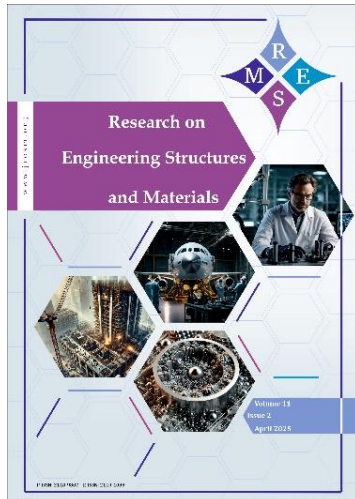




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Comparative sensitivity analysis and multi-objective optimization of CMP parameters for straight and arc edges of cemented carbide tools

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Abstract

Cemented carbide tools are widely used under demanding machining conditions such as deep-hole boring, where cutting-edge stability is essential for suppressing micro-chipping and maintaining machining quality. To improve edge stability, a three-factor three-level orthogonal experiment is constructed to investigate the effects of polishing disk rotational speed, slurry flow rate, and B-axis swing speed on the chemical mechanical polishing and passivation of cemented carbide tool edges. After passivation, the blunt radius increased by 20.50-42.00 μm for straight edges and 25.16-50.41 μm for arc edges, reaching 35.86-57.48 μm and 42.14-67.53 μm , respectively, with a stronger passivation response observed for arc edges. Increasing the polishing disk speed from 30 rpm to 90 rpm increased the average edge radius from 40.92 μm to 59.65 μm , with the response at 90 rpm being 1.46 times that at the 30-rpm baseline. The slurry flow rate had a weak effect, while increasing the B-axis swing speed enhanced passivation. A comprehensive multi-criteria evaluation integrating material removal, passivation stability, and forming consistency yielded sensitivity scores of 0.894, 0.616, and 0.318 for polishing disk speed, B-axis swing speed, and slurry flow rate, respectively. These results indicate that a polishing disk speed of 60-90 rpm, a slurry flow rate of 7 mL/min, and a B-axis swing speed of 3.6-4.8°/s provide a balanced process window for the chemical mechanical polishing passivation of cemented carbide tool edges.

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1. Introduction

Cemented carbide tools have a high proportion of applications in deep hole boring, precision turning and high-load continuous cutting. The microstructure of the cutting edge directly affects cutting force, cutting temperature, tool wear, and the quality of the machined surface [1-2]. For brittle cemented carbide substrates, Chemical Mechanical Polishing (CMP)-based edge rounding provides lower-force and more controllable material removal than brushing or sandblasting, thereby suppressing micro-chipping and producing a continuous transition surface that improves coating adhesion. For deep hole parts such as the inner hole of a hydraulic cylinder, the machining area is closed, the chip removal space is limited, and the cutting heat is not easily diffused, making the cutting edge more prone to micro-chipping, adhesive wear and local stress concentration. If the cutting edge is not stabilized and passivated, the initial micro-defects will continue to expand under the cutting load, resulting in shortened tool life and fluctuations in surface roughness [3]. Therefore, obtaining a cemented carbide cutting edge with controllable radius, continuous morphology and good surface integrity is a key step in improving the stability of deep hole machining. Abolaje A E et al. compared the performance of high-speed steel and tungsten carbide tools for turning 304 austenitic stainless steel using the response surface method. The tool wear

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was only 1.173 mm at the optimal parameters (cutting speed 1303 m/min, feed rate 0.354 mm/rev, and cutting depth 0.458 mm). This proved that tungsten carbide tools were more efficient [4]. Gangwar S et al. enhanced the cutting parameters of cemented carbide tools by combining plasma physical vapor deposition coatings, Taguchi L18 experiments, and grasshopper optimization algorithms. The coated tool performed best at a depth of 0.1 mm, a feed rate of 0.812 mm/rev, and a cutting speed of 70.45 m/min [5]. Umer U and Al-Ahmari A proposed a multi-objective optimization method based on the radial basis function response surface element model and the second-generation multi-objective genetic algorithm for tool geometry parameter optimization in hard turning. A 3D finite element model considering the radius of the cutting edge and the radius of the tool tip was established. Combined with the Usui adhesive wear model and coupled temperature-displacement explicit dynamics analysis for chip formation simulation and tool wear prediction, multi-objective optimization of tool temperature and material removal rate was achieved [6]. While geometrical optimization improves efficiency, the physical state of the cutting edge remains a bottleneck for tool reliability.

CMP achieves material removal through the synergistic effects of oxidation reaction, softening layer formation and abrasive micro-cutting, and improves the surface quality of cemented carbide tools under lower mechanical damage conditions. The chemically softened layer reduces the mechanical load required for abrasive removal, achieves low force polishing, maintains the geometric continuity of asymmetric straight arc edges, and suppresses local shape deformation [7]. For example, Deng Q et al. established a self-excited oscillation cavity model and simulated the fluid oscillation effect at different cavity lengths based on the abrasive water jet polishing method for optimizing the process parameters of carbide tool edge passivation [8]. Hung J C et al. proposed an electric CMP system integrated with a multi-axis robotic arm to address the rough surfaces, difficult and time-consuming polishing of additively manufactured titanium alloy parts. Based on offset grinding brush heads and jet electrolyte flow processes, combined with automated polishing parameter optimization, the surface roughness was reduced [9]. In response to the unclear effect of oxidant content in the polishing fluid of cemented carbide CMP, Wang B et al. analyzed the influence of hydrogen peroxide as an oxidizer on the surface corrosion behavior of cemented carbide and the polishing performance of CMP. It was found that the mass fraction of oxidizer in the range of 0-30% could accelerate the formation of soft loose oxide layer and promote mechanical removal [10].

However, existing studies have mainly focused on simple or straight cutting edges, whereas industrial inserts commonly contain asymmetric straight, arc combinations in which curvature-dependent contact can cause non-uniform material removal. Systematic comparisons of edge size, profile continuity, and surface integrity in these regions remain limited. Meanwhile, some studies mainly relied on overall processing performance or surface roughness as the evaluation basis, and did not fully reveal the specific effects of the Polishing Disk Rotational Speed (PDRS), the slurry flow rate, and the B-axis swing speed on the mechanical removal intensity, reaction product renewal, and edge contact trajectory distribution during the CMP process. Therefore, the study selects the PDRS, the slurry flow rate and the B-axis swing speed as experimental factors for orthogonal experiments. Based on edge profile detection, range comparison and multi-index comprehensive evaluation, the differences in the effects of each factor on the passivation quality are analyzed, aiming to reveal the influence law of CMP process parameters on edge passivation effect and determine the process parameter window that takes into account the controllability of the edge radius, surface integrity, and passivation stability. The novelty lies in the quantitative mapping of parameter sensitivity specifically for the transition zones between straight and arc segments, which is often overlooked in conventional polishing studies.

2. Methods and Materials

2.1 Setup and Measurement Scheme for Edge Passivation Experiments

To analyze the influence of CMP process parameters on the edge passivation quality of cemented carbide tools, a CMP edge passivation experimental platform is established, mainly consisting of a polishing unit, polishing plate, polishing disk, B-axis rotating swing fixture, polishing liquid supply

device, blade positioning fixture, and edge detection system [11]. The passivation experiment uses a modified platform of a UNIPOL-1200S automatic pressure grinding and polishing machine (Shenyang Kejing Automation Equipment Co., Ltd., China). The grinding and polishing disc diameter is 300 mm, the rotation speed range is 20-240 r/min, the minimum adjustment step is 10 r/min, and a polyurethane polishing pad is attached to the disc surface. The B-axis oscillating fixture is a self-made device with an angular velocity adjustment range of 0-10°/s and a control accuracy of $\pm 0.05^\circ/\text{s}$. The polishing fluid is delivered by a BT100-2J peristaltic pump (Baoding Lange Constant Flow Pump Co., Ltd., China), with a rotation speed adjustment resolution of 0.1 r/min. The three-dimensional profile of the cutting edge is measured using a VK-X1000 three-dimensional laser confocal profilometer (KEYENCE, Japan), with a vertical display resolution of 0.5 nm. The surface microstructure is observed using a VHX-7000 digital microscope (KEYENCE, Japan), equipped with a VH-Z100T lens, with a magnification of 100 to 1000 times and a high-precision image resolution of 6144×4608 pixels. The edge CMP passivation experimental platform and measurement process are shown in Figure 1.

