Simulation study on influence of coating thickness on cutting performance of coated ceramic cutting tools

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Abstract. The processes of cutting gray iron with coated ceramic tools were simulated using the cutting simulation software named AdvantEdge. The effect of coating thickness on cutting temperature, cutting force, and maximum equivalent stress of cutting tools were investigated. Firstly, a finite element cutting simulation model was established to investigate the influence of coating thickness of coated ceramic tools. The cutting simulation model was verified through cutting gray iron experiment. And the model has validity. Both the simulation and experimental results showed that the cutting temperature, cutting force and the maximum equivalent stress were obtained to be minimum when the coating thickness was 2 μm, reaching 444.5 °C, 102 N and 1949.8 MPa, respectively. Finally, the relationship between the interface characteristics and cutting performance of coated ceramic tools were qualitatively described by the functional relationship between the maximum equivalent stress and the coating thickness. Since the maximum equivalent stress of the tool can reflect the tool wear condition, the optimum coating thickness can be obtained corresponding to the minimum tool wear using the relationship between the maximum equivalent stress and the coating thickness.

1. Introduction
At present, the cutting tools employed in the market are mainly high-speed steel and cemented carbide cutting tools. Although high-speed steel has high strength and good toughness, its hardness and wear resistance are low. Hard alloy cutting tools have high hardness and good wear resistance, but they have poor strength and poor toughness. Ceramic cutting tools are suitable for high-speed finishing. Especially, ceramic coating can improve the hardness and wear resistance of cutting tools, and can prolong the service life of cutting tools by several times. However, due to the high cost of ceramic tools, ceramic tools account for less proportion in the market. In order to make up for the defects, the finite element simulation software AdvantEdge can simulate the cutting force, cutting temperature, residual stress, tool wear and other parameters involved in the cutting experimental process.

Finite element method has been proved as a very efficient approach in predicting the performance of cutting tools. AdvanEedg, a finite element simulation software (FESS), can simulate the cutting
force, cutting temperature, residual stress, tool wear and other parameters involved in the cutting experimental process. Simulation with the aid of FESS has become one of the important methods to study cutting experimental, which plays an important role in the development and application of cutting tools.

Peng et al. [1] used the finite element method to analyze the cutting process of conventional cutting and prestressed cutting of titanium alloy, and the constitutive model is described by Johnson-Cook model expressed by equivalent plastic strain flow stress. The results show that the prestress changes the initial stress of the workpiece and causes the stress distribution in the subsurface layer. Prestress has little effect on the temperature distribution and equivalent plastic strain on the workpiece. The cutting force curve has the same average amplitude and similar fluctuation rhythm. Lu et al. [2] carried out finite element simulation of temperature and stress distribution during micro-cutting of titanium alloy TiAl6V the distribution of cutting force, equivalent stress and strain and temperature are obtained. The effects of cutting speed and thickness of uncut chips on the maximum temperature and maximum shear stress are analyzed, and the size effect is observed. Lin et al. [3-5] simulated the nano-scale orthogonal cutting process of single crystal copper workpiece with diamond tool by quasi-steady state molecular statics method. Based on the simulation, the cutting force, equivalent stress and strain and temperature field are obtained. Wang et al. [6] established the ultra-precision machining process by using the three-dimensional finite element simulation model, and the simulation of the cutting formation process is successfully realized. The cutting force, cutting temperature, equivalent strain and equivalent stress are compared in orthogonal cutting process and oblique cutting process. Qin et al. [7] studied the influence of coating thickness on diamond coated tools. The residual stress in the tool caused by thermal mismatch was simulated by finite element method, and the influence of coating thickness on the tool interface stress was quantitatively calculated. Research shows that the coating thickness increases the residual stress at the coating-substrate interface, and increases the crack resistance and delamination of the coating. Thepsonthi T et al. [8] studied the 3D finite element modeling and simulation of Ti-6Al-4V titanium alloy micro-end milling process. The results show that tool wear has a significant impact on cutting force, cutting temperature, tool wear rate, chip flow and burr formation. In addition, a comparison between three-dimensional and two-dimensional finite element simulations is also provided. Ma et al. [9] also used the general finite element software ANSYS/LS-DYNA to simulate the cutting process of austenitic stainless steel. The results show that during cutting, the maximum equivalent stress extends below the machined surface, which is one of the reasons for work hardening. Shear plane temperatures are almost equal.

