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# Computational Fluid Dynamic Analysis of Coolant Flow in Milling of Titanium grade-2 under Multiple Nozzle

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**Abstract.** The application and behaviour of coolant in end milling of hard-to-cut material such as titanium alloy is very critical due to the high cutting temperature generated at the tool tip that can be more than 600°C. Titanium is generally well known to have a very low thermal conductivity that prevent a rapid dissipation of the heat generated during machining due to the friction that occur in the metal removal process. In addition, hard-to-cut material have a very high hardness that can range from 198 to 1300 HV at Vickers hardness. For all this reasons, the optimization of the coolant that includes positioning, inclination and distance of the nozzle to the tool tip is very vital to provide an efficient cooling during the machining operation. In this paper, a three dimensional static analysis of the application of coolant through two nozzles was studied by using computational fluid dynamics (CFD). It was found that the velocity of the coolant was more uniformly distributed and effective when two nozzles were applied at an angle of 12.5 ° and a distance of 25 mm from the tool tip.

## 1. Introduction

The milling operation of hard-to-cut material such as titanium has been subject to numerous investigation on the various ways of controlling the high heat generated during the cutting operation. The low thermal conductivity of titanium that can range from 14W/m.K for titanium grade 1 to 6.7 W/m.K for grade 5 contribute in the building up of high heat in the cutting zone between the tool tip and the workpiece interface due to a poor dissipation of the heat [1]. In addition, this issue trigger a rapid tool wear, poor surface finish, high cutting forces and high power consumption among others. In the machining of titanium, coolant is also necessary to prevent any types of oxidation due to the environment [2]. Without a proper cooling system in the machining of titanium, the build-up of the cutting heat within the material contribute in its embrittlement couple with a reduction in the overall strength of the material. Next, another works also suggest that coolant can directly influence the surface quality [3]. Furthermore, the most common types of coolant that are widely use in the industry are synthetic, semi-synthetic and mineral oil based [4]. These types of coolant offer a good stability in terms of chemical reaction during the machining operation. On the other hand, the high content of toxic substance and quick contamination of this coolant are consider as a hazard to human health and the environment [5]. The best alternate type of coolant that is slowly being accepted by the manufacturing community is the vegetable oils (VO) base cutting fluids because of its high biodegradability. The molecular structure of the vegetable oil that is thick, tenacious and vigorous film



layer is very useful in machining precisely for hard-to-cut material such as titanium because it can absorb the contact pressure at the tool-workpiece interface [6]. Furthermore, VO have two other attractive qualities namely a low thermal conductivity and coefficient of friction that are 0.172 W/m.K and 0.03 whereas mineral oil has a thermal conductivity of 0.125 W/m.K and a coefficient of friction of 0.07. The most common coolant supply system that is use in machining is flood cooling due to its low installation and maintenance cost, the flow rate in this system can range between 10 L/min to 225 L/min depending on the applied parameters [7]. It was demonstrated that supplying the cutting zone with plenty of fluid contribute in cooling down the heat generated and flush away the chips more efficiently [8]. However, the high fluid consumption added to a relatively low penetration to the cutting zone, especially at high-speed cutting, were considered as some major disadvantages in applying flood-cooling system. In addition, in the last decade, two other cooling system were introduce for machining purpose namely high pressure cooling (HPC) and cryogenic cooling [9]. HPC system can supply the cutting fluid to the cutting zone at pressure of up to 200 bars. This system was also compare against other system, and some researchers found out that it was very efficient in improving the tool life and the chips breaking [10]. Moreover, cryogenic cooling is another system where liquid nitrogen (LN<sub>2</sub>) is use in machining and it was reveal that it reduces tool wear and extend the tool life but the high investment cost of this system limit it to some selected application only [11].

