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Computational fluid dynamic model for machining using minimum quantity coolant

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Abstract. The cooling applications during machining has significant effects on the production costs, surface quality, and the mechanical properties of the final product. In conventional flood cooling, a large amount of continuous cooling fluid is usually used, and that increases the cost of the product as well as the harmful effects on the environment and the machining operator. This study focuses on simulating alternative cooling system, called minimum quantity coolant (MQC), which used an optimal flow rate compared to classical flood cooling. The cooling fluid is directly provided to the cutting edge through the insert holder. In the current work, a computational fluid dynamic (CFD) model has been developed to study the effects of the cooling fluid velocity on the accessibility of coolant to the chip-tool interface area under using various types of cooling fluids. Three types of coolant are used (i.e. water, mineral oil, and nano-fluid). The results of the proposed CFD model have been classified into two phases. The first phase obtains the coolant accessibility percentage into the chip-tool interface (MA%) with different coolant velocities (i.e., 0.5, 1, 1.5, and 2 m/s) for the three studied coolants. The second phase discusses the heat transfer effectiveness for the employed coolants with different inlet velocities since it is an important aspect, especially when machining hard-to-cut materials. It was found that increasing the coolant velocity would increase the coolant accessibility percentage into the chip-tool interface area. However, no significant effect has been found after 1.5 m/s for all employed coolants.

1. Introduction

Difficult-to-cut materials are largely used in several engineering applications, including and not limited to army, automotive, and aerospace industries. That is because of their superior properties, such as high corrosion resistance and high strength-to-weight ratio [1]. The main problem associated with machining hard to cut materials is the change in the tool geometry (i.e., wear) within a relatively short time because of high temperature levels. Thus, the tool performance indicator is directly depending on the ability of the cutting insert to maintain a good tool life (i.e., nearly the same geometry) at this severe temperature. The excessive temperature occurs due to the fact that most of the hard to cut materials have a low thermal conductivity which leads to concentrate the generated heat in the cutting zone. As a result, the tool wear rate is highly increased and also the mechanical characteristics of workpiece material are influenced [2]. The main reasons behind using the cutting coolant during the machining process are to reduce the temperature in the cutting zone and reduce friction between the tool and the chip (see figure 1) by providing a lubricant effect. Flood cooling is the commonly used technique in order to improve the machinability of difficult-to-cut materials; however, it has severe environmental and health impacts. Various studies showed that minimum quantity coolant (MQC) is a potential alternative to flood cooling that minimizes the amount of cutting fluid supplied to the cutting



zone [3, 4, 5]. MQC is an approach in which an optimal amount of cutting fluid is forced to penetrate the cutting zone by means of compressed coolant. It provides optimum amount of lubricant through a system consists of a compressor, base fluid container, tunings, flow control system and spray nozzles.

The direct measurements of the coolant accessibility to the chip-tool interface area or tool cutting edge is still a challenge due to the dynamic nature of cutting processes as well as the small contact area during chip formation. In such cases, finite element analysis and simulation could provide an acceptable prediction of different process characteristics such as coolant accessibility to the tool-chip interface, cutting temperature, and residual stresses under different machining conditions in a virtual environment.

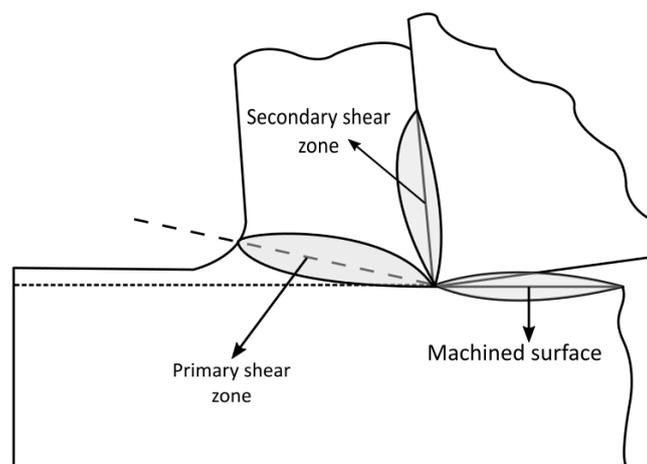


Figure 1. Heat generation zones in machining processes.

