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CFD Simulation of Fluid Flow and Heat Transfer of Internal Cooling Channels for Turning Tool

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ABSTRACT

The internal-cooling approach emerged as an alternative in sustainable machining practices due to its multiple benefits. Cooling channels have been applied to cutting inserts to remove heat concentrated in a small area during machining. As a result, these cooling channels are critical in lowering tool temperatures and wear rates. The design of the cooling channel influences the effectiveness of heat management. In the present study, three types of cooling channel designs have been developed to investigate the cooling effect on the insert from the variety of cooling channel profiles. Computational Fluid Dynamics (CFD) is utilized to simulate the cooling effect for all profiles. A temperature reduction has been observed for the internally cooled cutting insert compared to the conventional tool without a cooling channel. The temperature difference is observed when the profile of the channel is varied. In addition, the coolant profile has been observed to be more effective in heat removal when the inlet pressure of the cutting fluid is increased. Through the velocity vector results, it has been determined that the heat transfer rate increases as the flow velocity of coolant within the channel increases. The Turbulence Kinetic Energy (TKE) simulation's value shows that a heat transfer rate enhancement is attained by elevating the TKE value, which depends on the configuration of the coolant flow channel.

Keywords: Channel profile, Internal cooling, TKE.

1. INTRODUCTION

Machining is a method of material removal used to produce the intended form and size of a part. The machining process consists of various processes, including milling, grinding, turning, and drilling, which use specific tools. Material characteristics, including hardness, brittleness, ductility, and heat conductivity, significantly influence machining [1]. During machining, the material experienced an intense plastic deformation phenomenon by the shearing action of the cutting tool. The shearing process induced heat generation within the material and tool. The aforementioned phenomenon produces heat and increases the temperature in the tool-chip contact area [2]. As a result, managing the heat produced in the machining process effectively becomes one of the ways to increase the life of the cutting tool and the quality of the machining. When cutting materials with low thermal conductivity, heat cannot be transferred from the workpiece properly [3]. Consequently, the temperature can escalate significantly, reaching up to 1373 K. Recently, high-pressure cooling with cooling channels has been the subject of research. Polvorosa et al. conducted a turning process on alloy 718 and Waspaloy using a tool holder with the cooling channel to deliver high-pressure cooling directly to the high-temperature zone, and a comparison was made with conventional cooling. Their findings demonstrated that high-pressure cooling effectively reduced tool wear in both materials [4]. In modern machining

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*Corresponding author: syamil@unimap.edu.my processes, the effective management of heat generated during cutting operations is a pivotal factor in maintaining precision, extending tool life, and enhancing the quality of machined components. The internal cooling channels within cutting tools, such as turning inserts, have emerged as a critical component in achieving these objectives. Zakaria et al. proposed a submerged convective cooling tool by using the concept of internal cooling in turning magnesium alloy [5]. Singh et al. conducted CFD simulations on various internal cooling profiles for turning applications [6]. The results of the study underline that the performance of heat transfer depends on cooling channel configuration. In designing the internal cooling tool, Zakaria et al. emphasized the importance of tool integrity when having an internal cooling channel in the tool and the factor of channel diameter is vital in maintaining the tool's integrity [7]. The primary focus of this research is to delve into the intricate relationship between cooling channel geometry and heat transfer characteristics within turning inserts. Specifically, this study aims to comprehensively evaluate the effect of various cooling channel geometries on the efficiency of heat dissipation. Through rigorous analysis and simulations, the study seeks to pinpoint the optimal internal cooling channel geometry that can maximize heat removal and minimize thermal-induced tool wear and workpiece distortions. By addressing this fundamental problem, the research contributes valuable insights into the design and utilization of cooling channels in machining, ultimately enhancing machining efficiency and product quality while extending tool life.

