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Numerical Analysis of Internal Flow Embedded in a Cutting Tool

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Abstract

Embedding of internal microchannel into a standard cutting tool alters the thermal and mechanical behaviours of the tool in a machining process which consequently improves the machining performance in terms of wear mechanisms of the tool and surface roughness of the finished product. Obviously conditions of the fluid such as type, temperature, viscosities and speed need to be modelled accurately to determine their effects on the microfluidics performance although the development of ideal mathematical equations to precisely pose a machining process is almost impossible due to the geometrical, physical, thermal and chemical complexities of the process. This work aims at computational fluid dynamics modelling of the internal flow inside the microchannel of 0.8 μm diameter to quantify the flow regimes along the cooling manifold for improving the performance of a cutting tool. Two procedures have been performed in this work, namely (1) the determination of flow regimes in the internal microchannel and (2) the mapping of the flow speed topography of the cooling fluid. The fluid in this analysis is assumed to be Newtonian incompressible fluid since it will not change phase while exchanging the heat. The results show that the Reynolds Number in the microchannel manifold are distributed in the range of 528 and 6604 which the numbers higher than 2320 are considered turbulent flow. On the other hand, the empirical correlations show that with the inlet flow rate of 0.3 l/min, the fluid speed at the microchannel part that is closest to heated region can reach up to 7.706 m/min. The outcomes of this work determine the pump capacity of the system and the values obtained from the numerical analysis can be used in the thermodynamics analysis of the cooling performance of the microchannel in removing the heat generated during machining.

Keywords
Computational Fluid Dynamics; Internal Microchannel; Cutting Tool.

1. Introduction.

Through the increased environmental awareness and higher machining costs, there have lately been a strong thrive towards enhanced efficiencies for innovative machining cooling techniques [1-3]. In machining there has been increasing movement towards the application of embedded small cooling channels to replace the high volume external coolant to remove the heat effectively from the cutting area because it has been found that many small active elements are more efficient than few large ones [4-6]. McPhail [7] has defined in general the three categories of micro-systems typically utilised in industries:

- MEMS: Micro-Electro-Mechanical Systems (e.g. air bag acceleration sensors, HD readers, etc.)
- MOEMS: Micro-Opto-Electro-Mechanical Systems (e.g. micro-collimators, micro-endoscopes, etc.)
- MFDs: Micro-Flow-Devices (e.g. micro heat exchangers, micro-pumps, micro-mixer, etc.)

Current research in MFDs is investigating different applications of micro-cooling devices which intimately involve the dynamics of fluids, single-face and two-phase forced convection of heat transfer and implicit modelling of cooling mechanisms in various applications [6-8]. Micro-channels with circular internal cross sectional area are called micro-pipes or micro-tubes. In practical applications normally angular internal cross sections are preferred, because of their high proportion of wetted area to fluid volume, relatively strong mechanical-wise in comparison with their substrate and easier for device agglomeration [7].

The demands for higher productivity and excellent surface integrity of the machined parts cause concentrated heat generation in the vicinity of cutting area that is not favourable to the effective life span of a cutting tool. Despite the proportional relationship between the cutting speed and the cutting temperature, the specific tool wear shows that there is an optimum low cutting temperature between mechanical induced wear and thermal induced wear as in Figure 1. The increased localised pressure on the cutting tool due to increase in cutting speed requires sufficient cooling to keep the cutting tool, normally made of hard metal such as high speed steel (HSS) or cemented carbide (WC), below its maximum operating temperature of 800 - 1200℃ [8, 9].

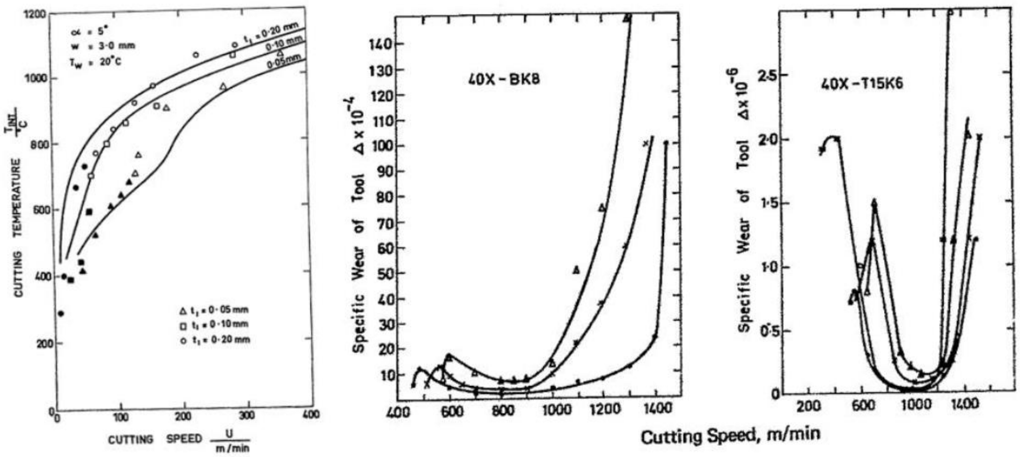

Figure 1: Relationship between cutting speed, cutting temperature and specific wear of tool [10].

