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A COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF SINGLE AND THREE NOZZLES MINIMUM QUANTITY LUBRICANT FLOW FOR MILLING

M.S. Najiha[1] and M.M. Rahman[1,2]

[1]Automotive Engineering Research Group, Faculty of Mechanical Engineering
Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
Email: mustafizur@ump.edu.my
Phone: +6094262239; Fax: +6094246222
[2]Automotive Engineering Centre, Universiti Malaysia Pahang,
26600 Pekan, Pahang, Malaysia

ABSTRACT

A 3-dimensional computational fluid dynamics analysis of minimum quantity lubricant flow for a four-tooth milling cutter operation with single and three nozzles is presented in this paper. CFD modelling is utilized to simulate the flow distribution around a four-tooth milling. The domain of a rotating cutter along with the spraying nozzle was defined. Operating cutting and boundary conditions were defined based on previous literature. A steady-state, pressure-based, planar analysis was performed with a viscous, realizable k-ε model. A 3-D transient-case, incompressible analysis for the minimum quantity lubricant is also performed. The domain of the milling cutter is rotated at a very high spindle speed, and a single nozzle is used to investigate the effects of MQL spray. A mixture of oils and air is sprayed onto the tool. Another analysis is performed with three nozzles placed at equal angles to each other around the periphery of the tool. A 2-dimensional steady-state analysis is also carried out using CFD. The obtained results verify that the single nozzle cannot fully lubricate the rotating tool. It was observed that flow penetration into the cutting zone is dependent on the flow velocity and the number of nozzles. Hence, it can be concluded that the MQL nozzle arrangement can be improved with three nozzles with a constant mass flow rate.

Keywords: CFD; milling; MQL; nozzles; flow fields; vector plot.

INTRODUCTION

Minimum Quantity Lubrication (MQL) has been demonstrated to be an effective near-dry machining technique as well as an efficient alternative to complete dry and wet cutting conditions from the viewpoint of cost, ecological and human health issues and machining process performance. MQL is a sustainable manufacturing technique that is safe for the environment, the worker and is cost-effective [1].The cost of cutting lubricants may range from 7 to 17% of the total machining cost [2], while the tool cost ranges from 2 to 4% [3-6]. Therefore minimization of metal working fluids can serve as a direct indicator of sustainable manufacturing. The goal of MQL is to machine parts using a minimal amount of metal working fluid, typically at a flow rate of 50–500 ml/h, which is about three to four orders of magnitude lower than the amount commonly used in the flood cooling condition [7-11] so that the workpiece, chips and environment remain dry after cutting. The concept of minimum quantity lubrication, sometimes referred to as near-dry lubrication [12] or microlubrication [13], was suggested a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. In the recent past, there has been a general liking for dry machining [14-18]. On the other hand, several researchers have started exploring the application of minimal cutting fluid. Minimum quantity lubrication offers considerable advantages over the conventional traditional wet machining processes, as well as dry machining. The machined parts are lubricated with a very small amount of fluid sprayed on them, resulting in a very low residue of lubricant on the chips, tool and workpiece, hence their cleaning is easier and cheap; recycling of chips is easy as is scrutiny of the machining process, since the machining area is not flooded. Machining with MQL has been extensively applied in many machining processes such as drilling [19-22], milling [23-29], turning [8, 21, 30-32], and MQL grinding [33-35]. MQL is contributing significantly towards performance and quality in the environment, working condition and economics of machining. Since it does not require the power-consuming auxiliary equipment like compressors, pumps and chillers that are used in a flooded lubricating system, it significantly reduces energy consumption. With MQL, when properly applied, both parts and chips remain dry and are easier to handle [36]. It therefore makes recycling of the metal chips easier. MQL is an achievement-oriented technology, which replaces the conventional lubrication techniques and takes over the lubrication task, assisting in sustainable development with mechanical manufacturing processes. Most of the research conducted with respect to minimum quantity lubrication and related issues is related to showing the overall advantages of MQL as opposed to the use of a conventional emulsion coolant, and there have been several successful experiences when it is used in the machining of different materials.