2. MATERIAL AND METHODS

This study utilized computational fluid dynamics (CFD) simulations to investigate the cooling effect on turning tool inserts of different shapes. ANSYS Fluent software was employed to construct a CFD model, setting parameters such as cooling channel profile, tool geometry, and workpiece geometry. The simulation process involved solving governing equations to predict temperature rise. The study analyzed design performance and behavior, ultimately contributing to efficient and effective turning tool insert processes. In order to study the cooling impact on turning tool inserts of varying shapes, three distinct profiles of the internal cooling channel were created. A validation is conducted to compare the published experimental data with the simulation data.

2.1 Internal cooling channel profiles

Three distinct profiles of internal cooling channels were developed as variables to study the cooling effect on turning tool inserts. Figure 1 illustrates the profiles 1, 2, and 3 of the cooling channels, each with a constant channel diameter of 0.5 mm.

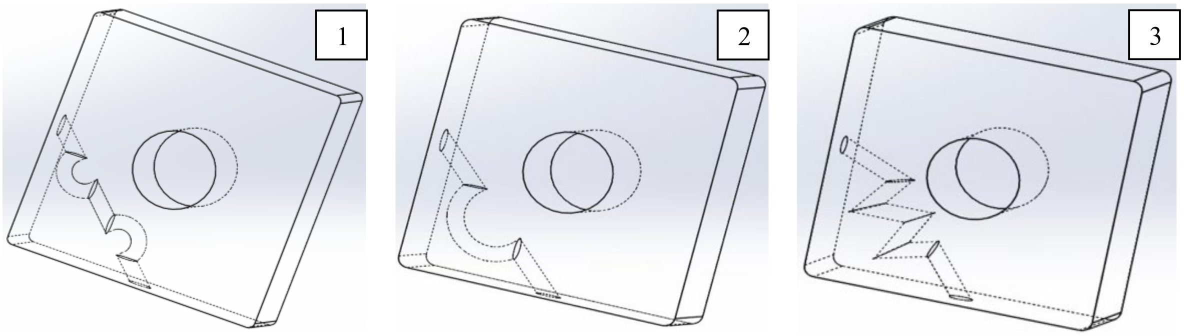


Figure 1: Internal cooling channel profile.

2.1.1 CFD boundary conditions

In the present CFD simulation, the following boundary conditions were applied to ensure a realistic representation, as shown in Figure 2. Using the proximity and curvature method, the fluid-solid model was meshed with a minimum element size of 0.1 mm. The fluid-solid interface was refined by adding an inflation layer with an initial thickness of 0.01 mm and a growth rate 1.2 to ensure optimal calculation accuracy. The inlet pressure was changed to examine the temperature increase resulting from heat generation. Boundary conditions for simulating channel flow were set with a pressure inlet at the cooling channel's inlet, varying at 0.2 MPa and 1 MPa. Simulations were conducted on all developed profiles, with other physical factors held constant, including the input coolant temperature. At the outlet, atmospheric pressure served as the boundary condition. At the heat source region, a heat flux of 63 W/mm2 was applied to the tool-chip contact area, as used in [6]. The standard k-ε model was implemented to account for turbulence for enhanced wall treatment in the simulation. The fluid-solid interface was modeled as a coupled system to improve heat transfer efficiency, while other areas were set with system coupling boundary conditions, allowing heat transfer within the insert through conduction. Convergence of the solution was achieved with a residual value of 1e-06. Table 1 lists the properties of the cutting tool and water used for the CFD simulation.

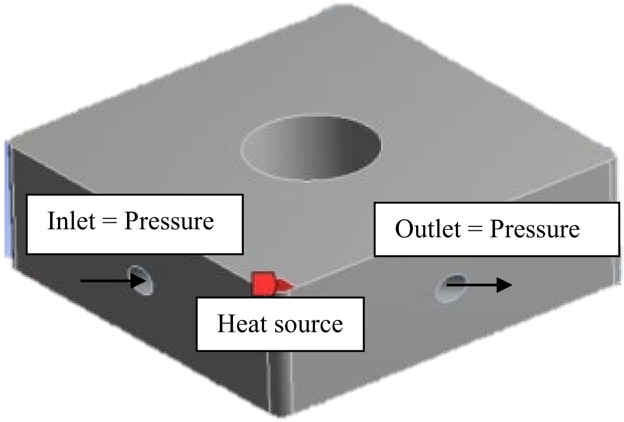


Figure 2: Boundary condition for internal cooling simulation.