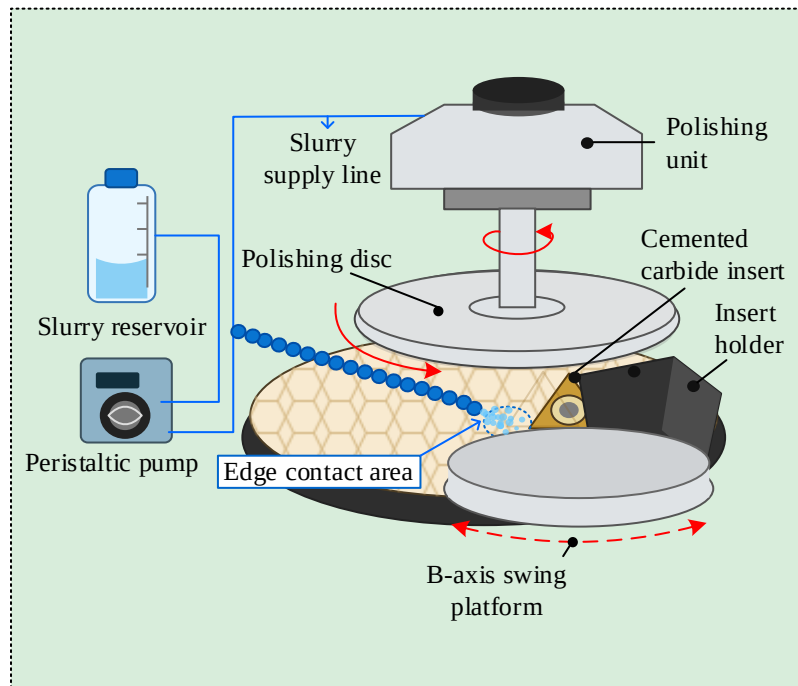


Fig. 1. Schematic of the cutting-edge CMP passivation experimental platform

In Figure 1, the study uses uncoated carbide inserts as experimental subjects. Before the experiment, the blade is placed in anhydrous ethanol and ultrasonically cleaned at 25 °C for 15 min, then rinsed thoroughly with deionized water and dried with dry air. To weaken the impact of the initial edge difference on the experimental results, the initial edge blunt-round radius and surface roughness are measured for each group of blades before passivation and used as the reference values for incremental analysis. The cutting-edge measurement area is divided into a straight cutting-edge area and a circular cutting-edge area. In the straight cutting-edge area, a 2 mm length from the center of the cutting edge is selected as the measurement range, and 5 measuring points are set at equal intervals along the cutting-edge length. In the circular cutting-edge area, 5 measuring points are set at equal intervals along an effective arc length of 2 mm. Each measuring point is measured 3 times, and the average value is taken as the blunt circle radius of the cutting edge at that position. The CMP passivation test parameters and horizontal settings are shown in Table 1.

The parameter ranges in Table 1 were determined based on the stable operating conditions of the experimental platform and preliminary single-factor experiments. Preliminary experiments showed that when the polishing disc speed is below 30 r/min, the softened reaction layer is not sufficiently removed, and the cutting-edge radius does not change significantly. When the speed

exceeds 90 r/min, the outward splashing of the polishing slurry and fluctuations in the cutting-edge contact intensify.

Table 1. CMP passivation experimental parameters, levels, and theoretical roles

Factor	Process parameter	Level 1	Level 2	Level 3	Theoretical role
A	Polishing disk speed (rpm)	30	60	90	Controls the relative sliding speed in the Preston relation, thereby regulating mechanical material removal intensity
B	Slurry flow rate (mL/min)	3	5	7	Regulates the effective Preston removal coefficient through abrasive and oxidant supply and reaction-layer renewal
C	B-axis swing speed ($^{\circ}$ /s)	3.6	4.8	6.0	Changes the local contact-pressure distribution and contact duration, thereby regulating removal uniformity between the straight-edge and arc-edge regions

Note: The B-axis performs a reciprocating oscillation within a limited angular range, rather than a continuous rotation. Therefore, its angular displacement change rate is expressed in $^{\circ}$ /s.

Therefore, 30-90 r/min is set as the investigation range, with three levels set at equal intervals. When the polishing slurry flow rate is below 3 mL/min, the supply of abrasive particles and oxidant is insufficient, while the stability improvement tends to saturate after exceeding 7 mL/min. Therefore, the flow rates are set to 3, 5, and 7 mL/min. When the B-axis oscillation speed is below 3.6° /s, the cutting-edge contact trajectory coverage is insufficient, while above 6.0° /s, the difference in forming straight and circular cutting edges increases. Therefore, the flow rates are set to 3.6, 4.8, and 6.0° /s. After each set of experiments, the blades are rinsed with deionized water, washed with anhydrous ethanol and dried. Next, the edge profile of the straight edge and the arc edge is measured and observed, respectively. The variation in the radius of the blunted edge is calculated according to Equation (1) [12].

$$\Delta R = R_p - R_0 \quad (1)$$

In Equation (1), ΔR is the increment of the blunt radius. R_p signifies the blunt radius after passivation. R_0 signifies the initial blunt radius before passivation. To improve the reliability of the measurement results, multiple measurement points are set in the straight edge and arc edge areas of the same blade, respectively. The average edge radius is calculated in Equation (2) [13].

$$\bar{R} = \frac{1}{n} \sum_{i=1}^n R_i \quad (2)$$

In Equation (2), $\bar{R}$ is the average blunted radius in a certain area. n signifies the number of measurement points in this area. R_i signifies the blunted radius of the i -th measurement point.

2.2 Chemical-Mechanical Synergistic Passivation Process Flow

CMP passivation typically begins with the reaction of the oxidizer in the polishing solution with the surface of the hard alloy to obtain a relatively softened oxide film or reaction layer on the edge surface. Next, the polishing disk and abrasive remove the softened layer under the action of relative motion and contact pressure, gradually weakening the micro-chipping defects, burrs and local peaks on the edge, and eventually forming a continuous, round and good-quality passivated edge. Therefore, the CMP passivation process flow is shown in Figure 2.

As shown in Figure 2, the study first pre-treats the carbide blade and measures the initial edge blunted radius and initial surface roughness. Secondly, the blade is fixed on the B-axis swing fixture to keep the edge to be blunted in stable contact with the polishing disk. To ensure the repeatability of the CMP passivation test, the slurry is prepared with reference to Wang et al. [10] using Al_2O_3

abrasive particles, H₂O₂ oxidant, sodium polyacrylate dispersant, and deionized water. The final mass fractions are listed in Table 2.