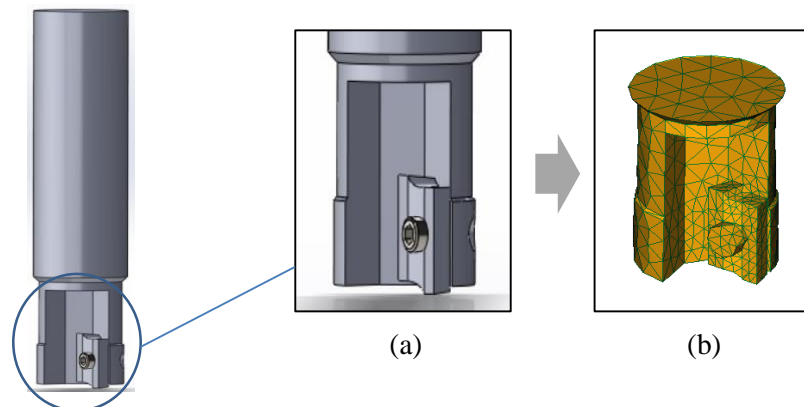
The minimum quantity lubrication (MQL) is yet another effective cooling system in terms of sustainability, environment friendly and economical [12,13]. The effectiveness of a cooling system like MQL can also be enhance by positioning the nozzle at the most appropriate location in a machining setup [14]. In a study on the influence of nozzle positioning, two specific position namely at 45° and 135° were analysed. The two nozzles were position in relation to the feed direction during the machining of AL5083 using MQL system. The authors concluded that when the nozzle is position at 135°, a lower tool flank wear of 0.098 and 0.095 mm is achievable with a flow rate of 0.04 and 0.06 ml/min [15]. In a further study, two different orientations were evaluated, one was position at 12.5° and the other at 45°. It was reveal that at an inclination of 12.5°, 50 % extension in the tool life was achieve with average flank wear of 0.3 mm compared to that of 45° [16]. In another experiment, micro-milling of Ti-6Al-4V using two different cooling system namely MQL and jet-cooling was investigated. It was concluded that the tool wear was 1.6 % less with feed direction under MQL compared to 6.15 % with jet cooling [17]. The spraying distance for the coolant is also a very important factor to consider in milling operation. In a study related to MQL, two scenarios of the positioning and distances of the spraying nozzle was investigated. In the first situation, the spraying nozzle was position at 135 ° with a distance of 25 mm to the cutting zone and in the second situation, it was position at 90° and 45 mm. It was found that the first scenario was more effective as the cutting temperature decreases by 2.5 and 20°C compared to 90° nozzle angle and 45 mm spraying distance [18]. MQL is mostly considered as a lubricating rather than a cooling method and this properties is very critical when apply in the machining of hard-to-cut material such as Inconel and Titanium due to the high heat generated couple with a low thermal conductivity [19].

The application of computational fluid dynamics (CFD) simulation is not well-establish in machining operation due to many challenges. Among the various challenges that arise in the modelling process of the fluid are geometrical boundary conditions, resistance coefficients, driving forces and interactions between different processes [20]. Moreover, the proper selection of the turbulence models and the types of meshing are very important to produce a more realistic situation with good accuracy [21,22]. In machining operation, the situation is more complex due to the various variables such as coefficient of friction that differ for each material due to their hardness. In addition, the meshing of smaller dimensions around the boundary layers is also another critical step in the CFD. Two major types of CFD simulation are currently available namely 2D and 3D simulation. The 3D simulation is more complex due to the high amount of mesh elements but better results can be generated compare to a 2D. Vortices is another element that are formed when a rotation is involve and it is define as a flow with circular and rotary route, dissipating energy. It is also form in different size and react according to the model of the boundary conditions. In a three dimensional simulation, the developed turbulence due to the rotation can be observe. Many methods had been define to identify vortices and the most popular for CFD simulation are the  $q$ -criterion and the  $\lambda_2$ -method [23,24]. The

work presented uses 3D CFD methods to investigate the velocity and flow direction of the coolant in a milling operation of titanium grade 2. The results presented could be used to improve the setup of the coolant nozzle especially during machining of hard-to-cut material such as titanium. In addition, a more efficient way of applying the coolant can contribute directly in lowering the energy consumption due to an excessive cutting forces from the machine tools.