Table 1: Properties of cutting tool and water [6].

Material	Thermal conductivity (W/m·K)	Density (kg/m^3)	Specific heat capacity (J/kg.K)	Viscosity (kg/m·s)
Tungsten carbide	69	15800	180	-
Water	0.6	1000	4182	0.001

The temperature fields of the tool are governed by heat conduction equation (1) for a 3D steady state for the tool without a cooling channel.

$$\rho c_p \dot{T} = k\Delta T \quad (1)$$

In the case of the tool with the internal cooling channel, the amount of heat flowing to the cooling fluid and the heat dissipation are determined by equation (2).

$$\dot{Q} = \dot{m} c_p (T_{out} - T_{in}) \quad (2)$$

In equations (1 and 2), T is temperature, ρ, c_p and k are, respectively, the mass density, the heat capacity per unit mass, and the heat conductivity while $\dot{m}$, T_{out}, and T_{in} are mass flow rate, outlet temperature, and inlet temperature, respectively. As the cooling fluid is flowing on the rake surface, conduction and convection are involved in the internal cooling channel. The equations below govern the case for the internal cooling technique.

Mass conservation equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

Momentum conservation equations

$$\begin{aligned}
\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)&=F_x-\frac{\partial \rho}{\partial x}+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\
\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)&=F_y-\frac{\partial \rho}{\partial y}+\eta\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\\
\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)&=F_z-\frac{\partial \rho}{\partial z}+\eta\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)
\end{aligned} \tag{4}$$

Energy conservation equation

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

Where u, v, w are the velocity of liquid in x, y, z directions, respectively, F_x; F_y; F_z is volume force in x, y, z directions, respectively, ρ is the density of the cooling liquid, η is the viscosity of the cooling liquid, α is the thermal conductivity of cooling liquid.

3. RESULTS AND DISCUSSION

In the case of a tool without a cooling channel, the maximum tool temperature at the tooltip reached approximately 1022 K. The results from the simulation show that the temperature increase that occurs on the cutting tool is within the data range in the experiment with a deviation value of 0.8 % [6], as shown in Figure 3. The slightly lower maximum temperature observed in the simulation is attributed to meshing criteria and the specific conditions of the machining process. However, the experimental results were equivalent to the highest temperature increase during dry cutting in the simulation. Figure 4 illustrates the temperature of the conventional tool with no cooling channel.

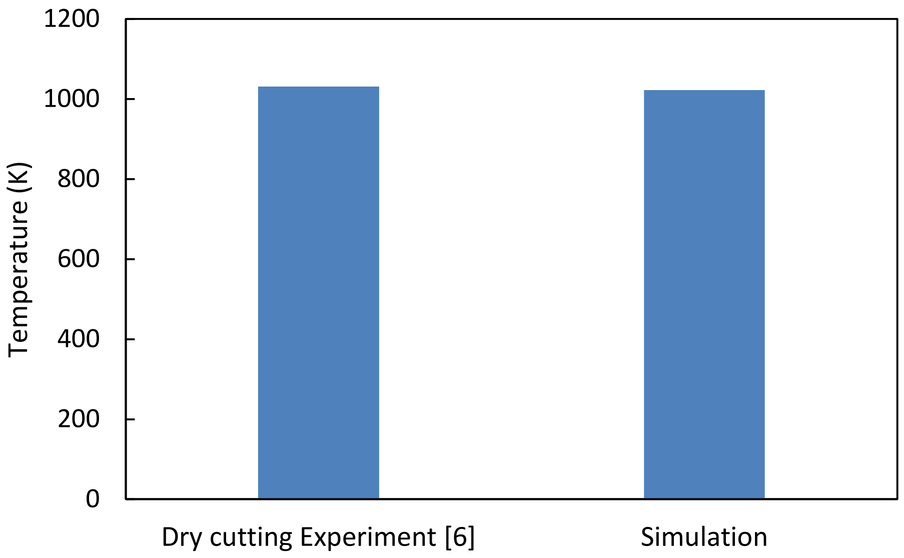


Figure 3: Validation of simulation on tool temperature.