Although MFDs have been used widely in many applications such as in cooling of computer CPU, the scientific requirements for MFDs in sustainable machining are still lacking especially when assembling of the device to the conventional machining configuration is concerned. Accordingly, the current work aims at modelling of computational fluid dynamics (CFD) of the internal flow inside the microchannel of 0.8 μm diameter to quantify the flow regimes along the cooling manifold for improving the performance of a cutting tool. Two procedures have been performed in this work, namely (1) the determination of flow regimes in the internal micro-channel and (2) the mapping of the flow speed topography of the cooling fluid. The fluid in this analysis is assumed to be Newtonian incompressible fluid since it will not change phase while exchanging the heat. The outcomes of this work determine the pump capacity of the system and the values obtained from the numerical analysis can be used in the thermodynamics analysis of the cooling performance of the microchannel in removing the heat generated during machining.

2. Basic Equations

Although development of ideal mathematical equations to precisely pose a machining operation is almost impossible, it is still important to maintain the upward drive of science in formulating new knowledge based on fundamental principles, i.e. theories of fluid-dynamics and heat transfer in this study.

Since a system is, by definition, an arbitrary collection of matter of fixed identity, it must be composed of the same amount of matter at all times, thus it needs to obey the conservation theory of mass for a control volume (CV) as in Equation (1).

$$\left.\frac{dm}{dt}\right)_{system} = \frac{\partial}{\partial t}\int_{CV} \rho dV + \int_{CS} \rho \vec{u} \cdot d\vec{A} = 0 \tag{1}$$

The first term of Equation (1) on the right hand side represents the rate of change of mass (with V is the volume of the fluid) within the CV; the second term represents the net rate of mass flux through the control surface (*CS*), where ρ is the fluid density, $\vec{u}$ is the vectorial velocity measured relative to the unit CS $d\vec{A}$. It is required for satisfying the conservation of mass theory all these terms summed to be zero. This is important to define that in whichever the boundary conditions might move or deform, the amount that get in must come out.

Since the fluid is single-phase in this study and in steady flow with constant fluid density, it will be considered as incompressible fluid. Thus, the simplification in terms of vector notation as in Equation (2) is valid.

$$\nabla u = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \quad (2)$$

The determination of motion equation (which is also known as momentum equation) is based on Newton's second law which states that the time rate of change of linear momentum of the system is always equal to the sum of all external forces acting on the system. The transcribed equation in the function of tensor and body forces is complicated to elaborate the tensor of surface tensions τ_{ij} which is out of scope of this paper. However, for the steady state fluid that is assumed to be Newtonian, incompressible and having constant thermophysical properties the simplications for three dimensional fluid can be formulated to the reduced form of *Navier-Stokes* equation (Equation (3) with separate equations for x, y and z coordinates).

$$\rho(\vec{u} \cdot \nabla)\vec{u} = \rho\vec{g} - \nabla p + \mu\nabla^2 u \quad (3)$$

Thus the Equation 3 can be used to find solution for the heat transfer and fluid regime in the internally cooled cutting tool following the first law of thermodynamics. The conservation of energy equation can be transcribed in temperature variables using Fourier's conduction law.

3. CFD Analysis of an Internally Cooled Cutting Tool

The exact determination of the heat transfer in laminar and turbulent flow requires a system of three partial differential equations. An integration to solve multiple numbers of heat transfer conditions simultaneously is not possible because of the dependent effects by the geometry, the boundary conditions (BC) and the initial conditions. Therefore, further analysis of the flow state and the calculation of the resulting flow velocity distribution are conducted on the principle of the similarity theory. A numerical calculation of the heat transfer with regards to the flow in the internally cooled tool based on the differential equation system using the CFD simulation is presented in Section 2.

The numerical calculation for the proposed internally cooled cutting tool consists of three main components as listed in Table 1.

Table 1: Components of the studied internally cooled cutting tool

System components	Modeling interest
Inlet	Modeling fluid velocity distribution profile to obtain inlet BC for micro-channel.
Internal cooling micro-channel	Modeling of flow regime characteristics and heat transfer behaviour in the micro-channel.
Outlet	CFD modeling to determine outlet BC of the micro-channel.

