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Optimization of Geometry Parameters of Silicon Nitride Ceramic Tools Based on Cutting Carbon Steel T10A

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Abstract: *To address the gap in the market of complex-edged silicon nitride ceramic tools, this paper investigates the influence of structural parameters of microwave sintered complex-edged silicon nitride-based ceramic tools on cutting forces, cutting heat and chip morphology by means of finite element simulation for the actual machining requirements of carbon steel T10A, and arrives at the optimized parameters of chip breaker geometry: straight chip breaker, ribbon width 0.15mm, rake angle of chip breaker 23°, counter chip angle 38°, width of chip breaker 1.9mm, depth of chip breaker 0.23mm and edge height 0.12mm. It provides data reference and theoretical support for the dimensional optimization of silicon nitride ceramic tool geometry.*

Keywords: *Silicon Nitride Ceramic Tools, Carbon Steel T10A, AdvantEdge, Optimize Simulation, Orthogonal Test Method*

1. Introduction

Ceramics are inorganic non-metallic materials containing metal oxides, which have good chemical stability, low friction coefficient, hardness of 92HRA~95.5HRA, wear resistance 3 times~5 times that of cemented carbide, and good high temperature performance, and their hardness can still reach 80HRA at 1200℃~1400℃, which is equivalent to that of cemented carbide at 200℃~400℃[1]. As the third generation of ceramic tools, silicon nitride ceramic tools are widely used in the field of high-speed cutting and difficult-to-cut machining materials because of their excellent properties such as high specific strength, high specific mode, high temperature resistance, creep resistance, fatigue resistance, and thermal shock resistance, which are suitable for high temperature, friction, heavy load and other environmental harsh working conditions[2].

However, due to the limitations of the traditional preparation process of ceramic tools, there is currently no complex edge type of silicon nitride ceramic tools on the market[3]. In recent years, with the development of science and technology, microwave sintering as a new sintering method, because of its integral heating, the material is uniformly heated, temperature gradient is small. The burning material is uniform, small in grains, and good denseness. It provides possibility for the overall forming of complex blade type silicon nitrite ceramic tools[4]. Lu Taiyi[5] conducted cutting tests on microwave sintered silicon nitride based ceramic tools to study their cutting performance under different cutting parameters and compared them with commercial ceramic tools SG4 and carbide tools YS8, fully demonstrating the high efficiency and energy saving features of microwave sintering and the advantages of high machining quality of silicon nitride based ceramic tools. As the current ceramic tool structure is simple (flat face is the main), low manufacturing efficiency and other drawbacks, Hong Dongbo[6] takes the complex blade SiAlON ceramic milling blade as an example, the microwave manufacturing technology research of complex edge-shaped ceramic tools, the results show that complex edge-shaped ceramic tools have excellent dense and mechanical properties, compared with the flat face, with better wear resistance, longer tool life.

In summary, ceramic tools are gradually becoming more widely used as tools with excellent cutting performance, while existing research shows that simple flat face ceramic tools cannot meet the requirements of high precision machining, and the advent of microwave sintering technology has made it possible to prepare silicon nitride ceramic tools with complex edge shapes. Prefabricated chip breaker on the tool is an important way to effectively improve the cutting performance and life of the tool, but for ceramic tools, there is less research on the effect of the geometrical structure parameters of the chip

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breaker on the cutting force, cutting heat and chip morphology[7].

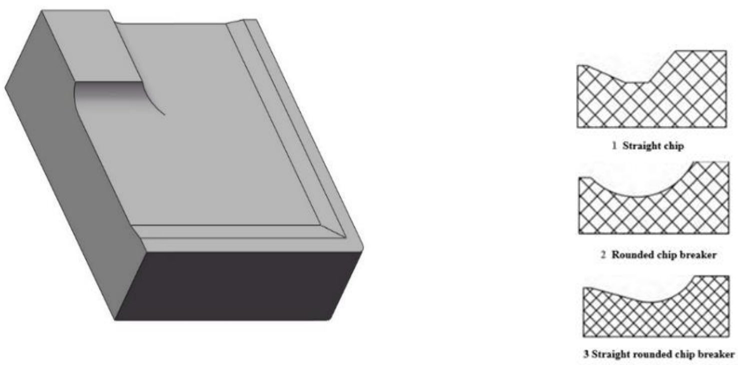
2. Design of Experiments and Finite Element Simulation

2.1. Tools and Workpieces

A 3D model of the tool was created using SolidWorks software. Fig. 1 (a) shows the model of the main cutting part of the tool, and Fig. 1 (b) shows the cross-section of the different chip breakers. The base material of the tool is silicon nitride, in order to avoid the influence of the three tools on the cutting temperature due to the different dimensions, the tool dimensions were set with the same dimensions except for the groove type, and the tool angle parameters were based on the results of a previous study[8], as shown in Table 1.