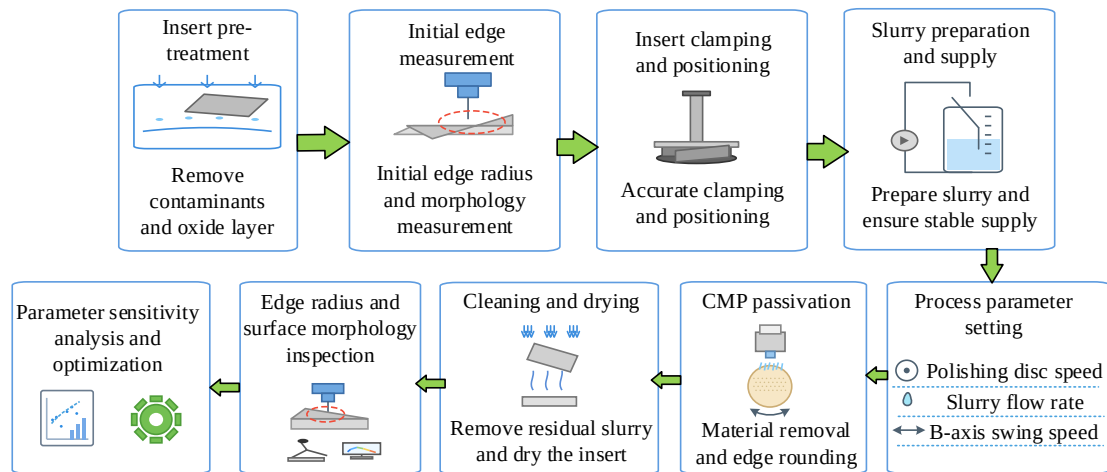


Fig. 2. CMP passivation process flowchart

Table 2. Composition and preparation parameters of the polishing slurry

Component	Material and specification	Final content	Main function
Abrasive	α -Al ₂ O ₃ , purity $\geq 99.9\%$, mean particle size of 50 nm	10.0 wt%	Micro-cutting removal of the softened reaction layer
Oxidising agent	H ₂ O ₂ , analytical grade, stock concentration of 30 wt%	5.0 wt%	Promotes surface oxidation and softened-layer formation
Dispersant	Sodium polyacrylate, analytical grade	0.5 wt%	Suppresses abrasive agglomeration and maintains suspension stability
pH regulator	Aqueous ammonia, analytical grade	As required	Adjusts the pH to 9.5 ± 0.1
Dispersion medium	Deionised water, resistivity $\geq 18.2 \text{ M}\Omega \cdot \text{cm}$	Balance to 100 wt%	Solvent and reaction medium

During preparation, sodium polyacrylate is first added to deionized water and magnetically stirred for 10 min. Al₂O₃ abrasive particles are then slowly added and ultrasonically dispersed for 20 min. Next, H₂O₂ is added, and the pH of the polishing solution is adjusted to 9.5 ± 0.1 using ammonia water. Magnetic stirring is continued for 30 min. The polishing solution is prepared fresh at 25 ± 1 °C and used immediately to minimize the impact of H₂O₂ decomposition and abrasive particle sedimentation on the experimental results. The polishing disk rotates at a set speed, and the B-axis swing platform drives the blade to swing periodically, causing the straight edge and arc edge areas to enter the effective contact area in sequence. The polishing fluid is continuously delivered through the supply system to the contact area between the edge and the polishing disk to maintain stable chemical reaction and abrasive renewal conditions. Material removal during the CMP passivation process can be expressed as the combined action of chemical softening and mechanical removal, as shown in Equation (3) [14-15].

$$M = M_c + M_m \quad (3)$$

In Equation (3), M is the total amount of material removed from the cutting edge per unit time. M_c signifies the contribution of surface softening or reaction layer formation caused by the chemical reaction. M_m is the amount of material removed by the mechanical action of abrasive grains and polishing disks. The mechanical removal is closely related to the contact pressure and the relative

motion speed. According to the Preston relation, the material removal rate per unit area is given in Equation (4) [16].

$$MRR = k_p PV \quad (4)$$

In Equation (4), MRR signifies the material removal rate. k_p signifies the Preston coefficient, reflecting the combined action characteristics of the polishing disk, abrasive grains, polishing liquid, and the material system. P signifies the average contact pressure between the cutting edge and the polishing disk. V is the relative velocity between the cutting edge and the polishing disk. The study sets the polishing disk rotation speed to mainly affect the mechanical removal intensity by changing V . The slurry flow rate mainly affects the reaction layer renewal and abrasive grain transport by changing the stability of k_p . The B-axis swing speed affects the removal uniformity of different edge areas by changing the local contact time of the edge. The linear velocity generated by the rotated polishing disk is calculated according to Equation (5) [17].

$$V_d = \frac{\pi DN}{60} \quad (5)$$

In Equation (5), V_d is the surface linear velocity of the polishing disk. D signifies the effective diameter of the polishing disk corresponding to the contact position of the cutting edge. N signifies the PDRS. Because the contact state of the arc edge area keeps changing during the swing, the contact time per unit length is different from that of the straight edge area. To characterize the intensity of local contact, the equivalent contact time is shown in Equation (6).

$$t_e = \frac{L_c}{v_s} \quad (6)$$

In Equation (6), t_e is the local equivalent contact time of the cutting edge. L_c is the effective contact path length of the cutting edge in one swing period. v_s is the equivalent movement speed of the cutting edge caused by the B-axis swing speed. To establish the relationship between the Preston material removal rate and the equivalent contact time of the asymmetric cutting edge, $j \in \{s, a\}$ represents the straight cutting-edge region and the circular cutting-edge region, respectively. The cumulative material removal amount in one effective contact process can be expressed as Equation (7).

$$\begin{aligned} Q_j(t_{e,j}) &= Q_{c,j}(t_{e,j}) + A_j \int_0^{t_{e,j}} k_p P_j(\tau) V_j(\tau) d\tau \approx Q_{c,j}(t_{e,j}) + A_j k_p \bar{P}_j \bar{V}_j t_{e,j} \\ &= Q_{c,j}(t_{e,j}) + A_j k_p \bar{P}_j \left(\frac{\pi DN}{60} \right) \left(\frac{L_{c,j}}{v_{s,j}} \right) \end{aligned} \quad (7)$$

In Equation (7), Q_j represents the cumulative material removal amount in the cutting-edge region j . $Q_{c,j}$ represents the material removal contribution corresponding to chemical softening within the equivalent contact time. A_j represents the effective contact area. $\bar{P}_j$ and $\bar{V}_j$ represent the average contact pressure and average relative velocity during a single contact process, respectively. Under the condition that the linear velocity of the polishing disc dominates, $\bar{V}_j$ is approximately taken as $\frac{\pi DN}{60}$. The local material removal amount depends not only on the polishing disc rotation speed and contact pressure, but also on the equivalent contact time formed by the B-axis oscillation. The differences between the straight cutting-edge region and the circular cutting-edge region in terms of effective contact path, local pressure, and equivalent contact time will further lead to inconsistencies in the material removal amounts between the two regions. The chemical and mechanical synergistic passivation mechanism is shown in Figure 3.

As shown in Figure 3, the key to the chemical and mechanical synergistic passivation process lies in controlling the dynamic balance between the reaction layer formation rate and the mechanical removal rate. If the chemical reaction is insufficient, the abrasive will act directly on the hard alloy substrate, which is prone to causing scratches and local chipping. If the chemical reaction is too

strong and the mechanical removal is insufficient, a reaction film may remain on the edge surface, affecting the sharpness of the edge profile and surface integrity. The PDRS, the slurry flow rate, and the B-axis swing speed regulate this balance from three aspects: mechanical energy input, polishing fluid renewal, and contact trajectory distribution.

