

Article

Study on Material Removal Mechanisms for TBCs in Drag-Finishing

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Abstract

Reducing the surface roughness of thermal barrier coatings (TBCs) improves engine aerodynamic efficiency and mitigates CMAS adhesion, but turbine blades' complex geometries demand low-cost, damage-mitigated finishing. This work employed drag finishing with spherical ceramic media, establishing a discrete element method (DEM) model to quantify abrasive trajectories, contact forces, and energy distributions, combined with surface characterization to study abrasive effects on columnar YSZ and modified GZO topcoats. Results show roughness reduction is constrained by fracture toughness and columnar unit local fracture, leading to different decay rates and late-stage improvement between YSZ and GZO. Introducing smaller abrasives enhances packing density via void filling, strengthens microscale cutting, and reduces strong normal impacts, promoting surface uniformization and suppressing localized damage. These findings guide mechanistic understanding of drag finishing on multi-material TBCs, as well as abrasive grading design and process parameter optimization.

Keywords: thermal barrier coatings (TBCs); drag finishing; discrete element method (DEM); surface roughness; abrasive size grading

1. Introduction

Thermal barrier coatings (TBCs) are a critical protection technology for the hot-end components of advanced aero-engines and gas turbines, playing an important role in extending component lifespan and improving engine performance. YSZ (yttria-stabilized zirconia) or YSZ combined with new ceramic topcoats fabricated by electron-beam physical vapor deposition (EB-PVD) are widely used for turbine blades. However, as the turbine inlet temperature continues to rise, CMAS (calcium–magnesium–alumino–silicate) deposits have become one of the key factors limiting the durability and reliability of TBCs. While the development of new ceramic materials and dense protective layers has helped to mitigate CMAS corrosion, the surface roughness of the ceramic topcoat directly affects CMAS wetting and spreading. Therefore, reducing surface roughness is beneficial in improving the CMAS resistance of TBCs [1–7]. Furthermore, surface roughness also influences film-cooling behavior and near-wall heat transfer boundary conditions on turbine blades. Studies show that increasing TBC surface roughness weakens film coverage and reduces overall cooling effectiveness. When surface roughness increases by 3 μm , the overall cooling effectiveness can decrease by approximately 7.90%–16.21% [8,9], which may further



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promote CMAS infiltration and corrosion. Moreover, reducing surface roughness can improve the aerodynamic performance of turbine blades and enhance engine efficiency [10]. Consequently, implementing low-damage and controllable finishing processes to reduce the roughness of TBC topcoats has significant engineering application value.

Surface finishing and controlled near-surface material removal for coatings in multi-material systems are important topics in coating engineering and advanced manufacturing. Drag-finishing, a representative abrasive-media finishing technique, has been increasingly used for surface finishing of complex components in recent years [11,12]. In this process, the workpiece is clamped by a fixture and undergoes a superimposed double-rotation motion within a stationary media container. Such kinematics enables a high-coverage relative motion path in the abrasive media, and the abrasive particles impose a coupled loading mode consisting of tangential sliding and normal impacts on the workpiece surface, thereby achieving surface finishing [13–16]. Tangential sliding refers to the relative motion of the abrasive particles parallel to the surface of the workpiece, primarily acting to grind the material through friction. Normal impacts occur when the abrasive particles interact with the workpiece surface normal, leading to localized indentation and micro-crack formation. Compared to conventional vibratory or barrel finishing, drag-finishing offers potential advantages in accessibility to complex surfaces and local regions, processing consistency, and process controllability. It is therefore promising for achieving roughness regulation and micro-defect state optimization of turbine-blade TBCs through controlled topcoat material removal.

Existing studies on the influence of drag finishing on surface roughness have primarily focused on empirical parameter optimization for single materials or dense workpieces. In contrast, hollow turbine blades with complex geometries contain numerous film-cooling holes in the airfoil. To prevent abrasive media from entering the internal cavity during finishing, using abrasive particles larger than the cooling-hole diameter is an effective strategy. Additionally, EB-PVD ceramic topcoats are brittle materials [17–19]. Their columnar microstructure near the surface typically consists of quasi-independent column tips together with inter-column gaps and pores, forming a non-uniform, partially dense architecture. Furthermore, the mechanical properties of YSZ and emerging rare-earth zirconates (e.g., $\text{Gd}_2\text{Zr}_2\text{O}_7$) differ substantially. However, studies addressing the interaction mechanisms between abrasives and different ceramic topcoats and the corresponding roughness evolution during finishing remain limited. A transferable and unified interpretive framework for the contact state, material-removal mechanism, and damage evolution in drag finishing of TBCs' multi-material systems is still lacking.

Fundamentally, drag-finishing is a multi-point contact wear process between abrasive particles and the coating surface under cyclic loading. The discrete element method (DEM) treats the granular media as discrete entities and can compute the forces, velocities, and trajectories of individual particles. It enables explicit tracking of particle trajectories under the imposed double-rotation kinematics and provides quantitative outputs such as normal/tangential contact forces, contact frequency, and contact-energy decomposition during particle–workpiece interactions. Therefore, DEM can characterize the local contact state and load input in the vicinity of the workpiece without relying on empirical assumptions [20–22]. In particular, for finishing processes involving both tangential scratching and normal impacts, DEM-based force and energy statistics can quantitatively support the relative contributions of cutting and collision, offering an operable tool to elucidate the causal chain of kinematics–contact mechanics–surface response in drag finishing.

In this work, EB-PVD columnar YSZ and modified GZO ceramic topcoats are selected as the model systems. Driven by the finishing requirement of “controlled material removal and uniform roughness reduction” for TBC topcoats, spherical alumina particles are used

as the abrasive medium and comparative drag-finishing experiments are conducted. The study focuses on clarifying the intrinsic correlations among material-removal behavior, roughness evolution, and defect response of the columnar microstructure during finishing. Furthermore, a bimodal abrasive system with $\phi 1$ mm/ $\phi 3$ mm particles is established with different volumetric fractions, to reveal how abrasive size distribution regulates the relative contributions of cutting versus collision and the resulting surface-uniformity capability.

2. Materials and Methods

2.1. Coating Preparation

Using GH4169 nickel-based superalloy coupons (Beijing Jinlun Kuntian Special Machinery Co., Ltd., Beijing, China) (40 mm $\times$ 20 mm $\times$ 3 mm) as substrates, the specimens were wet grit-blasted and subsequently ultrasonically cleaned. Two types of coating specimens were then prepared. (i) A NiCrAlYSi bond coat (Beijing Jinlun Kuntian Special Machinery Co., Ltd., Beijing, China) was deposited by multi-arc ion plating to a thickness of ~ 50 μ m. The multi-arc ion plating process was carried out by introducing argon gas at a flow rate of 200 sccm into the vacuum chamber, with the target arc current set to 90 A. The chamber pressure was maintained at approximately 0.2–0.3 Pa, and the deposition rate was 3–4 μ m/h. (ii) Ceramic topcoat specimens were fabricated by EB-PVD, where either a YSZ layer or a Yb₂O₃-doped, modified GZO ceramic layer ((Gd_{0.9}Yb_{0.1})₂Zr₂O₇) (Beijing Jinlun Kuntian Special Machinery Co., Ltd., Beijing, China) was deposited to a thickness of ~ 150 μ m. During bond-coat deposition, the arc current and substrate bias were set to 90 A and -30 A, respectively. During EB-PVD deposition, the substrate rotation speed was maintained at 30 rpm, and the substrate preheating temperature was controlled at 900–950 $^{\circ}$ C for YSZ and 850–900 $^{\circ}$ C for the modified GZO, respectively.

