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Evolution of Bonding Strength of WC-10Co-4Cr Coatings during Grinding Based on a Voronoi Polycrystalline Model

Tongkai Shi

University of Shanghai for Science and Technology, Shanghai 200093, China

Abstract: To investigate the degradation mechanism of bonding strength of WC-10Co-4Cr coatings during grinding, a Voronoi polycrystalline model combined with single abrasive grain explicit dynamic simulation and scratch experiments was employed. A coupled abrasive–coating–interface–substrate model was established in ABAQUS, and the effects of grinding depth and speed on stress distribution and load transfer were analyzed under purely mechanical conditions. Results show that increasing grinding depth intensifies stress concentration and promotes subsurface damage and interfacial degradation, leading to a reduction in bonding strength. In contrast, higher grinding speed produces a more uniform stress distribution, suppresses interfacial damage, and enhances bonding strength. The polycrystalline model further reveals that stress localization is governed by grain heterogeneity, with grain boundaries acting as preferential damage initiation sites. These findings provide insight into the relationship between grinding parameters and bonding performance, offering guidance for process optimization of WC-based coatings.

Keywords: WC-10Co-4Cr Coating; Grinding; Bonding Strength; Voronoi Polycrystalline Model; Single Abrasive Grain Simulation.

1. Introduction

WC-based cemented carbide coatings, owing to their high hardness, excellent wear resistance, and good corrosion resistance, have been widely applied in surface strengthening of critical components operating under severe service conditions, such as those in aerospace, energy, valve systems, and high-end equipment. As an effective alternative to electroplated hard chromium, HVOF-sprayed WC-10Co-4Cr coatings can significantly enhance the service stability of components subjected to abrasive wear, erosion, and oxidation. However, due to the inherently high surface roughness after thermal spraying, precision grinding is usually required to achieve the desired dimensional accuracy and surface integrity. Meanwhile, the grinding process inevitably alters the residual stress state, porosity, and interfacial load-bearing characteristics of the coating, thereby affecting the overall reliability of the coating–substrate system.

For WC-10Co-4Cr coatings, the performance changes induced by grinding are not limited to surface morphology but are closely related to subsurface damage and interfacial bonding conditions. Masoumi et al.[1] reported that grinding parameters significantly influence porosity, residual stress, microhardness, and adhesion/cohesion strength of HVOF WC-10Co-4Cr coatings. This indicates that grinding is not only a finishing process but also a key factor in reshaping the mechanical state of coatings. Similarly, Dai et al.[2] demonstrated that grinding parameters such as cutting depth, wheel speed, and wheel type jointly affect grinding forces, specific energy, surface roughness, and subsurface damage in WC/Fe coatings. These findings suggest that grinding parameters play a critical role in controlling subsurface damage evolution, which in turn affects load transfer capability and bonding strength at the coating–substrate interface.

However, existing studies on grinding of WC-based coatings mainly focus on macroscopic experiments and process optimization, while the understanding of local stress concentration, grain-scale deformation incompatibility, and interfacial damage initiation mechanisms remains limited. For brittle or multiphase materials, single abrasive grain scratching/cutting is commonly regarded as an effective approach to investigate the micro-scale material removal mechanism. Anderson et al. [3] indicated that the grinding process is governed by the combined effects of material behavior, friction, and cutting mechanics, and the macroscopic grinding response can be interpreted as the cumulative effect of numerous single-grain interactions. Studies on WC–Co systems further confirm that single abrasive grain scratching can effectively capture typical responses such as material removal, lateral pile-up, and local crack propagation, making it a suitable method for analyzing micro-scale damage evolution during grinding.

From a material perspective, WC-10Co-4Cr coatings are inherently heterogeneous polycrystalline systems composed of hard WC particles, binder phases, and complex grain boundaries. Previous experimental and numerical studies[4] have shown that local stress concentrations tend to occur near sharp contact regions and heterogeneous phase interfaces, indicating that microstructural features directly influence damage initiation and propagation paths. Conventional homogenized models, although computationally efficient, fail to accurately capture the effects of grain size distribution, grain boundary characteristics, and interfacial weakening on stress distribution and bonding strength evolution during grinding.

In contrast, Voronoi-based polycrystalline modeling provides an effective way to represent the random morphology and topology of grains in polycrystalline materials. The Neper platform proposed by Quey et al.[5] enables efficient generation and meshing of large-scale polycrystalline structures, facilitating grain-scale finite element analysis. Furthermore, Huang et al. [6] demonstrated that combining Voronoi polycrystalline models with cohesive elements can effectively capture crack initiation, propagation, and fragmentation behavior in grinding processes. Therefore, introducing Voronoi-based modeling into the study of WC-based coating grinding is expected to more accurately characterize subsurface damage, interfacial degradation, and load transfer mechanisms at the grain scale.