Many researchers employed finite element method to simulate the cutting process. The cutting force, cutting temperature, equivalent stress and other cutting process parameters were obtained and analyzes. The simulation results are consistent with the cutting process. Qin et al. [10] developed two-dimensional cutting to simulate the coating - substrate interface characteristics and deposition residual stress of diamond coated tools. It is proved that interface cohesive zone in diamond coated tool is feasible in two-dimensional cutting simulation, and the residual stress may lead to crack interface cohesive zone. Kumar et al. [11] investigated hard machining performance of Al2O3/TiCN based mixed ceramic insert as a function of thin film thickness. It is found that coating adhesion to the substrate increased with thickness for AlTiN coated tools whereas for AlCrN coating, 3 um thin coating film exhibited best substrate adhesion which affected the machining behavior. Wei et al. [12] established a finite element geometric model to simulate the bond strength of plasma sprayed thermal barrier coatings. At the same time, damage accumulation and microcrack growth can be vividly observed through simulation treatment. Wang et al. [13] studied the bond strength of coating/matrix by finite element method, and confirmed that the finite element model was consistent with Hertz's analytical solution. The finite element model could provide reliable stress values. Bouzakis et al. [14,15] studied the Before depositing nanocrystalline diamond coating, the effects of two different hard alloy substrate treatments on the fatigue strength of the coating interface at 25 °C and 300 °C were studied. The interface fatigue strength deteriorates with the increase of impact experimental temperature. At ambient temperature and high temperature, the substrate co-etched by the adhesive Cr
interlayer and the composite substrate have higher interfacial strength. In conclusion, the finite element simulation software AdvantEdge effectively simulates the cutting force, cutting temperature, residual stress and other parameters in the cutting process. In this paper, the effect of coating thickness on the cutting performance of coated ceramic tools was investigated by AdvantEdge simulation software. And the quantitative relationship between the interface characteristics and cutting performance of coated ceramic tools was analyzed.

2. Cutting experimental and simulation model

2.1. Experimental condition

The dry cutting experimental was carried out on a CDE6140A lathe (Dalian Machine Tool Group, China) and workpiece material was gray cast iron with the chemical composition is shown in Table 1. Specifications of the coated ceramic tools were shown in Table 2. The blade model is SNGN120412 and the handle model used is Kenna GSSN R/L 2525M12-MN7. The tool coating thickness was obtained by SEM inspection. The cutting parameters were selected as feed rate f=0.198 mm/r, back engagement a_p=0.5 mm, and cutting speeds v=200 m/min and v=300 m/min, respectively. The cutting force was measured by 9129AA dynamometer, and the cutting temperature was collected by FlIR infrared thermal imager.

| Brand     | Matrix | Coating (from outside to inside) | Coating method | Coating thickness (um) |
|-----------|--------|---------------------------------|----------------|------------------------|
| CS7050    | Si₃N₄  | TiN/Al₂O₃/TiC                   | CVD            | 2.5                    |
| GC6190    | Si₃N₄  | TiN/Al₂O₃                       | CVD            | 2.9                    |
| KY4400    | Al₂O₃+TiC | TiN                             | PVD            | 0.8                    |
| A66N      | Al₂O₃/TiC | TiN                             | PVD            | 0.5                    |

2.2. Simulation model

Fig.1 (a) shows the contact situation between the workpiece and the tool during the actual cutting process. In the cutting model, the geometry shape of the workpiece is equivalent to a cuboid, and the tool is simplified, as shown in Fig.1 (b), so that it can normally simulate the cutting process with AdvantEdge software.