Dry machining has always been associated with the traditional manufacturing processes, but the current surge in interest in dry machining is due to the growing global realization of the cost of cutting fluids management. Dry machining is described as an ideal replacement to the traditional conventional flooded cooling, and lubricating machining practices. However, one of the major obstacles in adopting dry machining is the belief of the machinists that no-fluid cutting may lead to a poor surface finish and dimensional inaccuracies. The most prohibitive part of switching towards dry machining is the initial capital expenditure associated with special expensive tooling, and non-retrofitting machines. Research on dry machining has been mainly concerned with the development of appropriate tools and coatings [12, 26, 37-41]. Although dry machining is possible in some situations, there are still several issues regarding lubricity, tool life, thermal damage of the workpiece, etc. [21, 36, 42]. In this context, MQL techniques have been proposed. Conventional wet machining requires pumping millions of gallons of metal-working fluids to cool and lubricate cutting tools and remove the metal chips from the machines. These fluids, typically a mixture of coolant and water, must be regularly treated to control their chemical composition, and they require special disposal to avoid contaminating the environment. Wet machining systems also require a large system of pipes, pumps, filters and tanks to circulate and store the fluids. MQL delivers significant benefits in environmental performance, quality, working condition and costs. It significantly reduces energy consumption, because it does not require the energy-consuming auxiliary machines like compressors, pumps and chillers used in a wet system. MQL also makes it easier to recycle the metal chips created during the machining process. Machining with a minimum quantity of lubricant is a greater opportunity for the world to manufacture new products for better overall performance with lower emissions, reduced risk and compliance with the regulations. Another characteristic of this technology is that when properly applied, both parts and chips remain dry and are easier to handle [36]. Most of the research conducted with respect to minimum quantity lubrication and related issues is related to showing the overall advantages of MQL as opposed to the use of a conventional emulsion coolant, and there are several successful experiences when it is used in the machining of different materials. This study presents the effect of the number of nozzles on MQL flow in the milling process. The analysis of the spray nozzle flow is studied in the domain of a rotating cutter. A three-dimensional CFD study will be performed to investigate the spraying of an oil–compressed air mixture onto the cutting zone with one nozzle placed at some angle with the tool feed direction. The nozzle distance and height from the cutting points are also included in the study. Factors studied include correct penetration of the MQL jet into the cutting zone and the relative position between the nozzle and tool. Three nozzles are placed equidistant from the cutting zone at equal angles.

METHODS AND MATERIALS

A milling cutter with four teeth is used as the model rotating at 2000 rpm. The cutting medium is assumed to be a mixture of compressed air and oil. The mixture properties are presented in Table 1. The mass-fraction of the oil is assumed constant throughout the compressed air. The three-dimensional model and steady-state, pressure-based, 2-D and 3-D analyses were performed utilizing the ANSYS Fluent solver. The viscous, realizable k-ε model is used. A pressure-velocity coupled scheme is used with 200 courant number. The diameter of the nozzle is considered to be 2 mm. In the case of 3-D analysis, the nozzle is placed at 45^{o} to the tool axis of rotation and at a height of 15 mm and 15 mm from the cutter–workpiece interface. The density of the air–oil mixture is taken as the weighted average of the air and oil densities. An unstructured mesh with tetragonal elements is used with a maximum edge length of 0.006 mm and minimum edge length of 0.00002714 mm. The three-dimensional meshed domain is shown in Figure 1. The nozzle is modelled for balanced mass flow rate within the domain. Smaller mesh sizes are selected for the geometry close to the tool and workpiece interface region, i.e. in the cutting zone, to obtain more accurate results. In the case of 2-D analysis for three nozzles, the nozzles are placed 120° apart. An equal flow rate is assumed from every nozzle. The two-dimensional meshed domain is shown in Figure 2.