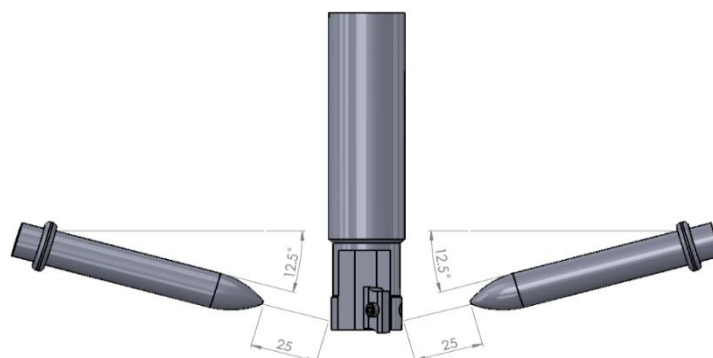
## 2. Methodology of simulation.

The overall simulation was carried out base on a one-tooth milling cutter with a diameter of 25 mm. In addition, the cutting insert are coated and especially design for machining of hard-to-cut material such as titanium. The spindle speed that was applied in this current study was set at 1000 rpm couple with water as cutting fluid. Figure 1 shows the steps in developing the meshing of the milling cutter. At the initial stage a CAD model is develop base on the actual dimension of the milling cutter by using Solidworks software. Next, Altair Hyperworks software, precisely Acusolve was used to construct the meshing model using tetrahedron elements for the cutting tool, with a maximum meshed of 5 mm. The region of fine meshing are located at all high turbulence region so that a more accurate prediction for the flow field can be generated. The complex features with very small dimensions are all fitted with small mesh. The CFD domain was set in an area of 100 x 100 mm and the simulated workpiece was



**Figure 1.** Building up process of (a) CAD model and (b) meshing of model

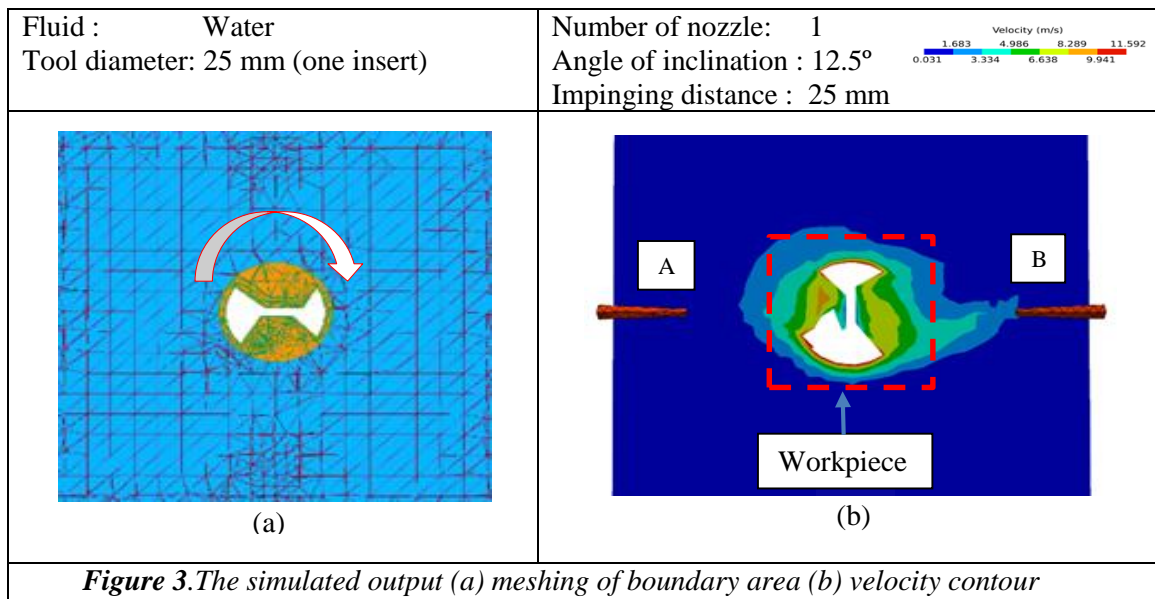
represented by a block with a dimension of 50 x 50 mm as shown in Figure 3 (b) under the cutting tool. In this current paper, the effect of multiple amount of nozzles on the fluid velocity was investigated. In the first scenario, one nozzle was position against the clockwise rotation of the milling cutter and in the second scenario, a second nozzle was position with the rotation of the milling cutter as shown in Figure 2. The nozzles are both incline at an angle of  $12.5^\circ$  with an impinging distance of 25 mm between the nozzle tip and the tool tip. Next, in both scenario, a constant flowrate of 3.1 L/min was applied through a nozzle diameter of 1.75 mm. This particular diameter was based on the contraction ratio (inlet to exit diameter ratio) to achieve high jet stream quality [25].



