Cooling performance improvement of circulating internal cooling turning tool by built-in additional spray cooling nozzle

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Abstract. Aiming at the demand of high efficiency green cooling cutting of difficult-to-machine materials, a novel composite cooling turning tool design concept based on circulating internal cooling combined with spray cooling is proposed in this paper. Thermal-fluid-solid coupling simulation models were developed based on FLUENT software, which are applied to investigate the cooling performance of two type of composite cooling tool which are single-nozzle type and double-nozzle type, and the circulating internal cooling tool. Simulations results shown that the tool-chip interface temperatures of the three tools are from low to high under the same conditions, followed by the composite cooling turning tool with double-nozzle, the composite cooling tool with single-nozzle and the circulating internal cooling tool. The double-nozzle type of the composite cooling tool exhibits a better cooling and lubrication performance.

1. Introduction

In recent years, in order to meet the requirements for high hardness, high toughness and high wear resistance of the parts in various industries, a number of difficult-to-machine materials such as titanium alloys and nickel-based alloys have been widely used. Heat is easily accumulated in the cutting zone when processing these materials, which results in rapidly tool wear and defects such as scales and burns on the surface of the workpiece. The traditional cooling method by pouring a large amount of cutting fluid in cutting zone not only pollutes the environment, but also causes harm to the human body. It does not conform to the current concept of sustainable green development[1-2]. To reduce or even eliminate the negative-side effects of using the cutting fluid, scholars have conducted in-depth research on cooling methods for green cutting.

Circulating internal cooling allows coolant to flow below the cutting zone through the internal channels of the tool, thereby decreasing cutting temperature and slowing the wear rate of the cutting edge and improving the quality of the workpiece. Vicentin et al.[3] designed an internal cooling turning tool, which is a hollow toolholder with cooling groove and flow channel, and coolant can circulate in the tool to take away heat in cutting process. Another internally cooled tool proposed by Carlo et al.[4] which mainly consists of a hollow cutting insert, a support seat with cooling channels and a toolholder. However, the circulating internal cooling method cannot cool the chips and assist the chip removal because the cooling liquid cannot wash the chips. Spray cooling dissipates heat by forced convection, droplets and thin fluid film evaporation and even nuclear boiling, so it has a large heat dissipation capability and can promote chip evacuation[5]. Therefore, integrating the spray cooling technology into the circulating internal cooling tool would further increase the cooling effect and promote chip removal.

To improve the integration, the flow channels and nozzle for spray cooling can be built in an internal cooling tool to form a composite cooling tool, which not only enables the cooling liquid to fully enter the workpiece-tool-chip interfaces, but also assists chip evacuation.

The CFD method based on Fluent software has been successfully applied to the research of circulating internal cooling and spray cooling in cutting process[6-8], but the research about the influence of the number of spray nozzle on the cooling performance of the composite cooling tool is rarely. In this paper, the composite cooling turning tool was designed and its three-dimensional CFD simulation model was developed. The thermal-fluid-solid coupling simulations were carried out by using Fluent software to investigate the cooling performance of the single-nozzle type and double-nozzle type composite cooling turning tools, and compared with the circulating internal cooling turning tool. This work provides the basis for the application of the composite cooling turning tool in reality.

2. Construction of the tool cooling structure

As shown in Fig.1(a), the circulating internal cooling tool proposed in this paper is a transformation design based on a standard turning tool which composed of the toolholder, insert, support seat and clamp. In order to bring the coolant closer to the cutting zone, the insert thickness is reduced to 1.8mm without seriously affecting the strength of the turning tool. There is an annular groove on top of the support seat and some micro holes are arranged in the toolholder and support seat, and cooling liquid channels can be formed after assembling. The inlet and outlet of the coolant channels are placed on the bottom surface of the toolholder to facilitate the installation of external cooling system.