Due to the complexity of the studied domain, developing an analytical model expressing the two-phase flow interaction (coolant with surrounded air), and coolant flow in all possible directions is still a challenge. Thus, using the numerical approach can be valid for studying and analyzing such cases. In the current work, a computational fluid dynamic model (two-phase flow) has been employed using the ANSYS-FLUENT module in order to simulate and analyze the coolant accessibility and behavior into the tool-chip interface area when using MQC system. Three base fluids have been used under MQC systems: water, mineral oil, and proposed nano-fluid oil. The coolant speed effect on the accessibility into the tool-chip interface area and heat transfer performance have been presented and discussed for all employed fluids. Also, another objective is studying the coolant type effect on the induced heat transfer coefficient.

2. Proposed CFD Model

A computational Fluid Dynamics (CFD) model is developed to simulate the MQC volume, which is bounded by the tool flank face and the workpiece newly generated surface, as shown in figure 2.

2.1. Domain Geometry, Materials, and Meshing

For the simulation purposes, the current model is followed the same geometry and operation conditions of Hegab et al. [6] work as follows:

- Three types of coolant are used (i.e. water, mineral oil, and nano-fluid). The thermophysical properties of the employed coolant are listed in table 1. The used nano-fluid is based on vegetable oil with dispersed multi-walled-carbon-nano-tubes (4 wt.%).
- The used workpiece is Ti-6Al-4V alloy (bar), which has a diameter of 50 mm and a length of 200 mm. The mechanical, thermal, and physical properties of the used alloy are provided in table 2 [7].

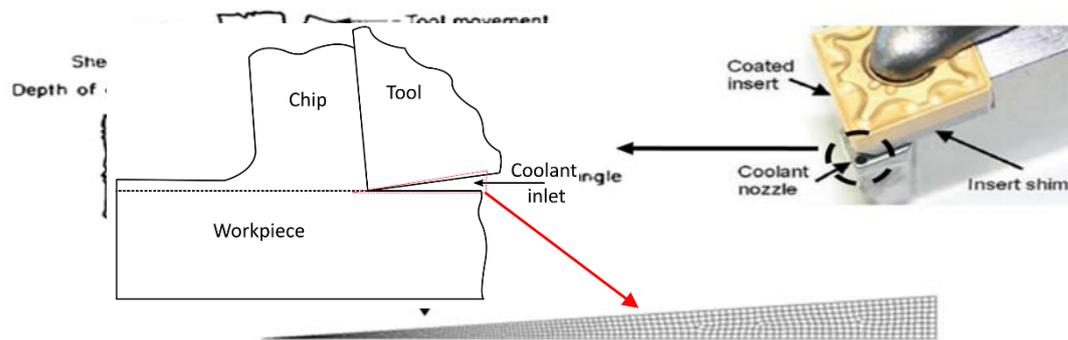


Figure 2. The developed domain used in the CFD simulation (coolant effect in tool-chip interface).

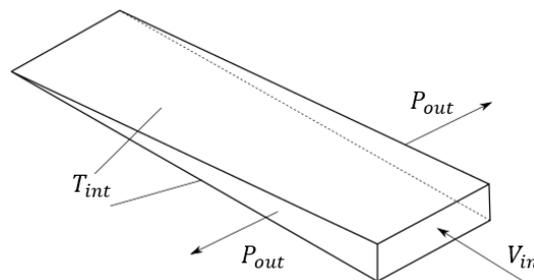


Figure 3. Model boundary conditions.

- The cutting conditions are; cutting velocity of 0.5 m/s, feed rate of 0.15 mm/rev, and depth of cut of 0.1 mm
- The temperature of the chip-tool interface is assumed to be about 600°C
- Throughout the proposed model, in order to accurately define the outlet boundary conditions of the chip-tool interface sides, a three-dimensional effect has been considered.

