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A numerical investigation on oil mist behavior used in Minimum Quantity Lubrication (MQL) milling process

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Abstract — This paper predicts MQL projection on cutting inserts for different rotating velocities of a milling tool. The numerical model is based on a steady Reynolds-Average Navier-Stokes (RANS) formulation and multiphase Eulerian-Lagrangian model to predict the air-oil flows. Pressure configurations and the orientation of the oil particles are studied. This study leads to a better understanding of the oil mist behavior in order to get the optimized design of the tool leading to various lubrication configurations taking into account the type of machining.

Key words — Minimum Quantity Lubrication (MQL), Computational Fluid Dynamics, Eulerian-Lagrangian, Multiphase Flow, Milling Tool.

1. Introduction

In the last years, investigations were carried out to reduce or eliminate the large amount of lubricants used in machining (oils or emulsions) for economic reasons. Investigations in the German automotive industry estimate that the cost of cutting fluids is between 7 and 17% of the total manufacturing cost [1]. For some materials that are more difficult to machine, this proportion can reach 20 to 30% [2]. This cost is several times higher than tool costs (design, manufacture, coating...) that varies between 2 and 4% of the total manufacturing cost [1]. Furthermore, there are environmental motivations since the avoidance of lubricants results in lower pollution. Due to the above mentioned reasons, dry machining could be highly desirable. However, dry cutting is not applicable in all machining operations. This is mainly due to excessive tool wear or low surface quality. In order to improve machinability, minimum quantity lubricant (MQL) may be more suitable. This technique consists of an injection of oil micro-droplets inside a high speed air jet. This alternative can be very economic compared to emulsions: instead of consuming 200 to 3000 L/min cooling fluid in emulsion, MQL uses only 5 to 100 mL/h oil cooling fluid (depending on the machining process, the cutting material, and the cutting configuration) [1]. Such a low lubricant consumption leads to machined parts and chips almost dry. Moreover, this technique decreases friction between chip and the rake face of the cutting tool and leads to better surface finish. All these parameters ensured with the minimal fluid process lead to a high production rate. For these reasons, the cutting zone has to be well lubricated and judiciously cooled by spraying the coolant on the cutting edge.

Lots of researches are focused on MQL applied by external nozzles as it doesn't require changes in tool design, it just needs the connection to an external MQL generator [3-5]. But today, in order to answer a large scale of industries' production requests and necessities, researchers are focusing on inner canalizations tools [6, 7]. This allows bringing out the mist to the tool's cutting edge in a better way; the distance from canalizations' exit sections to the cutting edge is reduced to a few millimeters instead of a few centimeters with external MQL. Moreover, nozzles positioning errors are eliminated. Each tool has its own internal pipes and the machining area is not cluttered with supply pipes. An efficient design of these systems will usually require an in depth understanding on how the two phases

behave under a rotating environment with varying conditions. As a key alternative to analyze these complex processes, numerical simulation makes use of the current computational power and efficiency to provide a powerful exploration tool for both institutional and industry researchers.

The context of the study is focused on a milling tool development with inner channels to ensure the micro quantity coolant efficiency. Due to the sluggishness of the experiments and to predict optimal MQL design, the numerical simulation of multiphase fluid flow is studied here.

2. Numerical model

Numerical simulations are performed using legacy finite element software Ansys-Fluent considering the multiphase flow physics. Previous work with an experimental test bench provided us measurements of velocities of the fluid in static conditions [8]. Those velocities reached 170 m/s. A very high flow velocity leads to a high Mach number around 0.5 where we are in subsonic compressible flow which is modeled with an ideal gas. The pressure based solver uses the Navier-Stokes equations based on the Reynolds-Average Navier-Stokes (RANS) formulations employing Realizable $k-\epsilon$ turbulence model. The air-oil flow is calculated with Eulerian-Lagrangian multiphase flow model in order to track the discrete phase (oil), as largely used for the diphasic flow study [9-11]. Finally, a multiple reference frame (MRF) is used in the steady state condition to ensure the rotation of the milling tool; indeed, a flow field which is unsteady when viewed in a stationary frame can become steady when viewed in a rotating frame. In this case the equations of motion are modified to incorporate the additional acceleration terms that occur due to the transformation from the stationary to the moving reference frame. Using this solution leads to low computational cost, and easier to post-process and analyze. An in-place interface is defined to separate the motion area (milling tool) and the outlet area. This interface is placed at 0.5 mm behind the external wall of the milling tool since it has to be a revolutionary interface. In these simulations, only the fluid is modeled as shown in figure 1: the negative of the milling tool (blue part) and the outside air (brown part).