Table 1. Mixture properties.

Description	Value
Compressed air pressure (MPa)	0.4
Air viscosity (kg/m-s)	1.7894×10^{-5}
Air density (kg/m^3)	1.225
Air volume flow rate (litre/min)	72.6
Compressed air inlet velocity (m/s)	231
Oil viscosity (kg/m-s)	88×10^{-4}
Density of oil (kg/m^3)	0.96×10^{3}
Specific heat of oil (J/kg)	2.0
Thermal conductivity of oil (W/Mk)	231
Oil volume flow rate (ml/hr)	15

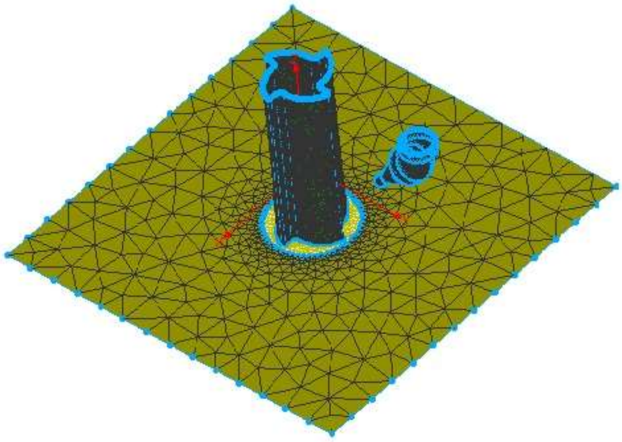
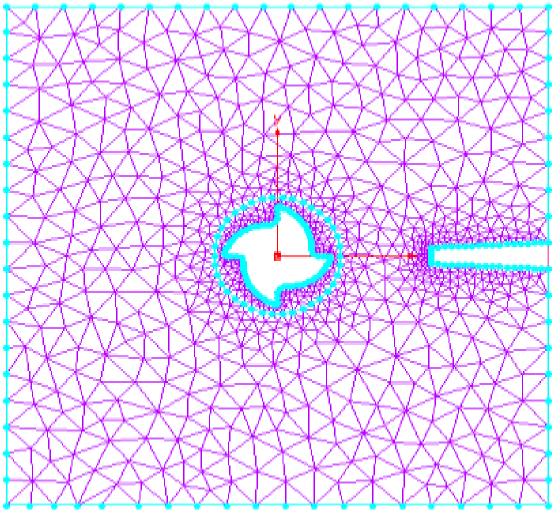
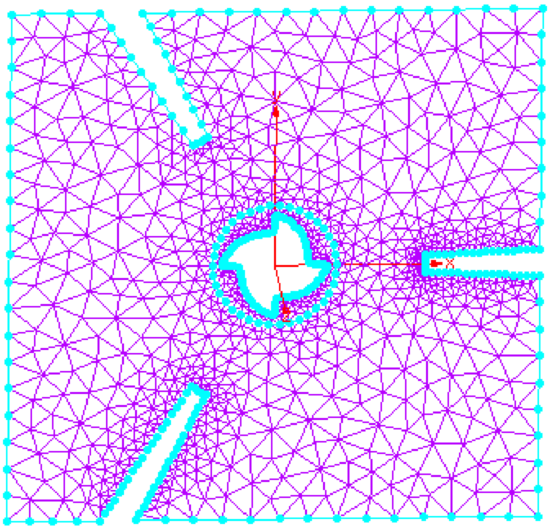


Figure 1. Two-dimensional meshed domains of single-nozzle MQL system.