Figure 3 shows the model boundary conditions. Mist inlet velocity is defined to the right side, while a zero gauge pressure outlet is assigned to the model sides. Constant interface temperature is considered at the top and bottom (i.e. the tool flank face and the newly generated workpiece surface). To consider the workpiece motion, the bottom of the model is defined as a moving wall.

Generally, quadrilateral elements with an average size of $1\mu\text{m}$ have been used in the meshing construction and laminar steady-state pressure-based solver was used. Then, mesh dependent study was performed in order to confirm that the results are not depending on the mesh size. This is done by comparing the current results with more fine mesh size results.

Table 1. Thermo-physical properties of the employed coolants.

	Coolant Types		
	Oil	Water	Nano-fluid
Density (Kg/m ³)	820	1000	930
Specific-heat (J/Kg. K)	1670	4182	1963.304
Thermal-conductivity (w/m. K)	0.162	0.6	1.191
Viscosity (kg/m. s)	0.015	0.001	0.07154

Table 2. Properties of Ti-6Al-4V alloy (work-piece material).

Chemical composition (wt.%)	Ti:Bal, Al:5.5-6.75%, V:3.5-4.5%, C:0.1%,Fe:0.3%, O:0.2%, N:0.05%, H:0.0125%
Density (Kg/m ³)	4470
Young's modulus (GPa)	114
Poisson's ratio	0.3
Tensile strength (MPa)	895
Yield strength @ 0.2% offset (MPa)	828
Elongation (%)	10
Hardness (Rc)	30-34
Specific Heat (J/kg °C)	560
Thermal Conductivity (W/m °C)	7.2
Melting Point (°C)	1649

2.2. Governing Equations

Navier-Stokes equations are considered in the proposed model to simulate the flow of the coolant-air interaction in the tool-chip interface area using MQC system attached in the tool holder. Equations for the conservation of mass, the linear momentum, the energy, and the volume fraction are described, respectively, as shown in equation (1-6) [8]. These equations must be solved simultaneously in order to obtain velocity components, temperature, pressure, and volume fraction of the coolant.

$$\nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\rho \left(U \frac{\partial U}{\partial x} \nabla \cdot (\rho \mathbf{v}) = 0 + V \frac{\partial U}{\partial y} \right) = -\frac{\partial p}{\partial x} + \rho g_x + \mu \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) \quad (2)$$

$$\rho \left(U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} \right) = -\frac{\partial p}{\partial y} + \rho g_y + \mu \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) \quad (3)$$

$$\nabla \cdot (\mathbf{v}(\rho E + p)) = \nabla \cdot (k \nabla T + (\boldsymbol{\tau} \cdot \mathbf{v})) + S_h \quad (4)$$

$$\rho = \alpha \rho_l + (1 - \alpha) \rho_g \quad (5)$$

$$\nabla \cdot (\alpha \mathbf{v}) + \nabla \cdot (\alpha(1 - \alpha) \mathbf{v}) = 0 \quad (6)$$

3. Results and Discussions

In order to confirm the solution convergence, the solution is continued until the difference between two successive iterations in each flow conservation equation (i.e., residuals) becomes less than 10^{-3} for the continuity equation and 10^{-4} for all other equations [9].

The results of the proposed CFD model have been classified into two phases. The first phase obtains the coolant accessibility percentage into the chip-tool interface (MA%) with different coolant velocities (i.e. 0.5, 1, 1.5, and 2 m/s) for the three studied coolants. The second phase discusses the heat transfer effectiveness for the employed coolants with different inlet velocities since it is an important aspect, especially when machining hard-to-cut materials. The results of the coolant accessibility percentage (phase I) are provided as shown in figures (4-5). As can be seen in these figures, the water-based coolant offers better results than oil and nano-fluid-based coolants. It is mainly due to its viscosity (see Table 1). Also, the lowest accessibility percentage has been obtained when using nano-fluid-based coolant, and it is also attributed to its viscosity because of the nano-tubes presence in the base oil. It can be also stated that increasing the nano-fluid dispersion stability could effectively decrease the resultant viscosity as has been mentioned in previous research works. Also, it

was clearly found in figure 4 that increasing the coolant velocity would increase the coolant accessibility percentage into the chip-tool interface area. However, no significant effect has been found after 1.5 m/s for all employed coolants.