2.2. Coating Characterization

A multi-scale, multi-technique characterization strategy was adopted to assess the surface state of the specimens before and after drag finishing. Surface roughness parameters (TIME3220, Beijing TIME High Technology Co., Ltd., Beijing, China) were measured using a handheld profilometer at 3–5 locations per specimen to ensure statistical representativeness. Surface roughness was evaluated using Ra (arithmetic mean roughness), Rz (ten-point height), Rsk (skewness), and Rku (kurtosis). For the cut-off settings, a 2.5 mm cutoff length was selected. Post-finishing surface and cross-sectional morphologies were examined by a benchtop scanning electron microscope (SEM) (Phenom Pro X, FEI, Hillsboro, OR, USA). Cross-sectional specimens were prepared via sectioning, mounting, grinding, and polishing to evaluate coating microstructure and defect evolution. To capture residual micro-grooves and localized brittle micro-pits that may persist after the macroscopic roughness has been substantially reduced, atomic force microscopy (AFM) (Oxford Jupiter AR, Oxford Instruments, Oxfordshire, UK) was employed to characterize local topography and micro-scale roughness. Three areas were scanned for each specimen with a scan size of 30 μ m $\times$ 30 μ m, which is closely related to the characteristic column width of YSZ and modified GZO. For AFM measurements, tapping mode was used with a tip radius of 7 nm and a scan rate of 1 Hz. Based on experimental data, the column widths of YSZ and modified GZO are both less than 10 μ m, and the selected scan size effectively covers these features, providing clear surface morphology information while ensuring that key surface features are observed without losing important details. In addition, a laser confocal microscope (DCM8, Leica Microsystems, Wetzlar, Germany) was used to obtain three-dimensional surface topography of the finished bond-coat specimens, enabling assessment of the spatial continuity and directional consistency of surface tracks, thereby indirectly reflecting the continuity of abrasive motion across the workpiece surface.

2.3. Drag-Finishing Process and Parameter Design

Drag finishing was performed using spherical ceramic media. The specimens were clamped onto the fixture of a drag-finishing machine, which drove the fixture to execute a coupled self-rotation–revolution motion within a media barrel, establishing a stable relative sliding motion and normal loading at the workpiece surface for coating finishing. Considering the complex geometry of turbine blades and the requirement for uniform finishing across different regions, both clockwise and counterclockwise rotations were applied during finishing, as illustrated in Figure 1. Spherical alumina particles with diameters of $\phi 1$ mm and $\phi 3$ mm were used as the abrasive media, with a prescribed amount of water added as a lubricating liquid. Media mixtures with $\phi 1$ mm: $\phi 3$ mm volume ratios of 0:1, 2:8, 4:6, and 6:4 were investigated, aiming to modulate interstitial filling and the effective contact scale to alter the abrasive–surface interaction mode and its influence on coating roughness. Drag-finishing trials were conducted on the NiCrAlYSi bond coat and for the YSZ and modified GZO ceramic topcoats. The spindle speeds were set to 10 rpm and 20 rpm, respectively. The NiCrAlYSi bond coat was processed under unidirectional rotation (without reversal), whereas YSZ and modified GZO were processed under a periodic reversal scheme of 2 min clockwise followed by 2 min counterclockwise. Specimens were sampled at 4 min intervals; the single-size media condition was run for 20 min, while the mixed-media conditions were extended to 28 min.

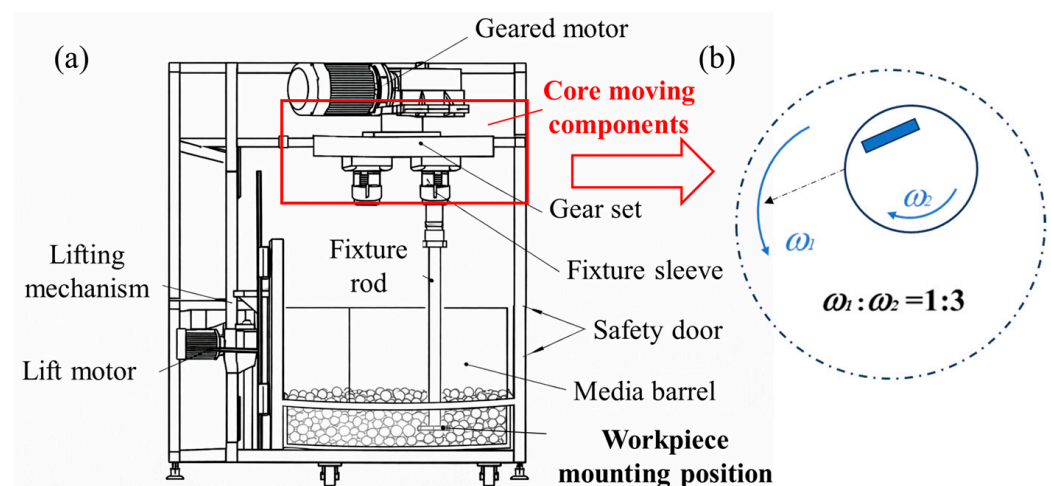


Figure 1. Drag-finishing apparatus and kinematic model: (a) schematic of the setup; (b) schematic of the motion model.

2.4. Development of the DEM Simulation Model

Drag finishing removes a limited amount of coating material through abrasive–surface interactions, making it a representative media-based mass-finishing technique. The Discrete Element Method (DEM) can reproduce particle motion and contact events under process kinematics, enabling mechanistic interpretation of media–workpiece interactions and estimation of effective polishing conditions. Accordingly, a DEM model was established for drag finishing of thermal barrier coatings (TBCs) coupons. As shown schematically in Figure 1b, the specimen undergoes a superimposed dual-rotation kinematic: it rotates about the fixture axis (self-rotation, ω_2) while simultaneously revolving about the central axis of the turntable (revolution, ω_1). This combined motion increases the relative velocity and enhances the coverage of contact trajectories. In the present study, the speed ratio was set to $\omega_1:\omega_2 = 1:3$. The workpiece and abrasive media constitute the two key components of the model. Spherical alumina particles with a diameter of 3 mm were used as the media, and a bulk filling fraction of 60% was generated in the container based on the packed volume of the spheres. The workpiece was modeled as a rectangular coupon with dimensions of

40 mm × 20 mm × 3 mm. The material properties and contact parameters assigned to the particles and the workpiece are summarized in Tables 1 and 2, respectively.