The design scheme of the composite cooling turning tool is set an additional spray cooling inlet on the bottom surface of the toolholder on the basis of the circulating internal cooling tool. As shown in Fig.1(b) and Fig.1(c) are two types composite cooling turning tool respectively. Due to the limitation of the size of the toolholder head, the single-nozzle located on the top surface of the toolholder head which mainly used for cooling and lubricating the tool-chip interface. For the double-nozzles type composite tool which one nozzle is located on the top surface of the toolholder and another nozzle is located on the lower front of the toolholder, thereby both tool-chip and tool-workpiece interfaces can be cooled and lubricated simultaneously. Because spray cooling needs to realize the function of assist chip removal, the outlet of the spray nozzle on the top of the toolholder should be close to the rake face and perpendicular to the main cutting edge. It is worth noting that the spray cooling channels should not interfere with the circulating internal channels due to the difference between the internal cooling and the spray cooling medium.
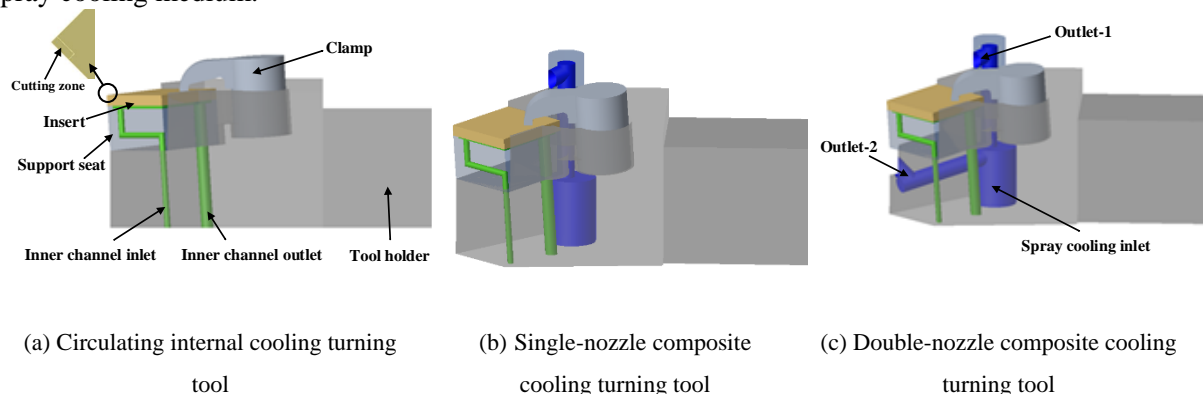

(a) Circulating internal cooling turning tool

(b) Single-nozzle composite cooling turning tool

(c) Double-nozzle composite cooling turning tool

Fig.1 The 3-D model of tools

3. CFD modeling of cutting temperature

3.1. Meshing

The tools geometry models were imported into ANSYS Workbench for meshing. The tetrahedral meshing have been used for all the turning tools model. Fig.2(a) shows an example of the mesh model of simulation. In order to make the simulation results closer to the actual situation, a fluid domain with a volume of 95 mm × 80 mm × 70 mm was established for all the analysis models to simulate the flow

of air and droplets near the cutting zone and the heat transfer process. The workpiece is added to all the analytical models to simulate the physical process of turning.

As shown in Fig.2(b), the mesh size around the cutting zone was refined, which can better capture changes in the temperature gradient of the tool-chip interface and improve the accuracy of the simulation results. The mesh was also inflated for the interface between solid and fluid, which can be seen as refinement of the mesh elements perpendicular to the interface. Fig.2(c) shows the mesh of the internal cooling channel. Both refinement and inflation can improve the calculation accuracy of the heat transfer between solid domain and fluid domain. Mesh independence test has been performed, and the number of mesh element is about 7.45×106 cells for all simulation models.

(a) Mesh of the simulation model   (b) Mesh of the insert   (c) Mesh of the cooling channel
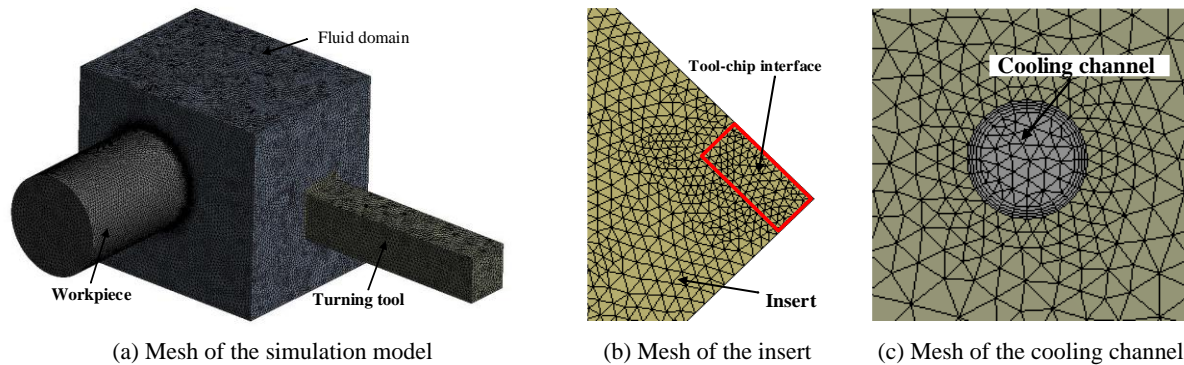
Fig.2 The mesh model of simulation

3.2. Boundary conditions

Boundary conditions applied to the simulation model should be reasonably defined according to the actual cutting process so as to simulate the actual turning process more realistically. The purified water was chosen as the cooling fluid for circulating internal cooling and spray cooling in this study. This is because it has a good heat transfer performance, and it is readily available and harmless to environment and human. The water temperature is set as 20°C, which is equal to the ambient temperature in the cutting process. The inlet of circulating internal cooling is set as velocity-inlet, the inlet velocity is 1 m/s, and the outlet of internal cooling is set as pressure-outlet.