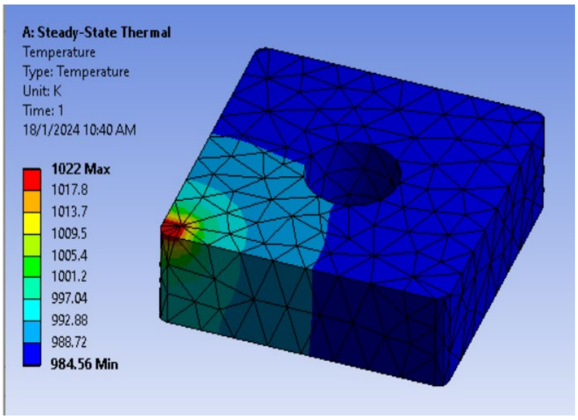


Figure 4: Temperature gradient for the tool without cooling channel.

At the tool's tip, the temperature reaches a maximum of 1022 K, while the remainder of the tool maintains room temperature. Figure 5 demonstrates that the simulation reveals the highest temperature occurred at an inlet pressure of 0.2 MPa for all profiles. In comparison, Profile 1 achieved the lowest temperature rise of 670 K while Profile 2 experienced an increase at 793 K, and the maximum temperature rise of 935 K was observed in Profile 3 with the same input. Variations in coolant inlet pressure led to fluctuations in tool temperature. Notably, increasing the inlet pressure from 0.2 MPa to 1 MPa during the simulation results in a significant temperature drop for all profiles. The temperature gradient of the cutting tool is illustrated in Figure 6 under three cooling profiles at an inlet pressure of 1 MPa. For Profile 3, the temperature decreases from 935 K to 699 K, indicating a maximum drop of 236 K. Similarly, profiles 1 and 2 exhibit temperature decreases of 123 K and 174 K, respectively, with varying inlet pressure. The configuration of the cooling channel affects the peak temperature increase during machining and the temperature decrease due to fluctuations in inlet pressure. A more noticeable drop in temperature results from greater fluid contacting the hot insert. Profiles 1 and 2, designed with a convex shape, enable the cooling fluid to cover a broader area of the tool, thereby absorbing more heat and leading to a lesser temperature rise than Profile 3.