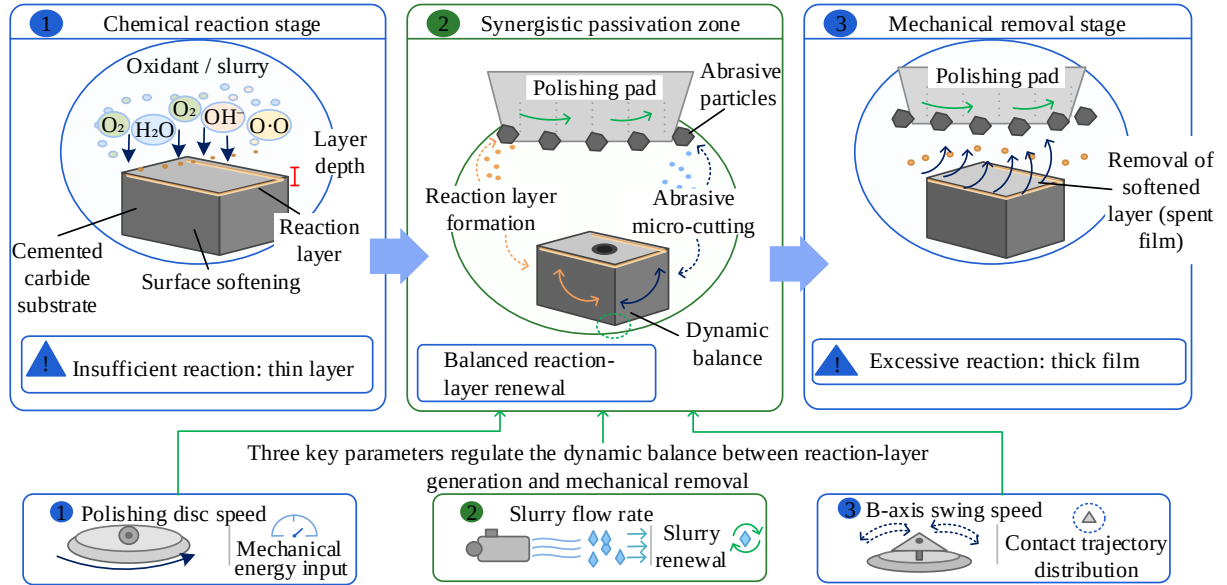


Fig. 3. Chemical and mechanical synergistic passivation mechanism schematic

2.3 Evaluation of Parameter Sensitivity and Statistical Analysis Methods

To quantitatively evaluate the effects of the PDRS, slurry flow rate, and B-axis swing speed on CMP edge passivation, range analysis, analysis of variance (ANOVA), and multi-index comprehensive evaluation are performed using the orthogonal experimental results. ANOVA is conducted at a significance level of $\alpha=0.05$. $p<0.05$ and $p<0.01$ indicate significant and highly significant differences, respectively. The parameter sensitivity evaluation process is shown in Figure 4.

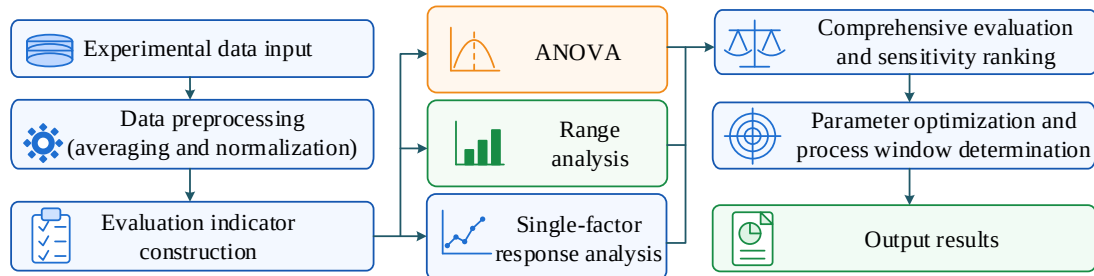


Fig. 4. Flowchart of parameter sensitivity evaluation and statistical analysis

From Figure 4, the study uses range analysis to determine the extent to which different process parameters affect the blunt circle radius of the cutting edge. For any evaluation index, the mean index of a certain factor at the l -th level can be expressed as Equation (8).

$$\bar{Y}_{ijl} = \frac{1}{m} \sum_{q=1}^m Y_{ijlq} \quad (8)$$

In Equation (8), $\bar{Y}_{ijl}$ is the mean value of the i -th evaluation index for the j -th process factor at the l -th level. Y_{ijlq} is the evaluation index value of the i -th evaluation index obtained in the q -th experimental run corresponding to that factor level. m is the number of experimental runs at the same level. The factor range is calculated according to Equation (9) [18].

$$R_{ij} = \max(\bar{Y}_{ij1}, \bar{Y}_{ij2}, \bar{Y}_{ij3}) - \min(\bar{Y}_{ij1}, \bar{Y}_{ij2}, \bar{Y}_{ij3}) \quad (9)$$

In Equation (9), R_{ij} represents the range of the i -th evaluation index for the j -th process factor. The larger the value, the more obvious the influence of this factor on the evaluation index and the higher the parameter sensitivity. Finally, to avoid the limitations of a single index evaluation, the study constructs a comprehensive sensitivity evaluation index from three aspects: material removal sensitivity, passivation stability, and forming consistency, and normalizes each index. The higher the comprehensive sensitivity score, the stronger the comprehensive influence of this parameter on the CMP passivation effect. Considering that effective material removal and edge-radius formation are the primary objectives of CMP passivation, followed by forming consistency between the straight and arc edges, while process stability serves as a supporting requirement, the weights of material removal sensitivity, stability regulation sensitivity, and forming consistency sensitivity are set to 0.50, 0.20, and 0.30, respectively.

3. Results and Analysis

3.1 Overall Response Characteristics of The Blunt Radius

To obtain the overall passivation response of carbide cutting edges under different CMP parameter combinations, a three-factor, three-level orthogonal experiment was conducted. Each parameter combination was independently polished three times with a new insert, and the blunt radius of the straight and circular cutting edges was measured. The results are expressed as the mean $\pm$ standard deviation of the three independent experiments. Table 3 presents the response results of the blunted radius of the cutting edge under different parameter combinations.

Table 3. Orthogonal experimental results of CMP passivation

No.	Polishing disk speed (rpm)	Slurry flow rate (mL/min)	B-axis swing speed ($^{\circ}$ /s)	Straight-edge radius (μm)	Straight-edge radius increment (μm)	Arc-edge radius (μm)	Arc-edge radius increment (μm)	Radius difference (μm)	Mean edge radius (μm)
1	30	7	6.0	39.08 $\pm$ 1.26	23.66	47.86 $\pm$ 1.42	30.80	8.78	43.47 $\pm$ 1.34
2	30	5	4.8	36.16 $\pm$ 1.18	20.98	44.45 $\pm$ 1.35	27.61	8.29	40.30 $\pm$ 1.27
3	30	3	3.6	35.86 $\pm$ 1.15	20.50	42.14 $\pm$ 1.28	25.16	6.28	39.00 $\pm$ 1.22
4	60	7	4.8	46.80 $\pm$ 1.41	31.53	54.27 $\pm$ 1.63	37.36	7.47	50.54 $\pm$ 1.52
5	60	5	6.0	48.69 $\pm$ 1.46	33.14	59.69 $\pm$ 1.78	42.55	11.00	54.19 $\pm$ 1.62
6	60	3	3.6	44.68 $\pm$ 1.37	29.37	51.01 $\pm$ 1.50	34.12	6.33	47.85 $\pm$ 1.44
7	90	7	6.0	57.48 $\pm$ 1.72	42.00	67.53 $\pm$ 2.05	50.41	10.04	62.50 $\pm$ 1.89
8	90	5	3.6	54.88 $\pm$ 1.65	39.64	61.30 $\pm$ 1.86	44.35	6.42	58.09 $\pm$ 1.76
9	90	3	4.8	52.74 $\pm$ 1.58	37.35	63.97 $\pm$ 1.92	46.89	11.22	58.36 $\pm$ 1.75

Note: Radius difference was calculated from the mean values of arc-edge radius and straight-edge radius.

As shown in Table 3, both the straight edge and the arc edge formed distinct blunting and rounding characteristics after CMP blunting, but there were differences in the response amplitudes of the two types of edge areas. The blunted radius of the straight edge ranged from 35.86 to 57.48 μm , and that of the arc edge ranged from 42.14 to 67.53 μm . Under the same passivation conditions, the arc-edge region exhibited a higher material removal response than the straight-edge region. According to the Preston equation, the material removal rate is proportional to the local contact pressure and relative velocity. The curved geometry of the arc edge reduces the effective contact area under a comparable normal load, thereby increasing the local contact pressure and material

removal response. From the perspective of parameter combinations, as the PDRS increased from 30 rpm to 90 rpm, the radius of the blunt circle of both the straight edge and the arc edge showed an overall increasing trend. This indicates that the PDRS has a direct impact on the removal strength of the CMP passivated material. A higher rotational speed can increase the relative sliding speed between the edge and the polishing disk, thereby enhancing the removal effect of the abrasive on the softening reaction layer. The comparison of response amplitudes of different factors indicates that the PDRS has the most prominent effect on the size evolution of the straight and arc edges, while the supply of polishing liquid has a relatively weak effect on the B-axis swing speed. The measurement results in the arc area further suggest that the combined effect of chemical reaction and mechanical friction can weaken the microscopic peaks of the edge, gradually transforming the original sharp profile into a smooth, continuous arc shape. Overall response results suggest that the PDRS is the main factor affecting the growth of the edge radius, and the arc edge area shows higher material removal sensitivity compared to the straight edge. To further analyze the overall response differences between the straight edge and the arc edge under different combinations of CMP parameters, the response index, Coefficient of Variation (CV), regional non-uniformity coefficient and form consistency index were calculated based on the measurement results of the edge blunt-round radius in Table 2, as illustrated in Figure 5.

