Research on the High-Temperature Strength of Heavy Drilling Tool in the Rough Machining Process

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Abstract. In the rough machining process, the thermal fatigue fracture is the destructive phenomenon which often affects the service life of cemented carbide insert. This paper explores the problem of hot crack production of super-heavy turning tool, and the 3D cutting model is established. In order to simulate the interrupted cutting as accurately as possible, supposing that the heat flow in this model is the rectangular wave, and then using finite element method to simulate the distribution state of both the alternating temperature and the thermal stress. However, for accurate analyzing and researching the contact state between the tool and chips, the intermittent cutting test is made under the condition of laboratory. The experimental result shows that in different cutting process, the temperature distribution on tool's surface is uneven and there are tensile stress together with compressive stress exist in the vicinity of the cutting edge. Besides the size of two kinds of stress depends on the performance of the tool material and cutting conditions, and they are the main reason for causing the thermal crack.

Introduction

The main processing objects of drilling are the super-heavy components whose blanks are forged straight. This machining is a special kind of intermittent cutting process, as the contact states of the super-heavy drilling tool and the work-piece surface (such as cutting depth a_p and cutting width a_w) change constantly, and there is very intense friction between rough surface of work-piece and drilling tool. As a result, the drilling tool is always under the effect of variable load of both the heat shock and the mechanical impact. In the super-heavy drilling process, the alternating high-temperature shock will cause the rake face of the super-heavy drilling tool to generate the crack, which is perpendicular to cutting edge. At present, most of the studies show that: the cutting heat makes the tool crack generate in some way[1-3]. Boston and Gilbert found that the hot crack would bring about on the rake face when the cemented carbide tools were used in the intermittent cutting process[4]. Then, Zorew N. N. further proposed that the temperature on the surface was lower than the internal in the non-cutting state, and this case would cause the tensile stress, which made the tool produce crack. The Recent studies of both Braiden P. M. and Hoshi T. showed that the plastic deformation in the tool internal overheating area was the real reason for tool crack formation. However, large numbers of researches on the mechanism of the tool's crack formation aim at the normal intermittent cutting, for the super-heavy drilling, there is no report on the study of production mechanism of the tool's hot crack. Therefore, it has a positive significance to explore the causes of tool's crack and establish the preventive measures after researching the high-temperature strength of the super-heavy drilling tool in the intermittent cutting process.

Analysis and Research on the Thermal Load of Heavy Drilling

The Distribution of Alternating Thermal Load

For a long time, the tool's temperature distribution is a research project in which the researchers are interested. And the early researches mainly focused on the study of cutting temperature among tools, chips and work-piece[5,6]. These studies have derived many empirical formulas, which are used for calculating the relationship of the interfacial temperature among the material properties of the tools and the work-pieces, cutting speed and feed rate, cutting depth (mainly used in continuous cutting process).

However, the research on the steady state temperature distribution can't satisfy the basic demand when analyzing the hot crack of heavy drilling tool in intermittent cutting process. Both the temperature gradient in tool's interior and the mechanical binding force on the tool's interface are the main reason that thermal stress generates[7], as a result, the analysis on the alternating temperature must be made. Since many reports showed that the rake face of the heavy drilling tool would generate the crack, which is perpendicular to cutting edge in intermittent cutting process[8]. Thus, in the light of the characteristics of heavy drilling, the alternating temperature near the cutting edge is analyzed carefully and the 3D cutting model is also established (as shown in Fig. 1). In order to simulate the tool's thermal loading conditions in intermittent cutting process, assuming that heat transfer is in the form of rectangular wave (as shown in Fig. 2). Last, the finite element analysis is utilized to solve the problem of effective heat transfer, then the instability distribution of tool's temperature is proved up (as shown in Fig. 3). From the cutting model, the thermal conduction equation about tool-chips-work piece is established as Eq. (1).

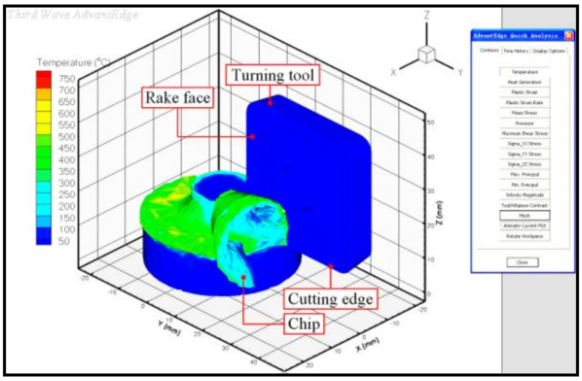


Fig.1 The Geometry and coordinates of 3D cutting model of the heavy drilling tool