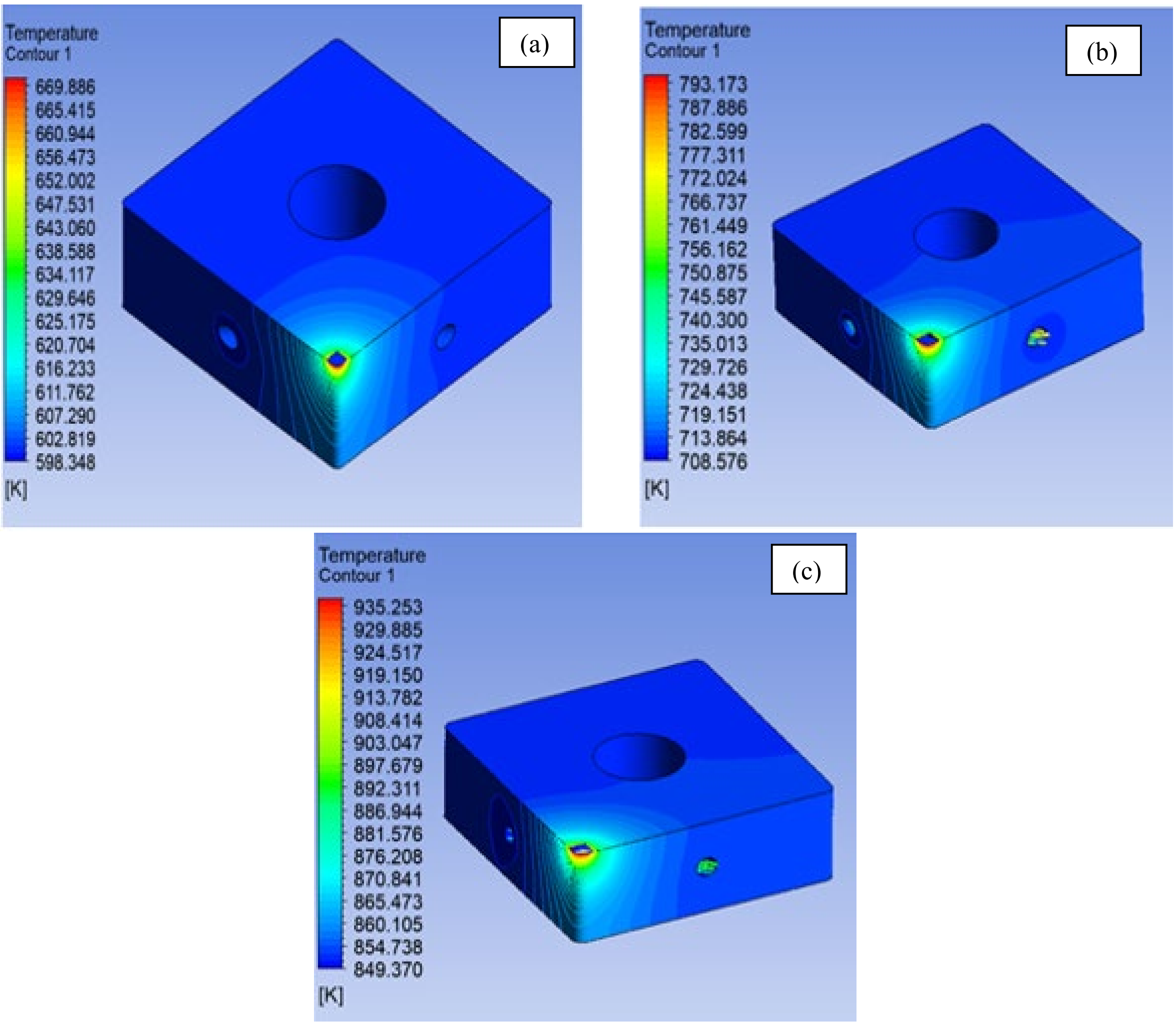


Figure 5: Temperature gradient of the tool for 0.2 MPa (a) Profile 1, (b) Profile 2, and (c) Profile 3.

The curvature of profiles 1 and 2 facilitates an increase in coolant flow closer to the tool's tip, thereby reducing the temperature rise in the insert. This design choice enables the coolant to travel closer to the hot zone, effectively absorbing more heat. Additionally, moving the fluid closer results in a lower overall temperature, as the tool's tip concentrates the maximum temperature.

The effects of inlet pressure on the inlet velocity and the rise in temperature were also examined. The results indicate that an increase in coolant inlet pressure leads to a reduction in temperature. Heat flow elucidates the difference in temperature across profiles via forced convection as the fluid flows through the channel. Figure 7 illustrates the velocity vector of the fluid for various pressure profiles. Velocity vectors represent the magnitude and direction of fluid velocity within a specified domain and are positioned at the center of each facet. The simulation results reveal that profile 1 attains the highest velocity compared to other profiles, related to the lowest temperature rise recorded for the respective inlet pressure. It is evident that Profile 1 reaches a maximum velocity of 18.516 m/s at 1 MPa, making it exhibit the most substantial temperature drop in response to pressure fluctuations due to its higher fluid velocity. Due to the shapes and variations in the channels, certain parts of the profile boundary have no contact with the fluid, diminishing the impact on heat transfer. However, Profile 3 geometry poses obstacles to full fluid flow through the channel, reducing the overall heat transfer effectiveness. The synergistic evaluation of channel profiles and coolant parameters suggests that cooling profiles, especially Profile 1, offer a viable solution for temperature management during turning processes. These profiles effectively balance heat dissipation, ensuring the reliability and efficiency of machining operations.