Table 1: Main parameters of tools

rake angle (°)	clearance angle (°)	cutting edge inclination (°)	cutting edge angle (°)	tip radius (mm)
-5	5	-4	30	0.1



(a) *(b)*

Figure 1: 3D model of the cutting part of the tool with different chip breakers

The workpiece model is set up using the AdvantEdge workpiece database. The base material chosen for this paper is T10A (carbon tool steel, which has an ultimate tensile strength of 2420/MPa and a hardness of 600 Bhn) and the tool material is a silicon nitride ceramic tool. Table 2 shows the material parameters of T10A and Table 3 shows the physical properties of the silicon nitride ceramic tool. The size of the workpiece is 20mm (D) * 3mm (L) and the relative position of the tool and the workpiece is shown in Fig. 2.

Table 2: Material parameters of T10A

Performance	Numerical
Young’s modulus (GPa)	192
Poisson’s ratio	0.325
Initial yield stress (MPa)	2420
Reference plastic strain	0.002
Reference plastic strain rate	1
Melting temperature (K)	1500
Specific heat	575
Density (kg/m^3)	7850

Table 3: Physical properties of Si3N4-based ceramic tools

Performance	Numerical
Young’s modulus (GPa)	304
Poisson’s ratio	0.25
Reference plastic strain	1
Reference plastic strain rate	1
Specific heat	710
Density (kg/m^3)	3200

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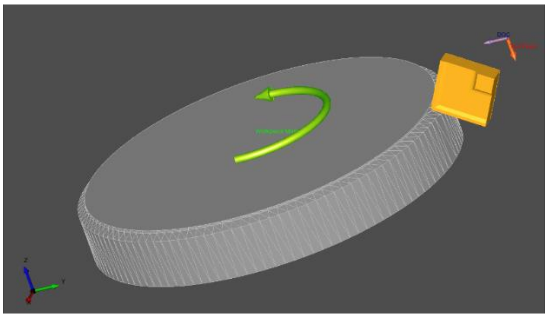


Figure 2: Relative position during cutting

2.2. Design of cutting experiments

In AdvantEdge software, a finite element model is established in the cutting process, where the workpiece material model is defined as a damaged elastoplastic material and the tool is defined as a rigid body. The Power Law constitutive model[9] in the AdvantEdge simulation software is used, including the strain strengthening coefficient $g(\varepsilon^p)$,the strain rate effect function $\Gamma(\dot{\varepsilon})$ and the thermal softening function $\Theta(T)$,The expression is

$$\sigma(\varepsilon^p, \dot{\varepsilon}, T) = g(\varepsilon^p)\Gamma(\dot{\varepsilon})\Theta(T) \tag{1}$$

Where: ε^p is the strain rate during material deformation; $\dot{\varepsilon}$ is the strain rate during material deformation; T is the temperature during material deformation.

In order to improve the operation speed, the adaptive meshing technology is used to reconstruct and divide the tool part and the workpiece part involved in the actual cutting, and the mesh of the tool part and the workpiece part that is not involved in the actual cutting is roughly divided.

2.3. Orthogonal experimental design

The range of values of chip breaker geometry parameters was obtained based on the previous experience of cutting T10A carbon steel tools development[8]. In this section, the simulation model uses a 3-level 6-factor orthogonal simulation test to obtain the integrated optimized geometric parameters under three chip breaker flute shapes. The factor level table is shown in Table 4, and the basic structure of the chip breaker is shown in Fig. 3. The effect of the chip breaker on the cutting process of carbon steel T10A with silicon nitride ceramic tools is investigated by orthogonal tests to obtain the optimized geometric parameters.

Table 4: Table of Factor Levels

Levels	Factors					
	A	B	C	D	E	F
	Ribbon width (mm)	Rake angle of chip breaker (°)	Counter chip angle (°)	Width of chip breaker (mm)	Depth of chip breaker (mm)	Edge height (mm)
1	0.15	13	28	1.3	0.17	0.08
2	0.18	18	33	1.6	0.2	0.1
3	0.21	23	38	1.9	0.23	0.12

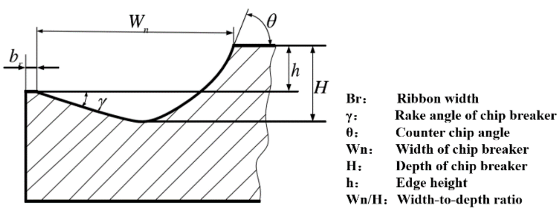


Figure 3: Basic structure of chip breaker

3. Results and Analysis

For the three different chip breaker slot type ceramic tools, orthogonal experiments were designed according to the factor level table in Table 4. The results of the orthogonal experiments are shown in Table 5, taking the straight chip breaker tool as an example for analysis.

