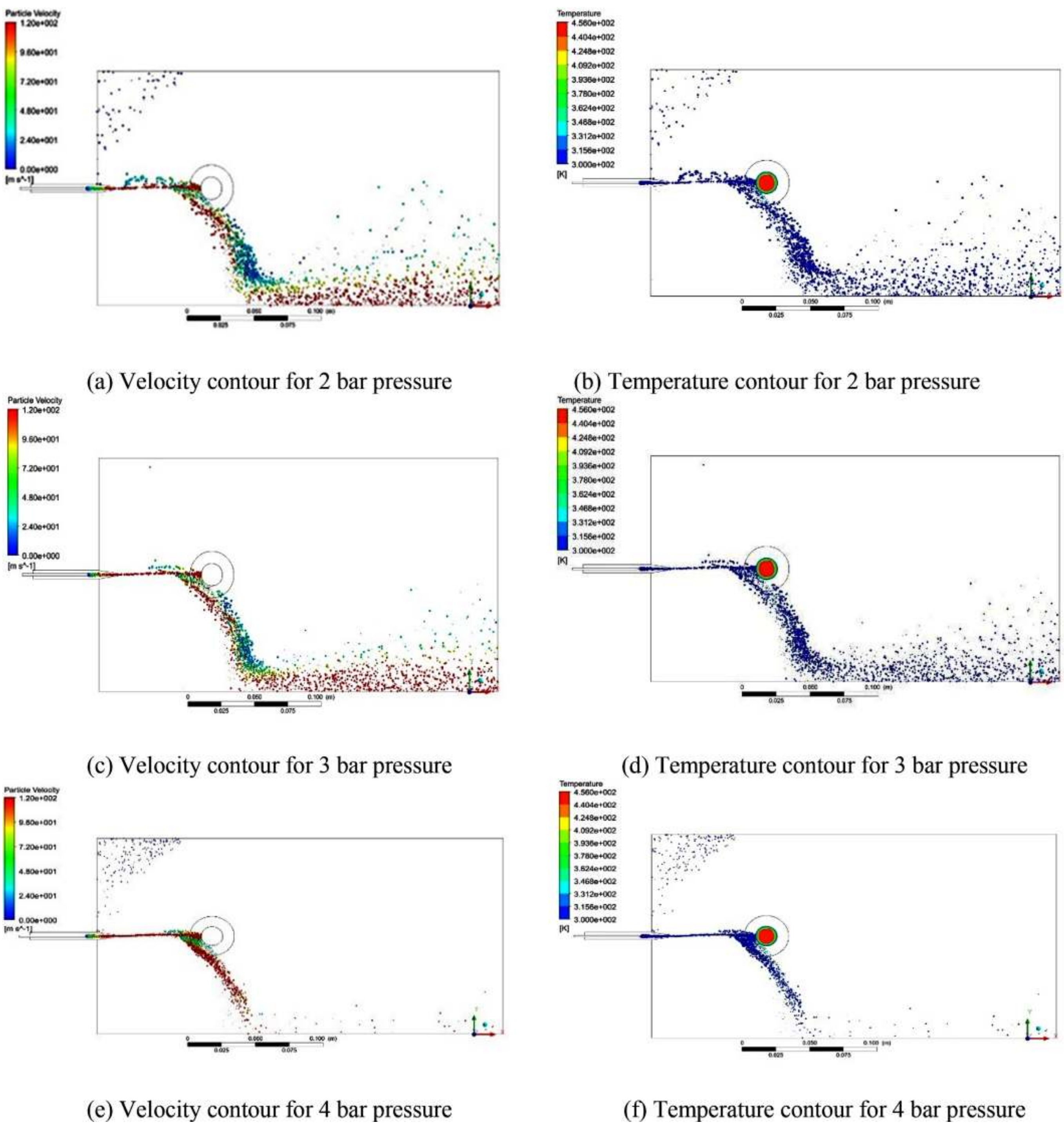

Fig. 3. Velocity of droplet particles and temperature of tool contour for different air pressure with constant oil flow rate of 100 ml/h.