Table 1. Material properties of the workpiece and particles.

Material	Density (kg·m ⁻³)	Poisson's Ratio	Shear Modulus (Pa)	Wear Coefficient
Al ₂ O ₃	3900	0.22	1.23×10^{11}	10^{-9}
YSZ	6065	0.3	2×10^8	

Table 2. Contact interaction parameters between materials.

Parameter	Coefficient of Restitution	Static Friction Coefficient
Particle–particle	0.5	0.6
Particle–workpiece	0.5	0.4

In the simulation, the workpiece was modeled as a dense block, and the material properties of alumina balls and YSZ were based on real test data from other researchers [23]. The selection of the wear coefficient took into account that real abrasives are a mixture of solid and liquid phases, with water playing a lubricating role. Preliminary trial calculations indicated that the selected magnitude of the wear coefficient better matched real-world conditions. At this magnitude, the wear trends of the workpieces remained consistent, with only minor variations in the final values, which did not affect the overall trend verification of the DEM simulations in this study.

During drag finishing, material removal is governed primarily by the combined effects of tangential abrasive scratching and normal impacts arising from the relative motion between the media and the workpiece. To focus on the effective interaction zone, only particles within the surface contact region were considered in the DEM simulations, while the transient influence of media outside the contact zone was neglected. The abrasives were assumed to be monodisperse, rigid spheres, and abrasive–abrasive wear was not considered. Particle–particle interactions were modeled using the Hertz–Mindlin contact law. For particle–workpiece interactions, the Hertz–Mindlin, Hertz–Mindlin with Archard, and Hertz–Mindlin with Relative Wear models were employed to represent different wear-calculation schemes. The integration time step was set to 35% of the Rayleigh time step. In the simulations, the revolution and self-rotation speeds were set to $\omega_1 = 20$ rpm and $\omega_2 = 60$ rpm, respectively; gravity was applied along the Z direction with $g = 9.8 \text{ m s}^{-2}$. The total simulation time was 4 s, consisting of 2 s of clockwise rotation followed by 2 s of counterclockwise rotation.

3. Results and Discussion

3.1. Microstructure and Defect Characteristics of As-Deposited Coatings

The material properties and microstructural features of coatings can substantially affect the abrasive–surface interaction and, consequently, the material removal behavior during drag finishing. In this study, a NiCrAlYSi bond coat was deposited by multi-arc ion plating, while columnar-structured YSZ and modified GZO ceramic topcoats were fabricated via EB-PVD. These three coatings, exhibiting pronounced differences in both intrinsic material properties and microstructural architectures, were employed to investigate surface morphology evolution and defect characteristics during drag finishing.

Figure 2 presents the as-deposited surface and cross-sectional morphologies of the NiCrAlYSi bond coat and the YSZ and modified GZO ceramic layers. The NiCrAlYSi bond coat shows an undulating surface, and its cross-section exhibits a typical metallic lamellar/stacked morphology, accompanied by a certain fraction of pores and local defects.

Overall, this coating displays relatively high structural continuity and bulk compactness, with pores mainly appearing as isolated voids or locally clustered regions. The YSZ ceramic layer exhibits a columnar microstructure with columns extending outward from the interface; inter-column gaps and porosity constitute its dominant structural features. On the surface, column tips and local asperities are the primary contributors to roughness. In cross-section, the continuity of columns, the distribution of column widths, and the scale of inter-column gaps reveal marked heterogeneity, which underlies spatial variations in micro-scale structural integrity. The modified GZO topcoat is also columnar, yet differs from YSZ in column morphology, inter-column bonding, and defect distribution: the columns are generally wider, the surface shows fewer fine column-tip asperities and is instead characterized by more irregular protrusions, and the cross-section contains more pronounced inter-column gaps, porosity, and potential defects, indicating higher sensitivity in microstructural uniformity and local integrity. Therefore, although both YSZ and modified GZO are columnar ceramic topcoats, differences in column scale, defect morphology, and spatial distribution are expected to lead to distinct surface morphology evolution pathways during drag finishing.

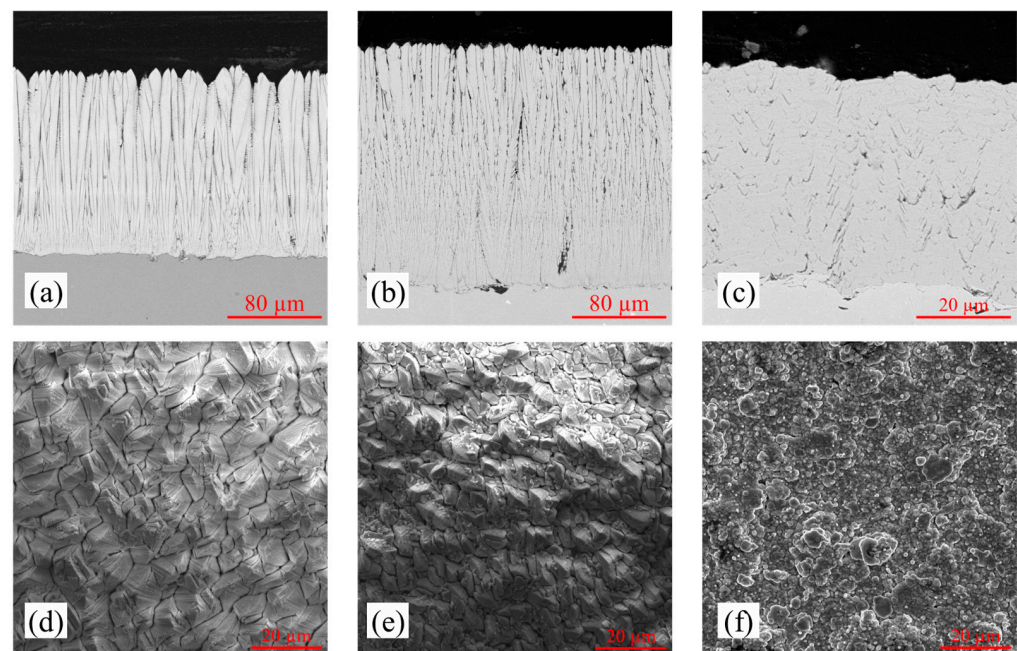


Figure 2. SEM micrographs of the three coatings: (a) cross-sectional view of GZO; (b) cross-sectional view of YSZ; (c) cross-sectional view of NiCrAlYSi; (d) top-surface view of GZO; (e) top-surface view of YSZ; (f) top-surface view of NiCrAlYSi.

Overall, distinct microstructural disparities are evident among the three coatings prior to drag finishing. The NiCrAlYSi bond coat exhibits a characteristic lamellar/stacked architecture, with pores distributed mainly as isolated voids or localized clusters, reflecting comparatively high structural continuity and overall densification. In contrast, both the YSZ and the modified GZO topcoats are dominated by a columnar microstructure, where inter-column gaps and pores constitute the primary heterogeneities; moreover, discernible differences exist between the two ceramics in terms of column scale, morphological integrity, and the spatial distribution of defects. This pre-finishing microstructural comparison provides a clear structural reference and an essential basis for interpreting subsequent differences in surface morphology evolution, defect response, and the associated variations in statistically derived roughness parameters across different coatings.