For the spray cooling of the composite cooling tool, the inlet of spray cooling is defined as pressure-inlet, the inlet pressure is 0.3 MPa, the coolant mass flow rate is 1.38639×10^{-5} kg/s and the corresponding flow rate is 50 mL/h, and the fluid domain wall is set as pressure-outlet. The DPM boundary conditions of the inlet and outlet of spray cooling are set to escape. The realizable k-ε turbulence model is used to model the disturbance caused by the fluid impingement on the wall and the rotation of the workpiece. The species transport model is activated in order to model the vaporization and boiling of the coolant droplets and fluid film. The Wall-film model is applied to the interfaces between solid and fluid domain, which can simulate the collision and heat transfer between wall and droplets.

For all turning tools used for simulation, the tool-chip contact area is 0.5 mm×1.5 mm, the heat flow rate conducted into the cutting insert is 20 W/mm^2, and the cutting speed of the turning tool is set to 100 m/s. In this simulation, the workpiece material is steel which adopt from Fluent, and the materials properties of the tool and other parameters used in the simulation can be referred to [6].

4. Simulation results and discussions

In the cutting process, the cutting temperature depends not only on the amount of heat transferred into the tool but also on the cooling method. Different cooling methods have different ways to dissipate heat, and their cooling performance will be different. This paper mainly examines the influence of different cooling methods on the tool-chip interface temperature. During the simulation, the temperature variation of the tool-chip interface was recorded until it was stable, then terminated the calculation and the results were output.

Fig.3 shows the temperature contour of each tool. It can be seen from Fig. 3 that under the same conditions, the maximum temperature of the circulating internal cooling turning tool is 591.4K, and that

of the composite cooling turning tool is 568.5K. It is clearly shows that the cooling efficiency can be improved by adding spray cooling to the circulating internal cooling tool. This is mainly because spray cooling increases heat dissipation through convection heat transfer of high-pressure air, evaporation and boiling of liquid droplets, and convection heat transfer, evaporation and boiling of liquid film formed after liquid droplets collide with the wall surface. It is worth noting that the tool-chip interface temperature of the single-nozzle type and double-nozzle type composite cooling tool is almost the same, thus the cooling efficiency of the two cooling methods is almost the same. From the cooling performance point of view, the choice of the two methods is indistinguishable.

(a) Temperature contour of the circulating internal cooling tool

(b) Temperature contour of the single-nozzle composite cooling tool

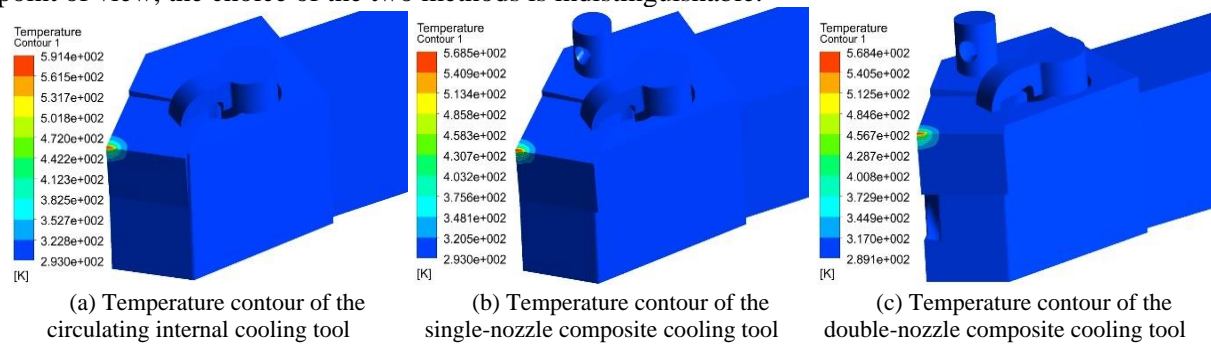(c) Temperature contour of the double-nozzle composite cooling tool