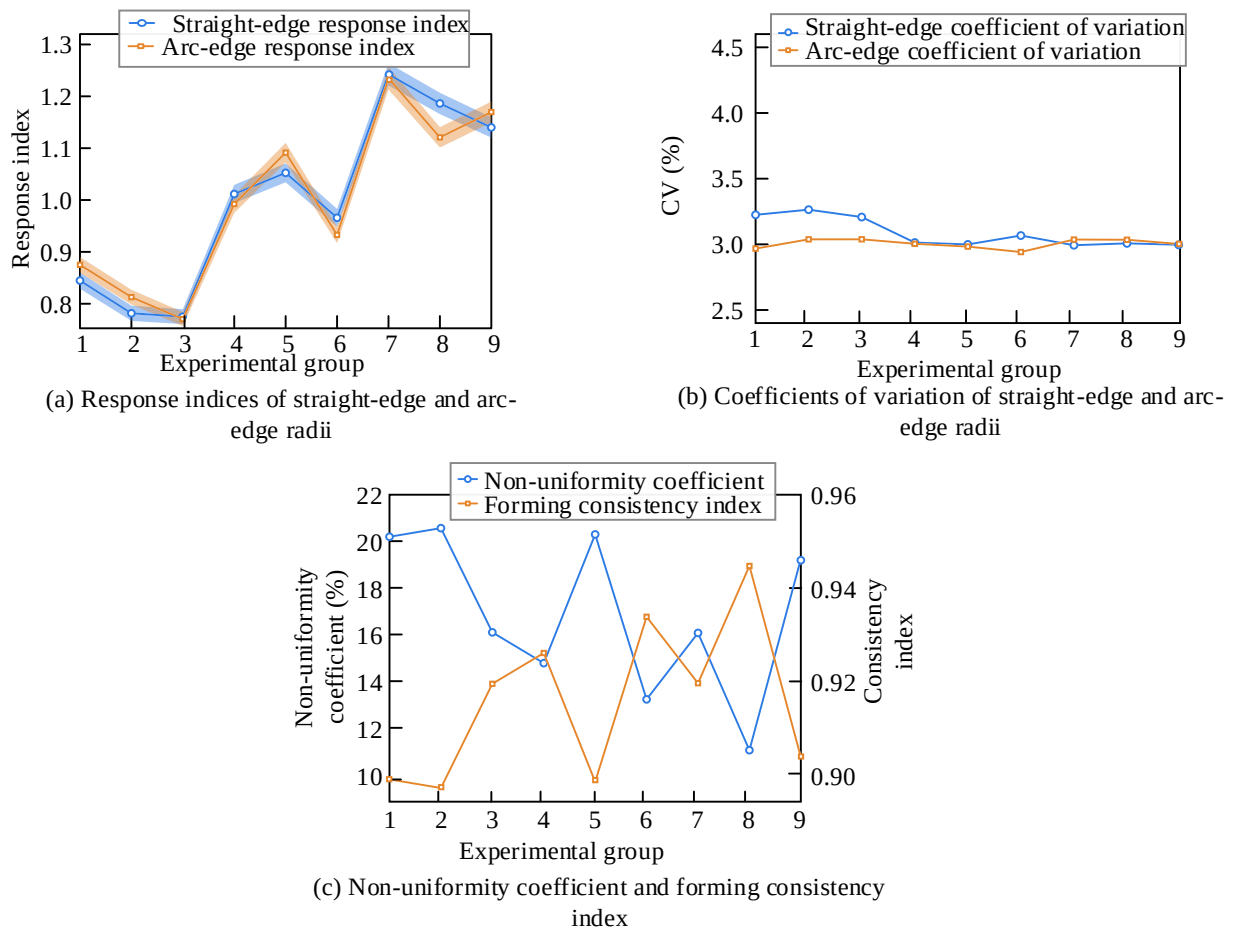


Fig. 5. Overall response characteristics of cutting-edge radii

From Figure 5(a), the variation trends of the response indices of the straight edge and the arc edge were basically the same. Both fluctuated with the combination of CMP parameters, and the response indices were distributed between 0.77 and 1.25. The high response group exceeded the low response group. The corresponding parameter combinations could enhance the edge rounding and material removal effects. The response index of the arc edge was slightly higher than that of the straight edge in some groups, indicating that it was more sensitive to CMP. In Figure 5(b), the CV of the straight edge and the arc edge was generally lower, mainly distributed in the range of 2.94%-3.26%, indicating good stability of the edge radius measurement results. The CV of the straight edge fluctuated slightly, indicating that there were differences in the local contact state and

the uniformity of abrasive action. The CV of the arc edge is relatively stable, indicating that the material removal process is more stable in the continuous curvature area. The forming consistency index was defined as one minus the absolute radius difference divided by the sum of the straight- and arc-edge radii, with a value closer to 1 indicating higher consistency. In Figure 5(c), the regional non-uniformity coefficient was inversely related to the forming consistency index. The non-uniformity coefficient was 11.05%-20.57%, corresponding to a forming consistency index of approximately 0.90-0.95. When the non-uniformity coefficient decreases, the form consistency improves, indicating a reduction in the blunting difference between the straight edge and the arc edge.

3.2 The Effect of The PDRS on Material Removal and Edge Roundness

The PDRS directly affects the relative motion speed between the edge and the polishing disk and is a crucial parameter for regulating the mechanical removal strength of CMP. To analyze its effect on material removal and edge roundness, the edge forming quality at different polishing disk speed levels was compared. The results are shown in Figure 6.