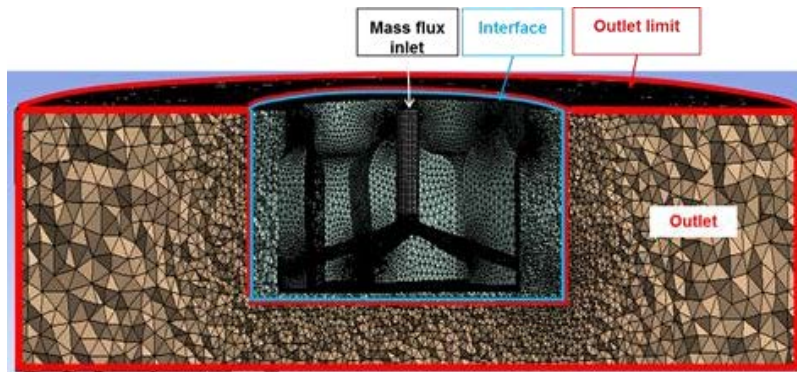


Figure 1: Illustration of the meshing model.

Initial boundary conditions are taken from previous work on an experimental test bench with prototypes [8]: inlet velocity 170m/s, mean particle sizes 10 μm and relative external atmospheric outlet pressure ($P_o = 1\text{bar}$). After that, an inverse problem without rotation of the milling tool was solved in order to adjust the velocity inlet and have a relative pressure on the exit of the central hole 0.3 bar as measured with pressure sensor, we get a mass flux inlet of 142.08 $\text{kg/m}^2\cdot\text{s}$ (corresponding to a velocity inlet 120m/s). Simulations were carried out for various spindle speed 5000, 10000 and 20000 rpm. As MQL droplets are very small (about 10 μm), their inertia is neglected, as well as particles interactions (leading to a loosely coupled problem). Therefore, the dispersed phase has no influence on the continuous phase behavior [12]. The wall boundary interaction model for the Lagrangian phase is set to reflect particles.

2. Results

Simulations results showed coherent results, increasing pressure on the cutting faces and small depression on the back of the milling tool teeth due to the rotation (Figure 2-a). Another depression is located at the secondary channels' connection to the central channel (Figure 2-b), thus, simulation can illustrate some undetectable problems in the design that can be improved. Focusing on contours of pressure on the milling tool teeth, simulations showed that, by increasing the rotating velocity, total relative pressure increases especially in the bottom of the tooth. This is due to projection of the MQL flow on this faces. Moreover, the more the velocity increases, the maximum pressure area moves toward the secondary canalizations' exit sections, this is due to two phenomenon: At high speed, the traveling time of the flow becomes shorter and confined air on the flute tends to force the flow to reach the cutting face (Figure 2-c,d,e).

