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Internal cooling techniques in cutting process: A review

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Abstract: The heat generated during the cutting process of titanium alloys and superalloys is a significant limitation that affects machining quality. Excessive heat can accelerate tool wear, increase cutting forces, alter material properties, and decrease productivity. To address this issue, alternative cooling techniques have been suggested to minimize heat generation during cutting. Among these alternatives, internal cooling techniques have emerged as a more efficient and cost-effective solution. This paper provides a comprehensive review of internal cooling techniques in the cutting process, including their effects on cutting fluid flow, chip formation, cutting temperature, cutting forces, surface roughness, tool wear, and chip morphology. The paper also presents methods to enhance cooling and lubrication performance by optimizing the internal cooling channels and outlet nozzles of cutting tools, as well as selecting appropriate fluid supply pressure. Additionally, the paper highlights important considerations when using internal cooling techniques and proposes future directions for their development, taking into account existing challenges.

Keywords: Difficult-to-cut materials; Cutting process; Cooling techniques; Cutting fluids; Cutting tool; Coolant channel

1. Introduction

In recent years, the aerospace industry has undergone rapid growth, marked by an increase in high-level aerospace activities and notable achievements. The utilization of high-performance materials has played a crucial role in these advancements. Among them, titanium alloys and superalloys are the most extensively used[1]. Titanium alloys offer a remarkable strength-to-weight ratio, excellent stiffness, and exceptional corrosion resistance, making them highly sought after. Superalloys exhibit exceptional strength at high temperatures and can withstand prolonged exposure to extreme heat. Consequently, both titanium alloys and superalloys find wide-ranging applications in the aerospace industry, contributing to enhanced performance and efficiency. Fig. 1 illustrates the application of titanium alloys and superalloys in aero-engines[2].

Despite the numerous benefits[3-7] (as listed in Table 1) and widespread usage of high-performance materials, they present new issues and challenges in the cutting process due to their unique properties. When compared with 45# steel, their machinability typically ranges from only 5 to 15 percent[8]. As a result, they are often categorized as difficult-to-cut materials, primarily due to their high strength, resistance to shear stress, work hardening, and low thermal conductivity[9,10]. Specifically, their high strength, resistance to shear stress, and work-hardening effect can result in significant cutting forces and heat generation. The cutting forces arise from the severe plastic deformation of materials in the three deformation zones and intense friction in the tool-chip and tool-workpiece interfaces. Consequently, the energy generated by plastic deformation and intense friction is converted into significant heat[11], as depicted in Fig. 2. The majority of the heat is generated when the workpiece material undergoes plastic deformation ahead of the cutting tool (primary shear zone). Another portion of heat is generated through friction along the chip-tool interface (secondary shear zone) and the ploughing of the tool flank face on the newly machined surface (tertiary shear zone). In general, the heat generated during the machining process is advantageous as it locally softens the workpiece, facilitating the cutting process. However, the low thermal conductivity of titanium alloys and superalloys hinders the transfer of heat from the cutting zone to the chip and workpiece, impeding the dissipation of excessive heat. This leads to a significant increase in cutting temperatures within the cutting zone.

Both high cutting forces and cutting temperatures have a detrimental impact on cutting tool life, machining quality, and cutting efficiency[12-14]. On one hand, elevated cutting temperatures result in significant adhesion between the chip and the tool rake face, as well as between the machined surface and the tool flank face. This leads to accelerated tool wear and shortened tool life due to the sticking effect, combined with the high friction force at the tool-

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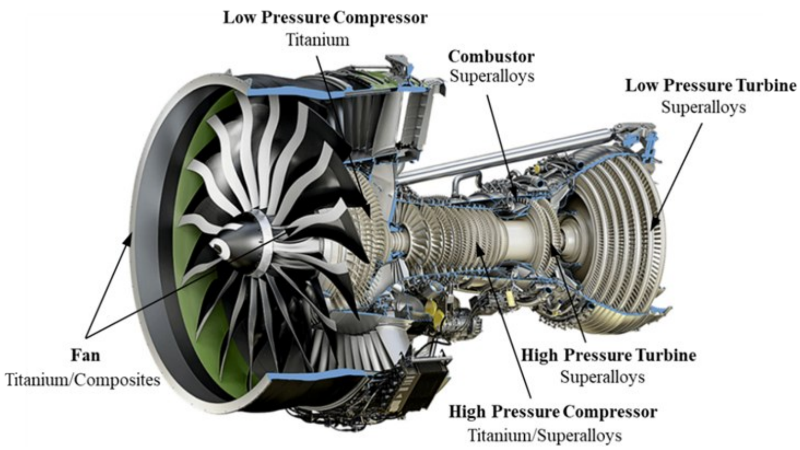


Fig. 1 Application of titanium alloys and superalloys in aero-engines[2].

chip and tool-workpiece interfaces[15]. Moreover, high temperatures can induce thermal deformation of the workpiece, resulting in reduced machining accuracy[16]. On the other hand, high cutting forces can cause severe vibrations, impeding the attainment of the desired surface finishes and adversely affecting machining quality[17]. Additionally, rapid tool wear not only compromises the surface integrity of the workpiece but also hampers productivity due to frequent tool replacements.

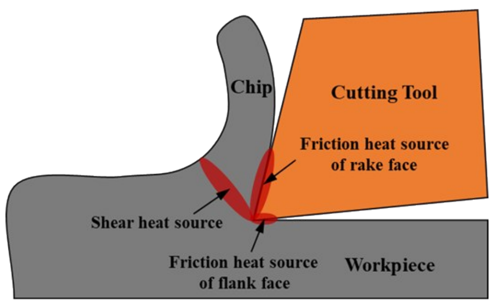


Fig. 2 Sources of heat generated in cutting process.

Undoubtedly, the presence of excessive cutting forces and high cutting temperatures during the cutting process can have detrimental effects. To prolong tool life and improve machining quality, significant efforts have been devoted to exploring methods that can minimize cutting forces and heat generation. These methods primarily involve the development of advanced cutting tool materials and coatings, optimization of process parameters and cutting tools through a comprehensive understanding of the cutting process mechanism, mechanics, and dynamics, implementation of advanced cooling techniques, utilization of non-conventional machining-assisted techniques, and more[18,19]. This article focuses primarily on providing a comprehensive review of internal cooling techniques and their benefits in the cutting process, as well as exploring approaches to further enhance the efficiency of these techniques. The framework of this review is illustrated in Fig. 3[20-23]. Section 2 introduces both existing cooling techniques and internal cooling techniques. In Section 3, the effects of internal cooling techniques on the cutting process are analyzed. Section 4 outlines the methods aimed at improving the efficiency of internal cooling techniques. Finally, Section 5 presents the conclusions drawn from the analysis and offers prospects for future research.

2. Existing cooling techniques and internal cooling techniques

Supplying cutting fluids during the cutting process is a practical approach to cooling the cutting zone[24]. It has been observed that by precisely supplying cutting fluids to the cutting zone, tool life can be extended and machining quality can be improved[25]. This is primarily due to the two roles played by cutting fluids in the cutting process[26]. On one hand, cutting fluids act as coolants, effectively dissipating heat from the cutting zone and reducing temperatures by absorbing a significant amount of heat[27]. On the other hand, cutting fluids also act as lubricants. By supplying cutting fluids into the contact interfaces between the chip and tool, as well as the machined surfaces and tool, friction is reduced[28], resulting in lower cutting forces and heat generation. In conventional cooling techniques, cutting fluids are commonly oil-based or water-based and are supplied to the cutting zone through flooding. However, these techniques are insufficient for cutting titanium alloys and superalloys. To address this, numerous studies on advanced cooling methods for the cutting process have been conducted, leading to the development of various cooling techniques. These techniques[29-57] can be categorized into three groups based on the physical state of the cutting fluids during application as shown in Table 2.

Table 1 Comparison of physical and mechanical properties of different metals[3-7].

Material	Density ($g \cdot cm^{-3}$)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
45# steel	7.8	450	585	38
Ti-15-3	4.7	1307	1459	8.5
Ti-6Al-4V	4.42	870	923	9.0
Inconel 718	8.19	1100	1375	11.4