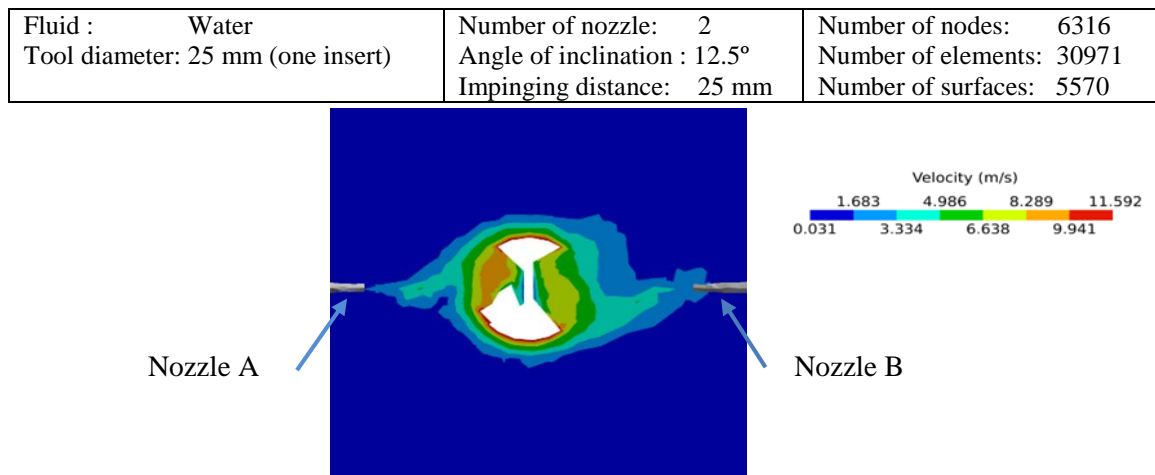
**Figure 2.** Schematic view for the nozzle setup

### 3. Results and discussion

The first scenario was the application of cutting fluid through nozzle “B” only as shown in Figure 3 (b). The simulated model generate the pathway created by the flow of the coolant around the milling cutter and the colors represent the variation in the velocity recorded when the cutter is rotating at a speed of 1000 rpm. The values of the velocity have a range of 0.031-11.592 m/s and the highest velocity was recorded along the edge of the cutter. It was also observe that an average velocity of 8.289 m/s was located in the section of the insert that suggest a proper penetration of the coolant towards the cutter edge. In addition, the velocity contours also indicate that the distribution of the coolant near the cutting zone is efficient as the velocity contour is not scattered but instead it creates a normal vortex that is triggered by the rotation of the milling cutter.