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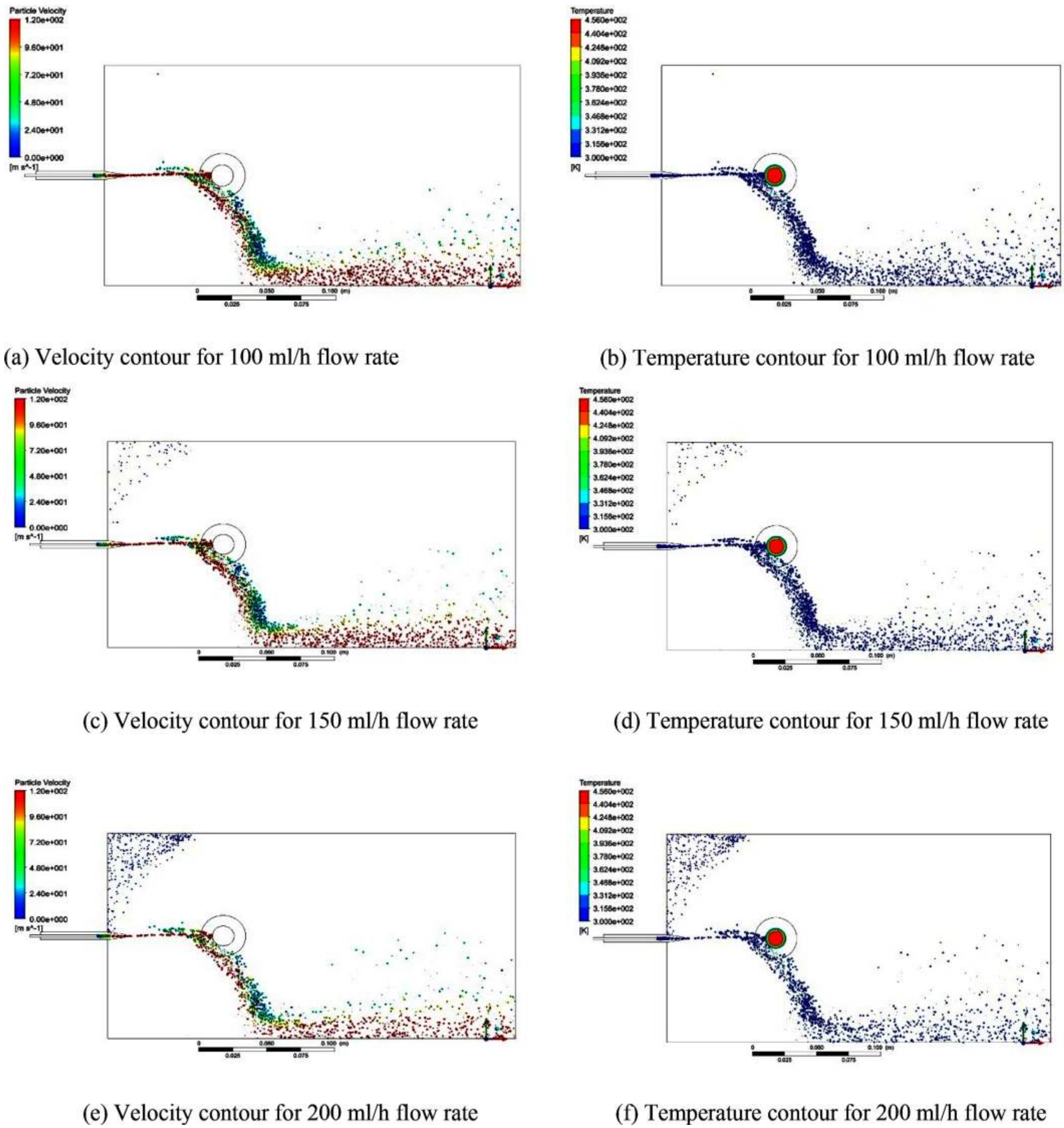

(a) Velocity contour for 100 ml/h flow rate

(b) Temperature contour for 100 ml/h flow rate

(c) Velocity contour for 150 ml/h flow rate

(d) Temperature contour for 150 ml/h flow rate

(e) Velocity contour for 200 ml/h flow rate

(f) Temperature contour for 200 ml/h flow rate

Fig. 4. Velocity of droplet particles and temperature of tool contour for different oil flow rate at constant air pressure 3 bar.

the atomization of the MQL need to be observed. The available input conditions are given by, Oil Nozzle Surface injection with the "Mass Flow Rate" condition and the Air Nozzle Area with "Pressure Inlet" condition. The Atmosphere is considered as "Pressure Outlet". The cutting tool region needs to be observed for the heat transfer as the atomized MQL is wetting the tool region to absorb the heat generated from the cutting tool which is rotating at the speed of 700 rpm with a fixed value of feed rate. A grid independence study has been carried out to find the best mesh for the analysis which helps to reduce the computational time. Around 54,000 2D mesh elements, with 0.96 average element quality are used for the analysis.

5. Results and discussion

As mentioned in the previous section, the numerical domain of 100×100 mm^2 is set for the given nozzle and cutting tool conditions. The cutting tool has been fixed at a stand-off distance of 85 mm from the nozzle and rotating at 700 rpm. The nozzle position is perfectly horizontal making an angle of 90° with tool and mixture outlet diameter of 2.3 mm. Numerical analysis is carried out to investigate the influence of air pressure and mass flow rate on the mist/spray parameters. Initially the analysis is performed for three different air pressures (2, 3, and 4 bar) and at a constant oil flow rate of 100 ml/hr. The oil flow rate is then changed to 150 ml/hr and 200 ml/hr while air pressure of 3 bar is kept constant. The results obtained from the numerical study are tabulated in Table 2. The initial temperature of the tool is assumed to be 456 K as minimum machining temperature.