(a) Single nozzle

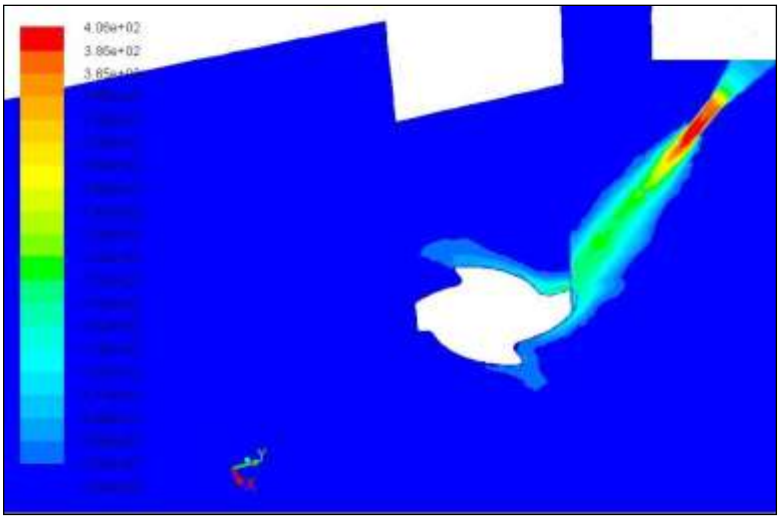


(b) Three nozzles

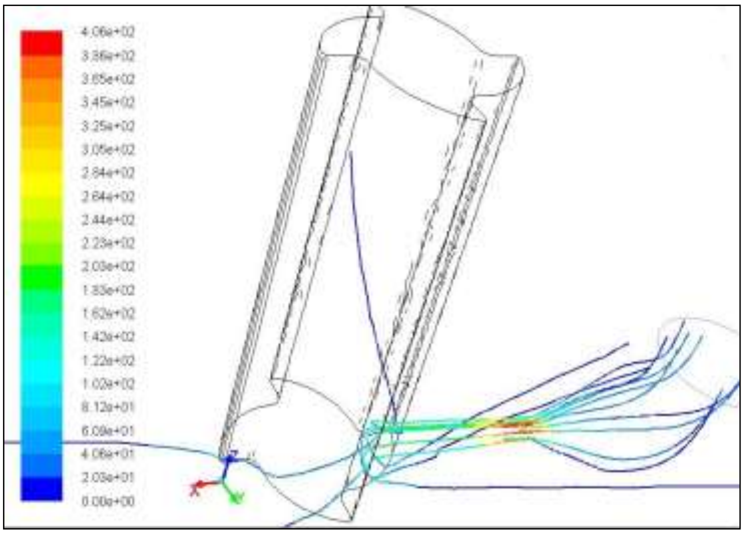
Figure 2. Two-dimensional meshed domain for single- and three-nozzle MQL system.

RESULTS AND DISCUSSION

The effects of minimum quantity lubricant flow are examined on a rotating end mill. The study is done to investigate the effects of nozzles in the spraying of a minimum quantity of lubricant onto the tool–workpiece interface. Figure 3 shows the velocity contour for the tool and path lines for the MQL jet in the case of three-dimensional single-nozzle analysis. The velocity vector plot for the MQL jet shows that the spray does not cover the periphery of the tool. The observation is in conformance with the results obtained in a previous study. The cutting surface is not entirely lubricated. The flow is scattered because of the high vortex created by the high speed of the cutter. The flow strikes the cutter but splashes back because of the turbulence.