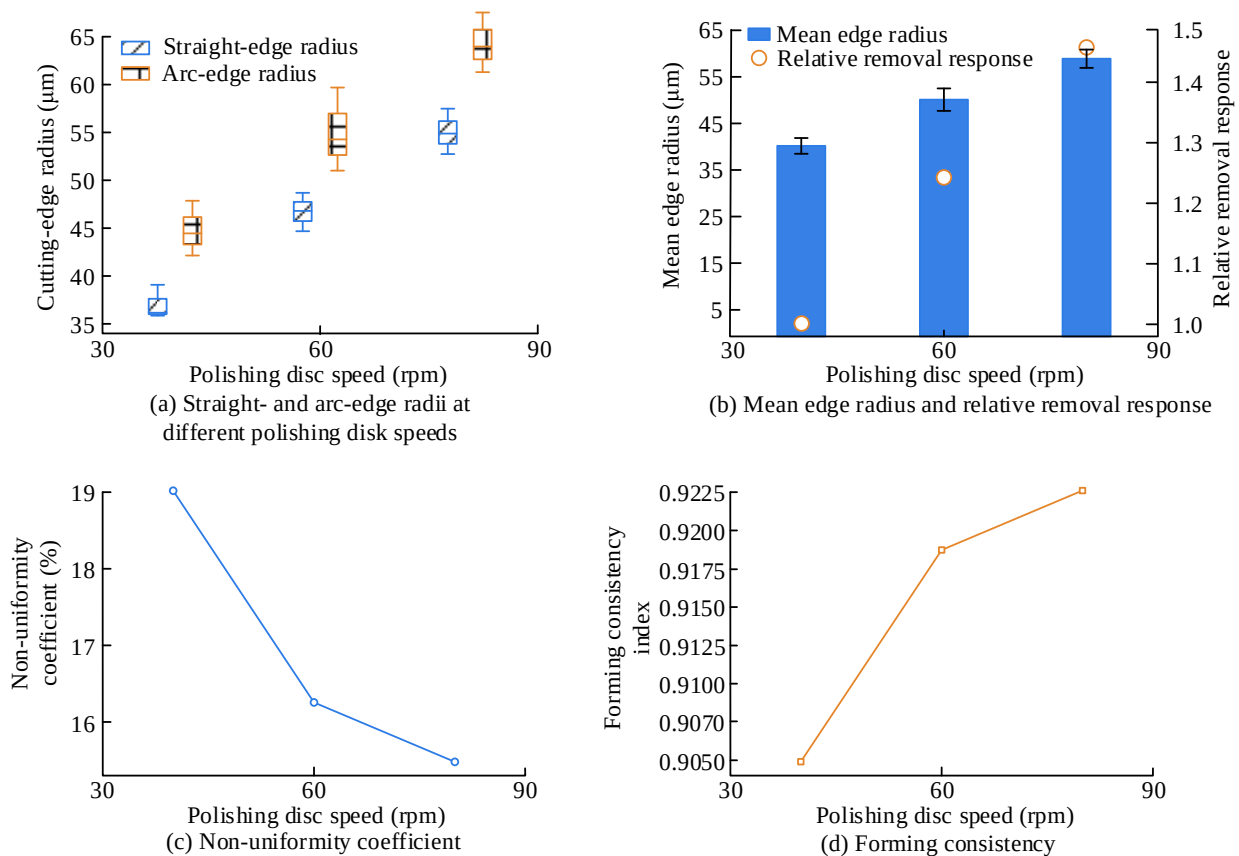


Fig. 6. Effect of polishing disk speed on material removal and edge rounding

In Figure 6(a), as the rotational speed increased from 30 rpm to 90 rpm, the average radius of the straight edge rose from 37.03 μm to 55.03 μm, and the average radius of the arc edge increased from 44.82 μm to 64.26 μm. This indicates that the increase in speed can enhance the relative sliding effect between the edge and the polishing disk, promoting more thorough removal of the surface softening reaction layer by abrasive grains. In Figure 6(b), the average edge radius increased continuously with the increase of the PDRS, and the relative material removal response increased from 1.00 to 1.46, indicating that the speed has a significant promoting effect on the material removal efficiency. When the rotational speed was low, the mechanical energy input was insufficient and the edge roundness was limited. As the speed increases, the micro-protrusions and local sharp areas are further removed, and the edge profile gradually becomes rounded. From Figures 6(c) and (d), the higher rotational speed enhances the material removal strength, and also improves the forming consistency between the straight edge and the arc edge. The rotational speed is a key factor affecting the blunt radius of the cutting edge and the degree of material removal.

However, the speed-dependent removal response should not be considered strictly linear. At excessively high speeds, centrifugal ejection may shorten the slurry residence time, while hydrodynamic lift may increase the liquid-film thickness and reduce abrasive-edge contact pressure, potentially causing removal saturation or decline. Therefore, the increasing trend observed from 30 to 90 rpm is valid only within the tested range.

To further verify the effect of the rotational speed on the roundness and surface integrity, the micromorphology of the straight edge and the arc edge was analyzed at different rotational speed levels, as shown in Figure 7.

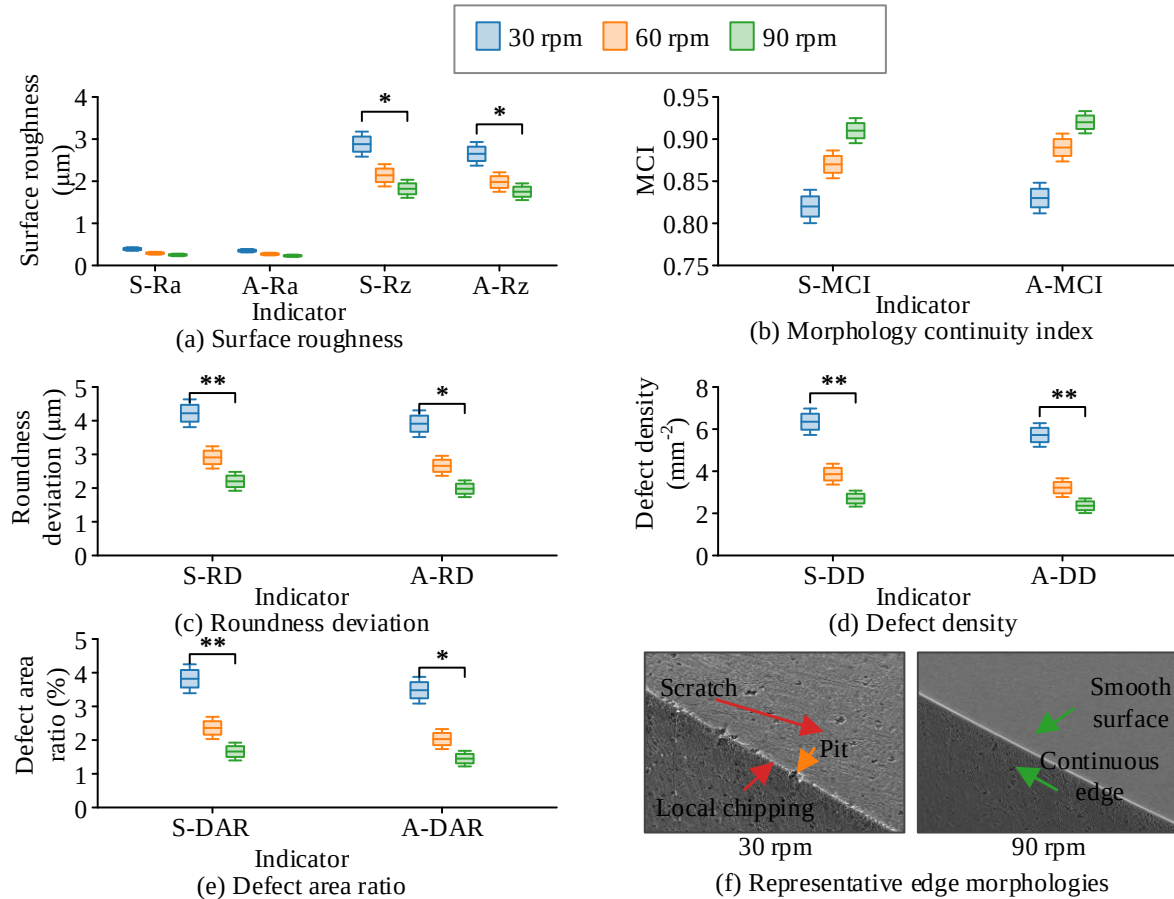


Fig. 7. Boxplots of edge morphology indicators under different speeds (Image source: Author's own photo)

Note: *S* and *A* denote the straight-edge and arc-edge regions, respectively. *Ra* and *Rz* represent arithmetic mean roughness and maximum profile height (μm), respectively. *MCI* represents the dimensionless morphology continuity index. *RD* represents roundness deviation (μm). *DD* represents defect density (mm^{-2}). *DAR* represents defect area ratio (%). * $p < 0.05$ and ** $p < 0.01$ indicate statistically significant differences between the connected groups.

In Figure 7(a), the *Ra* and *Rz* values of both straight and circular cutting edges decreased with increasing polishing disc speed, indicating that higher speeds enhance the abrasive particles' ability to remove micro peaks and soften the reaction layer. In Figure 7(b), *S-MCI* and *A-MCI* increased with increasing speed, indicating improved cutting-edge profile continuity. In Figure 7(c), *S-RD* and *A-RD* at 90 rpm were significantly lower than those at 30 rpm ($p < 0.01$ and $p < 0.05$), indicating a significant reduction in cutting edge roundness deviation. In Figures 7(d) and 7(e), *DD* and *DAR* continuously decreased with increasing speed, indicating a reduction in the number and coverage area of surface defects. In Figure 7(f), at 30 rpm, the cutting-edge surface had obvious scratches, micro-pits, and local chipping. At 90 rpm, the surface was smoother and the cutting-edge profile was more continuous. The morphological observation results were consistent with the changing trends of *MCI*, *RD*, *DD* and *DAR*, indicating that increasing the polishing disc speed within the experimental range is beneficial to improving the roundness of the cutting edge and the surface integrity.