Fig.3 The temperature contour of each tool

When the liquid droplets flow in the curved channel, some of them will collide with the wall of the channel and adhere to the wall to form liquid film. The accumulated liquid droplets or film on the wall would be re-atomized into bigger particles by high speed air flow and escape from the nozzle outlet to cool the cutting zone. As shown in Fig. 4, it illustrates the velocity and the spatial dispersion contours of the cooling droplets of the two type composite cooling turning tool. It can be seen that the maximum droplet velocity of the double-nozzle type composite cooling tool is slightly larger than that of the single-nozzle type composite cooling tool under the same inlet pressure. It can also be seen that some of the liquid droplets rebound or splash after colliding with the walls due to the high velocity of the liquid droplets after exiting the nozzles. The droplets only flow to the tool-chip interface after they flow out from the single-nozzle composite cooling turning tool, while the droplets flow to both the tool-chip and tool-workpiece interfaces after they flow out from the double-nozzle composite cooling turning tool. Therefore, it can be inferred that the lubrication performance of the double-nozzle composite cooling turning tool is better than that of the single-nozzle composite cooling turning tool. From the point of view of cooling and lubrication, the double-nozzle composite cooling tool has more research value than the single-nozzle composite cooling tool.
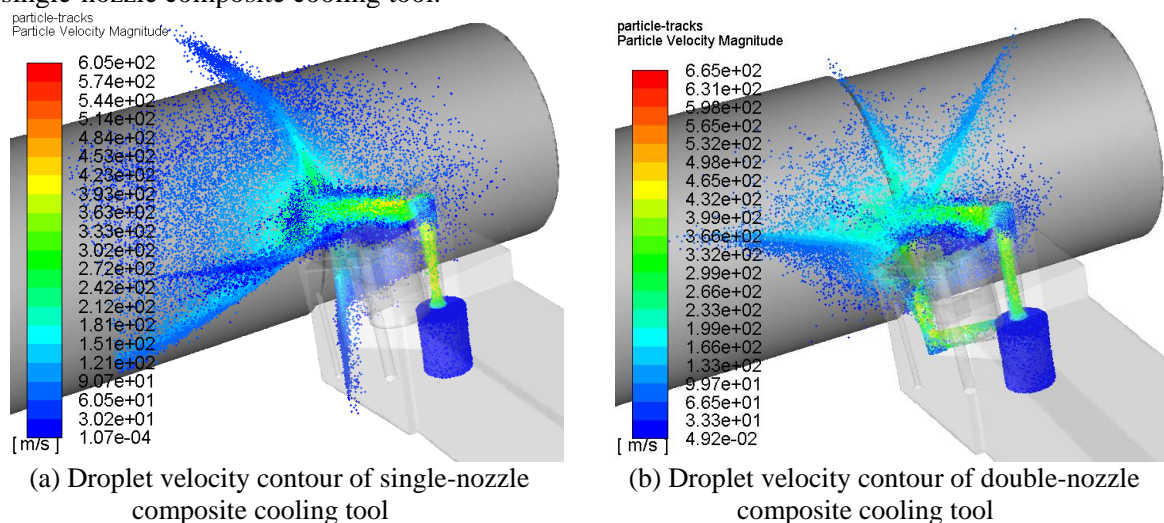

(a) Droplet velocity contour of single-nozzle composite cooling tool

(b) Droplet velocity contour of double-nozzle composite cooling tool

Fig.4 The droplets velocity contour of two type composite cooling tool

5. Conclusions

In this paper, the thermal-fluid-solid coupling simulations were carried out by FLUENT software to investigate the temperature in cutting process between the composite cooling turning tool and the circulating internal cooling turning tool. The composite cooling method based on circulating internal cooling and spray cooling can greatly reduce the temperature in cutting zone, and can lubricate the tool-chip interface thus extend the tool life. The influence of the number of spray nozzle on the cooling capacity of composite cooling tool was also studied. The simulation results show that the cooling performance of single-nozzle type and double-nozzle type composite cooling tool is almost the same, while the lubrication performance of the double-nozzle composite cooling turning tool is better. The cooling structure and nozzle of spray cooling can be further optimized to improve the cooling performance.

From above results, it is found that the composite cooling cutting tool has great potential for machining difficult-to-machine materials such as Titanium, Inconel and chemical explosive material. Furthermore, it is worthwhile to investigate the influence rule of cooling parameters such as inlet pressure, the temperature and flow rate of the cooling liquid on the cooling performance of the composite cooling tool, and to apply it for adaptive machining where abnormal temperature rising of the cutting tool and thus tool wear can be avoided.

6. Acknowledgments

7. References

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