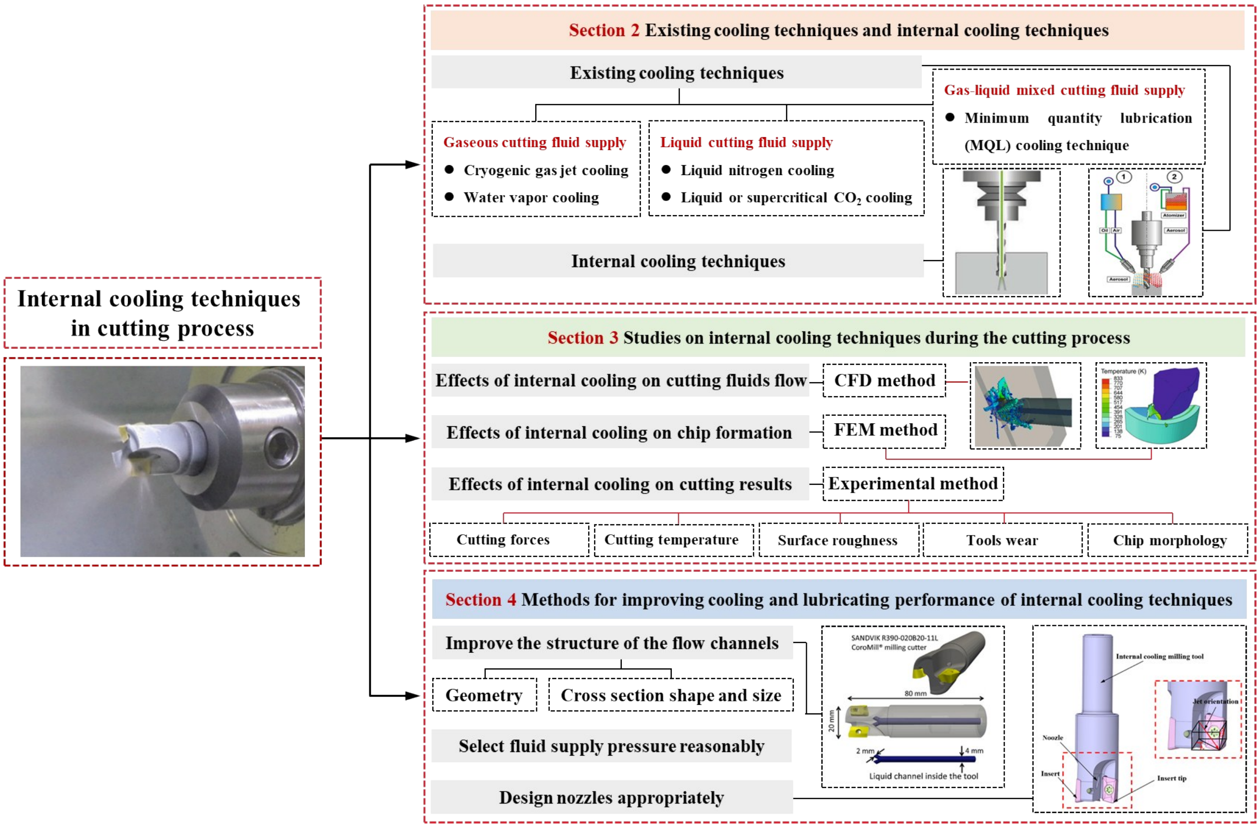


Fig. 3 Framework of this article[20-23].

Table 2 Comparison of different cooling techniques.

Cooling techniques	Physical state	Workpiece materials	Lubricant	Cooling	Affordability	Eco-friendliness
Dry cutting		Haynes 276[29], SGI70[30], Inconel 718[31], Haynes 242[32], Ti-6Al-4V[33].	Poor	Poor	Good	Good
Conventional cooling	Liquid state	Inconel 718[34], Ti-6Al-4V[35], AISI H-13 steel[36], M2 Steel[37].	Medium	Poor	Good	Poor
Cryogenic gas jet cooling	Gaseous state	A390 aluminium[38], Ti-6Al-4V[39], Inconel 718[40], AISIP 20[41], Carbon-Fiber-Reinforced Plastic (CFRP)[42].	Poor	Good	Medium	Good
Water vapor cooling	Gaseous state	Grey cast iron[43], Ti-6Al-4V and 1Cr18Ni9Ti[44], 45# steel[45], GH4169[46].	Medium	Medium	Good	Good
Liquid nitrogen cooling	Liquid state	Inconel 718[47], 304 stainless steel[48], AISI H13 steel[49], 2014-T6 Aluminium alloy[50], Ti-6Al-4V[51].	Poor	Good	Poor	Good
Liquid or supercritical CO_2 cooling	Liquid or supercritical state	Ti-6Al-4V[52], AISI 1045 medium carbon steel[53], Inconel 718[54].	Poor	Good	Poor	Good
Minimum quantity lubrication	Gas-liquid mixed state	AISI 4340 steel rings[55], Ti-6Al-4V[56], Inconel 718[57].	Medium	Good	Medium	Medium

2.1. Cutting fluids in the gaseous state

2.1.1. Cryogenic gas jet cooling

Cryogenic gas jet cooling is a technique that involves spraying cryogenic gas, typically ranging from -10 °C to -100 °C, onto the cutting zone[58]. This method increases the heat exchange areas by supplying the cutting fluids in the form of a gas jet. Moreover, due to the significant temperature difference between the cryogenic gas and the cutting zone, the gas exhibits strong heat-absorbing capabilities when it comes into contact with the cutting zone. Experiments have shown that cryogenic gas jet cooling can effectively and uniformly reduce the temperatures of the cutting zone, tools, and workpiece. This cooling technique successfully inhibits tool wear, enhances the machining quality of the machined surface, and improves the machining accuracy of the parts[59,60]. Some Japanese companies have introduced machine tools equipped with cryogenic gas jet cooling techniques, leading to the commercialization of cryogenic gas jet devices[61]. However, a notable limitation of the cryogenic gas jet cooling technique is its inability to provide lubrication during the cutting process, which poses a significant challenge.

2.1.2. Water vapor cooling

Water vapor cooling is a technique that uses water vapor as a cooling medium in the cutting process, initially proposed by Podgorkv and Godelvski in the 1990s[62,63]. A prominent advantage of this technique is its low cost and eco-friendliness, as water vapor is readily available. Additionally, water vapor can easily penetrate the cutting zone, forming a lubrication film between the tool and the chip. This lubrication film significantly reduces both the friction coefficient and the chip deformation coefficient, consequently decreasing cutting forces, cutting temperatures, surface roughness, and tool wear. Specifically, experimental studies conducted on C45 steel cutting have shown that water vapor cooling can reduce cutting forces by approximately 30% to 40% compared to dry cutting. Furthermore, when applied to milling grey cast iron, 45# steel, and 1Cr18Ni9Ti stainless steel, water vapor cooling has shown considerable potential in increasing tool life by 1-3 times[43].

2.2. Cutting fluids in the liquid state

2.2.1. Liquid nitrogen cooling

The liquid nitrogen cooling technique effectively reduces cutting temperatures by utilizing the low boiling point of liquid nitrogen. This technique employs two primary approaches. The first approach involves spraying liquid nitrogen directly into the cutting zone under high pressure. The second approach indirectly cools the tools or workpiece by utilizing the evaporation cycle of liquid nitrogen after heating[64]. When compared to conventional cooling methods, liquid nitrogen cooling demonstrates significant reductions in cutting temperatures. For example, when cutting titanium alloys, a temperature reduction of approximately 30% can be achieved[49]. Similarly, when working with 304 stainless steel and H13 steel, the cutting temperatures can be reduced by 44% to 51%[48] and 37% to 42%, respectively[65]. It is important to note that the efficiency of this method is influenced by the spraying velocity, with higher velocities resulting in better cooling outcomes[66]. However, the application of this technique is often limited due to the extremely low-temperature requirements of liquid nitrogen, as well as the challenges associated with storage and transportation.

2.2.2. Liquid or supercritical CO_2 cooling

Cooling with liquid or supercritical CO_2 operates on a principle similar to liquid nitrogen cooling. However, compared to liquid nitrogen, liquid or supercritical CO_2 can reach temperatures equal to or higher than room temperatures, making it more convenient for use in cutting process. Researchers have found that liquid CO_2 and liquid nitrogen exhibit comparable cooling capabilities at the same mass flow rate[67]. Nevertheless, liquid CO_2 cooling is considered more sustainable due to its lower overall energy consumption throughout the usage process[68]. Liquid or supercritical CO_2 cooling techniques have been applied in various drilling processes and have been shown to effectively reduce cutting temperatures while simultaneously enhancing the quality of holes and extending tool life[69-72].

2.3. Cutting fluids in the gas-liquid mixed state

Among the techniques for supplying cutting fluids to the cutting zone in a gas-liquid mixed state, minimum quantity lubrication (MQL) is a common method[73,74]. This technique involves mixing a small amount of cutting fluids with gas to create an aerosol, which is then sprayed at high pressure into the cutting zone using nozzles. By doing so, the amount of cutting fluids required is significantly reduced. Research has shown that MQL machining surpasses dry machining, resulting in a reduction of cutting forces by up to 17.07% and tool-tip temperatures by up to 6.72%[75]. To enhance the material removal rate, MQL can be combined with other cooling techniques. For example, supercritical CO_2-MQL systems have been utilized in the turning process, leading to approximately 40% increases in tool life and material removal rates compared to flood cooling[76]. Furthermore, MQL has demonstrated numerous advantages in the drilling process when combined with nanofluids[77].

Although the techniques mentioned above have improved the cooling and lubrication during the cutting process, their full potential is not realized due to the limitations of conventional cutting fluid supply methods. The traditional approach, called external cooling or flood cooling, involves supplying cutting fluids to the cutting zone through external nozzles, but this method has inherent drawbacks. It is challenging to precisely target the external nozzles to the cutting edges, which means that cutting fluids cannot accurately reach the tool-chip interface. This limitation becomes more apparent as spindle speeds increase during the milling process[78]. In addition, during the tapping and drilling process, the cutting fluids supplied by flood cooling have difficulty reaching the cutting edges since the hole is nearly blocked by the cutting tool. Consequently, the cooling effect is significantly reduced, ultimately limiting cutting efficiency.

To overcome these limitations, the concept of internal cooling for tools has emerged as an effective technique to enhance cooling and lubrication capabilities. Internal cooling involves pressurizing cutting fluids and precisely spraying them into the cutting zone through internal cooling channels within the tool and specialized nozzles. This approach eliminates cooling dead corners, mitigates the adverse effects of workpiece shapes on heat transfer, and ensures sufficient cooling of the cutting zone to effectively control temperatures and improve cutting performance[79]. The schematic diagram illustrating the operation of internal cooling techniques is presented in Fig. 4[80]. Fig. 5 illustrates both external and internal cooling techniques for the milling process, along with the specific positions where the cutting fluid can be supplied[81,82].

The following sections will elaborate on the specific effects of internal cooling techniques in the cutting process and discuss methods to enhance the effectiveness of internal cooling.