3.2. Surface Morphology Changes in Coatings Under the Action of a Single Large-Sized Abrasive

To establish the fundamental response of ceramic topcoats during drag finishing, spherical alumina abrasives with a diameter of 3 mm were first used to finish YSZ and modified GZO coatings. As shown in Figure 3, both types of ceramics exhibit an overall trend of decreasing roughness with time, but there are significant differences in processing uniformity and damage types. To comprehensively characterize the surface evolution of columnar EB-PVD coatings during finishing, R_a , R_z , R_{sk} , and R_{ku} were used as roughness parameters, with the corresponding evolution curves shown in Figure 3. R_z is used to reflect the variation in peak-to-valley values, while R_{sk} and R_{ku} characterize the skewness and kurtosis of the height distribution, respectively, helping to distinguish between “peak-reduction leveling” and “damage-dominated” surface fluctuations. As shown in Figure 3, after starting the finishing process, the R_{sk} value of modified GZO immediately becomes less than 0 and significantly larger than that of YSZ, indicating that its height distribution exhibits a more prominent “valley-dominated” negative skewness. At the same time, the R_{ku} of modified GZO is much higher than that of YSZ, indicating that its surface height distribution has a stronger “heavy-tail” feature, where most areas tend to flatten, but still retain a few extreme features with large amplitudes, typically corresponding to deep pits or localized debris accumulation. This provides a statistical basis for the subsequent damage-dominated stage.

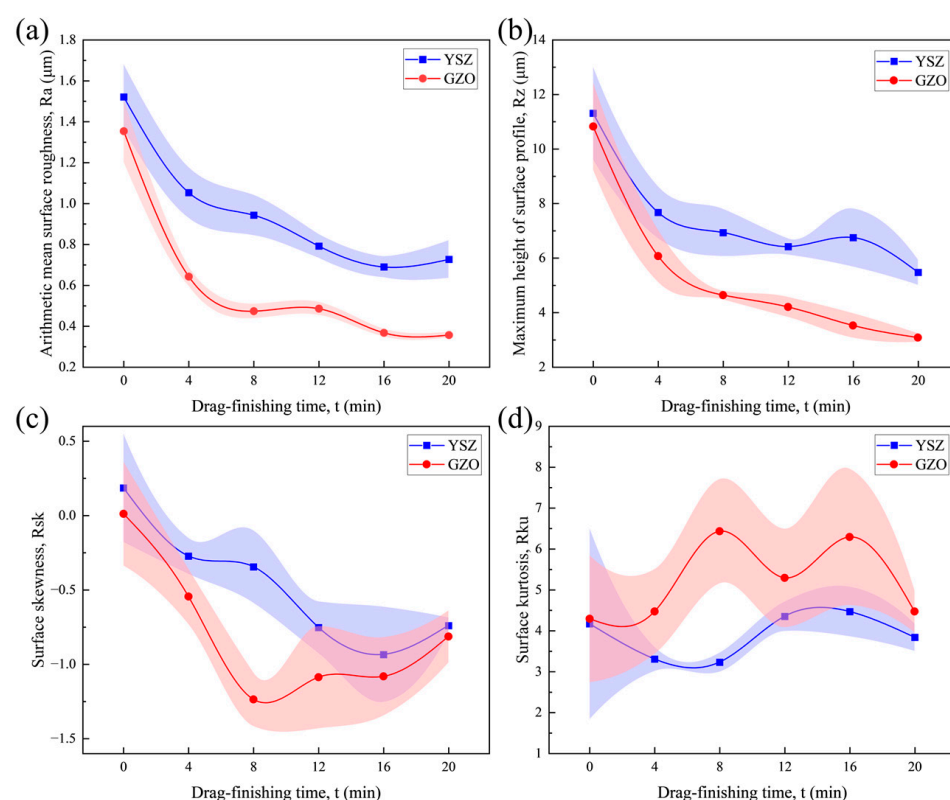


Figure 3. Variation in roughness parameters with processing time: (a) R_a ; (b) R_z ; (c) R_{sk} ; (d) R_{ku} .

For YSZ, the surface mainly exhibits column tip flattening and local cutting planes after finishing, but several poorly processed areas can still be observed. The corresponding cross-sections also show insufficient removal in some areas, suggesting that single-particle abrasives have difficulty achieving equivalent coverage across all micro-regions on the significantly undulating columnar crystal surface, thereby introducing spatial non-uniformity. After 20 min of finishing, the average material removal for YSZ is approximately 1–3 μm , and the surface roughness is reduced to $R_a \approx 0.7 \mu\text{m}$ (Figure 3). Combined with the

evolution of R_z , R_{sk} , and R_{ku} , YSZ mainly undergoes peak-reduction/leveling, but in some regions, the original surface features are retained, suggesting that its main bottleneck stems from insufficient local coverage rather than overall removal ability.

In contrast, the surface of modified GZO is more thoroughly processed, with significantly higher removal (over $5\text{ }\mu\text{m}$). After 12–16 min of finishing, recognizable columnar crystal fracture/pull-out pits and fracture defects appear, and multiple inter-column cracks can be seen in the cross-section (Figure 4b). In contrast, no similar inter-column cracks were observed in the YSZ cross-section (Figure 4a), indicating intrinsic differences in their damage evolution pathways.