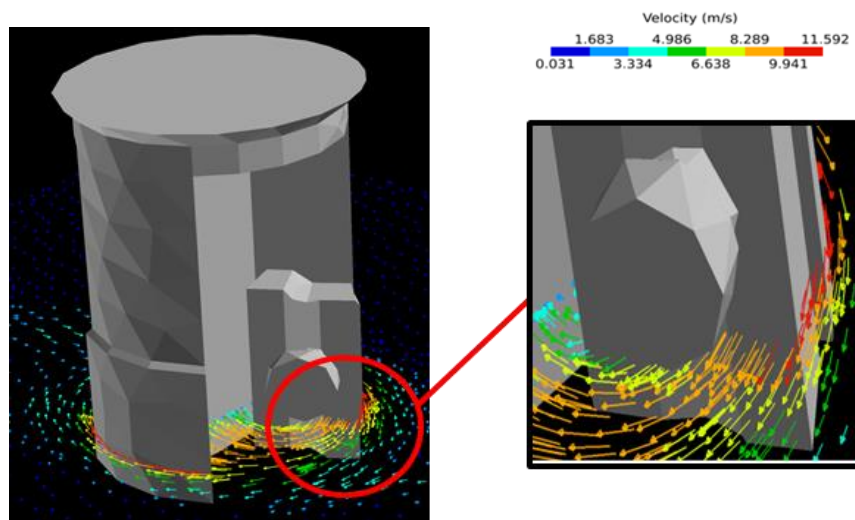


Furthermore, for the second scenario, the water jet was applied through both nozzles A and B simultaneously. The flow rate was maintained at 3.1 L/min. Then the simulated results were analysed. The generated velocity contour for the second scenario suggest that the application of two nozzles offer a wider cooling area around the cutting zone. More importantly, the inner section of the insert experience a higher velocity as shown in Figure 4. Biermann et al. state that a higher velocity of the coolant at the cutting edge prevent high thermal load on the cutting edges which most of the time results in higher tool wear [24].



**Figure 4.** Velocity contour for two nozzles

Furthermore, the application of the two nozzles setup provides a more efficient supply of coolant to the cutting zone that is vital in machining especially when dealing with hard-to-cut material such as Inconel and Titanium among others that generate high intensity of heat due to their unique properties such as low thermal conductivity and low elastic modulus. Figure 5 shows the velocity field developed when the water jet is apply through both nozzles towards the rotating cutting tool that was set at a spindle speed of 1000 rpm. A high velocity of water jet in the range of 9.287 to 11.592 m/s were recorded around the edge of the cutting tool. In addition, a higher velocity in the range of 6.981 to 9.287 m/s was also noted nearby the cutting insert that is much higher than in the first scenario with the one nozzle setup. The high velocity of the coolant at the cutting edge allow it to be more wetted.



*Figure 5. Velocity contour at the insert cutting edge*

#### 4. Conclusion

In this paper, CFD simulation was used to evaluate the efficiency of cooling a cutter with single and two nozzles setup together with a specific angle and distance. It was possible to define the path line of the coolant from the nozzle tip towards the cutting tool and its surrounding. It was also noted that in both cases whether with one or two nozzles, a zone of turbulence was created at the edge of the cutter and a high velocity was recorded. The turbulence also show that the stream that are closer to the cutting tool tend to have a high velocity compare to those away from the tool. The parameters for both setup was quite efficient in supplying the coolant at the cutter because the cutting fluid was not totally thrown away from the cutting zone. Next, when using one nozzle only, the coolant tend to scatter outside the cutting zone whereas when both nozzles were apply, the cooling zone remain more compact around the cutting zone that allow the milling cutter temperature to remain at a reasonable intensity and also contribute to extend the tool life and delay the tool wear. According to the stream flow, it also suggest that the region of high cutting temperature that is at the cutting edge of the insert is well wetted when two nozzle setup are used compare to a single one. Additionally the results will be examined by temperature and cutting test with the insert.

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