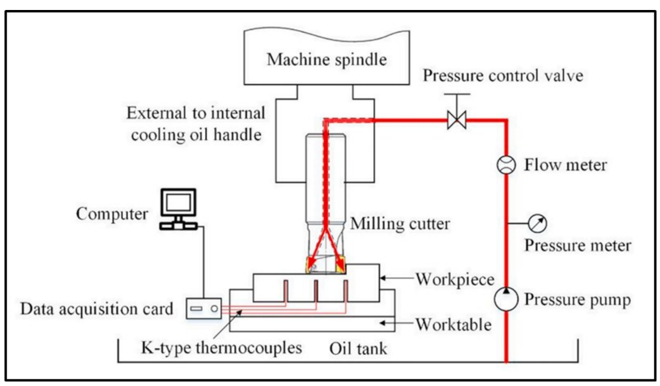
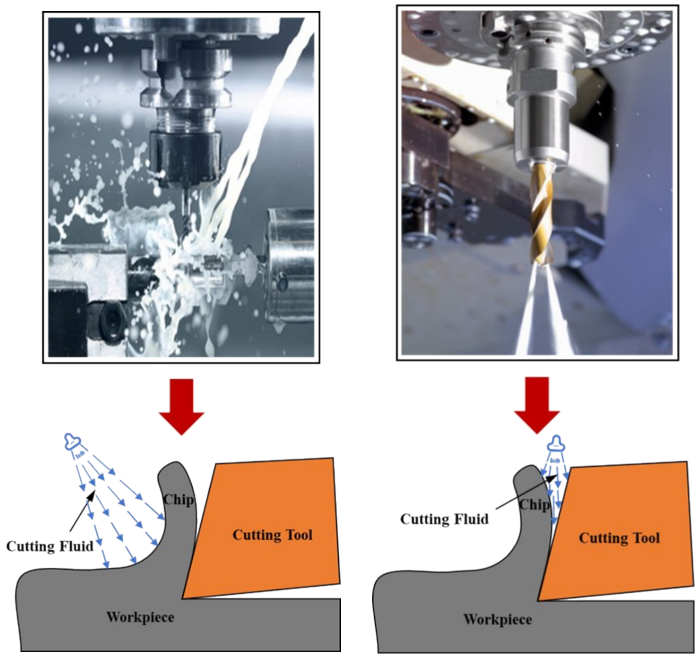


Fig. 4 A schematic diagram of operation of internal cooling techniques[80].

3. Studies on internal cooling techniques during the cutting process

Extensive studies have been conducted to investigate the cooling and lubrication effects of internal cooling techniques during the cutting process. These studies primarily focus on the movement of cutting fluids, chip formation, cutting forces, cutting temperatures, and



(a) External cooling (b) Internal cooling

Fig. 5 Cutting fluids supply under external and internal cooling techniques[81,82].

other related factors.

3.1. Effects of internal cooling on cutting fluids flow

Understanding the flow behavior of cutting fluids is crucial for designing internal cooling tools. However, due to the complexity of fluid flow during the cutting process and practical limitations in setting up experiments, it is often impractical to directly investigate the behavior of cutting fluids through experimental or theoretical analysis alone. Computational Fluid Dynamics (CFD), a powerful simulation tool capable of solving complex fluid problems, can be employed to study internal cooling and offer an economical alternative for advancing theoretical understanding under experimentally unfeasible conditions[83,84]. As a result, several researchers have conducted CFD-based studies on the flow behavior of cutting fluids during the cutting process.

Oezkaya et al.[85] conducted a simulation on the flow of cutting fluids during the complex drilling process. The presence of cooling dead zones near the cutting edge and counter edge is revealed as depicted in Fig. 6. These cooling dead zones cannot be eliminated by adjusting the pressure or diameter of the internal cooling channel. Based on the work of Oezkaya et al., Biermann and Oezkaya[86] analyzed and controlled the modification of cutting fluids flow in the tapping process. They discovered that by altering the outlet of the internal cooling channels, a more focused flow of cutting fluids with higher velocities near the cutting edges could be achieved. Thus, the cooling dead zones can be effectively eliminated. Duchosal et al.[87,88] investigated the flow of cutting fluids at high rotational speeds of milling tools. They proposed that a high supply pressure should be employed to ensure that the cutting fluids are effectively sprayed onto the inserts. In contrast, the cutting fluids at lower supply pressures, suffering from the high centrifugal forces due to the high rotation speed, can easily deviate from their intended path and fail to reach the inserts. Zachert et al.[89] examined the velocity distribution of cutting fluids based on CFD simulations. They discovered that sharp-edged transitions can cause an uneven distribution of cutting fluid velocity as shown in Fig. 8. Similar findings (shown in Fig. 9) were also observed by Peng et al.[80]. The geometry of the internal cooling channel, characterized by sharp intersections and poor surface smoothness in conventionally manufactured tools, contributes to the occurrence of flow separation at these intersections. This leads to high turbulence intensity of the cutting fluids near the channel walls, resulting in inhomogeneous distributions of velocity and pressure. It is worth noting that the rotation of internal cooling milling tools has a significant influence on the fluid flow within the cooling channels. Experimental evidence has demonstrated that the turbulence intensity of the cutting fluids in the cooling channels increases with spindle speed, resulting in losses in terms of the velocity of the cutting fluids flow[90].

The Leidenfrost Phenomenon is frequently observed during the cutting process. When the temperature in the cutting zone surpasses the boiling point of the cutting fluids, the fluids rapidly vaporize, creating a vapor layer within the cutting zone. Consequently, when the velocity of the cutting fluids jet is too low, the fluids are hindered from reaching the tool-chip interface. CFD analyses of the cutting fluids flow in turning have demonstrated that when the flow velocity of the cutting fluids is less than twice the cutting speed, it becomes challenging for the fluids to access the tool tip through the narrow gap between the flank face of the tool and the machined surface. This issue directly impacts the cooling and lubricating effects[91]. Similar problems also arise in the milling process. Excessive rotational speeds of the milling tool can result in a fluid cavitation phenomenon, impeding the appropriate distribution of cutting fluids around the tool[92]. However, unlike turning, in a specific range of spindle speeds, the flow of cutting fluids around the cutting edge is stimulated by the increasing tool speed, leading to an elevation in the horizontal velocity component of the cutting fluids. This contributes to effective chip removal[93].

Following the CFD analysis, several beneficial measures can be implemented to decrease the turbulence intensity of the cutting fluids flow and enhance the velocity of the cutting fluids jet. As a result, the internal cooling techniques can be optimized to enhance their cooling and lubricating capabilities.

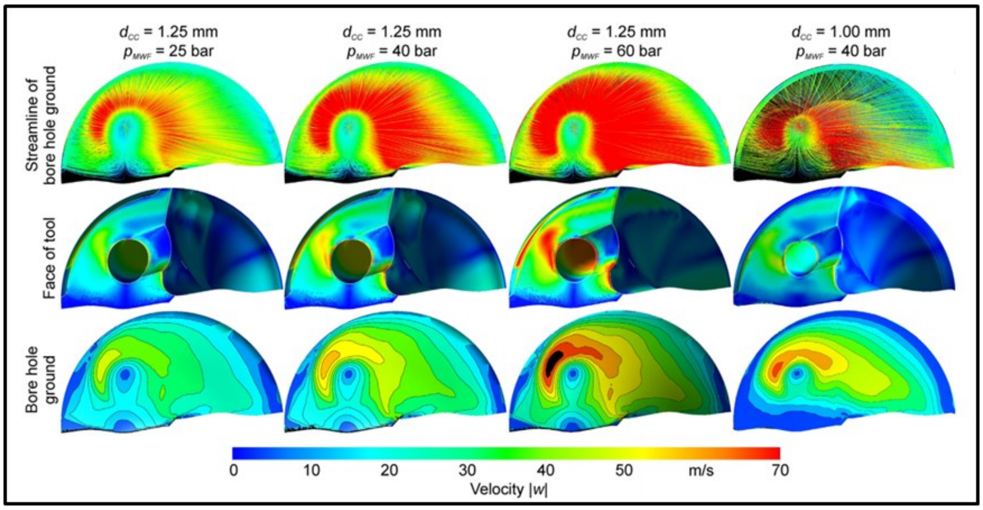


Fig. 6 Streamlines, volume velocity and contour plots for different operation conditions. (CFD simulations of Oezkaya et al.[85])

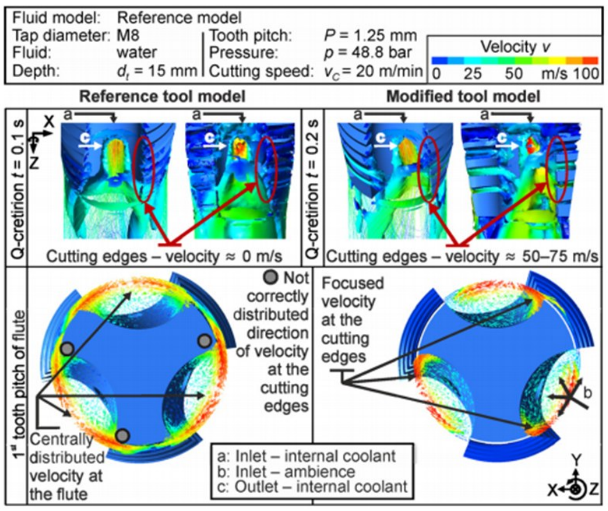


Fig. 7 Distribution of fluid volume. (CFD simulations of Biermann and Oezkaya[86])

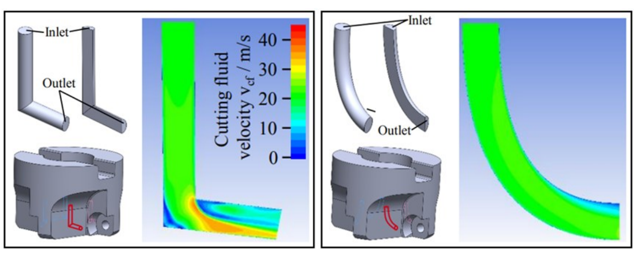


Fig. 8 Cutting fluids velocity distribution of different transition conditions. (CFD simulations of Zachert et al.[89])

3.2. Effects of internal cooling on chip formation

Understanding the chip formation process in cutting is crucial for optimizing cutting tool geometries, selecting cutting parameters, and optimizing cooling conditions. However, studying chip formation directly through experimental and theoretical methods becomes challenging when internal cooling techniques are applied, similar to the behavior of cutting fluids flow. To overcome this challenge, the Finite Element Method (FEM) is employed to model the chip formation process while considering the presence of cutting fluids. This modeling approach is of significant importance for gaining a deeper understanding of the role of internal cooling in the cutting process. However, it should be noted that the influence of internal cooling techniques on chip formation involves a complex fluid-structure interaction (FSI) process between cutting fluids injection and chip formation. Modeling this multiphysics interaction is challenging. As a result, chip formation simulations have predominantly been conducted without considering the presence of cutting fluids, and only a few researchers have explored this topic with the inclusion of cutting fluids.