![Simulation cutting model](image)

The maximum cell grid needs to be set during the parameter setting process and the maximum unit position of the grid needs to be farthest from the cutting edge. This modeling takes 1mm as the largest
size of the unit. The closer the size of the unit is the cutting edge, the smaller it is, so the smallest unit size nearest to the cutting edge is set as 0.15 mm. Since the grid level determines how quickly the coarse mesh changes to the fine mesh, that is, the larger the grade value of gridding is, the faster it changes [16, 17], so it is set at 0.5 mm here. The physical dimension of mesh cannot be lower than the minimum cutting edge size in the setting process, otherwise, the grid cells will not be able to obtain the normal situation, so the minimum cutting edge size is less than 30% of the minimum blade size [18]. The workpiece material is gray cast iron; the length is set to 5 mm; the height is set to 2 mm, and arc radius of the nose $r_e=0.02$ mm, rake angle $\gamma_0=5^\circ$, relief angle $a_0=10^\circ$, and an ambient temperature of 20 °C

3. Comparison of Experiment and Simulation results

3.1. Cutting temperature

Fig. 2 shows the cutting temperature comparison between the simulated and the experiment when the cutting speed is 200 m/min and 300 m/min. When the cutting speed is 200 m/min, the maximum error between the simulated value and the experimental value is 6.7%, and the minimum error is 3%. The variation trend of the simulated value is the same as the experimental value. When the cutting speed is 300 m/min, the maximum error between the simulated value and the experimental value is 7.8%, and the minimum error is 2%. The variation trend of the simulated value is the same as the experimental value. The results show that it is reliable to investigate the cutting temperature of the coated ceramic tools in cutting gray cast iron using the finite element cutting simulation model established in this work.

![Figure 2](image.png)

**Figure 2.** Comparison of maximum cutting temperature between simulation and experiment: (a) 200 m/min; (b) 300 m/min

3.2. Cutting force

Fig. 3 shows that the comparison between the simulated results and the cutting force obtained from the experiment when the cutting speed is 200 m/min and 300 m/min. It can be seen that the experimental value and the simulated value maintain good consistency and have the same variation trend at this cutting speed, which indicates that it is reliable to research the cutting force of coated ceramic tools cutting gray cast iron using the model established in this research.
Based on the above comparison, it can be observed that the simulation and experimental results of tool cutting temperature and cutting force obtained are consistent.

4. Effect of coating thickness on tool cutting performance

4.1. Effect of coating thickness on cutting temperature

The influence of the coating thickness on the cutting temperature of the tool cannot be ignored. The effect of coating thickness on cutting temperature of tool is simulated by AdvantEdge cutting simulation software. Parameter setting: speed \( v = 300 \text{ m/min} \), depth of cut \( a_p = 0.5 \text{ mm} \), feed rate \( f = 0.198 \text{ mm/r} \). The tool substrate is Si₃N₄ and the coating is TiN. The thickness of TiN coating is 0.5 μm, 1.0 μm, 1.5 μm, 2.0 μm, 2.5 μm and 3.0 μm, respectively.

Fig. 4 shows that the change of cutting temperature under 6 different coating thicknesses. The simulation results are presented in Table 3. It can be observed that the maximum temperature increases first and then decreases with the increase of coating thickness. When the coating thickness is 2.0 μm, the highest temperature of the tool is the lowest. At this time, the separation length of tool chips is the shortest, and the highest point of the tool temperature is located closer to the tool nose. It is indicated that TiN coating thickness of 2 μm is helpful to improve cutting performance of the tool.
Table 3. Comparison of cutting temperatures under different coating thicknesses

| Coating thickness (μm) | maximum temperature (°C) | The position from the highest point of the tip temperature (mm) | Tool-chip separation length (mm) |
|-----------------------|--------------------------|---------------------------------------------------------------|---------------------------------|
| 0.5                   | 449.0                    | 0.08; 0.17                                                   | 0.25                            |
| 1.0                   | 467.5                    | 0.17                                                         | 0.28                            |
| 1.5                   | 454.5                    | 0.18                                                         | 0.21                            |
| 2.0                   | 444.5                    | 0.18                                                         | 0.18                            |
| 2.5                   | 449.9                    | 0.15                                                         | 0.26                            |
| 3.0                   | 450.8                    | 0.13                                                         | 0.25                            |

