Investigation on cooling performance of a composite cooling turning tool based on CFD and Taguchi method

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Abstract. In order to decrease the cutting temperature and assist the chips removal while reduce or eliminate the generation of cutting waste liquid in metal cutting process, a novel turning tool cooled by combining circulating internal cooling with spray cooling is proposed. In this paper, the cooling performance of the composite cooling tool is investigated by the combination of CFD based thermal-fluid-solid coupling analysis which were carried out by Fluent and Taguchi design. A discussion on the influence of cooling parameters on the cooling performance of the composite cooling tool is conducted. The results show that the order of the influence of each parameter on the cutting temperature is as follows: coolant temperature of circulating internal cooling, spray pressure, air temperature of spray cooling, coolant flow rate of circulating internal cooling and coolant flow rate of spray cooling. The optimal parameters in this study are: spray pressure is 0.45 MPa, coolant flow rate of spray cooling is 150 ml/h, air temperature of spray cooling is 2 °C, coolant flow rate of circulating internal cooling is 2 m/s, coolant temperature of circulating internal cooling is 2 °C.

1. Introduction

Cooling technology plays a very important role in the machining process. Good cooling methods in the machining process can improve the tool life and machining dimensional accuracy while reducing the cutting temperature and surface roughness. In recent years, the concept of green manufacturing has attracted the attention of many countries, and some clean and efficient cooling methods have been developed[1-2]. The purpose of these technologies is to reduce or eliminate the hazards to the environment and workers caused by the use of traditional cutting fluids. Among them, it is a promising method to realize green cutting by using a proper internal cooling tool system during the machining process. The circulating internal cooling technology can guide the coolant pass through the internal channels of the tool to reach the cutting area where the external cooling method is difficult to access, thereby decreasing the wear rate of the tool and improving the machining quality of the workpiece. Because the contact between the coolant and the surface of the workpiece is avoided in this way, the processed workpiece does not need to be cleaned, which greatly reduces the production cost.

In metal cutting process, heat energy gathers in the tool-chip interface. Most of the heat energy is conducted into the chips and some portion of which dissipate into the cutting insert and the support seat and the tool header. The common design method of internal cooling tool is to reduce cutting
temperature by cooling toolholder and support seat with built in cooling structures[3-4]. This method can increase the temperature gradient between the tool holder and the insert. Therefore, more cutting heat would conducted away from the insert, which reduces the tool-chip interface temperature. However, it should be noted that the cooling liquid only circulates inside the tool, it cannot cool the chips, workpiece and assist the chip removal. The spray cooling technology can assist chip removal well due to the high spray pressure and fast droplet speed[5]. Moreover, spray cooling technology can reduce cutting temperature through forced convection heat transfer, film evaporation, and nuclear boiling. Therefore, spray cooling channels can be embedded inside the tool holder of the circulating internal cooling tool, and the cutting zone can be cooled by the spray outlet. Such a tool design concept not only allows the cooling medium to fully enter the workpiece-tool-chip interfaces, but also assist chip removal while cooling the cutting zone.

The influence of spray cooling parameters on cooling performance is often reported in the application of external nozzle[6-7], but the research on the embedded nozzle and particularly on the cooling performance of composite cooling tool is rarely. In this work, a three-dimensional CFD simulation model of the tool was built and the fluid-solid thermal coupling simulations were carried out by using Fluent software to reveal the cooling performance of the composite cooling tool. A combination of CFD and Taguchi design method were used to study the influence of spray pressure, coolant flow rate of spray cooling, air temperature of spray cooling, coolant flow rate of circulating internal cooling and coolant temperature of circulating internal cooling on the cooling performance of the composite cooling tool, and the optimum cooling parameters levels combination was obtained. This work provides a basis for the application in industry of the composite cooling tool based on internal cooling and spray cooling.

2. Establishment of the simulation model

2.1. The 3-D model of the composite cooling turning tool

As shown in Fig.1, the cooling structure of the composite cooling turning tool proposed in this paper include circulating internal cooling structure and internal spray cooling structure. The design of the circulating internal cooling structure is to set an annular groove on top of the support seat and decrease the cutting insert thickness so that the coolant can get closer to the cutting zone. 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 arranged on the bottom surface of toolholder to facilitate the installation of external cooling system.

![Fig.1 The 3-D model of the composite cooling turning tool](image-url)
the rake face and parallel to the minor cutting edge and the spray direction of the lower spray outlet should be aligned with the cutting tip as much as possible. It is worth noting that the spray cooling channels cannot interfere with the circulating internal channels due to the difference between the circulating internal cooling and the spray cooling medium.