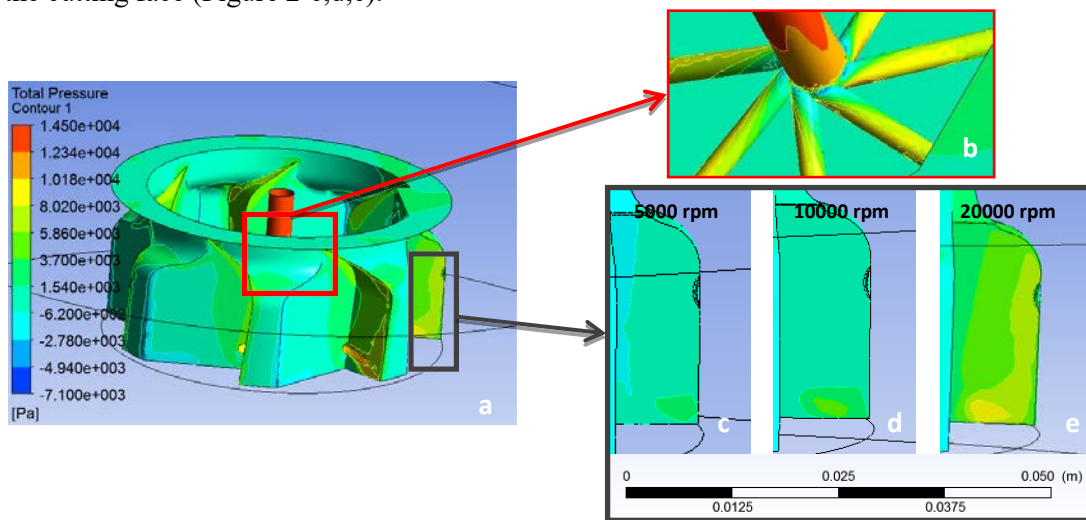


Figure 2: Contours of total relative pressure: a) milling tool at 20000 rpm, b) canalization connections at 20000 rpm, c) tooth at 5000 rpm, d) 10000 rpm, and e) 20000 rpm.

Focusing on oils droplets path-lines, it can be seen that at 5000 rpm (Figure 3-a), the MQL is aiming the corner of the tooth.

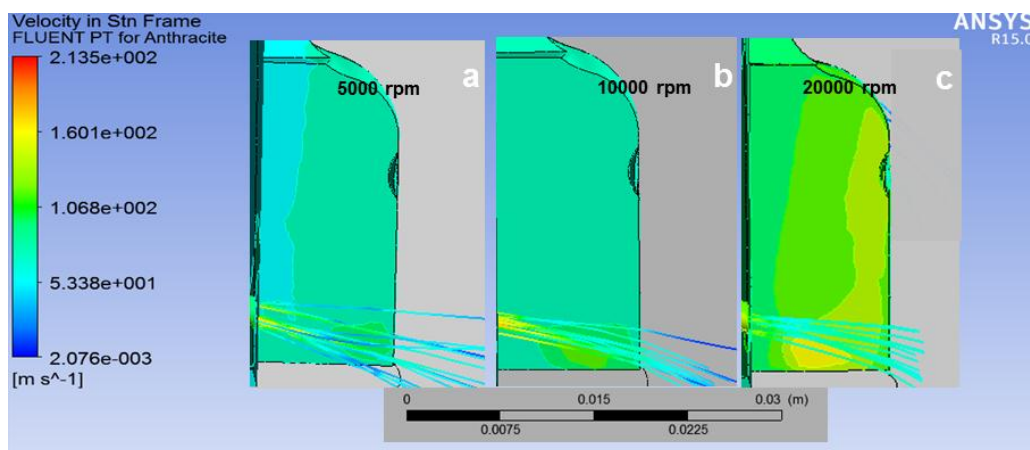


Figure 3: Contours of total relative pressure and particles traces colored by velocity magnitude on a milling tool tooth at: a) 5000 rpm, b) 10000 rpm, and c) 20000 rpm.

By increasing the velocity to 10000 rpm (Figure 3-b), the path-lines are aiming only at the secondary cutting edge (vertical edge) and begins to be projected up and have a tendency of an horizontal direction especially at 20000 rpm (Figure 3-c).

Such phenomenon was observed in experimental part. This can be explained by the spindle rotation and the positive axial angle (6°) that generate a vacuum effect. In fact, spindle and tool holder rotation aspire the air from the cutting area to the top of the tool, the more the rotational speed increases, the more this phenomenon will take place.

3. Conclusions and perspectives

This study aimed to better understand the oil mist behavior in order to get the optimal design of the tool. The rotational speed was considered and the numerical results allowed identifying the following conclusions:

- At low rotation speed, the MQL is aiming at the corner of the milling tool tooth and by increasing this speed; the flow is more affected by the aspiration effect of the equipment upstream
- Increasing rotating speed leads to MQL projection closer to the tool axis.
- Canalization connections design lead to small depression

The present model could be coupled to an optimization approach to automatically adapt the MQL tool design to the milling conditions.

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