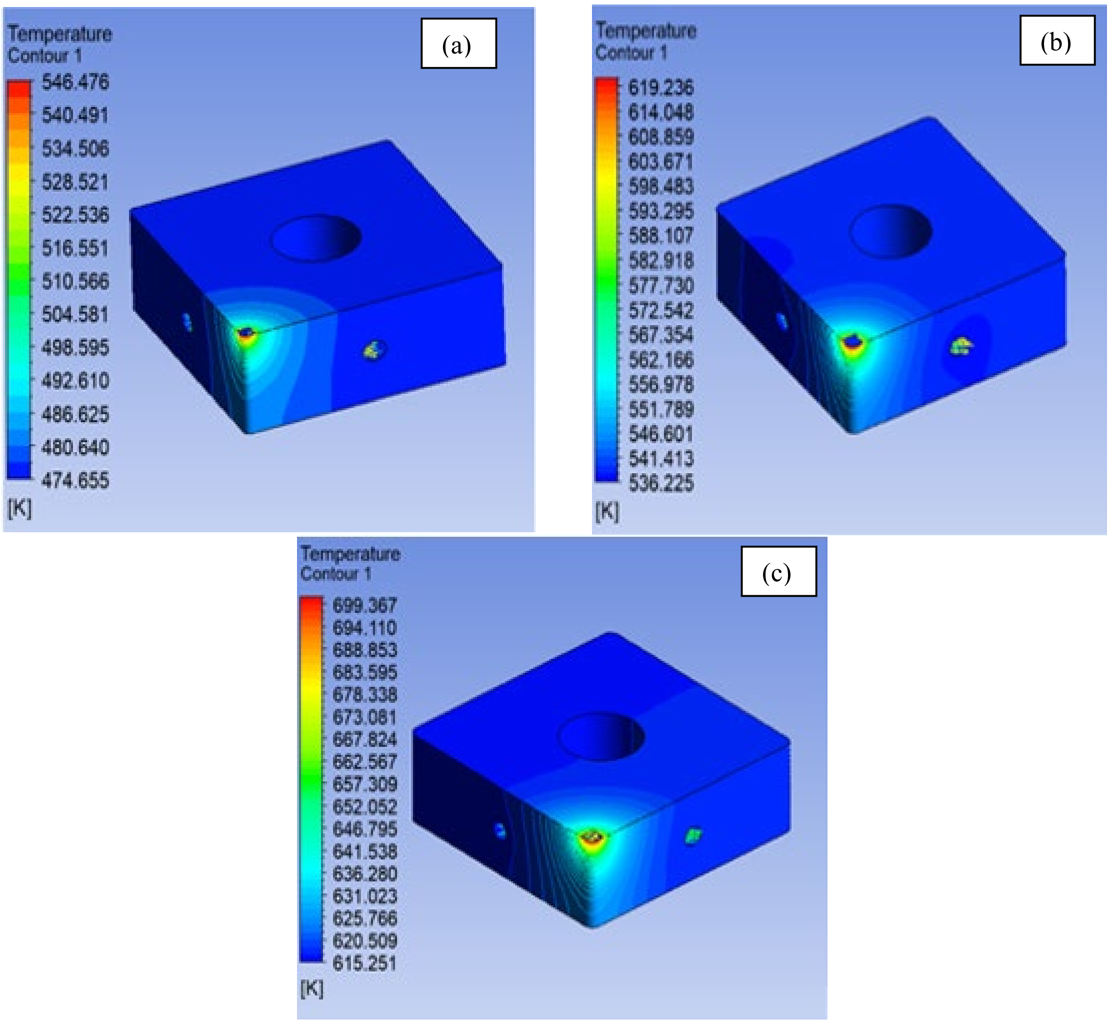
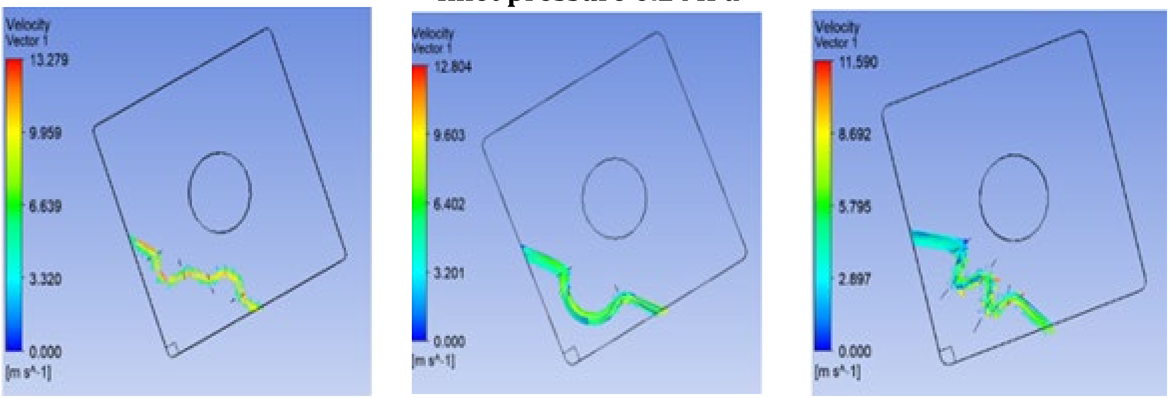