Table 5: Orthogonal test designs and results

Entry	A	B	C	D	E	F	F_X max/(N)	T/(℃)
1	0.15	13	28	1.3	0.17	0.08	678.21	1195.25
2	0.15	18	33	1.6	0.2	0.1	672.01	1396.26
3	0.15	23	38	1.9	0.23	0.12	667.32	910.15
4	0.18	13	28	1.6	0.2	0.12	703.29	1335.12
5	0.18	18	33	1.9	0.23	0.08	684.49	1074.42
6	0.18	23	38	1.3	0.17	0.1	676.66	958.32
7	0.21	13	33	1.3	0.23	0.1	675.2	1232.41
8	0.21	18	38	1.6	0.17	0.12	689.51	1027.59
9	0.21	23	28	1.9	0.2	0.08	695.09	1273.68
10	0.15	13	38	1.9	0.2	0.1	677.89	1397.92
11	0.15	18	28	1.3	0.23	0.12	679.97	1411.56
12	0.15	23	33	1.6	0.17	0.08	702.54	963.43
13	0.18	13	33	1.9	0.17	0.12	691.7	980.67
14	0.18	18	38	1.3	0.2	0.08	684.06	1412.33
15	0.18	23	28	1.6	0.23	0.1	681.47	1411.58
16	0.21	13	38	1.6	0.23	0.08	679.56	1205.61
17	0.21	18	28	1.9	0.17	0.1	696.84	1325.91
18	0.21	23	33	1.3	0.2	0.12	713.81	1412.62
K1(F_X)	679.652	684.302	689.143	684.647	689.242	687.32		
K2(F_X)	686.942	684.477	689.952	688.057	691.017	680.007		
K3(F_X)	691.663	689.478	679.162	685.553	677.998	690.93		
R(F_X)	12.011	5.176	10.79	3.41	13.019	10.923		
K1(T)	1212.428	1224.496	1325.517	1270.414	1075.193	1187.453		
K2(T)	1195.406	1274.678	1176.634	1223.264	1371.322	1287.066		
K3(T)	1246.303	1154.962	1151.986	1160.458	1207.622	1179.618		
R(T)	50.897	119.716	173.531	109.956	296.129	107.448		
19/T	0.18	23	38	1.9	0.17	0.12	673.84	1199.97
20/F_X max	0.15	18	38	1.3	0.23	0.1	683.64	1315.50

From the results of the extreme difference analysis in Table 5, it can be seen that the effect of the six factors on the cutting force in order is depth of chip breaker (E) > ribbon width (A) > edge height (F) > counter chip angle (C) > rake angle of chip breaker (B) > width of chip breaker (D), and the effect on the cutting heat in order is depth of chip breaker (E) > counter chip angle (C) > rake angle of chip breaker (B) > width of chip breaker (D) > edge height (F) > ribbon width (A) in order of magnitude. Among the six factors, the effect of depth of chip breaker is the most significant. In this test, the cutting force and cutting heat are the optimization targets, and within the experimental design, the cutting force optimization scheme is A1B1C3D1E3F2, i.e. ribbon width 0.15mm, rake angle of chip breaker 13°, counter chip angle 38°, width of chip breaker 1.3mm, depth of chip breaker 0.23mm, and edge height 0.1mm, and the cutting heat optimization scheme is A2B3C3D3E1F3, i.e. ribbon width 0.18mm, rake angle of chip breaker 23°, counter chip angle 38°, width of chip breaker 1.9mm, depth of chip breaker 0.17mm, edge height 0.12mm, with two sets of optimization scheme for the test, the test results for test 19 and test 20 in Table 3, comparing cutting force and cutting heat optimization results, test 3, that is, when the ribbon width 0.15mm, rake angle of chip breaker 23°, counter chip angle 38°, width of chip breaker 1.9mm, chip breaker depth 0.12mm, depth of chip breaker 0.23 mm and edge height 0.12 mm, the cutting force and cutting heat are the lowest, which can be used as the optimal parameter selection for straight chip breaker tools.