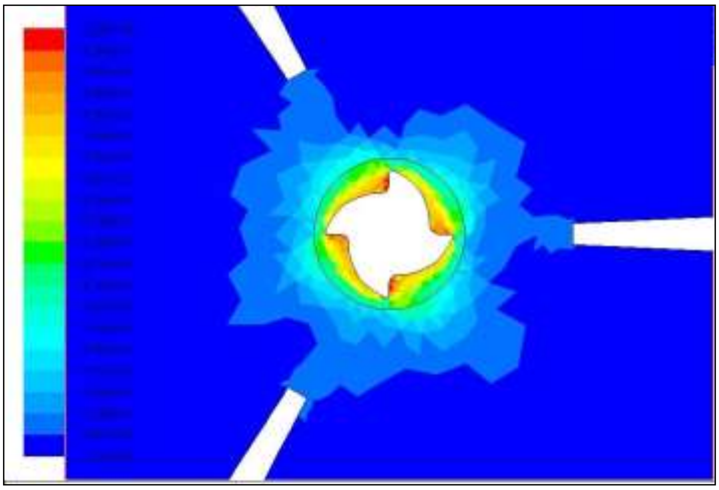
(a) Velocity contours



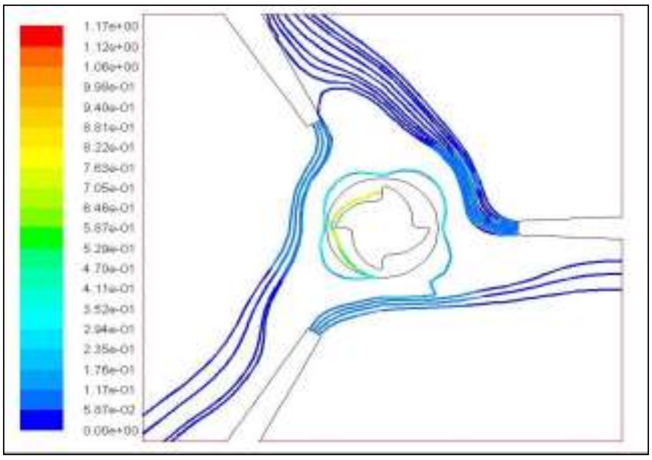
(b) Path lines

Figure 3. Velocity contours and path lines for the jet of single-nozzle MQL system.

The fluid flow rate is not sufficient to penetrate into the cutting zone. This is in conformance with the results and observations obtained from the 2-D single-nozzle analysis. It is observed that the fluid flow rate has to be increased in order to ensure that the fluid penetrates into the cutting zone. The problem of incomplete lubrication, i.e., uneven distribution of the fluid along the periphery of the tool, can be solved by using more than the single nozzle. The nozzle position in relation to feed direction is very important in order to obtain the optimum effect of the MQL flow. In the case of 3-D analysis, the position of the nozzle (nozzle height and axial distance) produces some improvement in the distribution of the fluid compared to the results obtained from 2-D analysis.



(a) Velocity contours



(b) Path lines

Figure 4. Velocity contours and path lines for the jet of three nozzles MQL system.

A steady-state, pressure-based 2-dimensional analysis is performed. The mass fraction of the oil is assumed constant throughout the compressed air. Three nozzles are used instead of the single nozzle. The nozzles are placed at 120° to each other. Figure 4 shows the velocity contour of the flow field and path lines of the MQL jet in the case of the three-nozzle analysis. The flow field shows that spray from the three nozzles, equidistant from each other, covers the periphery of the tool. A turbulence region is created around the rotating tool as it is rotating at a very high speed. This turbulent region prevents the penetration of the fluid into the cutting zone.

CONCLUSIONS

The CFD analysis of the arrangement of the nozzles around the tool periphery is performed in order to study the effect of the MQL jet and number of nozzles on the lubrication region. It was observed that flow penetration into the cutting zone is dependent on the flow velocity and the number of nozzles. A single nozzle with a very small flow velocity cannot achieve complete lubrication using MQL fluid. A three-dimensional analysis is performed in order to verify the results and observations from the 2-dimensional study. The results show that the nozzle height and distance from the cutting zone play a vital role in the analysis. The 3-dimensional analysis shows that a single nozzle is not sufficient for complete lubrication of the rotating tool in MQL. The three nozzles may work well for the complete lubrication of the rotating tool. Three nozzles placed at equal angles to each other and equidistant from the tool are modelled, and the MQL flow pattern is analysed using steady-state planar assumptions. Hence it can be concluded that the most effective MQL nozzle performance is with the three-nozzle arrangement keeping the mass flow rate constant.

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