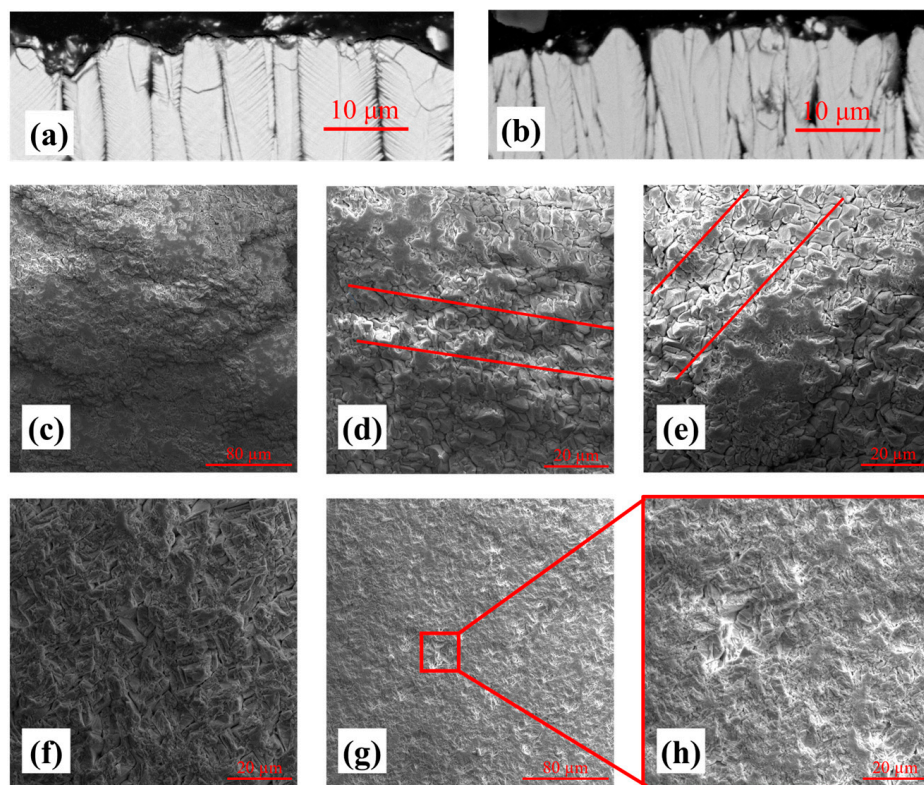


Figure 4. Cross-sectional morphologies and surface morphologies of YSZ and modified GZO ceramic topcoats after drag-finishing with single-size abrasive media: (a) cross-section of YSZ; (b) cross-section of modified GZO; (c) surface morphology of YSZ at the initial finishing stage (4–8 min); (d,e) surface morphologies of YSZ at the fully finished stage (16–20 min); (f) surface morphology of modified GZO at the initial finishing stage (4–8 min); (g) surface morphology of modified GZO at the fully finished stage (16–20 min), $1000\times$ magnification; (h) surface morphology of modified GZO at the fully finished stage (16–20 min), $3000\times$ magnification. (h) surface morphology of modified GZO at the fully finished stage (16–20 min), $3000\times$ magnification.

The finishing process of modified GZO uses a periodic reversal strategy, i.e., 2 min of clockwise rotation followed by 2 min of counterclockwise rotation, with a 4 min kinematic cycle. Based on a large number of repeated experimental results, the surface/cross-sectional evolution of modified GZO under this condition can be divided into three stages: (I) Rapid leveling stage (4–8 min), where the column tips are quickly removed in a short time, and the surface roughness significantly decreases, with few or no visible columnar pull-out and fracture defects; (II) Crack initiation and stable accumulation stage (8–12 min), where small micro-cracks start to be observed in the cross-section, but columnar pull-out remains rare, and the surface morphology shows minimal change compared to the 4–8 min stage; (III) Damage instability and pull-out dominated stage (12–16 min), where the cracks accumulated earlier begin to propagate, and a large number of pull-out defects are observed

on the surface, along with a small amount of short continuous cutting planes. Based on the morphology criterion of “appearance of micro-cracks in the cross-section—significant increase in pull-out pits” and the trend of changes in R_z , R_{sk} , R_{ku} , and other statistical parameters within this time window (Figure 3), we identify 12–16 min as the characteristic time window for the transition of modified GZO from a “leveling-dominated” to a “damage/pull-out-dominated” phase.

Further comparison of the surface morphologies at different times for both YSZ and modified GZO (Figure 4c–h) reveals that even after 16–20 min, YSZ retains many regions with the original surface morphology, whereas GZO shows little of the same “insufficiently processed area” at 4–8 min. Under these processing conditions, modified GZO has a wider column width, meaning the column tip characteristic scale is larger, and the individual column top is “wider,” making it more susceptible to normal impacts and triggering crack initiation. However, whether the cracks further propagate and evolve into columnar crystal fractures/pull-out removal is ultimately controlled by the material’s fracture toughness.

AFM was used to further analyze the micro-region morphology of the coatings: discrete micro-grooves/shallow micro-pits and local irregular undulations can still be identified in the areas of significantly reduced roughness for YSZ (Figure 5a), while GZO shows more pronounced height-field discontinuities due to irregular cross-sections, debris accumulation, and pit defects (Figure 5b). This difference is corroborated by the trends of changes in R_{sk} , R_{ku} , and other height distribution statistical parameters, indicating a clear divergence in the “leveling-dominated” and “damage-dominated” evolutionary paths for the two materials.

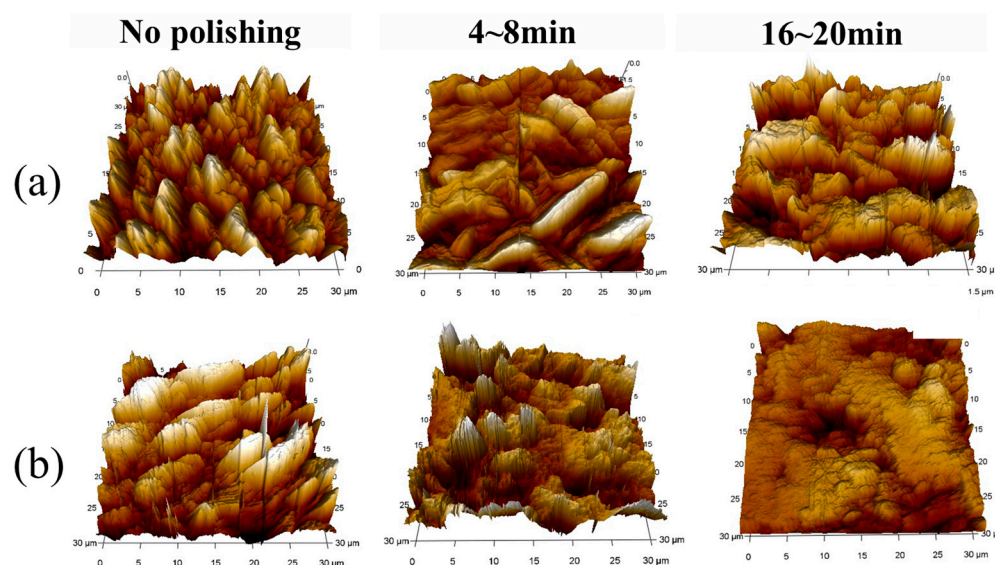


Figure 5. AFM topography of YSZ and modified GZO ceramic topcoats: (a) YSZ; (b) GZO.

The results correspond to two core issues: first, the formation mechanism of inadequately processed areas in YSZ; second, why modified GZO, despite a more complete coverage, tends to experience excessive material removal and columnar crystal pull-out. To verify the contact state and load input characteristics, a relatively soft NiCrAlYSi bond coat was chosen as a reference sample, and the surface forces of samples of the same size were analyzed using DEM. Experimentally, under relatively “extreme” unidirectional rotation conditions, the bond coat was continuously polished for 20 min (without reversal), and surface grooves extending in specific directions appeared (Figure 6), indicating that abrasive particle movement has a strong directional stability. Corresponding DEM results (Figure 7) showed that under the combined rotational kinematics, abrasive particles on the specimen surface exhibited quasi-directional rolling/sliding trajectories, accompanied by about 0–30°

of vertical offset. The areas with longer sliding paths had more concentrated contact, which easily led to the formation of directional grooves. Further, both simulation and experiment pointed to a stable source of spatial non-uniformity: abrasive particle clusters could form tight arrangements in local areas, and the unavoidable geometric gaps between particles would project stable low-contact-probability regions on the surface, resulting in spatial “shadowing effects” of material removal. This effect is particularly prominent under prolonged unidirectional rotation, presenting as continuous grooves in fixed directions that correspond to “unpolished/unprocessed” shadow bands, reflecting the local structure of the media and the “path memory” feature of abrasive motion.