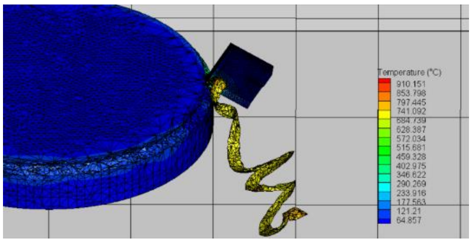
Repeating the above steps, three sets of optimized parameters were obtained as shown in Table 6. Among them, the optimized parameters of the straight chip breaker tool result in the lowest cutting force and cutting heat. The optimal selection of parameters for rounded chip breaker and straight rounded chip breaker tools gives priority to the selection of cutting force when the cutting temperature does not exceed 1200℃. This is due to the good high-temperature performance of silicon nitride ceramic tools, the hardness of their material does not decrease significantly at high temperatures, when the cutting force has a greater impact on the machining quality[10].

Table 6: Comprehensive optimization parameters for different chip breaker groove shapes

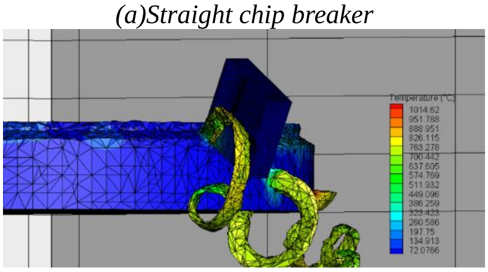
Chip breaker type	A	B	C	D	E	F
Straight	0.15	23	38	1.9	0.23	0.12
Rounded	0.18	18	38	1.3	0.2	0.08
Straight rounded	0.18	18	38	1.3	0.2	0.08

4. Comparison of cutting chips in ceramic tools with different flute configurations

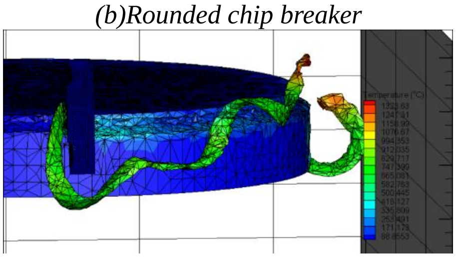
Based on the results of orthogonal simulation tests, the chip morphology after optimization of three different groove types was obtained with the objective of obtaining smaller cutting forces and cutting heat during cutting, see Fig. 4.



(a)Straight chip breaker



(b)Rounded chip breaker



(c)Straight rounded chip breaker

Figure 4: Cutting patterns with different chip breakers

The results show that the chips produced during cutting of ceramic tools with different groove structures are all ribbon chips. In (a), the chips enter the chip breaker groove and form a good ribbon chip, proving that the cutting process is smooth at this point; in (b), the chips scratch the surface of the tool during the discharge process, curling and then changing to a spiral shape, scratching the surface of the workpiece, which is not conducive to chip breaking; in (c), the chips curl freely during the discharge process and unconstrained by the chip breaker groove, flowing out along the machined surface and scratching the surface of the workpiece.

Comparing the results, it can be concluded that among the optimal parameters of the three different groove types mentioned above, the straight chip breaker has the best effect on the cutting force, cutting heat and chip morphology of the tool.

5. Conclusion

In this paper, a finite element model of the cutting process of silicon nitride ceramic tools was established by using AdvantEdge software. The influence of the geometrical structure parameters of the chip breaker groove shape on the cutting force, cutting heat and chip morphology when cutting T10A with silicon nitride ceramic tools was investigated through orthogonal tests, so as to optimize the design of the geometrical structure parameters of silicon nitride based ceramic tools. The specific conclusions

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are as follows:

① Through orthogonal tests, it can be concluded that the variation of width of chip breaker and rake angle of chip breaker has little effect on cutting force, and the effect of depth of chip breaker and ribbon width is relatively large. For cutting heat, only the influence of ribbon width is small.

② Combined with the results of the orthogonal tests, 38 °is more suitable as a choice of counter chip angle for the three types of cutting edge chip breakers, and the optimal flute parameters are the same for rounded chip breaker and straight rounded chip breaker.

③The analysis obtained three chip breaker groove shape comprehensive optimisation parameters, compare the chip morphology of different chip breaker groove shape, in order to cut smaller cutting force, cutting heat and good chip morphology as the goal, obtained the final optimisation parameters: straight chip breaker, ribbon width 0.15mm, rake angle of chip breaker 23 °, counter chip angle 38 °, width of chip breaker 1.9mm, depth of chip breaker 0.23mm, edge height 0.12mm.

The experimental results can provide data reference and theoretical support for the dimensional optimisation of the geometry of silicon nitride ceramic tools for cutting carbon steel.

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