In summary, although previous studies have confirmed that grinding parameters significantly affect surface integrity, residual stress, and bonding performance of WC-based coatings, grain-scale investigations on the evolution of bonding strength of WC-10Co-4Cr coatings during single abrasive grain grinding remain insufficient. In particular, there is a lack of systematic analysis that couples polycrystalline microstructure, interfacial damage behavior, and grinding parameters. Therefore, in this study, a two-dimensional Voronoi polycrystalline model of WC-10Co-4Cr coatings is established using Neper, and a single abrasive grain grinding model consisting of abrasive, coating, interface, and substrate is developed in ABAQUS/Explicit. Under purely mechanical conditions, the effects of grinding depth and speed on stress transfer, interfacial damage evolution, and bonding strength are systematically investigated. By comparing the responses of the coating surface, interface, and near-surface region of the substrate, the mechanism by which grinding parameters influence the bonding performance of the coating–substrate system is revealed, providing theoretical guidance for process optimization and high-quality grinding of WC-10Co-4Cr coatings.

2. Materials and Experimental Procedures

2.1. Materials

In this study, WC-10Co-4Cr coatings prepared by High-Velocity Oxy-Fuel (HVOF) spraying were selected as the research object. The coating thickness is approximately 300 μm, and the substrate material is 9Cr18 bearing steel. WC-based coatings produced by the HVOF process exhibit a dense microstructure and high bonding strength; however, their surface roughness is relatively high, and subsequent grinding is usually required to achieve the desired surface quality and dimensional accuracy.

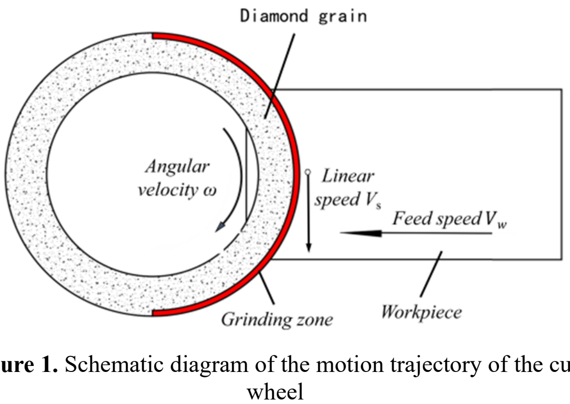

Figure 1. Schematic diagram of the motion trajectory of the cup wheel

To investigate the effects of grinding parameters on subsurface damage and interfacial bonding performance of the coating, a resin-bonded cup-shaped diamond grinding wheel was employed for surface grinding. The kinematic configuration of the cup wheel is illustrated in Fig. 1, where V_s denotes the wheel speed, V_w represents the workpiece feed speed, and ω is the angular velocity of the wheel. The distance between the lowest point of the grinding wheel and the workpiece surface is defined as the grinding depth a_p.

Previous studies have shown that subsurface damage in WC-based coatings during grinding is primarily influenced by grinding depth and grinding speed. Therefore, in this work, the grinding depth a_p and grinding speed V_s were selected as the main control variables, and the corresponding parameter combinations are listed in Table 1.

Table 1. Grinding process parameters

NO.	a_p /μm	V_s /(m/s)
1	10	7.86
2	15	7.86
3	20	7.86
4	10	2.62
5	10	5.24
6	10	7.86

2.2. Experimental Procedure

To elucidate the stress transfer and interfacial damage evolution mechanisms of the coating–substrate system during grinding from a micro-mechanical perspective, a combined experimental and numerical approach was adopted. In the numerical model, a representative abrasive grain located at the outer edge of the grinding wheel was considered, and its action was simplified as a single abrasive grain grinding process.

Considering that the wheel speed is significantly higher than the workpiece feed speed and that the contact zone of a single abrasive grain is much smaller than the wheel radius, the actual trajectory of the abrasive grain can be approximated as a straight-line motion along the tangential direction. Based on the microscopic morphology of diamond abrasives, the grain geometry was simplified as a conical shape to achieve a balance between computational efficiency and geometric realism. During the grinding process, the abrasive grain moves along the tangential direction with a velocity of VsV_sVs, and different grinding conditions are simulated by varying the grinding depth apa_pap and grinding speed VsV_sVs.