2.2. Meshing and boundary condition

In order to make the simulation results closer to the actual situation, in addition to the geometry model of the turning tool, a fluid domain was established for all the analysis models to simulate the heat transfer between fluid and solid, and the workpiece and a small curved chip were also created to consider their effects on fluid flow and heat transfer. In the process of simulation, the mesh density and quality will affect the accuracy and convergence of the analysis results. In general, dense mesh leads to high calculation accuracy, but too many grid will significantly increase the computation time. Due to the very small of the tool-chip interface and complex geometric model around the cutting zone, it is easy to cause mesh division difficult. For example, the mesh will be severely distorted or even appear negative volume, thus affecting the convergence of calculation. In view of the above, the simulation model uses tetrahedral mesh, the mesh size of the fluid domain around the cutting zone was small, and the mesh was inflated for the interface between toolholder and cooling channel. The overall mesh model of simulation is shown in Fig. 2.

![Fig. 2 The overall mesh model of simulation](image)

Reasonable boundary condition can not only speed up the convergence of the flow field, but also improve the accuracy of the simulation. The cooling methods of the composite cooling turning tool are divided into circulating internal cooling and spray cooling, and are set different boundary conditions. For the circulating internal cooling method, the purified water is used as the cooling liquid, the inlet is set as velocity-inlet and the outlet is defined as pressure-outlet. For spray cooling, the inlet is set as pressure-inlet and the outlet is set as pressure-outlet. The DPM boundary conditions at the inlet and outlet are set as escape. The wall-film model is applied to the interfaces between spray cooling domain and the tool and workpiece which used to simulate the collision and heat transfer between the wall and the droplets. For all the simulations, the tool-chip contact area is 0.5mm×1.5mm, and the heat flow rate conducted into the cutting insert is 20W/mm², the cutting speed of the tool is set to 100m/s. The remaining parameters are defined according to different experimental design schemes.

3. Taguchi's experimental design

Because Taguchi's experimental design can significantly reduce the number of experiments and improve the efficiency of the optimization process. Therefore, the orthogonal table combined with the CFD based thermal-fluid-solid coupling simulation analyses is used to integrate into account the influence of the cooling parameters on the cutting temperature. Five cooling parameters spray pressure (A), coolant flow rate of spray cooling (B), air temperature of spray cooling (C), coolant flow rate of circulating internal cooling (D) and coolant temperature of circulating internal cooling (E) were selected as design parameters, and each parameter has three levels. Generally, the maximum tool temperature appears in the tool-chip interface. The maximum tool-chip interface temperature can reflect the cooling efficiency of different cooling schemes and thus it is selected as the output response. The orthogonal experiment design using Taguchi's Table L18(3^5) which is shown in Table 1.
4. Simulation results and discussions

4.1. The influence order of each parameter on cooling performance

ANOVA is the quantitative estimation of the variation caused by each factor to obtain which of the many experimental factors are the variables that have a significant impact on the experimental index. In order to find the parameters that have an important influence on the cooling performance of the tool to improve its cooling efficiency. The significance test of each cooling parameters on maximum temperature was performed by ANOVA, and the results were shown in Table 2.

### Table 2 Analysis of variance for maximum temperature

| Source         | Sum Sq. | d.f. | Mean Sq. | F      | Prob>F |
|----------------|---------|------|----------|--------|--------|
| A(MPa)         | 203.431 | 2    | 101.716  | 93.186 | 0.000009 |
| B(ml/h)        | 1.132   | 2    | 0.566    | 0.519  | 0.616612 |
| C( ℃)          | 105.619 | 2    | 52.809   | 48.381 | 0.000080 |
| D(m/s)         | 82.854  | 2    | 41.427   | 37.953 | 0.000175 |
| E( ℃)          | 298.195 | 2    | 149.098  | 136.595| 0.000002 |
| Error          | 7.641   | 7    | 1.092    |        |         |
| Total          | 5670862.71 | 18 |        |        |         |

It can be seen from Table 2 that the P-value of the coolant flow rate of spray cooling (B) is above the significance level 0.05, which indicating that it has no significant influence on the cutting temperature. The spray pressure (A), air temperature of spray cooling (C), coolant flow rate of circulating internal cooling (D) and coolant temperature of circulating internal cooling (E) have significant effects on the cooling performance of the composite cooling tool because their P values are much small than 0.05. The influence order of each parameter on the cooling efficiency of the composite cooling tool can be deduced by their P values in Table 2, which is as follows: coolant temperature of circulating internal cooling, spray pressure, air temperature of spray cooling, coolant flow rate of circulating internal cooling, and coolant flow rate of spray cooling.
4.2. Discussion on the influence of each parameter on cooling performance

In order to be able to more intuitively indicate the influence of each cooling parameter on the cooling performance of the composite cooling tool and obtain the optimal level of each cooling parameter. The mean effect chart of each parameter in Table 1 is shown in Fig. 3.