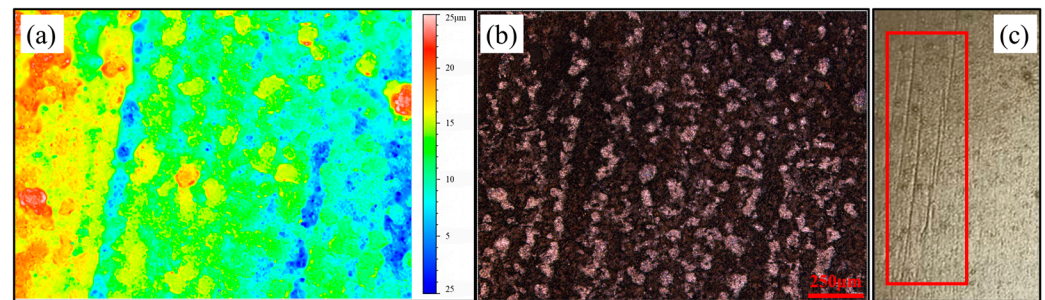


Figure 6. Surface morphology of the NiCrAlYSi bond coat after drag-finishing: (a) Laser confocal morphology; (b) Optical microscope morphology; (c) Macroscopic morphology.

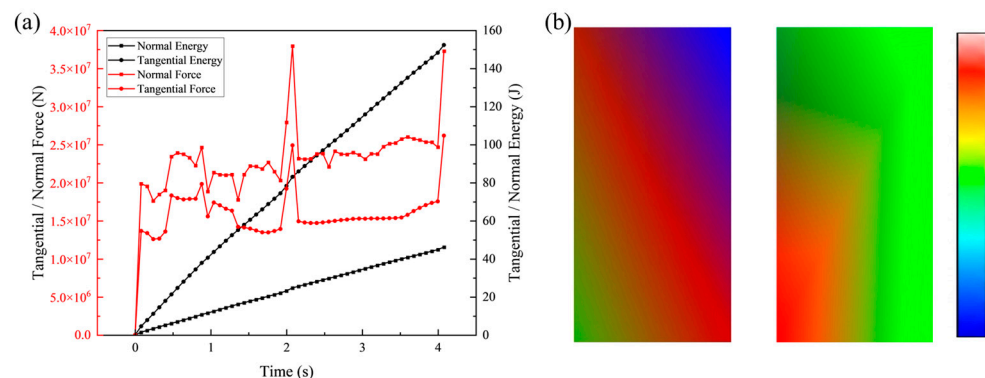


Figure 7. DEM simulation results: (a) time histories of stress/force and contact energy; (b) wear distribution contours on both sides of the coupon.

In addition to the non-uniformity caused by abrasive contact, DEM force and energy statistics also indicate that drag finishing is not a “pure cutting” process: both tangential and normal loads occupy significant portions, and although normal forces have higher peaks, the accumulated tangential energy is still greater. This suggests that the contact process is primarily dominated by friction work input caused by sustained sliding, with a certain degree of normal collisions/indentations superimposed.

Such composite load input on relatively low-hardness, ductile metal surfaces usually manifests as continuous plowing and surface smoothing, without leading to fracture of structural units. However, for non-dense columnar ceramic topcoats, the fracture toughness of the material significantly modulates the micro-fracture and defect formation processes induced by normal impacts. Both YSZ and GZO have non-dense columnar structures, but YSZ has higher fracture toughness (about $1.8\text{--}4.5 \text{ MPa}\cdot\text{m}^{1/2}$), making the columns less likely to undergo large-scale fracture and pull-out under the same load input. Therefore, the removal process is mainly characterized by column tip flattening and localized cutting planes, with the primary issue being insufficient local coverage caused by the shadowing effect. In contrast, GZO has lower fracture toughness (about $1.0 \text{ MPa}\cdot\text{m}^{1/2}$), and the column

width scale difference increases the loading characteristic of individual columns under normal impacts, making them more prone to micro-crack formation and expansion, thereby entering the damage-dominated stage earlier, resulting in higher material removal and stronger defect features. It should be noted that factors such as porosity, column spacing, and residual stress states may also contribute to the damage evolution process and affect the damage threshold and expansion rate. Within the scope of this study, based on the drastically different damage modes presented by the two coatings under similar load inputs, we believe that the difference in fracture toughness is one of the key controlling factors leading to the divergence in their material removal behavior.

Thus, under single-particle-size large-diameter spherical abrasives, the two ceramic topcoats exhibit differential removal behaviors: YSZ primarily involves limited peak shaving/smoothing, but localized insufficient polishing occurs due to abrasive particle packing and shadowing effects; modified GZO is more prone to micro-crack formation under normal impact, which evolves into columnar crystal fracture removal, resulting in excessive removal and an increased risk of over-polishing. This further indicates that tangential smoothing can be partially controlled by the process path, while normal impacts are harder to suppress, causing low-toughness ceramics to enter the damage-dominated stage earlier.

3.3. Surface Finishing Behavior Regulation Under Multi-Scale Abrasive Mixing Ratio

To mitigate the shadowing effect induced by monodisperse, large-size media on columnar surfaces and thereby improve finishing uniformity—while also reducing the risk of uncontrolled damage in low-fracture-toughness ceramics under normal-impact loading—a multiscale spherical media system with diameters of 1 mm and 3 mm was introduced. Three volume-fraction ratios ($\phi 1\text{ mm} : \phi 3\text{ mm} = 2:8, 4:6, \text{ and } 6:4$) were employed to finish the YSZ and modified GZO coatings. The role of the multiscale media can be summarized in two aspects. First, the 1 mm particles can fill the interstices among the 3 mm spheres and access local micro-regions where large particles cannot stably engage, thereby increasing contact-point density, weakening low-contact-probability zones, and improving areal coverage. Second, the fine-scale multi-point contacts introduced by the smaller particles tend to promote tangential-scratching-dominated, stable removal, whereas the 3 mm particles maintain a certain level of normal load input and macroscopic shaping capability. Consequently, multiscale gradation provides an effective degree of freedom to tune the relative contributions of “cutting” versus “impact,” enabling a balance among removal efficiency, uniformity, and surface integrity.