Courbon et al.[94] developed a finite element (FE) model of orthogonal machining to study the impact of cutting fluid jets on the cutting process. The model considers the constant forces and thermal loads induced by the cutting fluid jet. The results demonstrate that the cutting fluid jet can reduce cutting forces, chip radius, and tool-chip contact length. Additionally, it decreases the contact pressure and temperature fields on the cutting tool. Klocke et al.[95] presented a 2D FE model that combines fluid dynamics simulation with structural dynamics simulation using FSI. The study investigates the effects of cutting fluid application on chip formation through simulations. The size of the chips is influenced by the impact angle of the cutting fluid jet on the cutting zone and the supply pressure of the cutting fluid. As illustrated in Fig. 10, increasing the impact angle or supply pressure leads to smaller chips. Mohd Hadzley et al.[96] utilized a series of FE models to investigate high-pressure jet-assisted machining of Ti-6Al-4V alloy and compared the results with experimental data. Their findings revealed that supplying high-pressure cutting fluids to the cutting zone result in the chips bending and curling away from the rake face at the tool-chip interface. As a result, the tool-chip contact is reduced and more space is created for penetration of the cutting fluids into the cutting zone. Oezkaya et al.[97] developed an FSI model to simulate the drilling process. They observed that the chip formation process impedes the flow of cutting fluids in the cutting zone. As shown in Fig. 11, even a small chip significantly reduces the flow velocity of cutting fluids.

The cutting fluid jet has been found to have positive effects on chip formation. However, the specific mechanisms underlying these effects remain unclear in many aspects. Further research should concentrate on investigating these aspects, as they form the basis for determining the optimal impact position and supply pressure of the cutting fluid to minimize chip size.

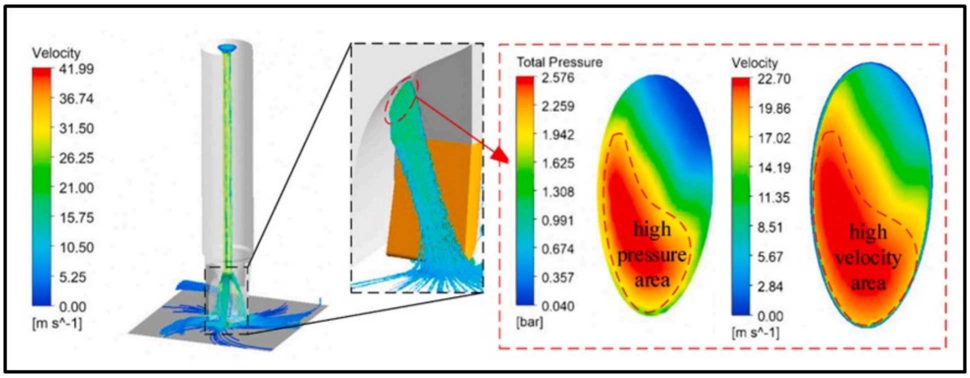
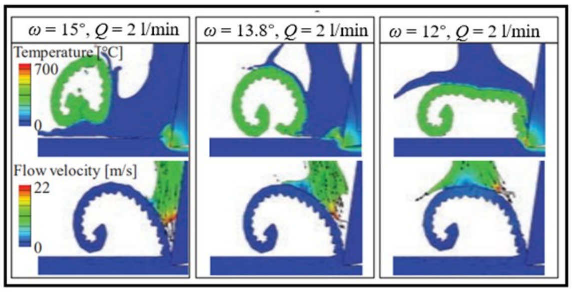
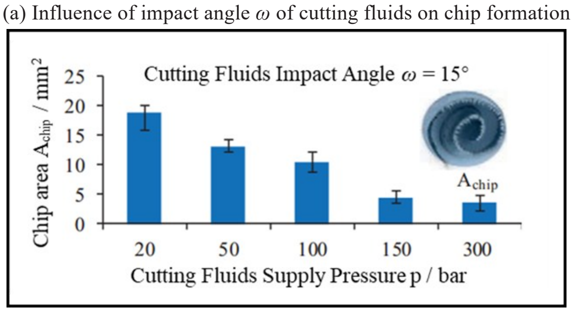


Fig. 9 Streamline of cutting fluid, outlet pressure and velocity distribution of cutting fluid. (CFD simulations of Peng et al.[80])



(a) Influence of impact angle ω of cutting fluids on chip formation



(b) Influence of supply pressure of cutting fluids on chip formation

Fig. 10 Formation of chips under different impact angles and supply pressure of cutting fluids. (Workpiece material: Ti-6Al-4V)[95]

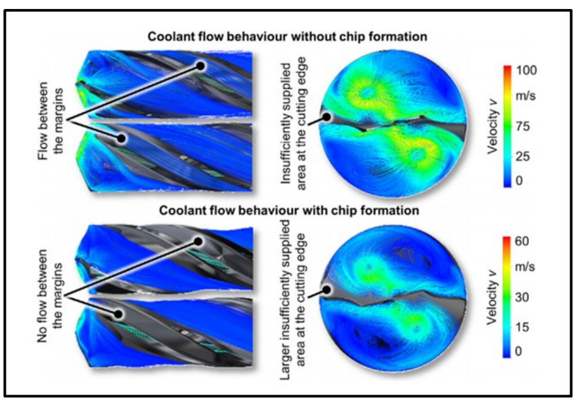


Fig. 11 Cutting fluids flow analysis with and without chip formation. (FSI simulations of Oezkaya et al.[97])

3.3. Effects of internal cooling on cutting results

In contrast to sections 3.1 and 3.2, the impact of internal cooling on cutting results is primarily investigated through experimental approaches, which provide more intuitive and comprehensive findings. A significant number of experimental studies on internal cooling cutting have been conducted to analyze the effects of internal cooling on cutting results from various perspectives such as cutting forces, cutting temperatures, surface roughness, tool wear and chip morphology. These studies have greatly enhanced our understanding of the cutting mechanism.

3.3.1. Cutting forces

Cutting forces play a critical role in determining cutting performance, and internal cooling has shown promising potential as a replacement for conventional flood cooling methods due to its ability to reduce cutting forces. For instance, Riaz et al.[98] designed a double straight channel internal cooling milling tool and conducted Zig-zag milling tests, demonstrating that internal cooling resulted in lower cutting forces compared to flood cooling. Islam et al.[99] revealed that cryogenic internal cooling reduces cutting forces when compared to dry cutting and flood cooling. In turning Ti-6Al-4V, minimal quantity cooling lubrication (MQCL) has been implemented, and the results indicated that internal MQCL performs better at lower feed levels, leading to lower cutting forces compared to external MQCL and flood cooling[100]. Qin et al.[101] conducted a comprehensive investigation on drilling forces in Inconel 718 utilizing external and internal cooling techniques with nitride-coated tools. They observed significantly reduced drilling forces under internal spray cooling conditions when drilling the same number of holes. In general, internal cooling has proven effective in reducing cutting forces during machining by enabling deeper penetration of cutting fluids into the tool-chip interface, thereby reducing the friction coefficient between the tool and chips and improving overall tool-chip contact conditions.

However, it should be noted that internal cooling does not always result in a reduction of cutting forces[102,103]. Fernandes et al.[104] conducted a study comparing the performance of internal cooling and flood cooling during turning of grey cast iron, and found that cutting forces increased by 42% with internal cooling compared to flood cooling. The reason is that internal cooling effectively dissipates heat at the tool-chip interface, which plays a crucial role in reducing temperatures and increasing material hardness. As a result, cutting forces are increased. Therefore, it is important to maintain a balance between cutting forces and cutting temperatures when optimizing the cutting process.

3.3.2. Cutting temperature

The effectiveness of internal cooling has been validated through the observation of temperature changes in various cutting experiments[105]. Since the motion of tools in the turning process is translational, it is relatively easy to implement internal cooling techniques. Researchers have developed innovative turning tools with internal cooling channels on the insert. These tools can be divided into two categories based on their cooling methods. The first category is direct cooling, where cutting fluids are injected into the cutting zone through the cooling channel, directly removing the heat. The second category (as illustrated in Fig. 12.) is indirect cooling[110,] where cutting fluids circulate through the internal channels within the cutting inserts instead of being directed to the cutting zone. The generated heat is transferred through the tool and extracted by heat convection between the tool and coolant. Sun et al.[106] conducted cutting tests on an aluminum alloy using this type of turning tool. It was observed that this method significantly reduced turning temperatures by 308K. Li et al.[107] further enhanced the cooling effect of the internal cooling channel through CFD simulation and topology optimization, resulting in a temperature reduction of 453 K.