![Mean effect chart of each parameter](attachment:image)

**Fig. 3** Mean effect chart of each parameter

It can be seen from Fig. 3 that the influence order of each parameter on cooling performance can be obtained by comparing the influence range of each cooling parameter on cutting temperature. The influence order of each parameter on cooling performance is the same as that inferred from the p-value in the above section. As for the spray pressure (A), the cutting temperature decreases as the spray pressure increases and it has a significant effect on the cooling performance of the composite cooling tool. This may be mainly because the increase in spray pressure leads to the increase in the impact velocity of the droplets, which makes it easier for the droplets to enter the tool-chip interface for heat exchange. Similarly, the air temperature of spray cooling (C) and the coolant temperature of circulating internal cooling (E) also have a significant effect on the cutting temperature. The cooling performance becomes better with the coolant temperature decreases. This may be due to the increased temperature difference between the coolant and the cutting zone, which makes it easier for heat to be conducted from the high-temperature the insert to the low-temperature coolant. For the coolant flow rate of circulating internal cooling (D), the cutting temperature decreases as the coolant flow rate increases. When the coolant flow rate of circulating internal cooling is less than 1 m/s, the cutting temperature decreases rapidly with the increase of the coolant flow rate. However, when the flow rate increased from 1 m/s to 2 m/s, the reduction of the cutting temperature slowed down, which indicating that there was a turning flow rate. For the coolant flow rate of spray cooling (B), the cutting temperature decreased as the spray flow rate increased, but the trend was not obvious. On one hand the increase of flow rate may give rise to increasing the droplets velocity and thus strengthen the forced-convection heat transfer, but on another hand the presence of chip has a blocking effect on the spreading of droplets, which hinder the heat transfer between the droplets and the cutting zone.

Based on the above results and discussions, the optimal cooling parameters levels combination is A3B3C1D3E1. The optimal parameters are spray pressure (A) = 0.45 MPa, coolant flow rate of spray cooling (B) = 150 ml/h, air temperature of spray cooling (C) = 2 °C, coolant flow rate of circulating internal cooling (D) = 2 m/s, coolant temperature of circulating internal cooling (E) = 2 °C. It can be seen that it is different from each combination in Table 1, so another simulation under the optimal levels combination of cooling parameters should be performed to validate its effectivity.

In order to verify that the cooling efficiency of the composite cooling turning tool under optimal cooling parameter combination is higher than that of all the schemes in orthogonal array Table 1, the fluid-solid-thermal coupling simulation analysis of the composite cooling tool was carried out under the combination of optimized cooling parameters. In the simulation, the setup of solution is the same as the above analyses. Fig. 4 shows the tool temperature contour of the composite cooling turning tool under the optimal cooling condition. It can be seen from Fig. 4 that the maximum temperature of the composite cooling turning tool is located in the tool-chip interface, and the maximum temperature is 547.867K. The maximum tool temperature of the cooling scheme with the best cooling performance in Table 1 is 548.31 K, which indicates that the optimal cooling parameter levels combination A3B3C1D3E1 has better cooling ability.
Fig. 4 Tool temperature contour of the composite cooling turning tool under A3B3C1D3E1

5. Conclusion
In this paper, a combination of Taguchi method and CFD based thermal-fluid-solid coupling simulations was used to investigate the cooling performance of the composite cooling turning tool. The influence of spray pressure, coolant flow rate of spray cooling, air temperature of spray cooling, coolant flow rate of circulating internal cooling and coolant temperature of circulating internal cooling on the cooling performance of the composite cooling turning tool was studied. From the results, the spray pressure, the air temperature of spray cooling, the coolant flow rate of circulating internal cooling and the coolant temperature of circulating internal cooling have a significant effect on the cutting temperature. The effect of coolant flow rate of spray cooling on cutting temperature is not obvious. The optimal levels combination of cooling parameters was obtained by the Taguchi method, which laid the foundation for its practical application in factory.

6. Acknowledgments
The authors would like to acknowledge the funding support for this research by the National Natural Science Foundation of China (Grant No. 51705153) and the Jiangxi Provincial Natural Science Foundation of China (Grant No. 20192BAB206029).

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