The roughness evolution directly reflects the removal-mode transition induced by media blending (Figure 8). For YSZ, the 6:4 condition yields a near-linear decay with the most stable reduction process, whereas the 2:8 and 4:6 groups exhibit more pronounced fluctuations without a consistent rate advantage. In contrast, the modified GZO curves are overall smoother; however, as the fraction of 1 mm particles increases, the roughness-reduction rate becomes progressively suppressed, suggesting a shift from “impact-driven rapid removal” toward “cutting-dominated gradual planarization.” Consistently, the surface-morphology comparisons (Figures 9–11) show that, unlike the 3 mm monodisperse condition where clear cutting marks are difficult to identify on both ceramics, introducing 1 mm particles produces discernible grooves and/or cutting facets on both YSZ and modified GZO, indicating that fine-scale tangential scratching is significantly activated. Notably, for modified GZO, distinct grooves and cutting facets—nearly absent under the 3 mm monodisperse condition—become evident under mixed media, serving as direct morphological evidence that small particles enhance tangential cutting. Moreover, the grooves on ceramic surfaces are generally sparse and short-ranged rather than developing into the long, con-

tinuous channels commonly observed on the bond coat, implying that multiscale media disrupt particle trajectories and weaken “path memory,” thereby promoting more uniform material removal.

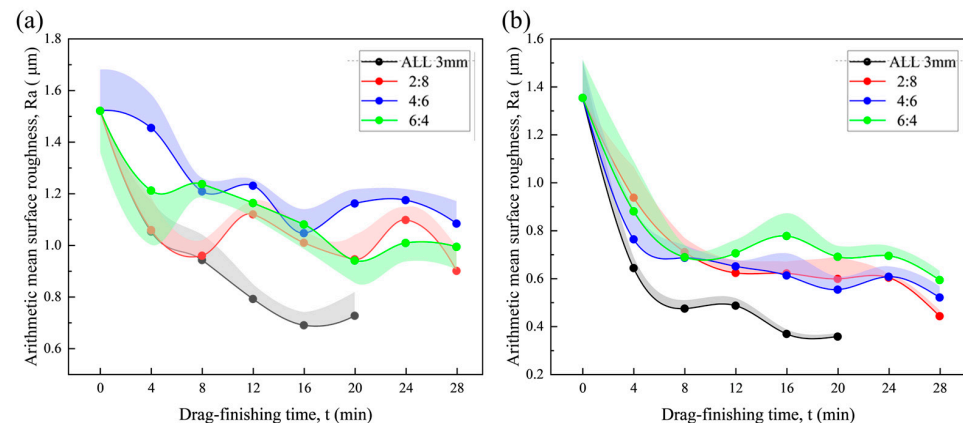


Figure 8. Surface roughness evolution after drag-finishing under different 1 mm/3 mm mixed-abrasive volume ratios: (a) YSZ; (b) GZO.

Under the 2:8 ratio, the 1 mm abrasives primarily occupy the interstitial spaces between the 3 mm balls, leading to a denser packing state and stronger local confinement, which in turn restricts the free rolling and migration of the large balls in localized regions. This interstitial-filling effect modifies both load transfer pathways and the effective contact scale, shifting the abrasive–surface interaction toward multi-point, fine-scale tangential sliding. Accordingly, the surfaces are characterized by dispersed shallow grooves and fine scratching marks. In terms of specific morphology, YSZ still exhibits a limited number of relatively longer and more distinct furrows, indicating that the 3 mm balls can locally establish a larger contact scale and generate sliding ploughing. By contrast, GZO shows only sparse and shallow cutting traces, suggesting that the morphological expression is more readily attenuated by the pervasive columnar-fragmentation background; i.e., under the same tangential action, the low-toughness columnar system is more prone to concurrent micro-fracture, which reduces the apparent height contrast of groove features.

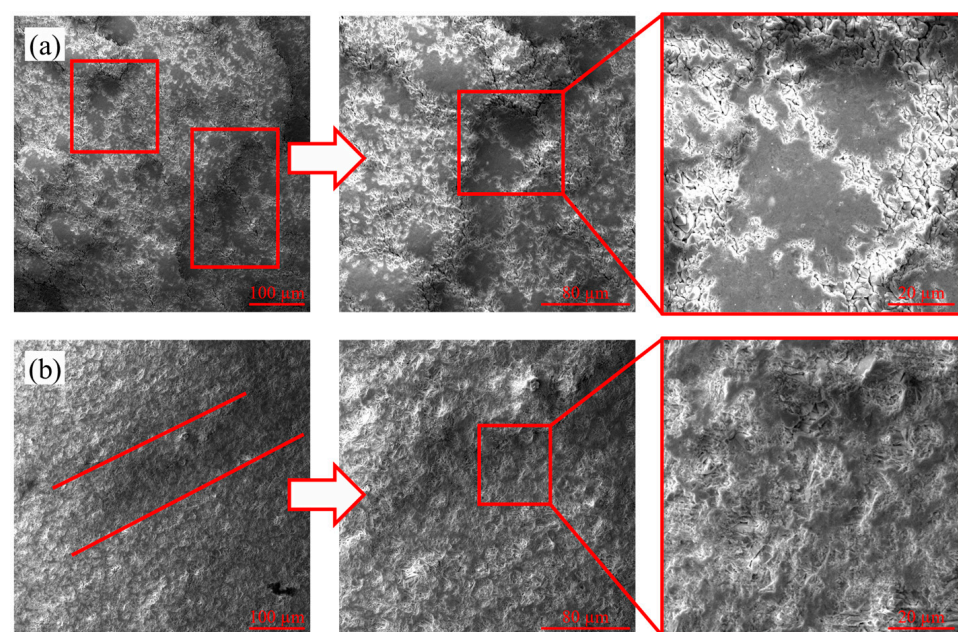


Figure 9. Cross-sectional morphologies of the coatings after drag-finishing with a 1 mm/3 mm mixed-abrasive volume ratio of 2:8: (a) YSZ; (b) GZO.

When the ratio is increased to 4:6, the two particle sizes become more comparable in both number and load contribution. The 1 mm abrasives impose a more pronounced semi-encapsulation/interstitial constraint on the 3 mm balls, making the rolling and sliding trajectories of the large balls more frequently perturbed and interrupted. Consequently, the post-finishing surfaces are more likely to exhibit multiple discontinuous short ploughing grooves. On YSZ, these short grooves appear clearer and more strongly oriented, indicating that tangential cutting is locally intensified but tends to distribute in a “short-range, multi-site” manner rather than developing into long continuous furrows. GZO also shows groove features, albeit shallower; this does not necessarily imply weaker cutting. Instead, it is more plausibly associated with the greater propensity of its columnar asperities to undergo widespread fragmentation—when extensive fracture/spallation occurs beyond the groove regions, the top layer is effectively “uniformly reduced,” thereby diminishing the relative height contrast and visual prominence of the grooves.