4.2. Effect of coating thickness on cutting force of cutting tool

The change curve of cutting force with cutting length under 6 different kinds of TiN coating thicknesses condition was simulated. The coating thickness of 3.0 μm was taken as an example, as shown in Fig. 5(a). It can be found that the cutting force of the tool gradually increases to the maximum when the tool first contacts the workpiece, then decreases, and finally the cutting force tends to stabilize. The main cutting forces simulated under 6 different kinds of coating thicknesses are summarized, as shown in Fig. 5(b). It can be seen intuitively that during the process of TiN coating thickness increasing gradually from 0.5 μm to 3.0 μm, the main cutting force first increases, then decreases, and finally slightly increases, when the coating thickness is 2.0 μm, the cutting force appears the minimum, which shows that the ceramic cutting tool under this coating thickness has the best cutting performance.

4.3. Effect of coating thickness on maximum equivalent stress of tool

The magnitude of the tool’s equivalent stress can reflect the wear condition of the tool. When the equivalent stress of the ceramic tool is small, the lower the wear of the tool during cutting is, the longer the life of the tool is. Therefore, the influence of the interface characteristics on the dry cutting performance of the tool is discussed by studying the maximum equivalent stress of the tool.

Fig. 6 shows the simulation diagram of tool equivalent stress under different TiN coating thickness. The simulation results are summarized as shown in Table 4. It can be found that the maximum equivalent stress decreases with the increase of coating thickness when coating thickness is 0.5-2 μm. When the coating thickness is 2-3 μm, the maximum equivalent stress increases with the increase of the coating thickness. The maximum equivalent stress of the tool is lowest when the coating thickness is 2.0 μm.
Figure 6. Influence of the coating thickness on maximum equivalent stress of cutting tool

Table 4. Maximum equivalent stress under different coating thicknesses

| Coating thickness (μm) | 0.5  | 1.0  | 1.5  | 2.0  | 2.5  | 3.0  |
|------------------------|------|------|------|------|------|------|
| Maximum equivalent stress (MPa) | 2857.3 | 2447.0 | 2353.7 | 1949.8 | 2290.3 | 2327.0 |

4.4. Relationship between interface characteristics and cutting performance

It is of great significance to explore the relationship between coated ceramic tools interface characteristics and cutting performance on the research progress of coated ceramic tools. The matrix of the ceramic coating tool in this research is Si$_3$N$_4$, the coating material is TiN, the coating thickness is 1-10 μm, and the workpiece material is gray cast iron. The relationship between the maximum equivalent stress of the tool and the coating thickness under different cutting parameters is studied, and the fitting curve is shown in Fig. 7.
According to the fitting curve of the maximum equivalent stress for different coating thickness in Fig. 7, the relationship between coating thickness and the tool maximum equivalent stress under the corresponding cutting parameters can be obtained, as shown in Table 5.

**Table 5.** The relationship between coating thickness and maximum equivalent stress of tool under different cutting parameters

| Cutting parameter | Cutting speed \(v_c\) (m/min) | Depth of cut \(a_p\) (mm) | Feed rate \(f\) (mm/r) | The relationship between coating thickness and maximum equivalent stress of tool |
|-------------------|-----------------------------|------------------------|----------------------|--------------------------------------------------------------------------------|
| (a) \(300\)       | 0.5                         | 0.2                    | \(\sigma = 7.355x^4 - 156.2x^3 + 1092x^2\) \(-2781x + 4541\) |
| (b) \(400\)       | 1                           | 0.4                    | \(\sigma = -2.471x^4 + 51.1x^3 - 352.5x^2\) \(+885.1x + 2406\) |
| (c) \(500\)       | 1                           | 0.6                    | \(\sigma = 2.873x^4 - 60.45x^3 + 427.9x^2\) \(-1210x + 4346\) |
| (d) \(600\)       | 0.5                         | 0.2                    | \(\sigma = 8.333x^4 - 176.6x^3 + 1255x^2\) \(-3412x + 5179\) |
| (e) \(700\)       | 0.5                         | 0.4                    | \(\sigma = -2.811x^4 + 76.75x^3 - 660.7x^2\) \(+1924x + 1607\) |
| (f) \(800\)       | 0.5                         | 0.6                    | \(\sigma = 5.789x^4 - 138.1x^3 + 1097x^2\) \(-3220x + 5474\) |