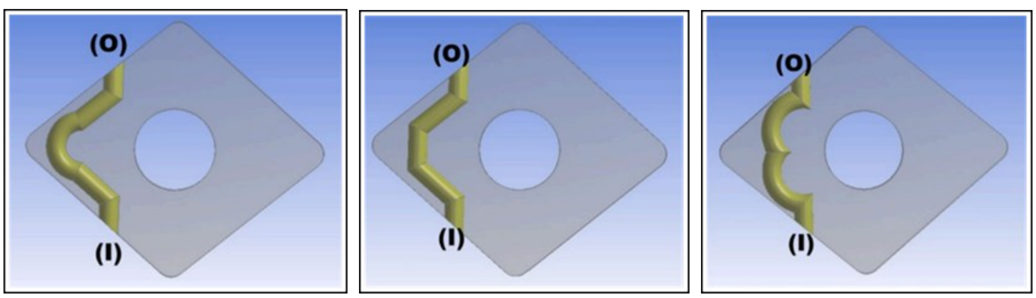
Furthermore, separate drilling experiments have been conducted under external cooling and internal cooling conditions. Zeilmann et al.[108] observed that internal cooling led to a significant reduction in cutting temperatures compared to external cooling. Jessy et al.[109] examined the cutting performance of glass fiber-reinforced polymer (GFRP) composite material under both external and internal cooling conditions. The results indicated that internal cooling reduced average temperatures by 66% compared to external cooling. Internal cooling is important for delivering cutting fluids to the interfaces between the tool and workpiece. This serves a dual role: firstly, cutting fluids help to dissipate the heat generated during the cutting process. Secondly, cutting fluids penetrate the contact area between the rake face and chips and enhance the friction conditions in the secondary shear zone. This remarkably reduces the amount of heat generation.

3.3.3. Surface roughness

Surface roughness serves as a crucial parameter in evaluating the quality of machined workpieces. Excessive surface roughness can lead to the formation of micro-cracks, stress concentration, and a decrease in the fatigue life of components. Experimental cutting tests conducted under different conditions, including dry cutting, external cooling, and internal cooling, have shown that employing internal cooling greatly enhances the surface quality of the workpiece. This can be observed in the comparative analysis depicted in Fig. 13, where the surface processed under internal cooling exhibits a higher level of regularity, cleanliness, and overall neatness[111]. Furthermore, at higher cutting speeds, the benefits of using internal cooling tools in reducing surface roughness become more pronounced[104]. By utilizing liquid nitrogen as the cooling medium, even smoother machined surfaces can be achieved. For instance, when employing internal cooling techniques with liquid nitrogen in the machining of Ti-6Al-2Zr-1Mo-1V alloys, the machined surface roughness can be reduced by up to 28%[112]. The improvement in surface roughness can be attributed directly to the reduction in both cutting forces and cutting temperature. The reduction of cutting forces leads to mild vibration of the cutting tool, which stabilizes cutting process and improves surface quality. Additionally, the reduction of heat generation during the cutting process with internal cooling results in decrease in the risk of thermal damage to the machined surface. Therefore, surface quality is enhanced.

3.3.4. Tool wear

Internal cooling techniques offer significant advantages over dry cutting and flood cooling when it comes to improving tool wear. Zhao et al.[113] conducted a study using simplified orthogonal cutting to investigate the effects of internal cooling on tool flank wear. The analysis revealed that by utilizing internal cooling cutting tools, a



(a) Profile 1 (b) Profile 2 (c) Profile 3

Fig. 12 Internal cooling channel inserts with different profiles[110].

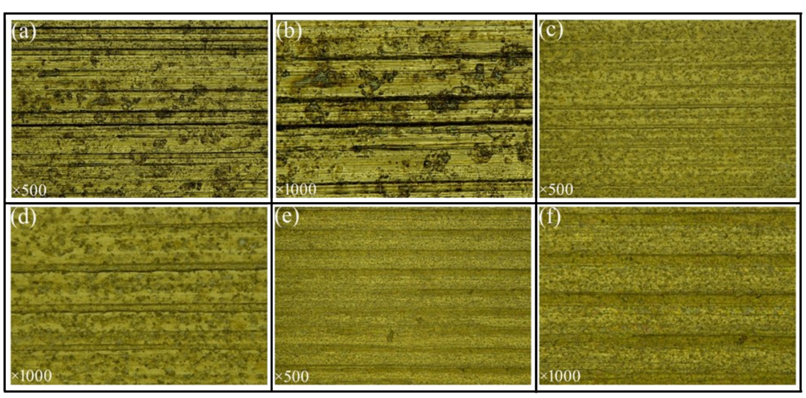
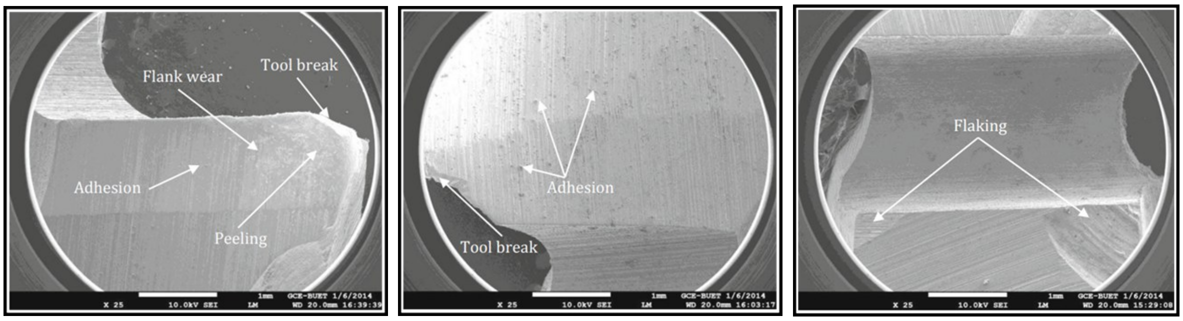


Fig. 13 Surface morphology of the workpiece (workpiece material: Inconel 718). (a), (b) Dry cutting. (c), (d) External cooling. (e), (f) Internal cooling[111].



(a) Dry cutting (b) Flood cutting (c) Internal cooling cutting

Fig. 14 SEM views of milling tools wear under different cooling conditions (Workpiece material: EN 24 steel; Cutting parameters: cutting velocity: 22 m/min, table feed: 34 mm/min, depth of cut: 0.60 mm)[99].

reduction in flank wear and an extension of lifespan of up to 15% can be achieved compared to cutting tools without internal cooling. SEM images (shown in Fig. 14) of milling tools worn under different cooling conditions further support these findings. It can be observed that under internal cooling conditions, the tool exhibits only slight skin flaking, and complete tool breakage is eliminated. Lakner et al.[114] conducted research on tool wear in additively manufactured tools with internal cooling channels during cutting of Ti-6Al-4V. The results demonstrated that additively manufactured tools achieved more effective cooling closer to the cutting edge, leading to a reduction in adhesive wear of the cutting tool. Klocke et al.[115] discovered that crater wear was eliminated when milling Ti-6Al-4V using internal cooling techniques. Meanwhile, light flank wear was observed when the cutting fluids were supplied specifically to the corner of the cutting insert. Uhlmann et al.[116] reported a 10% reduction in flank wear during turning of AlSi7Mg0.3 with internal cooling, compared to machining with flood cooling as the reference. Furthermore, they found that adjusting and increasing the cutting speed could reach the minimum wear if the temperatures of the cutting fluids were kept constant. Bleicher and Reiter[117] presented findings on the influence of different cutting fluids supply methods for simultaneous machining of wire-arc-sprayed cylinder running faces. They discovered that a combined internal and external cutting fluids supply method significantly reduced flank wear and prevented notch wear on the main cutting edge. Additionally, Gan et al.[112] analyzed the influence of liquid nitrogen flood cooling and liquid nitrogen internal cooling on tool wear during turning of Ti-6Al-2Zr-1Mo-1V alloy. The results showed a maximum reduction in tool wear of 34% with liquid nitrogen internal cooling.

Since the cutting forces can be reduced using internal cooling techniques, the normal pressure and impact on the cutting tool become light, thereby eliminating the tool wear and the risk of tool breakage. Furthermore, the implementation of internal cooling reduces cutting temperature and provides lubrication. These two benefits can reduce the friction and adhesion between the workpiece material and the tool. Thus, the possibility of tool surface spalling can be minimized.

3.3.5. Chip morphology

Under internal cooling conditions, chip length and curling degree are reduced compared to dry conditions. Klocke et al.[115] investigated the impact of cooling nozzle orientation on the machinability of Ti-6Al-4V in internal cooling milling. They found that the up-curling radius of the chip was smaller with a cutting fluids jet impacting into the wedge between the rake face of the tool and the emerged chip. Chen et al.[118] studied the effects of using MQL strategy with internal cooling tools on chip morphology when turning superalloy GH4169. They reported that internal cooling displayed good performance on chip breaking under high flow rates of cutting fluids. Furthermore, Liao et al.[119] reported a internal cooling cutting insert with multi-channel irrigation at the chip-tool interface for turning Inconel 718. The insert breaks chips more effectively even at low cutting speeds than a conventional insert. Their results (shown in Fig. 15) also demonstrated that the conventional insert generated more severe serrated chips with larger thickness than the novel insert. This considerable crushing and deformation can be attributed to the more severe chip compression phenomenon resulting from adiabatic shearing, as well as the friction effect of the conventional insert during the chip formation process. Fig. 16 illustrates the chip morphology under different cooling conditions[120]. It is commonly accepted that higher supply pressure of internal cooling cutting fluids leads to smaller chips. The reason is that the high-pressure cutting fluids supplied by internal cooling techniques play a positive role in chip breaking during the cutting process. In turning processes, chips become shorter and less prone to curling. Hence, curling degree is low when internal cooling techniques are employed. However, further studies have revealed that this conclusion does not always hold true. When cryogenic gas is used as the cooling medium, the chip obtained from high-pressure cryogenic cutting resembles that obtained during dry cutting, as shown in Fig. 17. Conversely, the chip obtained in low-pressure cryogenic cutting is damaged. The reason behind this phenomenon is that the low-

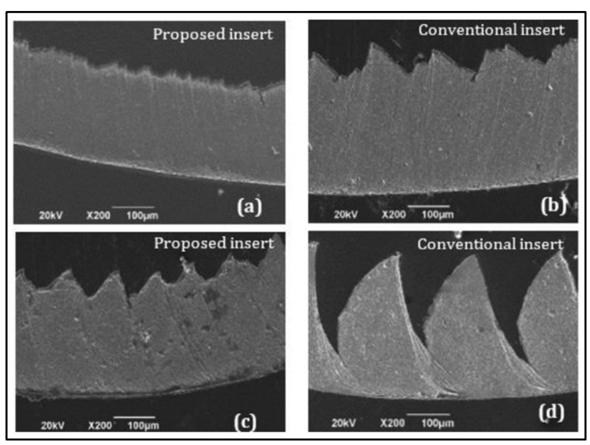


Fig. 15 Chip morphology (Workpiece material: Inconel 718): (a) and (b): Cutting speed *V*=30 m/min, (c) and (d): Cutting speed *V*=60 m/min[119].

pressure cryogenic jet fully cools the chip, making it more fragile and susceptible to damage.