It should be noted that this study focuses on the stress transfer and damage evolution mechanisms within the coating and at the interface during grinding. Therefore, thermal effects and thermo-mechanical coupling were neglected in the numerical simulation, and only the mechanical response was analyzed using an explicit dynamic method. This assumption is based on the consideration that, at the scale of a single abrasive grain, material removal behavior is primarily governed by transient contact stress and plastic deformation, while thermal effects play a secondary role in interfacial failure. Such simplification allows a clearer interpretation of the dominant influence of grinding parameters on stress distribution and bonding strength evolution.

In the experiments, scratch tests were conducted using an MFT-4000 multifunctional material surface performance tester to quantitatively evaluate the bonding performance of the coating–substrate system. A diamond indenter with a tip angle of 120° was employed. By applying a progressively increasing load, the critical load and failure characteristics were obtained, which were used to assess the variation in bonding strength under different grinding conditions. By comparing the experimental results with the simulated interfacial damage evolution and stress distribution, the mechanisms governing bonding strength evolution during grinding were further validated and interpreted.

3. Construction of the Polycrystalline Model and Numerical Implementation

WC-10Co-4Cr coatings are typical multiphase polycrystalline materials, whose microstructure consists of hard WC particles, a CoCr binder phase, and a small amount of pores. Under external loading, the mismatch in mechanical properties among different phases, together with the random orientation of grains, leads to local stress concentration and non-uniform deformation. These factors significantly affect damage evolution within the coating and the interfacial bonding state. Therefore, adopting a polycrystalline model that can capture grain-scale geometric features is essential for understanding stress transfer and interfacial failure mechanisms during grinding.

3.1. Voronoi-Based Polycrystalline Model Using Neper

The Voronoi diagram, also known as a tessellation based on the nearest-neighbor principle, is an effective method for partitioning space and describing randomly distributed grain structures in polycrystalline materials. The Neper software[7] (Quey et al., 2011) provides functionalities for generating polycrystalline geometries, mesh discretization, and direct export of ABAQUS-compatible input files, enabling efficient construction of polycrystalline finite element models.

Figure 2 shows the SEM microstructure of the WC-10Co-4Cr coating, where the bright regions correspond to the WC hard phase, the dark regions represent the CoCr binder phase, and the black regions indicate pores. It can be observed that the coating exhibits a pronounced heterogeneous multiphase microstructure.

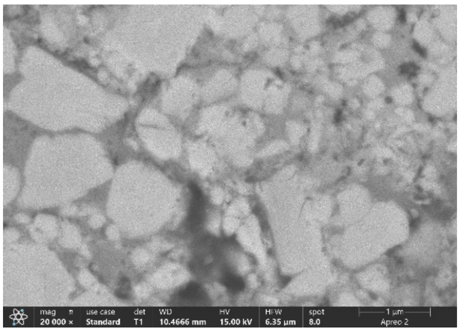

Figure 2. Microstructural morphology of the WC–10Co–4Cr coating

Since the average size of WC particles is approximately 1 µm, constructing a full-scale polycrystalline model for the entire 300 µm-thick coating would result in excessive computational cost and is therefore impractical. Considering that the bonding performance is mainly governed by the region near the coating–substrate interface, a locally refined modeling strategy is adopted in this study. Specifically: The region within approximately 10 µm from the interface is modeled as a Voronoi polycrystalline structure (denoted as the refined coating);

The remaining part of the coating is treated as a homogeneous continuum (denoted as the simplified coating). This approach ensures computational efficiency while retaining the essential microstructural features near the interface, as illustrated in Fig. 3.

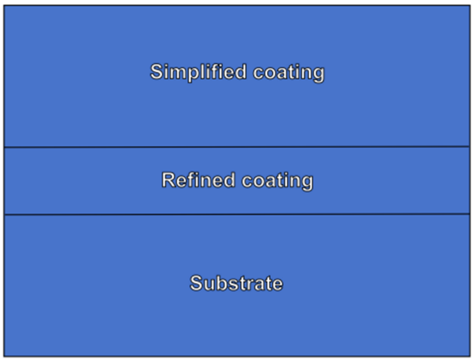

Figure 3. Schematic diagram of the modeling approach

In Neper, the two-dimensional polycrystalline model is generated using the following command:

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-V -n 1000 -id 1 -domain "square(1,0.01)" -dim 2 -o a
```

This command produces a 2D polycrystalline structure with dimensions of 1000 µm × 10 µm, containing 1000 grains, which are used to represent WC particles.

In addition, by introducing the -cohesive option, cohesive interface elements are automatically inserted between adjacent grains to model the behavior of the CoCr binder phase. The mesh is defined as follows: Two-dimensional solid elements are used within the grains; Zero-thickness cohesive elements are applied along grain boundaries; The mesh density parameter is set to rcl = 0.1, which provides a good balance between computational efficiency and accuracy based on prior studies.

The final polycrystalline model is shown in Fig. 4.

Figure 4. Polycrystalline Model

3.2. ABAQUS Model Preprocessing and Parameter Definition

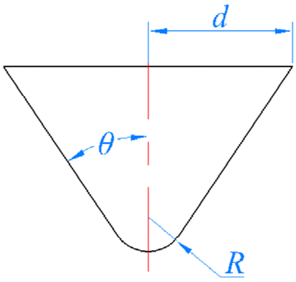


Figure 5. Abrasive Particle Size

After importing the *.inp file generated by Neper into ABAQUS, each grain is automatically identified as a set named “POLY-X” (where X denotes the grain index), while grain boundary elements are classified as “BOUND-Y”. Through Boolean operations, all POLY sets are merged to form the WC phase, and all BOUND sets are combined to represent the CoCr interfacial phase. In this way, a multiphase structural model consisting of WC particles and CoCr interfaces is established.

The abrasive grain is simplified as a rigid body, and its geometric parameters are determined based on the morphology of actual diamond abrasives. The apex angle is set to θ=30ₒ, the edge radius is R=10 μm, and the maximum radius is d=30 μm, as illustrated in Fig. 5.

The material properties of the WC phase and CoCr phase in the refined coating are listed in Table 2. The simplified coating is modeled as an equivalent homogeneous continuum, and its failure behavior is described using the Johnson–Cook damage model. Since thermal effects are not considered in this study, only the stress triaxiality-dependent and strain-dependent terms are retained in the model, while the temperature and strain rate effects are neglected. The expression can be written as:

$$\varepsilon_{\mathrm{f}} = \left[d_1 + d_2 \exp\left(d_3 \cdot \frac{\sigma_{\mathrm{p}}}{\sigma_{\mathrm{q}}} \right) \right] \left(1 + d_4 \ln \frac{\varepsilon_{\mathrm{a}}}{\varepsilon_{\mathrm{b}}} \right) \left(1 + d_5 \cdot \frac{\mathrm{T} - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}} \right)$$

where ε_f is the equivalent plastic fracture strain; d_1, d_2, d_3 are material damage parameters; σp\sigma_σ_p is the hydrostatic stress; and σ_q is the equivalent stress. The damage parameters for the WC phase are listed in Table 3[8].

Table 2. WC-10Co-4Cr Base Material Property Definitions

Material	Density(kg/m^3)	Young's Modulus	Poisson's Ratio
WC	15800	710000	0.24
CoCr	8411	240000	0.3

Table 3. Johnson-Cook Failure Strain Parameters for WC Material

d_1	d_2	d_3	d_4	d_5
0.0	0.0018	-3.0	0.0	0.0

The complete assembly model is shown in Fig. 6, where the initial distance between the bottom of the abrasive grain and the coating surface is defined as the grinding depth. The analysis is carried out using the ABAQUS/Explicit dynamic solver, and the time step is controlled to ensure a consistent grinding path under different grinding speeds.

The boundary conditions are defined as follows: the bottom and lateral boundaries of the model are fixed, while the top surface is free. A displacement is applied to the abrasive grain along the negative x-direction to simulate the grinding process.

This modeling approach has been validated in previous studies through comparison with experimental results, demonstrating its capability to accurately capture material removal and damage evolution during grinding. Therefore, no additional validation is presented in this work.

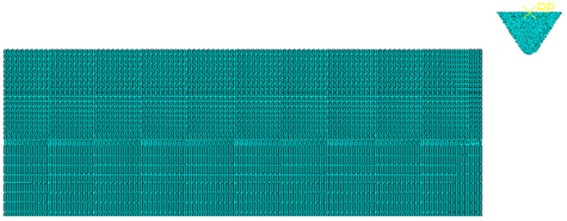
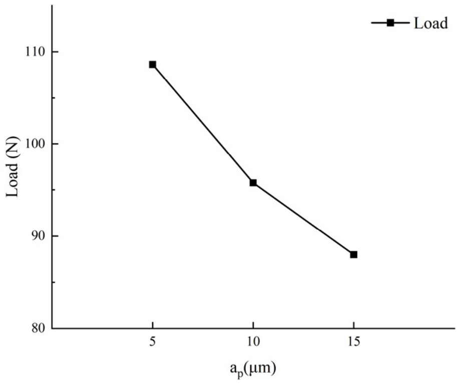