5.1. Effect of air pressure

The effect of air pressure is investigated by varying the pressure of compressed air and keeping the oil flow rate constant. From Table 2, it can be observed that the maximum SMD is 16.85 μm at a pressure of 2 bar and minimum SMD is 13 μm at a pressure of 4 bar with corresponding increase in velocity from 57.61 m/s at 2 bar to 82.74 m/s at 4 bar. The increase in particle velocity at higher air pressure results in fine atomization, which tends to decrease SMD. It is noticed that at low velocity average droplet size (SMD) is large and such droplets are difficult to carry to cutting zone, whereas smaller droplets with high velocity may bounce off the cutting zone causing ineffective penetration into the cutting zone. Therefore a numerical analysis is performed to study the effect of compressed air pressure on Sauter mean diameter and average temperature of tool and workpiece.

Fig. 3(a-f) shows particle velocity and temperature contours for the compressed air at 2, 3 and 4 bar respectively, with constant oil flow rate 100 ml/hr after 0.2 s. From Fig. 3(a) it can be seen that at 2 bar pressure, the larger quantity of low velocity oil particles are less effective in cooling the cutter. In Fig. 3(c) it is seen that the oil particles are focussed towards the cutter but particles with high velocity are diverting over the cutter periphery, whereas in Fig. 3 (e), even though the particles reach the cutter as in earlier case, they bounce back and are seen as a stream having minimum contact with the cutter. Temperature analysis is done to investigate the effect of nozzle spray on the tool temperature. From the temperature distribution shown in Fig. 3(b,d,f) it is seen that, the outer layer of the tool is cooled due to application of coolant and the centre part of the tool is at maximum 456 K. With oil flow rate at 100 ml/hr, the average temperature of the tool is found to be 442.029 K for 2 bar pressure and reduces to 440.986 K at 4 bar pressure.

5.2. Effect of oil flow rate

The effect of coolant flow rate on the droplet diameter and the average tool temperature was analysed by varying the flow rate of coolant. Three flow rates (100 ml/hr, 150 ml/hr, 200 ml/hr) are changed by keeping constant compressed air pressure at 3 bar.

It can be seen from Table 2 that, at a constant 3 bar pressure, increasing the mass flow rate of oil slightly decreases the SMD from 15.664 μm at 100 ml/hr to the 15.390 μm at 200 ml/hr. The maximum and minimum diameter of the droplet for all three flow rate is also mentioned in Table 2. The marginal change in droplet size by varying the flow rate is due to the fact that, in the two fluid two phase system like MQL, the primary phase (air) has more impact on droplet size than secondary phase (oil) [5]. However, increase in coolant flow rate at constant pressure increases shear force between coolant and air which decrease droplet size with nearly same velocity but, there is significant reduction in average temperature of the tool after 0.2 sec. The minimum temperature was found 437.107 K for the case of 200 ml/hr oil flow rate and 3 bar air pressure. The average temperature of the tool found to be decreased with increase in coolant flow rate.

The velocity and temperature contours at different oil flow rate and constant air pressure are shown in Fig. 4(a-f). From the Fig. 4(a, c,e), showing the particle stream at 3 bar pressure, the oil particles are seen to be well focussed at the cutter, minimum dispersed, having broader contact area, thus producing good lubrication and cooling. Here also, at lower oil flow rate, the high velocity particles are diverting over the cutter periphery. The SMD variation is seen to be closely in tune with the air pressure rather than the mass flow rate. From Fig. 4(e,f), we see that maximum cooling of the tool is obtained as the particle velocity is reduced over a range of 0.36 m/s at 200 ml/hr, compared to other cases. Moreover, at lower mass flow rate the oil particles tend to lose their momentum after hitting the tool.

6. Conclusion

The turbulence modelling capability of ANSYS Fluent software with discrete phase model is helpful for the analysis of MQL machining. Numerical analysis has been done to investigate the impact of compressed air pressure and oil flow rate on the particle diameter and average temperature of tool. Three different compressed air pressure and oil flow rates are used in the analysis with constant initial temperature and rotation of the cutting tool. The following conclusions can be drawn,

- There is a significant effect of the compressed air pressure and the oil flow rate on the Sauter mean diameter of the particles and the average tool temperature. The SMD variation is found to be in tune with air pressure variation rather than oil flow rate.
- The value of Sauter mean diameter of the particle decreased with increase in compressed air pressure. The maximum diameter was found 16.85 μm for 2 bar pressure and the 100 ml/hr oil flow rate, but with comparatively low average velocity of 57.613 m/s. The minimum Sauter mean diameter of the particle was found 13 μm for 4 bar pressure and 100 ml/hr oil flow rate, characterized by comparatively highest velocity of 82.735 m/s.
- There is a significant change found in average temperature of the tool after application of the spray for 0.2 sec to an extent of 19 K. The average temperature of the tool is found to be reduced with increased amount of the compressed air pressure and the oil flow rate.
- It is concluded that, a selection of the compressed air pressure and the flow rate of oil is an important aspect while studying the influence of MQL in machining the Ti alloy. Under the conditions analyzed, air pressure of 3 bar and mass flow rate of 200 ml/hr is found to be optimum values for an effective MQL machining process giving the minimum tool temperature of 437.1 K, SMD of 15.39 μm and average particle velocity of 71.36 m/s.

CRediT authorship contribution statement

Prasad A. Jadhav: Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft. **R. Deivanathan:** Conceptualization, Writing - review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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