Regarding the second phase analysis, the average heat transfer coefficient has been used to express the used coolant heat transfer effectiveness. The results (see figure 6) showed that the water-based coolant has offered the best performance. Also, the nano-fluid based coolant has shown better results than mineral oil, and that is mainly attributed to the superior thermal properties (higher thermal conductivity and heat convection coefficients) of the added nano-additives. Also, increasing the coolant velocity showed a noticeable increase in the average heat transfer coefficient. Although water-based coolant offers better results for both studied characteristics (i.e., accessibility percentage & average heat transfer coefficient), water-based coolant is an undesirable approach for cutting hard-to-cut materials due to its poor tribological and chemical characteristics (e.g., flash point, tool wear resistance, and corrosion resistance).

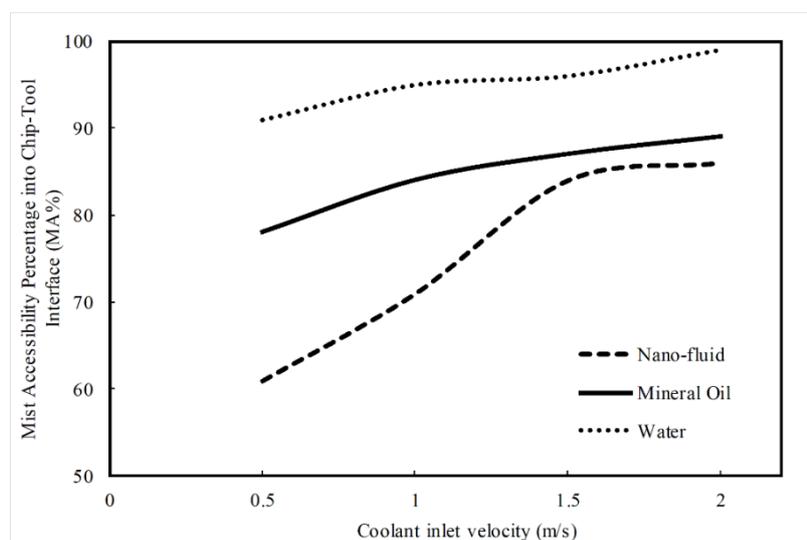


Figure 4. Results of coolant accessibility percentage with different coolant velocities.

Conclusion

Flood coolant is widely used to dissipate the generated heat, which occurs during the machining processes; however, it is not a sustainable technique because it has high harmful effects on the environmental and operators' health as well. Besides, using a large amount of coolant increases the machining cost by approximate 10-15 %. In this paper, the utilization of different alternative techniques is studied, where the optimal coolant can be directly fed to the cutting zone through a nozzle in the tool holder located below the insert flank face. CFD model for this technique is developed in order to study the accessibility distance and heat transfer coefficient of three kinds of coolant: water, mineral oil, and nano-fluid. The results show the water-based coolant has the best accessibility distance due to its low viscosity, which leads to an increase in the heat transfer coefficient. However, water-based coolant cannot be used as it has poor tribology aspects. The mineral oil coolant shows a higher accessibility distance than the nano-fluid. However, the nano-fluid provides a better heat transfer coefficient even at its short accessibility distance. This can be explained by the superior thermal properties of the added nano-additives. Future works need to be done in order to study the effect of higher inlet pressure on the accessibility distance of the nano-fluid, as the heat transfer coefficient is found to be mainly affected by the accessibility distance.