Figure 6. Schematic of the Simulation Model

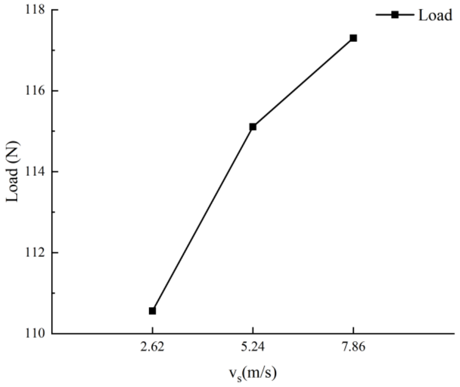
4. Results and Discussion

4.1. Effect of Grinding Parameters on Bonding Strength

Based on the scratch test results, the variation of bonding strength of WC-10Co-4Cr coatings under different grinding conditions is obtained, as shown in Fig. 7.



(a)Different grinding depths



(b)Different grinding speeds

Figure 7. Bonding strength under different grinding parameters

As illustrated in Fig. 7(a), the bonding strength decreases significantly with increasing grinding depth apa_pap. When the grinding depth increases from 5 μm to 15 μm, the critical load decreases from approximately 108 N to 88 N, corresponding to a reduction of about 18.5%. This is attributed to the increased penetration depth of the abrasive grain, which leads to higher normal and tangential stresses in the coating surface and subsurface regions, resulting in pronounced stress concentration. With increasing stress levels, the material removal mechanism gradually shifts from plastic deformation to brittle fracture. Microcracks are initiated and propagated along grain boundaries and interfaces, reducing the effective load-bearing area of the interface and consequently decreasing the bonding strength.

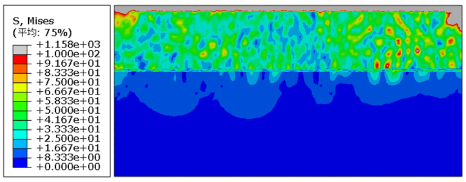
As shown in Fig. 7(b), the bonding strength increases with increasing grinding speed VsV_sVs. When the grinding speed increases from 2.62 m/s to 7.86 m/s, the critical load increases from approximately 110 N to 117 N, corresponding to an increase of about 6.4%. This behavior is mainly attributed to the reduced contact time between the abrasive grain and the material under high-speed conditions. The local stress does not fully develop before unloading occurs, thereby suppressing the initiation and propagation of microcracks. In addition, the increased strain rate enhances the instantaneous deformation resistance of the material, weakening ploughing and tearing effects and reducing the accumulation of interfacial damage.

In summary, grinding depth and grinding speed exhibit opposite effects on bonding strength. Grinding depth primarily governs the stress magnitude and promotes damage accumulation, whereas grinding speed regulates the loading duration and strain-rate effect, thereby suppressing damage evolution.

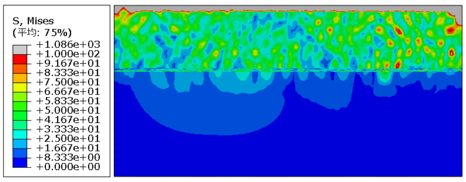
4.2. Analysis of Single Abrasive Grain Simulation Results

To further elucidate the mechanism by which grinding parameters influence bonding strength, the stress distribution and load transfer behavior under different grinding conditions are analyzed based on the single abrasive grain model.

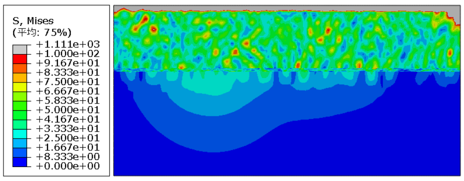
Figure 8 presents the equivalent stress distribution under different grinding depths. It can be observed that both the magnitude and affected region of stress within the coating and at the interface increase significantly with increasing grinding depth.



(a) ap = 10 μm



(b) ap = 15 μm



(c) ap = 20 μm

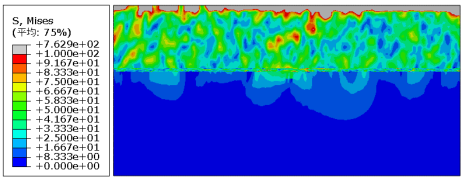
Figure 8. Stress Distribution Contours under Different Grinding Depths

At a grinding depth of 10 μm, the stress is mainly concentrated in the coating surface, and the high-stress region is relatively limited, with weak stress transfer to the interface and substrate. When the grinding depth increases to 15 μm, the stress propagates toward the interface along the thickness direction, and noticeable stress concentration appears near the interface, accompanied by an expansion of the stress-affected region in the substrate. At a further increased depth of 20 μm, the high-stress region extends to the interface and further into the substrate, forming a broader stress influence zone.

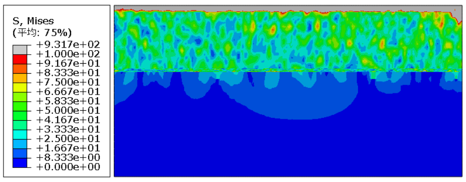
Although increasing grinding depth enhances stress transfer to the interface, excessive stress promotes the initiation and propagation of microcracks in the interfacial region, leading to damage accumulation and a reduction in bonding strength. This observation is consistent with the experimental results presented in Section 4.1.