3.3 The Effect of Slurry Flow Rate on Passivation Stability

The slurry flow rate affects the transport state of abrasive grains, oxidants and reaction products in the edge contact area and is a crucial factor in maintaining the stability of the CMP passivation process. Therefore, to analyze the effect of slurry flow rate on passivation stability, the stability of materials at different flow rate levels was compared. The results are shown in Figure 8.

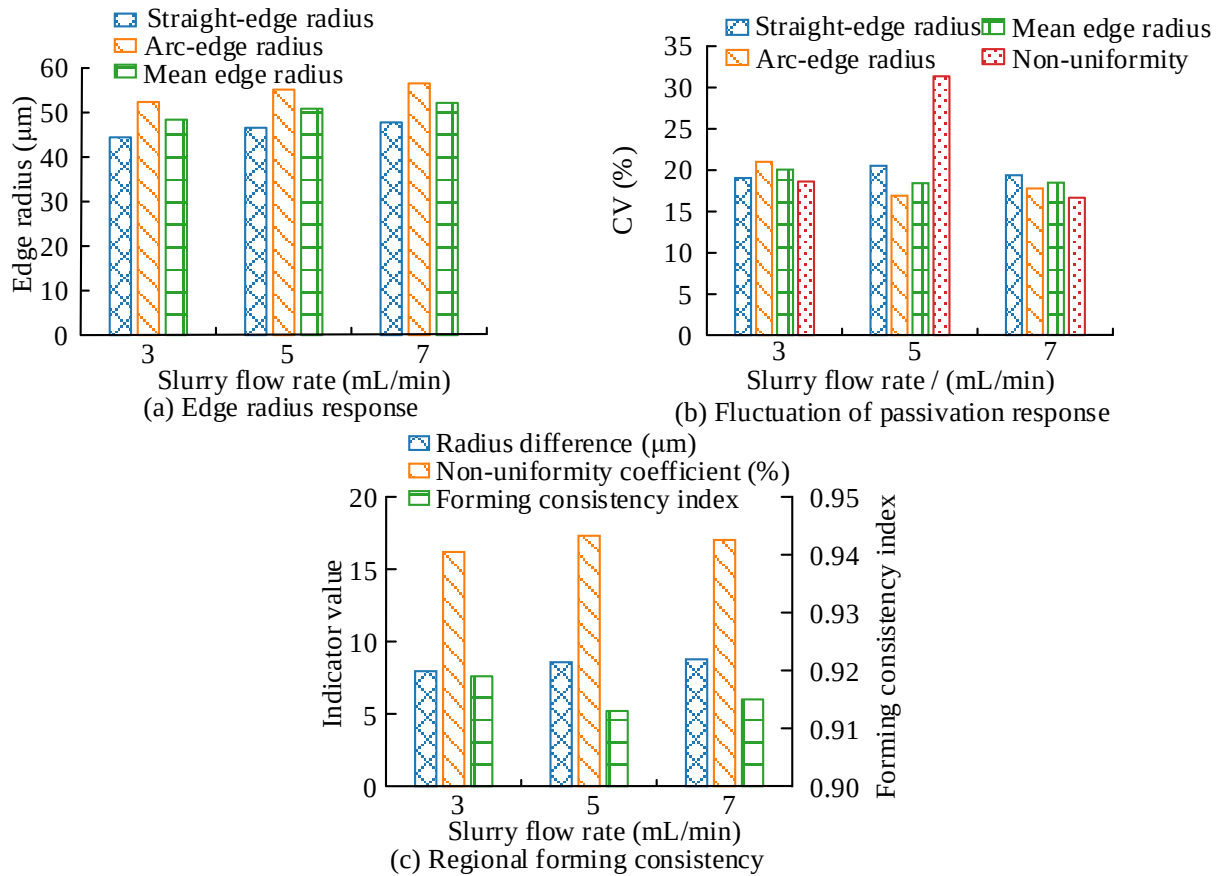


Fig. 8. Effect of slurry flow rate on passivation stability

Figure 8(a) shows that increasing the slurry flow rate from 3 to 7 mL/min raised the mean edge radius from 48.40 to 52.17 μm , an increase of 7.79%, which was substantially lower than that caused by the polishing disk speed. This limited response suggests that the tested flow-rate range was already supply-sufficient, with further increases mainly promoting slurry renewal and reaction-product discharge rather than directly enhancing material removal. From Figure 8(b), the average cutting-edge radius CV at different flow rates was mainly distributed between 18.38% and 20.02%. Within these parameters, the effect of the slurry flow rate on the overall radius fluctuation was relatively limited. A local CV peak was observed at 5 mL/min, suggesting a transitional slurry-transport state rather than a monotonic stability response. At this intermediate flow rate, intermittent transport of abrasive particles and reaction products, potentially amplified by supply pulsation, may have caused fluctuations in liquid-film thickness and local contact conditions. At 7 mL/min, more continuous slurry renewal reduced these fluctuations and improved process repeatability. In Figure 8(c), as the slurry flow rate increased, the radius difference declined from 2.84 μm to 1.29 μm . In addition, the non-uniformity coefficient remained between 16.19% and 17.31%, and the overall variation in the form consistency index was relatively small. Overall, the slurry flow rate mainly serves to stabilize the renewal of the polishing fluid and regulate the consistency of area removal. Compared with 3 mL/min and 5 mL/min, 7 mL/min can carry away reaction products and shedding particles more promptly, but the improvement in material removal is limited.

3.4 The Effect of B-Axis Swing Speed on The Forming Accuracy of Asymmetric Cutting Edges

The B-axis swing speed determines the contact trajectory distribution and local action time of the blade edge on the polishing disk and is a crucial factor affecting the forming accuracy of the asymmetric edge. To analyze its effect on the co-blunting effect of the straight edge and the arc edge, the edge forming accuracy at different B-axis swing speed levels was compared, as shown in Figure 9.

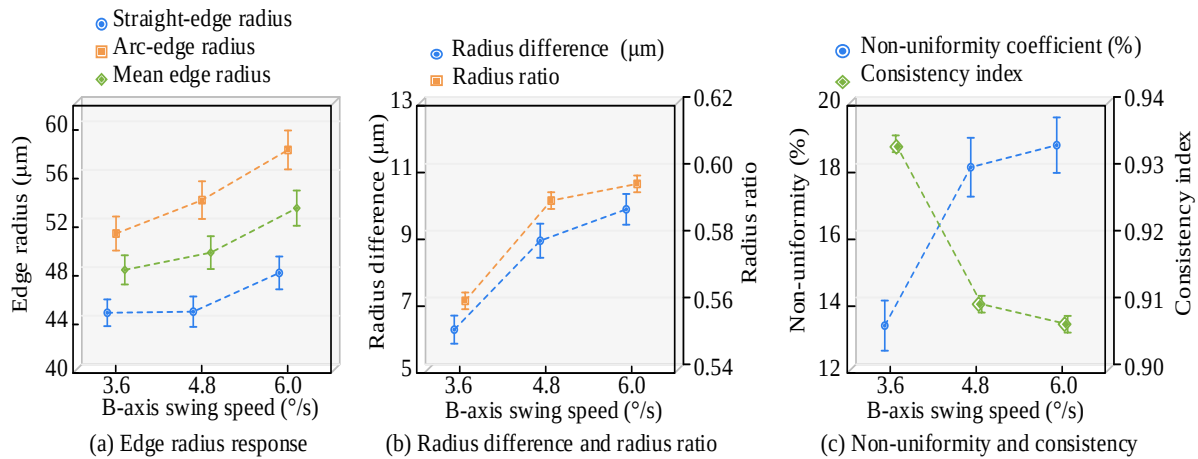


Fig. 9. Effect of B-axis swing speed on asymmetric edge forming accuracy

From Figure 9(a), as the B-axis swing speed increases from 3.60°/s to 6.00°/s, the straight cutting edge, arc cutting edge and average cutting-edge radius all show an increasing trend. The average edge radius increased from 48.31 μm to 53.39 μm. With the increase in swing speed, the edge contact trajectory coverage and local repeated contact effect were enhanced. From Figure 9(b), the radius difference increased with the B-axis swing speed. According to Equation (6), a higher swing speed shortens the equivalent contact time during a single pass but increases the frequency of repeated contact and trajectory overlap within the fixed processing period. Owing to its continuous curvature and longer effective contact path, the arc edge experiences greater cumulative contact exposure, resulting in disproportionate material removal and increased forming asymmetry. In Figure 9(c), the regional non-uniformity coefficient increased from 13.46% to 18.86%, while the form consistency index decreased from 0.933 to 0.906. It shows that an excessively high B-axis swing speed reduces the form consistency between the straight edge and the arc edge. Overall, the B-axis swing speed has a significant regulating effect on the forming accuracy of asymmetric cutting edges. A lower swing speed is beneficial for maintaining regional consistency, while a higher swing speed is beneficial for reinforcing material removal and edge rounding.