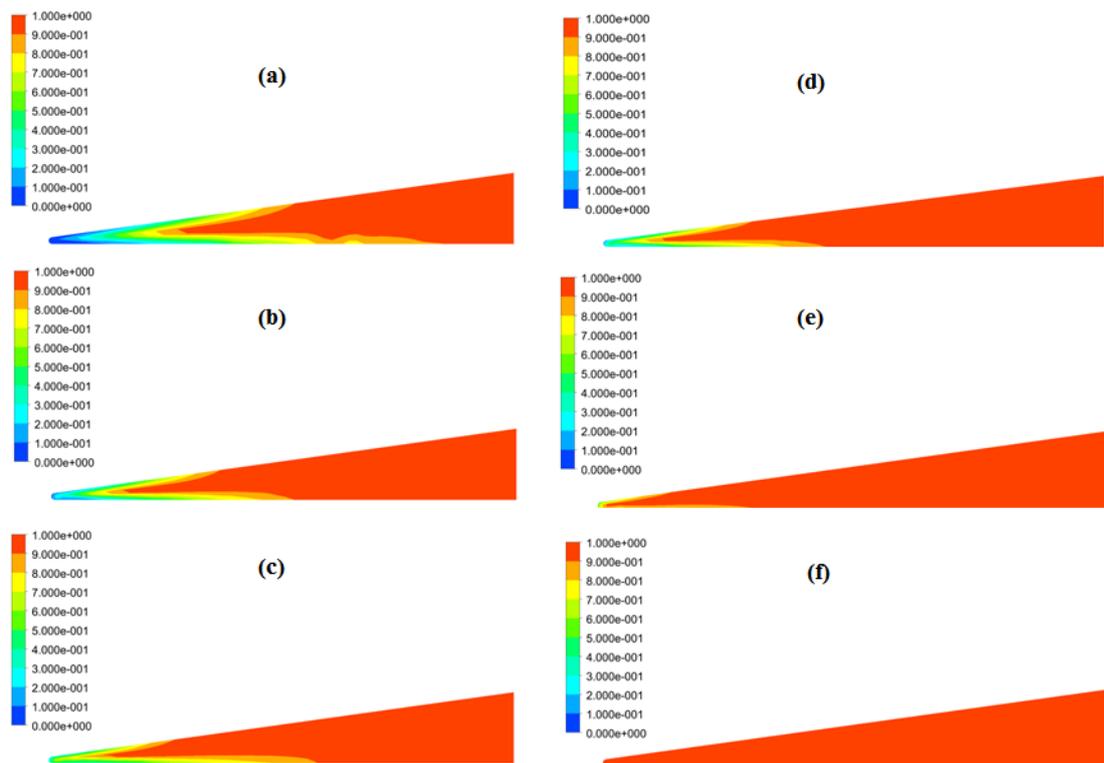


Figure 5. Contours of coolant volume fraction for some studied cases; (a) nano-fluid at 1 m/s, (b) nano-fluid at 2 m/s, (c) mineral oil at 1 m/s, (d) mineral oil at 2 m/s, and (e) water at 1 m/s, (f) water at 2 m/s.

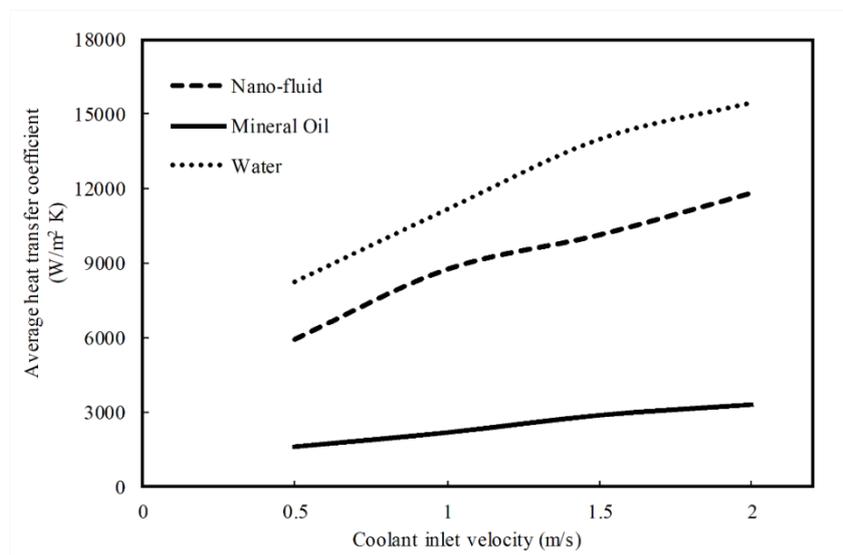


Figure 6. Results of average heat transfer coefficient with different coolant velocities.

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