Figure 6: Temperature gradient of the tool for 1 MPa (a) Profile 1, (b) Profile 2, and (c) Profile 3.

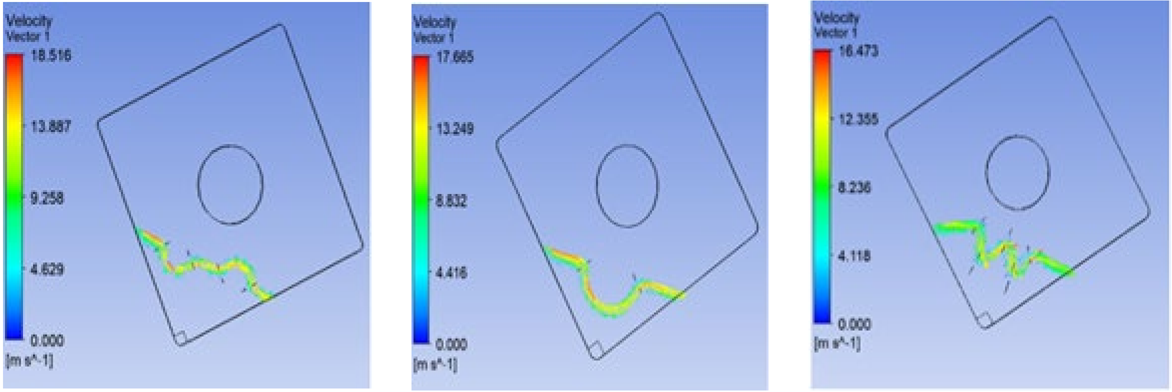
In addition to profile design and coolant velocity, Turbulence Kinetic Energy (TKE) plays a crucial role in enhancing the heat transfer rate. The flow velocity of the fluid or coolant within the channel generates the specific kinetic energy known as TKE. The fluid flow velocity within channels varies with changes in inlet pressure. Simulations revealed fluctuations in TKE due to variations in incoming fluid pressure. The introduction of turbulence into the flow can enhance heat transmission efficiency. Among the approaches to inducing turbulence inside the channel are fin addition, groove design, and by altering flow patterns to increase turbulence in the flow [8]. Through the exploration of different profiles, it has been found that shaping flow patterns can influence TKE values. Figure 8 shows TKE values at various pressures for all three profiles. All three profiles exhibit an increase in values as the pressure changes. A significant alteration in TKE values leads to the most remarkable drop in temperature in relation to pressure. Profile 1 demonstrates a superior TKE value relative to the other two profiles at an inlet pressure of 0.2 MPa, resulting in the most significant temperature reduction in Profile 1. Research has shown that the heat transfer rate increases as TKE increases, which is consistent with Fang's findings [9]. At an inlet pressure of 1 MPa, profile 3 showed the highest TKE compared to the other two profiles. However, the nature of the W shape hinders the liquid from flowing well in the channel, leading to a loss of fluid velocity.