Figure 9 shows the stress distribution under different grinding speeds. As the grinding speed increases, the stress distribution gradually transitions from localized concentration to a more uniform state.

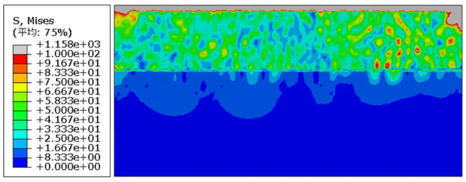
At a low grinding speed of 2.62 m/s, stress is highly localized and unevenly distributed, with evident stress concentration near the interface. As the speed increases to 5.24 m/s, the stress distribution becomes more uniform, and the stress-affected regions in both the interface and substrate expand. When the speed further increases to 7.86 m/s, a more continuous stress distribution band is formed along the coating surface, while the stress gradient at the interface decreases, indicating a more stable load transfer behavior.



(a)Vs = 2.62 m/s



(b)Vs = 5.24 m/s



(c)Vs = 7.86 m/s

Figure 9. Stress distribution under different grinding speeds

This phenomenon suggests that under high-speed conditions, the reduced contact time and increased strain rate effectively alleviate stress concentration and reduce local peak stress at the interface, thereby suppressing interfacial damage evolution.

Overall, the combined experimental and simulation results indicate that grinding parameters influence bonding strength by regulating stress distribution and interfacial damage evolution. Increasing grinding depth raises stress levels and accelerates interfacial damage, leading to reduced bonding strength, whereas increasing grinding speed reduces stress concentration and inhibits damage propagation, thereby enhancing bonding strength.

Furthermore, the polycrystalline structure results in significant stress heterogeneity among grains. Grain boundaries are more prone to stress concentration and serve as preferential sites for damage initiation, highlighting the importance of the Voronoi polycrystalline model in capturing the micro-scale damage behavior of coatings.

5. Conclusion

Based on the Voronoi polycrystalline model, single abrasive grain explicit dynamic simulations, and scratch test results, the influence of grinding parameters on the bonding strength of WC-10Co-4Cr coatings was systematically investigated. The main conclusions are summarized as follows:

(1) Grinding depth has a significant detrimental effect on bonding strength. With increasing grinding depth, the stress level within the coating and at the interface increases markedly, and stress concentration propagates from the surface toward the interface. This promotes the initiation and propagation of microcracks along grain boundaries and interfaces, reduces the effective load-bearing area, and consequently leads to a decrease in bonding strength.

(2) Grinding speed has a positive effect on bonding strength. As the grinding speed increases, the contact time between the abrasive grain and the material is reduced, and the duration of stress application decreases. Meanwhile, the strain-rate effect is enhanced, leading to a more uniform stress distribution and reduced local stress concentration. As a result, interfacial

damage accumulation is suppressed, and the bonding strength is improved.

(3) Grinding parameters affect interfacial bonding performance by regulating stress transfer paths and damage evolution processes. Specifically, grinding depth primarily controls the stress magnitude and damage severity, whereas grinding speed governs the loading duration and strain-rate characteristics. The coupling of these factors determines the overall bonding strength of the coating–substrate system.

(4) The Voronoi polycrystalline model effectively captures the heterogeneous stress distribution within the coating and the stress concentration at grain boundaries, providing a reliable numerical approach for analyzing micro-scale damage mechanisms and interfacial failure behavior during grinding of WC-based coatings.

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