(a) dry cutting (b) internal cooling cutting

Fig. 16 Chip morphology under different cooling conditions. (Workpiece material: QT500-7)[120]

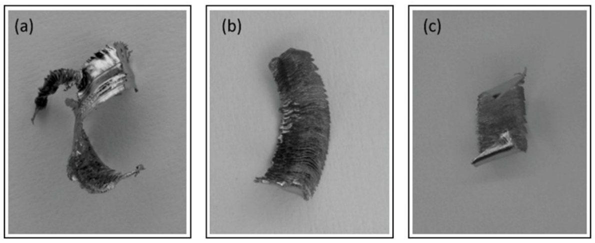


Fig. 17 Chip morphology comparison (Workpiece material: Ti-6Al-4V) (a) internal cooling with cryogenic low pressure, (b) dry cutting, (c) internal cooling with cryogenic high pressure[20].

While the specific cutting results may vary depending on the internal cooling techniques and cooling mediums used in different cutting processes, it is generally recognized that these techniques have a consistent impact. These include lower cutting temperatures, smoother machined surfaces, reduced tool wear, and smaller chip sizes.

4. Methods for improving cooling and lubricating performance of internal cooling techniques

In order to fully utilize the cooling and lubricating benefits of internal cooling, it is crucial to design the tools and cutting fluid supply pressure in a reasonable manner to ensure optimal spraying of cutting fluids into the cutting zone. Below are specific measures that can be taken to enhance the cooling and lubricating capabilities of internal cooling.

4.1. Optimization of the geometry of the flow channels

One of the most important measures for making full use of the cooling and lubricating effect of the cutting fluids is to minimize the fluid mechanical losses. Thus, Optimizing the geometry of flow channels is a powerful way to achieve this goal. The flow channel can be considered as a shell extracted from a solid which is constructed by sweeping one or multiple cross-sections along one or multiple sweep paths. Its geometric feature includes cross-sections and paths that influence the fluid flow. Therefore, lots of studies have concentrated on these two aspects.

4.1.1. Path of flow channels

The design of internal cooling channels in cutting tools must meet two important requirements: delivering cutting fluids to specific positions and minimizing fluid mechanical losses within the channels. Straight channels offer the lowest flow losses and minimal pressure drop between the inlet and outlet. However, using a single straight internal channel is often impractical in most cutting processes. This is because the cutting fluids cannot directly reach the tool-chip interface when a cutting tool with a single straight internal channel is used, as illustrated in Fig. 18[121,122]. To address this limitation, branched channels (as shown in Fig. 19) can be employed to deliver the cutting fluids to the desired point[80,86]. However, the conventional method of drilling flow channels tends to create sharp intersections between the straight main channel and the straight branched channels. This results in a significant issue known as pressure drop[123]. When the cutting fluids flow through these intersections without any curvature, backflow can occur easily, leading to unnecessary pressure losses. Moreover, the pressure of the cutting fluids at the outlet is greatly reduced, and the jet velocity may become too low to effectively enter the cutting zone[91] .

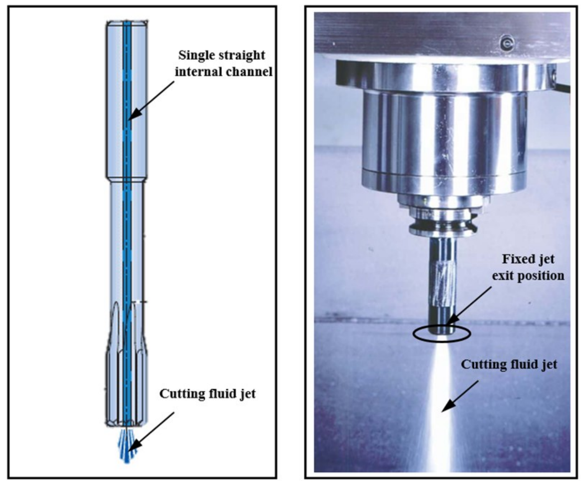


Fig. 18 An internal cooling tool with a single straight channel[121,122].

To address the issue of pressure drop resulting from the intersection of flow channels, internal cooling channels with transition radius have been designed and studied using CFD methods. Kelliger et al. [124] demonstrated the significant impact of a smooth intersection between two vertical coolant channels on flow losses and velocity profiles, as shown in Fig. 20. A smooth intersection with a 5mm transition radius can increase volume flow by 27% compared to a sharp intersection. Doubling the transition radius from 5mm to 10mm has little effect on flow losses but improves the homogeneity of the velocity profile at the outlet. A similar study conducted by Zachert et al. [89] found that changing a sharp-edged internal cooling channel to a channel with a 30-degree circular radius increased the volumetric flow rate by approximately 23%. It is evident that internal cooling channels with transition radius exhibit better flow characteristics.

However, the conventional drilling approach falls short when it comes to fulfilling complex geometries, even with a transition radius. The advancement of additive manufacturing (AM) technologies has opened up new possibilities for designing and manufacturing parts with more intricate geometries[125.126]. The enhanced freedom of design offered by AM has also proven its applicability in manufacturing cutting tools with improved features. Several additively manufactured indexable drilling and milling tools have been introduced to the market, and scientific papers discussing the machining performance of additively manufactured turning tools have been published[127]. A comparison between an additively manufactured tool with enhanced internal cooling channels and a conventional tool[123] revealed that when machining quenched and tempered AISI 4140,

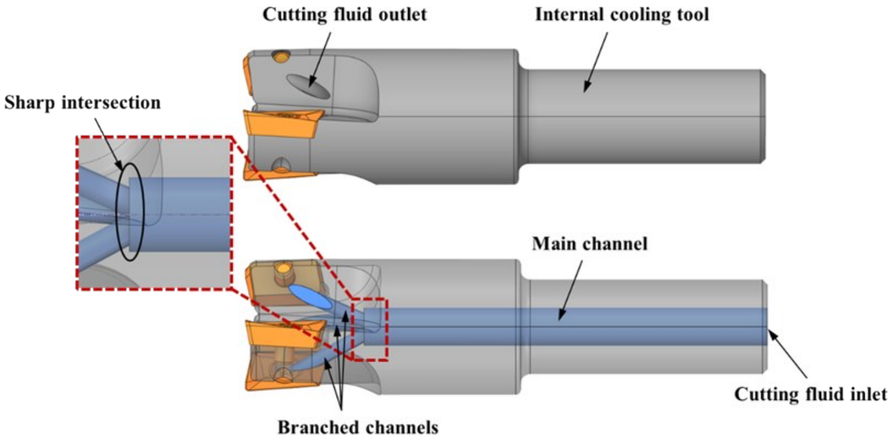


Fig. 19 An internal cooling tool with branched channels.

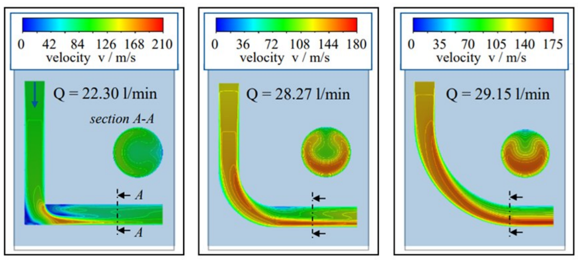


Fig. 20 Velocity profiles were obtained from CFD analysis of internal cooling channels with different transition radius under different surface roughness[124].

the additively manufactured tool exhibited lower tool wear compared to the conventional tool. Kugaevskii et al.[128] explored the potential of using AM technologies for manufacturing cutting tools. Their analysis demonstrated that the tool manufactured using selective laser melting (SLM), as shown in Fig. 21, displayed comparable strength and hardness to those manufactured using traditional machining methods. It is worth noting that the surface quality of the internal cooling channels in cutting tools produced through AM may differ from those made using conventional methods. Therefore, it may be necessary to employ a surface finishing process such as abrasive flow machining to smooth the channels and improve the flow of cutting fluids[129]. Additionally, studying the impact of abrasive flow machining on geometric parameters like channel diameter can inform the design of the channels.

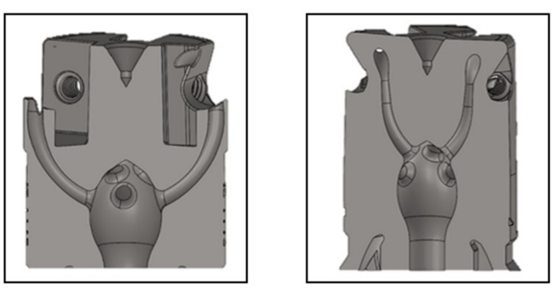


Fig. 21 Milling tools with complex internal cooling channels[128].