The relationship between the six groups of coating and the maximum equivalent stress of tool was compared, and they satisfy the following relationship:
\[ \sigma = ax^4 + bx^3 + cx^2 + dx + e \]  

The change of cutting parameters affects the coefficient in front of the coating. The following relation is obtained by fitting the cutting parameters of the coefficients \(a, b, c, d\) and \(e\):

\[ a = -7.182(v_c a_p f)^2 + 30.81v_c a_p f. \]  

\[ b = 0.094(v_c^2 a_p f)^3 + 8.481(v_c^2 a_p f)^2 - 1021v_c^2 a_p f. \]  

\[ c = -2 \times 10^{-8}(v_c a_p f)^3 + 2.413v_c a_p f. \]  

\[ d = 2 \times 10^{-9}(v_c a_p f)^3 - 9 \times 10^{-6}(v_c a_p f)^2 + 1.47v_c a_p f^2. \]  

\[ e = 0.006(v_c^3 a_p f)^3 - 42.83(v_c^3 a_p f)^2 + 69117v_c^3 a_p f. \]

The variable coefficients \(a, b, c, d, e\) are brought into the relational expression between the coating and the maximum equivalent stress of the tool to obtain the following relation between the cutting parameters, the coating thickness and the maximum equivalent stress of the tool:

\[
\sigma = \left[ -7.182(v_c a_p f)^2 + 30.81v_c a_p f \right] x^4 \left[ + 0.094(v_c^2 a_p f)^3 + 8.481(v_c^2 a_p f)^2 - 1021v_c^2 a_p f \right] x^3 \\
+ \left[ -2 \times 10^{-8}(v_c a_p f)^3 + 2.413v_c a_p f \right] x^2 \left[ + 2 \times 10^{-9}(v_c a_p f)^3 - 9 \times 10^{-6}(v_c a_p f)^2 + 1.47v_c a_p f^2 \right] x \\
+ 0.006(v_c^3 a_p f)^3 - 42.83(v_c^3 a_p f)^2 + 69117v_c^3 a_p f
\]

Where: \(\sigma\) is maximum equivalent stress of the tool; \(x\) is coating thickness of the tool.

The tool wear condition can reflect the tool cutting performance. The maximum equivalent stress of the tool can reflect the tool wear condition. When the maximum equivalent stress of the ceramic tool is small, the lower the wear of the tool in the cutting process is, the higher the service life of the tool is. The interface characteristics of the tool are mainly reflected by the interface adhesive strength, and the thickness of the coating is an unignorable factor in affecting the interface adhesive strength. Therefore, the relationship between the interface characteristics and cutting performance of ceramic coating tools can be qualitatively described by the functional relationship between the maximum equivalent stress and the coating thickness.

5. Conclusions
In this study, the influence of coating thickness on the cutting performance of ceramic tools was studied from three aspects of cutting temperature, cutting force and maximum equivalent stress by using AdvantEdge simulation software, and the relationship between the interface characteristics and cutting performance of coated ceramic tools were qualitatively described by the functional relationship between the maximum equivalent stress and the coating thickness. The major results are summarized as follows.

A finite element cutting simulation model was established to study the cutting of gray cast iron by coated ceramic tools with different coating thicknesses, and the validity of the model is proved by experiment.

When the coating thickness is 2.0 \(\mu m\), the cutting temperature, cutting force and maximum equivalent stress are the lowest.
The functional relationship between cutting parameters, coating thickness and the maximum equivalent stress is obtained through simulation. It can then be used to predict qualitatively the relationship between the interface characteristics and cutting performance of ceramic coating tools. Otherwise, it can also be utilized to design coated ceramic tools with optimum coating thickness according to the requirement of cutting performance under certain cutting parameters.

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