Each component is assumed to have a circular cross section and geometrical length. Each section will be dealt separately (Figure 2). Water is chosen to be the cooling fluid because of its availability and environmental friendliness. The physical properties of water are also an advantage in removing heat in machining with internally cooled cutting tools. Water has respectively high heat capacity and very high heat conductivity; two vital properties in determining heat removal capability of the cooling system.

No.	Part	Length (mm)	ϕ (mm)	Surface
1	Tube	5000	2.0	Smooth
2	Hole	5.0	2.0	Smooth
3	µ-channel	10.0	0.8	Smooth
4	Heat sink	$\pi \times (3.0\text{mm})^2 \times 0.3\text{mm}$		Smooth
5	µ-channel	12.0	0.8	Smooth
6	Hole	5.0	2.0	Smooth
7	Tube	5000	2.0	Smooth

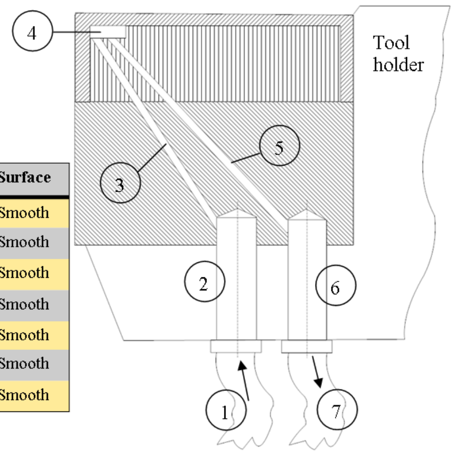

Figure 2: Schematic diagram of an internally cooled cutting tool

4. Results and Discussion

For modeling purposes, the flow velocity is assumed with its mean velocity at water temperature of 20˚C. The Reynolds number of the flow at each part is then calculated. The results of the calculation are recorded in Table 2. The results show that Reynolds number are distributed in the range of 528 and 6604. In the table, the grey highlighted Reynolds numbers are the numbers that are higher than 2320 which indicates turbulent flow.

Table 2: Reynolds number of the cooling fluid (20˚C) flow inside the parts of internally cooled cutting tools

Volumetric rate	Reynolds Number						
l/min	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7
0.1	528	528	1321	2553	1321	528	528
0.2	1057	1057	2641	5107	2641	1057	1057
0.3	1585	1585	3962	7660	3962	1585	1585
0.4	2113	2113	5283	10214	5283	2113	2113
0.5	2641	2641	6604	12767	6604	2641	2641

By taking the assumption that the flow with Re>2300 is turbulent, it can be seen that the majority of the flow types in part 3 and 5 (the micro-channels) is turbulent. Only for the flow rate of 0.1 l/min laminar flow can be obtained throughout the internally cooled cutting tool. Based on the advantage of turbulent flow in exchanging heat as explained before, it is specially intended to have high turbulent flow in the Part 4 (heat sink). Thus, minimum volumetric rate of 0.3 l/min is safe to be supplied by the pump in order to ensure the turbulent flow in the micro channel, which consequently can allow the cooling device to achieve the optimal heat transfer.

So the complete velocity profile, v at specific position, r of fluid in the micro-channel can be formulated in an equation to be used as boundary conditions for the later CFD simulation as in Equation (4).

$$v(r) = 5.61 \cdot \left(1 - \frac{r}{0.0004}\right)^{\frac{1}{4}} \ \frac{\text{m}}{\text{s}} \tag{4}$$

As stated in the theory, the fluid velocity at the wall of the conduit is zero. The isotach of the velocity is in circular form about the conduit axis. Considering n is empirical number for slowly function of Reynolds number and the surface roughness of the wall the velocity profile, v can be mapped using Equation (5) and the results shown in Table 3.

$$\frac{\bar{v}}{v_{max}} = \frac{2 \cdot n^2}{(n+1) \cdot (2n+1)} \tag{5}$$

Table 3: Fluid profile in internally cooled cutting tool.

Part	D mm	$\bar{v}$ m/s	Re	n	v_{max} m/s
1	2.0	0.0008	1584.9	N/A	0.0016
2	2.0	0.159	1584.9	N/A	0.319
3	0.8	0.3986	3962.2	4	5.61
4	0.3	7.706	7660.1	6.3	9.74
5	0.8	0.3322	3962.2	4	4.66
6	2.0	0.16	1584.9	N/A	0.322
7	2.0	0.0004	1584.9	N/A	0.0008

5. Conclusion

The presented study has demonstrated the fluid-dynamics analysis for water supplied at 0.3 l/min in an internally cooled cutting tool with micro-channel of circular cross section with diameter of 800 µm. The results show that turbulent flow can be controlled in the heat sink region whilst at the other region laminar flow can be maintained. This is vital to determine the capacity of the pump as well the level of confidence in modelling of fluid-dynamics in the controlled domain.

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