Finally, to further determine the relative influence of different CMP process parameters on the edge passivation response, a multi-dimensional sensitivity evaluation form was constructed. Material removal sensitivity was normalized based on the average edge radius, stability adjustment sensitivity was normalized based on the variation range of the coefficient of variation of average edge radius, and form consistency sensitivity was normalized based on the variation range of the form consistency index. The comprehensive sensitivity score is calculated by weighting three types of normalized indicators, with the weights of material removal sensitivity, stability adjustment sensitivity, and form consistency sensitivity being 0.50, 0.20, and 0.30, as presented in Table 4.

In Table 4, the combined sensitivity score of the rotational speed of the trajectory was the highest, at 0.894, indicating that it has the strongest influence on the CMP passivation process. The material removal sensitivity score reached 1.000. The rotational speed mainly enhances the removal effect of abrasive particles on the softening reaction layer by increasing the relative motion speed between the edge and the polishing disk, and is the dominant parameter controlling the edge roundness. The combined sensitivity score of the B-axis swing speed was 0.616, ranking second. Although its material removal sensitivity was lower than that of the polishing disk speed, it had the highest forming consistency sensitivity score. This indicates that the parameter mainly affects the

distribution of the edge contact trajectory and the forming differences in different edge areas. Therefore, the B-axis swing speed is more suitable as a key parameter for adjusting the forming accuracy and regional consistency of asymmetric cutting edges. The combined sensitivity score of the slurry flow rate is the lowest at 0.318, indicating a weaker direct impact on the amount of material removed from the cutting edge. However, its stability regulation score still reached 0.777, indicating that the flow rate mainly affects the stability of the passivation process by improving the state of polishing fluid renewal, abrasive transport and reaction product discharge. Overall, the three types of parameters have different effects: the PDRS dominates material removal, the B-axis swing speed regulates forming consistency, and the slurry flow rate mainly improves passivation stability.

Table 4. Comprehensive sensitivity evaluation of CMP process parameters

Process factor	Material removal sensitivity score	Stability regulation score	Forming consistency sensitivity score	Comprehensive sensitivity score	Sensitivity rank	Main action characteristic	Practical controllability
Polishing disk speed	1.000	1.000	0.648	0.894	1	Dominant material removal	High-direct regulation of material removal
Slurry flow rate	0.201	0.777	0.206	0.318	3	Slurry renewal and transport stability	Moderate-mainly regulates slurry transport stability
B-axis swing speed	0.271	0.900	1.000	0.616	2	Contact trajectory and regional consistency	High-regulates contact trajectory and forming consistency

Note: Sensitivity scores were normalized to 0-1 using Min-Max normalization. A higher comprehensive score indicates greater process sensitivity. Controllability represents the practical adjustability of each factor and its dominant response.

4. Discussion

PDRS produces the largest change in edge radius among the three investigated parameters. This result can be explained by the Preston equation, because increasing the disk speed directly raises the relative velocity between the polishing disk and the cutting edge. Therefore, the softened surface layer is removed more rapidly. The morphological changes in Figure 7 support this explanation. At 30 rpm, scratches, pits and local chipping are still observed, whereas the edge obtained at 90 rpm is smoother and more continuous. The decreases in Ra, Rz, RD, DD and DAR indicate that removing surface peaks and defects is more effective. These observations agree with the chemical-mechanical balance described in Figure 3. However, as the reaction layer is not directly measured, the morphological results should be regarded as indirect evidence of this mechanism.

Similar effects of chemical oxidation and abrasive removal have been reported in previous CMP studies [7,10]. Wang et al. [10] found that an oxidizer promoted the formation of a loose reaction layer on cemented carbide and facilitated its subsequent removal. Studies using abrasive water jets and magnetic-field-assisted polishing also demonstrate that abrasive transport and mechanical action strongly affect carbide-edge formation [8,13]. Most of these studies evaluated surface roughness or overall passivation performance. In contrast, the present results distinguish between straight and arc edges and show that the same process parameters do not produce equal material removal in the two regions.

The arc-edge radius is 6.28-11.22 μm larger than the straight-edge radius. This difference indicates that edge formation is not completely uniform. The curved region has a different contact area and contact path, which changes its local pressure and cumulative removal response. In addition, Equation (6) shows that the B-axis swing speed affects the equivalent contact time. When the swing

speed is too high, repeated contact and trajectory overlap become more pronounced in the arc region, increasing its removal relative to the straight region. A large radius difference may lead to uneven cutting loads and variations in local edge strength or coating thickness. Cutting and coating tests were not conducted in this study; therefore, 11.22 μm cannot yet be defined as a general acceptance limit. However, it can be used to identify parameter combinations with poor regional consistency. A low-to-moderate B-axis swing speed is more suitable when reducing the difference between the two edge regions is the main requirement.

The comprehensive sensitivity ranking is PDRS (0.894), B-axis swing speed (0.616) and slurry flow rate (0.318). This ranking also suggests a practical adjustment sequence. PDRS can first be used to bring the edge radius close to its target value. The B-axis swing speed can then be fine-tuned to reduce the forming difference between straight and arc regions. The slurry flow rate mainly maintains abrasive supply and removes reaction products, and therefore acts as a stability parameter rather than the primary means of controlling edge size. Within the tested range, a medium-to-high PDRS, a flow rate of 7 mL/min and a low-to-moderate B-axis swing speed provide a more balanced combination of material removal, surface quality and regional consistency.

5. Conclusion

This study focuses on the parameter sensitivity issues in the CMP passivation process of cemented carbide tool edges, systematically investigating the effects of PDRS, slurry flow rate, and B-axis swing speed on the edge radius response, regional removal uniformity, and forming consistency of asymmetric cutting edges (straight-edge and arc-edge regions), while quantitatively characterizing the governing laws and primary-secondary relationships among the process parameters. Orthogonal experiments showed that both the straight edge and the arc edge formed a distinct blunted round edge, and the radius of the arc edge was generally larger than that of the straight edge, with a difference of 6.28-11.22 μm . The rotational speed is the dominant factor affecting the strength of material removal. When the speed increased from 30 rpm to 90 rpm, the average edge radius range of the straight edge and the arc edge was 18.72 μm . The combined sensitivity ranking was: polishing disk speed > B-axis swing speed > slurry flow rate. The slurry flow rate has a weak direct effect on the cutting-edge radius, but it can improve the stability of abrasive transport, reaction product discharge and polishing fluid renewal. The B-axis swing speed mainly regulates the contact trajectory distribution. Although a higher swing speed can increase the passivation, it will increase the forming difference between the straight edge and the arc edge.

However, only one cemented-carbide grade is examined. Variations in cobalt content and WC grain size may alter the electrochemical interaction between the slurry and binder phase, thereby affecting reaction-layer formation and removal. Based on the main-effect results, a PDRS of 90 rpm, a slurry flow rate of 7 mL/min and a B-axis swing speed of 3.6°/s are recommended for balancing surface quality and edge uniformity. As this combination is inferred from the orthogonal results, further confirmation through cutting, coating-adhesion and tool-life tests is required.

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