Inlet pressure 0.2 MPa



Profile 1 Profile 2 Profile 3

Inlet pressure 1 MPa



Profile 1 Profile 2 Profile 3

Figure 7: Velocity vector for the three profiles.

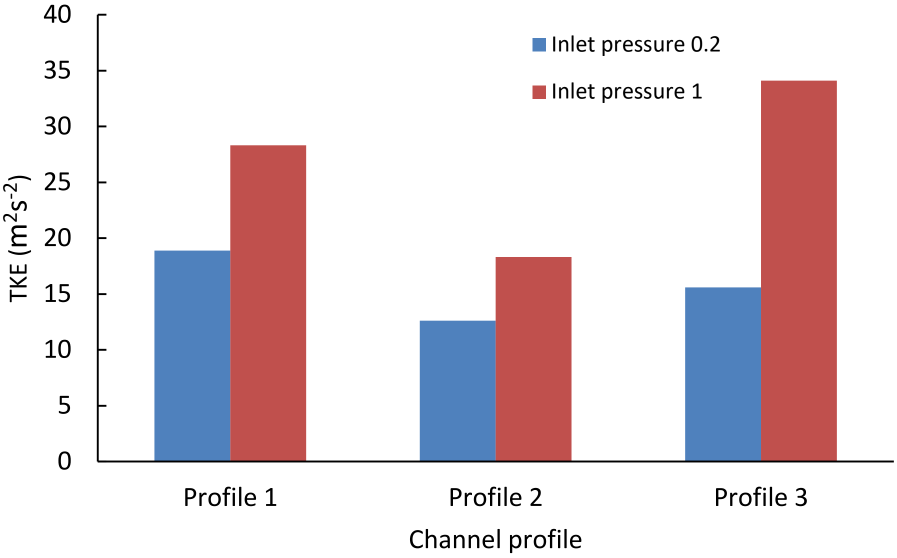


Figure 8: TKE vs. Pressure for profiles.

4. CONCLUSION

In conclusion, the thorough examination of temperature distribution in cutting inserts across different cooling profiles and varying inlet pressures provides comprehensive insights into temperature management during machining. The localized region at the tooltip, reaching a maximum temperature of 1022K, emphasizes the need for effective cooling strategies. Notably, Profiles 1 and 2, featuring a curved design, exhibit lower temperature rises than Profile 3, showcasing the influence of coolant channel geometry on temperature control. The impact of coolant inlet pressure becomes apparent as the study demonstrates significant temperature drops with increased pressure. Profile 3 experiences a substantial decrease of 236 K from 935 K to 699 K when the inlet pressure rises from 0.2 MPa to 1 MPa. Profiles 1 and 2 also exhibit considerable reductions of 123 K and 174 K, respectively. This underscores the critical role of pressure modulation in temperature regulation during machining. The non-linear relationship between coolant pressure and temperature suggests that corner designs and chamfers, despite potential turbulence, have minimal impact on the overall heat transfer rate. Optimized pressure and velocity conditions exist for each profile, beyond which further changes in temperature become marginal. Profile 1 emerges as the most efficient, achieving the highest velocity of 18.516 m/s at 1 MPa, resulting in a maximal temperature drop during the turning process. Additionally, considering TKE as a factor influencing heat transfer rate underscores the importance of profile structure. The results show that the shape of the profile significantly influences the fluid's velocity, which in turn affects the heat transfer process. Notably, Profile 1, with its optimal fluid flow characteristics, stands out in maximizing the temperature drop.

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