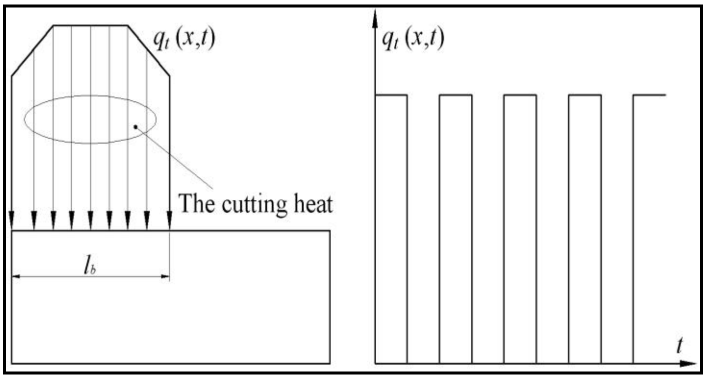


Fig.2 Cutting heat transfer model of intermittent cutting

$$Q \cdot c = \frac{\partial \delta}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial \delta}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial \delta}{\partial y}\right) \qquad (1)$$

Where, c is the thermal ratio of material. k_x and k_y are the thermal conductivity.

Seen from the Fig. 1, most of the heat generated in the cutting process is taken off by chips, and the tool's heat distribution is uneven. In view of this situation, the Fig. 2 is the scheme, which simulates the thermal load tool withstanding in intermittent cutting process, that is, the model in the form of rectangular wave is adopted[9]. And supposing that the heat distribution area were only on the interface between tool and chips in drilling process, and the state of interface have nothing to do with the time. Now, the intermittent cutting process is analyzed as follows:

1) The cutting process of contact

$$k \times \frac{\partial \delta}{\partial n}\bigg|_{\omega} = q(x,t) \left.\begin{matrix} 0 \le x \le l_b \\ y = 0 \end{matrix}\right\} \tag{2}$$

$$k \times \frac{\partial \delta}{\partial n}\bigg|_{\omega} = \text{-}h(\delta_{\omega} - \delta_s) \left.\begin{matrix} x > l_b \\ y \ne 0 \end{matrix}\right\} \tag{3}$$

2) The cutting process of non-contact

$$k \times \frac{\partial \delta}{\partial n}\bigg|_{\omega} = \text{-}h(\delta_{\omega} - \delta_s) \Big\} \tag{4}$$

The result of analysis shows that the conduction relationship of cutting heat can be calculated through using finite element method. And then using the differential method to find the equivalent set of the first-order differential equation of the unit heat that the temperature describing. Finally, the Gaussian elimination and computer is used for calculating these equations further and then the actual temperature distribution is obtained.

Distribution Characteristics of Tool's Thermal Stress

As to the problem of the stress distribution on the tool rake face in the 3D cutting process, the elastic equation can be obtained ad Eq. (5)[10]:

$$\begin{cases} e_{xx} = \frac{1}{E}(\sigma_{xx} - \upsilon\sigma_{yy}) + \alpha(\delta - \delta_0) = \frac{\partial u}{\partial x} \\ e_{yy} = \frac{1}{E}(\sigma_{yy} - \upsilon\sigma_{xx}) + \alpha(\delta - \delta_0) = \frac{\partial \upsilon}{\partial y} \\ e_{xy} = \frac{1}{G}\sigma_{xy} = \frac{\partial u}{\partial x} + \frac{\partial \upsilon}{\partial y} \end{cases} \tag{5}$$

Where, α is the linear expansion coefficient. δ is the alternate temperature. δ_0 is the reference temperature when there is not stress on the tool's rake face.

The alternate temperature is obtained based on the earlier analysis of temperature distribution. For the mechanical binding force, supposing that the cutting force were limited on the contact surface of tool and chips, and the tool could be bent arbitrarily. Then, the thermal stress equation of the tool in heavy drilling process will be obtained as Eq. (6) and Eq. (7):

1) The cutting process of contact

$$\begin{cases} F_y = f(x);\ 0 \le x \le l;\ y = 0 \\ u = \upsilon = 0;\ x = 0;\ y = b \\ \upsilon = 0;\ y = b \end{cases} \tag{6}$$

2) The cutting process of non-contact

$$\begin{cases} u = \upsilon = 0;\ x = 0;\ y = b \\ \upsilon = 0;\ y - b \end{cases} \tag{7}$$

Through the two formulas above, the distribution of thermal stress on the cutting area which is under the condition of alternate thermal load can be calculated.

Experimental Analysis on the Generation of Hot Crack

In order to simulate the contact state of the tool and the chips in the super-heavy drilling process as accurately as possible, the intermittent drilling experiment is made. Taking the drilling parameter including "feed rate f=0.2mm/r and drilling speed v_c=60~100m/min" as standard, then improving the value of the cutting parameters gradually. The mechanical properties and chemical composition of the materials of cutting test is shown in Tab.1, and The performance parameters of the testing tool is shown in Tab.2, the result is shown in Fig. 4.