In the aforementioned studies, the design of cooling channels is based on empirical knowledge. However, topology optimization techniques offer an alternative approach to achieve optimal performance for internal cooling channels. While topology optimization has been extensively used in structural design within industries such as aerospace[130,131], automotive[132], and heavy industries[133-135], its application in the design of cooling channels for cutting tools remains limited. Li et al.[107,136] utilized topology optimization and CFD to optimize the internal cooling channels of inserts, enabling efficient recirculation of cutting fluids. Their work resulted in a reduction of 180.4° in the temperatures at the cutting edge of the new insert compared to those without internal cooling channels. However, there are few studies that address the topology optimization of the path of internal cooling channels to minimize mechanical losses in cutting fluid flow.

4.1.2. Cross-section of flow channel

The shape and size of the cross-section are two significant parameters that determine both the overall geometry and cooling performance of internal cooling channels. Typically, a circular cross-section is adopted since it effectively prevents stress concentration on the channel walls during cutting fluids flow, owing to its largest hydraulic radius, superior through-flow capacity, and strong pressure resistance. However, this cross-section may not always be the best choice when channels are additively manufactured. Kelliger et al.[124] reported that in horizontally built additively manufactured internal cooling channels, a triangular cross-section can improve surface roughness and geometrical accuracy of machined surfaces compared to a circular channel with the same cross-sectional area. Nevertheless, incorporating the triangular channel profile into additively manufactured cutting tools with curved channel pathways within geometrical boundaries poses a challenge, as the sides of the triangle must be oriented according to the build-up direction. Avoiding overhang areas may cause a twist in the channel, which could affect the flow characteristics.

The cooling performance of internal cooling channels is influenced by the volumetric flux of the cutting fluids[137]. A larger cross-sectional area results in a higher volumetric flux. Klocke et al.[138] demonstrated that increased volumetric flux leads to lower tool temperatures, while Oezkaya et al.[85] found that the volumetric flux of cutting fluids increases nearly linearly with cross-sectional area, resulting in reduced surface defects when drilling the superalloy Inconel 718 using twist drills. The reason behind this is that a high volumetric flux helps to flush away chips from the cutting zone and prevents them from getting welded onto the tool or workpiece, which would otherwise lead to surface defects and tool wear[139-141].

However, it should be noted that a larger cross-sectional area of internal cooling channels can reduce the static and dynamic stiffness of the cutting tools. Therefore, there is a trade-off between the volumetric flux and the stiffness of the cutting tools.

4.2. Selection of supply pressure of cutting fluids

High-pressure cutting fluids facilitate easier penetration of the cutting zone compared to those with conventional pressure, making it a critical factor that affects the cooling and lubrication efficiency of internal cooling techniques. Kaminski and Alvelid[142] investigated the effects of conventional cutting operations on tool temperature, cutting forces, chip shape, and surface roughness. The results indicated that the conventional method of fluid supply was not very effective since low-pressure jet has limited penetration in the cutting zone. In contrast, the potential of high-pressure jet cooling has been demonstrated in numerous recent studies, particularly in enhancing the machining ability of difficult-to-cut materials during cutting[143-146].

High-pressure cutting fluids jet can shorten the chip-rake face contact length, as depicted in Fig. 22, thereby reducing friction between the tool and chips[25,142]. This reduction in friction can lead to several benefits in the cutting process, such as decreased heat generation, and reduced cutting forces. Through experiments, Mohd Hadzley et al.[96] observed that increasing the pressure of cutting fluids could significantly decrease the cutting temperatures and cutting forces when machining Ti-6Al-4V alloy. The effect becomes more pronounced with higher pressures, as also noted by other researchers[111,147]. However, some researchers have reported that high-pressure cutting fluids have little to no effect on cutting forces. This could be because the pressure used was too low to drive the cutting fluids into the tool-chip interface[138]. Moreover, decreasing cutting forces can also reduce vibration in the cutting system. As a result, the surface roughness of the workpiece can be improved, resulting in a smoother surface. For example, Peng et al.[80] observed that increasing the pressure from 2 bar to 10 bar reduced surface roughness by 12.0% during milling of Inconel 718.

At an earlier time, due to the limited capability of the experimental equipment, direct measurements of cutting temperatures and cutting forces were difficult. Therefore, the other benefits of increasing cutting fluids pressure, such as an increase in tool life and surface quality, are studied[101,148-151]. For instance, in turning the steel with high-speed cutting tools under high-pressure cutting fluids supply conditions, Pigott and Colwell[148] observed about a twenty to hundredfold increase in tool life compared with flood cooling.

Both high cutting fluid pressure and large volumetric flux can enhance the cooling and lubrication capabilities of the cutting fluids. However, high cutting fluids pressure plays a more significant role. Ozekaya et al.[85] found that high pressure is more effective in reducing tool wear compared to large volumetric flux during the drilling of Inconel 718. The reason is that the penetration of the high-pressure cutting fluid jet into the cutting zone decreases the temperature gradient, providing sufficient lubrication at the tool-chip interface and significantly reducing friction. Additionally, high pressure increases the velocity of the cutting fluid, resulting in a higher heat transfer rate as the cutting fluid flushes the cutting edge during the milling process. Therefore, for improved cooling and lubrication capabilities, higher pressure is recommended in high-speed milling processes[87,140,152,153].

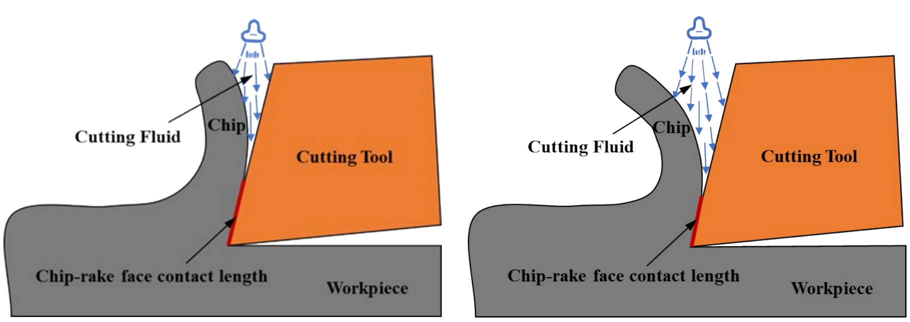
High pressure also plays a role in chip breaking. The high-pressure cutting fluid jet is capable of creating a hydraulic wedge between the tool and workpiece, as illustrated in Fig. 23. This jet can penetrate the interface at high speed and alter the chip flow conditions[154,155]. The hydraulic wedge formed by the cutting fluid can break the chip into smaller pieces by inducing upward bending and premature, excessive curling[156,157]. Remarkable chip-breaking capabilities have been observed when machining difficult-to-cut materials using a high-pressure cutting fluid supply[140,158]. Additionally, high pressure aids in the quick evacuation of chips from the cutting area.

However, it is important to note that excessively high pressure can have negative effects. When chip particles adhere to the cutting tool, a high-pressure jet is used to remove them. However, this can also result in the removal of material from the tool coating and substrate, leading to increased crater wear. Machado et al.[156] conducted experiments on turning Inconel 901 with an uncoated tool and found that a pressure of 14.5MPa increased tool wear and reduced tool life. Similarly, Ezugwu et al.[159] reported that increasing the cutting fluid pressure, under certain conditions, does not always improve tool life when finishing the turning of Ti-6Al-4V alloy with a cubic boron nitride (CBN) tool. Naves et al.[160] studied the effect of cutting fluids at high pressures on tool wear and observed that tool wear was less under pressures of 10MPa compared to pressures of 15MPa and 20MPa.

Hence, it is crucial to regulate the pressure of the cutting fluids at an optimal level. This ensures that the cutting fluids possess sufficient penetration capability and facilitate the desired curl deformation of the chip, all while minimizing any detrimental effects on tool wear.

4.3. Design of the nozzles on internal cooling cutting tools

The precise delivery of cutting fluids to the cutting edge can be achieved through the design of nozzles on internal cooling cutting tools. This approach involves three critical aspects: posture selection, shape design, and the determination of the number of nozzles



(a) Conventional cutting fluids supply (b) High-pressure cutting fluids supply

Fig. 22 Chip-rake face contact length under different cutting fluids supply methods.

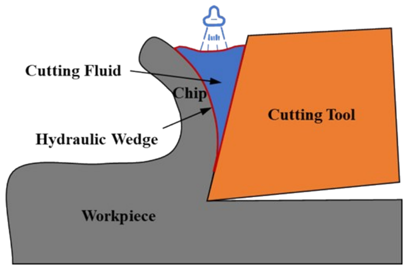


Fig. 23 Hydraulic wedge between cutting tool and workpiece.

required. While many cutting tool manufacturers have explored and designed a wide range of internal cooling tools with different nozzle designs (as depicted in Fig. 24[161-165]), theoretical guidance is crucial for optimizing the cooling and lubricating performance of these tools.

The optimal posture of internal cooling nozzles, which refers to the position and orientation of the nozzle, plays a crucial role in enhancing the efficiency of cooling and lubrication within the tool[166]. Fig. 25 illustrates three types of nozzle positions: (a) towards the tool-chip interface; (b) towards the tool-workpiece interface; and (c) towards both the tool-chip and tool-workpiece interfaces. Numerous researchers have investigated the distinct advantages offered by these nozzle positions in improving the cutting process.

Cutting temperatures and forces can be significantly reduced when cutting fluid is precisely delivered to the interface between the rake face and emerging chip. However, some studies[115,152] have shown that this method of cutting fluids supply changes wear mechanisms and may lead to severe crater wear of the tool. In contrast, although supplying cutting fluid to the tool-workpiece interface results in a smaller reduction of cutting temperatures and forces, it is more effective in improving the finished surface[167]. The reason is that the cutting fluids form a lubricating film between the flank face and workpiece, preventing chips from scratching the machined surface. As expected, supplying cutting fluids to both the tool-chip and tool-workpiece interfaces can result in the longest tool life and lowest cutting temperatures and forces[168,169]. However, due to limitations in tool structure, it is often challenging to achieve this nozzle position in internal cooling techniques.