Tab.1 Mechanical properties and chemical composition of the materials of drilling test

Materials	Heat-treated condition	Hardness HB	σ_s [MPa]	σ_b [MPa]	δ %
2.25Cr-1Mo-0.25V steel	Quenching and tempering	235	809.7	760	18
45 steel	Normalization	163~218	285.4	568.9	15
Main chemical composition					
Materials	P	S	Cr	Si	C
2.25Cr-1Mo-0.25V steel	≤0.009	≤0.006	2.0	≤0.12	0.16
45 steel	≤0.05	≤0.045	——	0.28	0.475

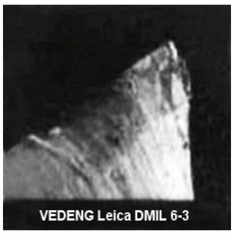
Tab.2 The chemical composition and physical properties of testing tool

Grade	C [%]	Co [%]	Ti [%]	Fe [%]	Hardness [HV]
A	5.3	20	0.3	0.1	1300
B	8.3	9	15	0.3	1600

The crack of tool *A*

The crack of tool *B*

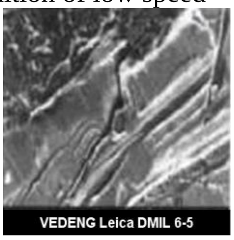
a) Broken cutter in the condition of low speed



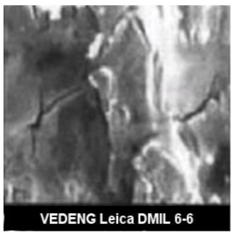
The crack of tool *A*

The crack of tool *B*

b) Broken cutter in the condition of moderate speed



The crack of tool *A*



The crack of tool *B*

c) Broken cutter in the condition of moderate-high speed

Fig.4 The thermal crack on tool's surface under the conditions of different cutting parameters

During the experiment, we found that both the tool *A* and *B* appear the cracks after cutting two minutes. Seen from the Fg. 4, we can know that the cracks on both the tool *A* and *B* become more and more obvious along with the increase of drilling parameters, and this explains that drilling parameters has conspicuous influence on the cutting heat. Comparing Fg. 4-a with Fig. 4-b and Fig. 4-c, the result shows that both tool *A* and *B* appear transverse cracks, however the growth degree of tool *B* is slighter than tool *A*. All these show that the tool's composition has a greater impact on its cutting performance. According to the thermal stress distributional equation, when the tool is under the action of alternating thermal load purely, the temperature distribution of cutting area can be shown as Fig. 5.

Seen from Fig. 5, both the distribution situation and the changing amplitude of cutting temperature at different distances of main cutting area are very obvious. The temperature near the cutting area was significantly higher than the temperature of other parts of the tool, as a result, in different cutting process the temperature distribution on tool's surface is uneven and there are tensile stress together with compressive stress exist in the vicinity of the cutting edge. Owing to the existence of these two stresses, the original stress equilibrium of the tool is destroyed, and the hot crack is produced. Alternating high-temperature load and thermal stress will increase the development of the hot crack, and lead to tool's damage.

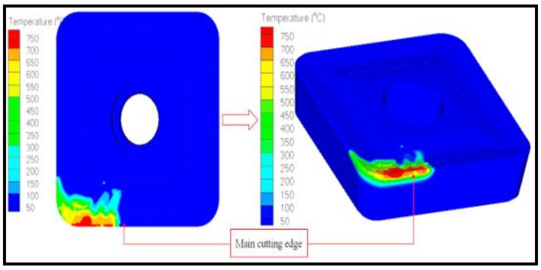


Fig.5 The state of cutting temperature distribution in cutting area

Conclusions

The heavy drilling is a special kind of intermittent cutting process, and the drilling tool is always under the effect of variable load of both the heat shock and the mechanical impact. The alternating high-temperature shock will cause the rake face of the heavy drilling tool to generate the crack, which is perpendicular to cutting edge, and the fracture will happen when the tool is affect by the mechanical impact. Through analyzing and researching the production mechanism of hot crack of heavy drilling tool, the following conclusions will be obtained:

1) In intermittent cutting process, owing to the uneven temperature distribution on tool's cutting area, the tensile stress together with the compressive stress will be produced. The existence of these two stresses, the original stress equilibrium of the tool is destroyed, and the hot crack is produced.

2) The hot crack mainly causes the cutting edge to generate breakage, and sometimes the one near the tool's tip will even lead to it fracture. In view of this situation, the larger nose radius can be taken for prevent it from happening.

3) The position that the hot crack appears densely, the phenomenon about the materials exfoliated will happen on the tool's rake face.

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