Moreover, the cooling and lubricating performance of internal cooling is also influenced by the orientation of the nozzle. However, there is a lack of consensus on the definition of nozzle orientation in different studies. Currently, determining the nozzle orientation often involves trial-and-error methods. The optimal orientation of the nozzle, as reported in various studies[170], shows significant variations. Therefore, it is crucial to establish a clear definition of nozzle orientation and develop a criterion for determining the appropriate nozzle orientation.

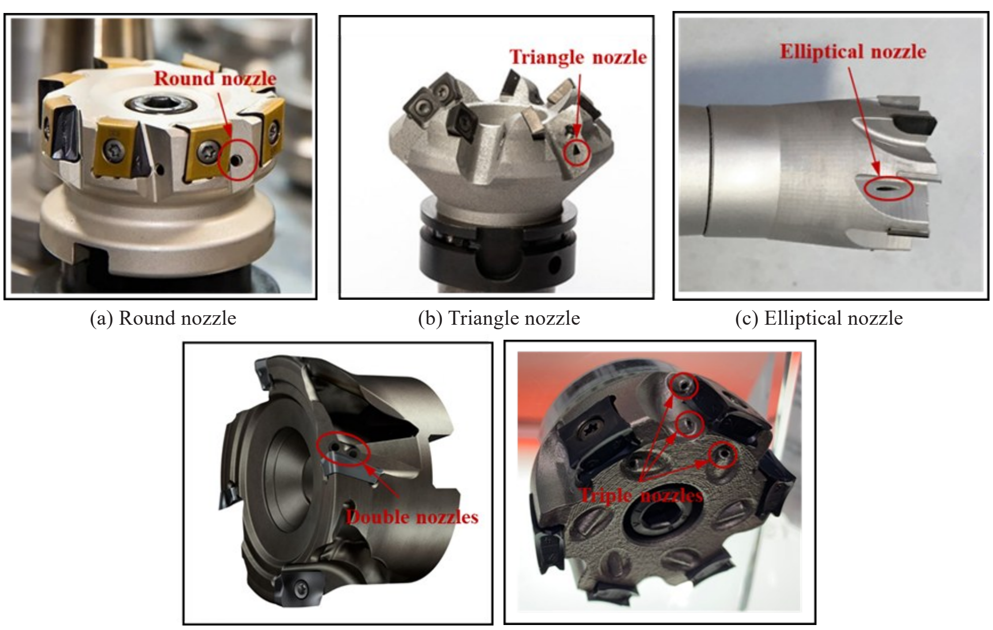
Furthermore, it is important to ensure focused cutting fluids without jet expansion and uneven fluid energy distribution in order to maximize the effectiveness of cooling and lubrication during cutting fluid supply. Kelliger et al. discovered that reducing the distance between the nozzle and the cutting edge can achieve this objective[124]. Similarly, the design of the nozzle shape should also be based on this principle.

In terms of the number of nozzles, it is crucial to ensure that each cutting edge is matched with at least one nozzle to facilitate the cooling and lubrication of the rake face. However, supplying cutting fluids to both the rake face and flank face of the tool is desirable. Therefore, designing tools with multiple effective nozzles is expected to effectively address this requirement.

In summary, to achieve a focused cutting fluid jet without jet expansion and uneven fluid energy distribution aimed at the cutting edge, it is necessary to optimize the posture, shape, and number of nozzles.

5. Conclusions and outlook

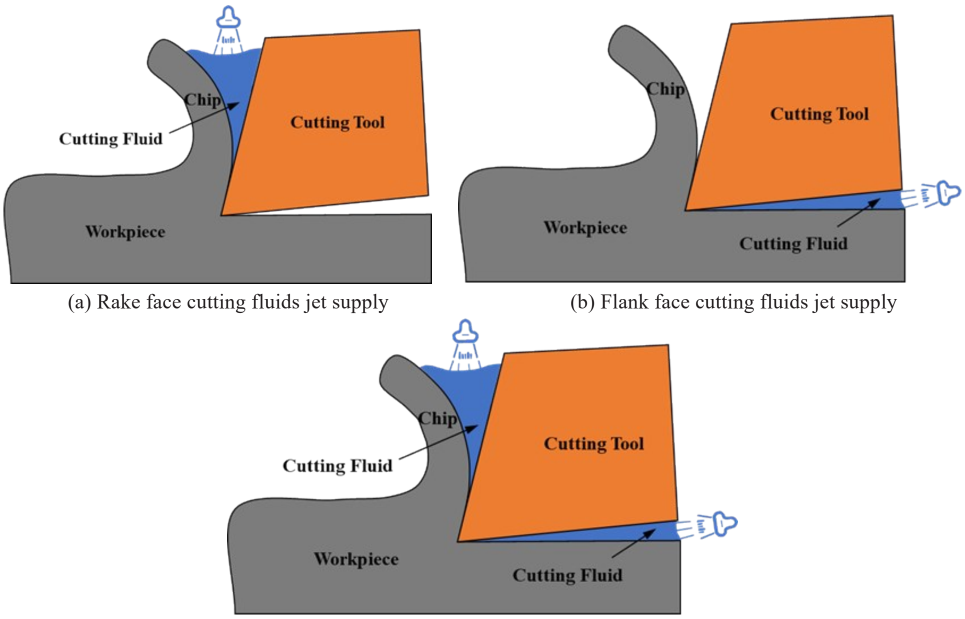
Internal cooling techniques have shown better cooling and lubrication performance in the cutting process than flood cooling. Generally, internal cooling techniques result in lower cutting temperatures and cutting forces, lighter tool wear, longer tool life, smaller chip, and better surface quality. By reviewing the current studies on internal cooling techniques, it can be concluded that the cooling and lubrication performance can be maximized by optimizing the



(a) Round nozzle (b) Triangle nozzle (c) Elliptical nozzle

(d) Double nozzles (e) Triple nozzles

Fig. 24 Internal cooling tools with different nozzles[161-165].



(a) Rake face cutting fluids jet supply (b) Flank face cutting fluids jet supply

(c) Combined rake and flank face cutting fluids jet supply

Fig. 25 Cutting fluids supply under different nozzle positions.

internal cooling channels and outlet nozzles of cutting tools and by reasonably selecting the fluids supply pressure. However, the following points must be noted when use internal cooling techniques in cutting process.

(1) Sharp-edged transitions between the internal cooling channels can lead to flow separation of the cutting fluids. Additionally, the rotation of the tool during milling and drilling processes increases the turbulence intensity of the cutting fluids, which in turn affects the cooling and lubrication performance. Therefore, it is recommended to use smooth transitions and consider the rotational action of the tool when designing internal cooling channels.

(2) Chip formation is influenced by both the pressure of the cutting fluids supply and the angles at which cutting fluids impact the chip. Higher pressure and closer proximity of the cutting fluids jet to the rake face of the cutting tool result in smaller chips. However, if chips are not discharged promptly in drilling process, they can impede the flow of cutting fluids, thereby affecting the supply of cutting fluids to the cutting edge.

(3) The reduction in cutting temperature resulting from internal cooling techniques may cause hardening of the workpiece material, leading to increased cutting forces. Therefore, when using internal cooling techniques in the cutting process, it is important to find a balance between cutting forces and cutting temperatures.

(4) The velocity of the cutting fluids should be sufficient to overcome the Leidenfrost Phenomenon. Reducing mechanical losses in the cutting fluids flow is an effective way to increase velocity. To achieve this, it is recommended to design the internal cooling channels of a cutting tool using topology optimization and manufacture them using AM techniques.

(5) Both high cutting fluids pressure and large volumetric flux can enhance the cooling and lubrication capabilities of the cutting fluids. However, it should be noted that high cutting fluids pressure plays a more significant role. Excessive pressure may have a negative effect, such as increasing tool wear. Therefore, the cutting fluids should be supplied at an appropriate pressure considering the trade-off between effective cooling and minimal tool wear.

(6) It should be noted that supplying cutting fluids to the interface between the rake face and the new emerging chip can result in better cooling and lubrication effects, while supplying cutting fluids to the interface between the flank face and workpiece can improve the finished surface. Supplying cutting fluids to both the tool-chip and tool-workpiece interfaces can achieve the best cutting performance.

In addition, theoretical guidance for the optimization and application of internal cooling techniques in different cutting tools should be further investigated. The existing problems and directions for future studies can be summarized as follows:

(1) Designing the internal cooling channels of cutting tools using CFD-based topology optimization techniques is an effective way to reduce cutting fluids flow losses in internal cooling techniques. However, the application of this kind of flow channel optimization is currently very limited, and many optimizations are still based on experience. Therefore, optimizing the internal cooling channels is a key area for future improvement of internal cooling techniques.

(2) Nozzles designed for supplying cutting fluids to both the rake face and flank face of the tool are desired. However, due to the limitations of the tool structure, it is usually difficult to realize targeting cutting fluids to the flank face. Although some conceptual cutting tools have been proposed, their cooling performance has not been adequately verified. Further studies should be carried out to design appropriate nozzles.

(3) The chip formation process in internal cooling involves a FSI problem. To understand the effect of cutting fluids on chip formation, it is crucial to develop a comprehensive fluid-solid-thermal multi-physical model. This model can provide theoretical guidance for selecting the nozzle posture and better comprehend the impact of cutting fluids. However, there have been limited successful attempts in modeling chip formation under internal cooling due to the associated challenges. Therefore, it is worthwhile to focus efforts on advancing research in this aspect.

(4) Cutting tools with complex internal cooling channels and nozzles are ideally manufactured using AM techniques. However, it is important to note that the surfaces of additively manufactured cooling channels are typically rough and require post-treatment

with abrasive flow machining. This additional process can potentially introduce deviation in dimensions and surface roughness from the original design. Therefore, it is crucial to consider manufacturing factors during the design procedure to ensure that the final product meets the desired specifications.

Acknowledgements

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