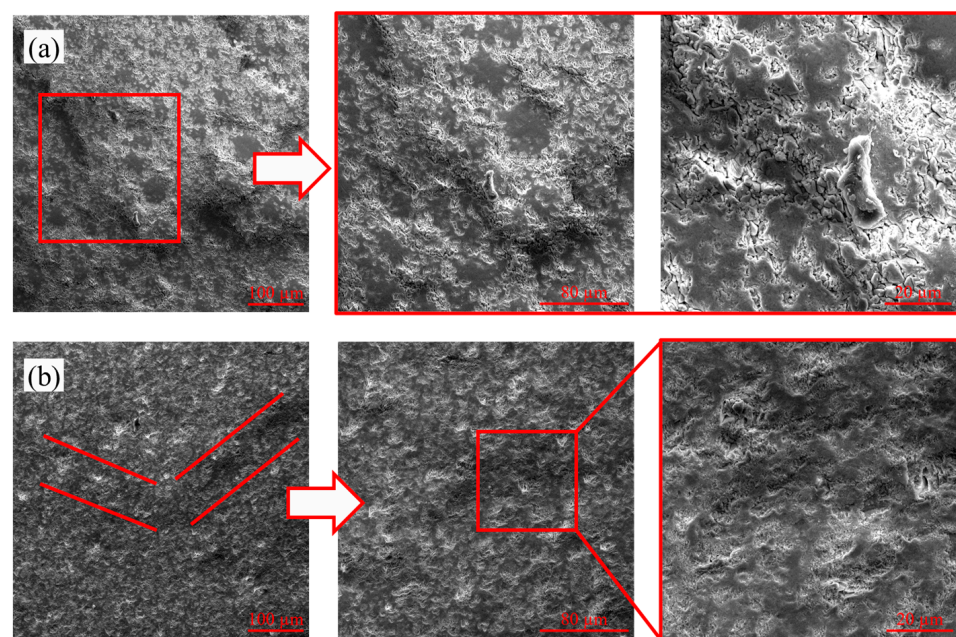


Figure 10. Cross-sectional morphologies of the coatings after drag-finishing with a 1 mm/3 mm mixed-abrasive volume ratio of 4:6: (a) YSZ; (b) GZO.

When the 1 mm fraction is further increased to 6:4, the packing density of the media rises markedly and the motion of the 3 mm balls becomes more strongly constrained. On YSZ, the number of ploughing grooves decreases substantially and the remaining traces become spot-like or segmented, indicating that long-range sliding contributed by the large balls is effectively suppressed and that cutting marks can no longer propagate persistently along a fixed path. This observation is consistent with the more stable roughness decay of YSZ in Figure 9, suggesting a gradual transition from removal dominated by a few large-scale trajectories to a more uniformly distributed, multi-contact interaction. On GZO, a limited number of shallow grooves are still observed; local magnification reveals more distinct cutting facets and abrasion marks, further confirming that the addition of fine abrasives significantly enhances microscale tangential cutting. Nevertheless, the morphological expression remains influenced by the pervasive fragmentation of columnar features, resulting in weaker groove contrast and a greater tendency for grooves to coexist with pit-type defects.

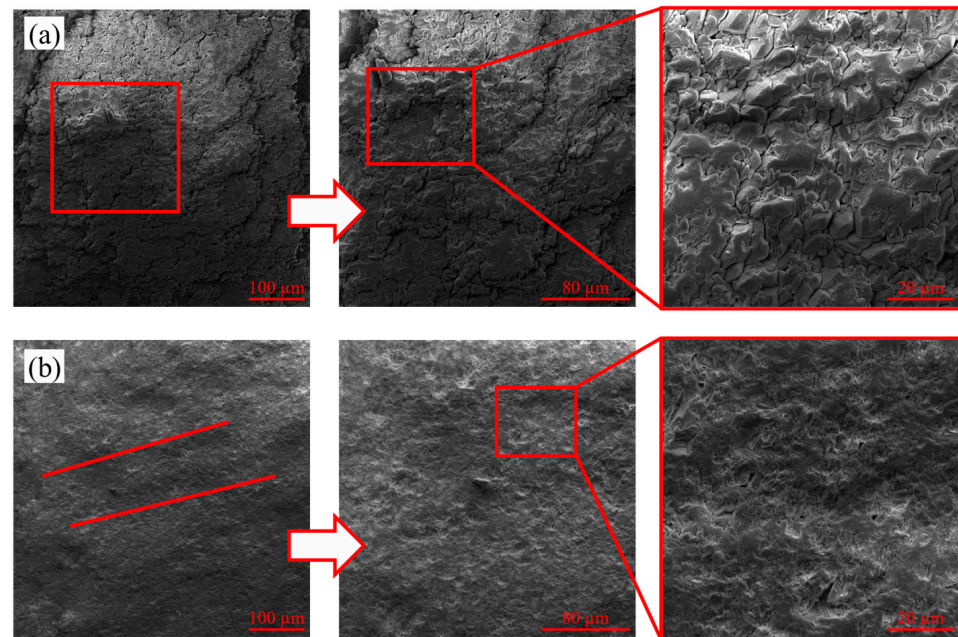


Figure 11. Cross-sectional morphologies of the coatings after drag-finishing with a 1 mm/3 mm mixed-abrasive volume ratio of 6:4: (a) YSZ; (b) GZO.

In summary, the multi-particle-size mixed abrasive system enhances the micro-cutting on the ceramic surface through gap-filling effects and increased spatial density, making cutting features that were not significant under single-particle-size conditions more apparent. As the proportion of 1 mm abrasive particles increases, the strong impacts and long-range continuous sliding dominated by large particles gradually decrease, and the groove morphology shifts from relatively clear to shorter and more dispersed. During this process, the tangential force becomes more prominent, as smaller particles have higher spatial density and greater mass per unit volume, leading to more cutting effects. The sliding and scraping of abrasive particles help smooth the surface. In contrast, the normal force is more dominated by larger particles, resulting in impact forces and surface micro-crack formation. During the finishing process, YSZ coatings tend to retain cutting planes and short grooves more easily, as their higher fracture toughness makes the cutting process dominant. On the other hand, GZO coatings exhibit more frequent columnar-crystal breakage due to their lower fracture toughness, which weakens the contrast of cutting marks and is more easily dominated by pit-like defects. This is primarily because the normal force causes GZO surfaces to form more cracks and defects under normal impact.

As the proportion of 1 mm abrasive particles increases, although smaller particles help enhance the cutting effect, they also significantly reduce finishing efficiency, particularly in material removal rate. To balance removal efficiency and surface quality, using a mixed abrasive system proves more advantageous than single-particle-size abrasives. Smaller abrasive particles improve cutting precision and more effectively reduce surface roughness, while larger particles help increase removal efficiency. By optimizing the abrasive ratio, both removal efficiency and finishing precision can be improved, achieving effective reduction in surface roughness.

The abrasive ratio not only affects the stability and rate of roughness reduction but also reshapes the surface morphology and defect characteristics of the two types of ceramics by adjusting the relative contributions of “cutting” and “collision” forces. In particular, changing the abrasive ratio effectively modulates the interaction patterns of tangential and normal forces, further influencing the surface evolution characteristics of both ceramics during the finishing process. Additionally, finer abrasives represent higher finishing

precision, while larger abrasives correspond to higher removal efficiency. The ratios studied in this research also provide a microscopic basis for the directional design of abrasive-based finishing process windows.

4. Conclusions

This work addresses the drag-finishing requirements for multi-material TBC systems. By integrating DEM simulations with roughness statistics and multiscale surface/microstructural characterization, the particle–surface contact coverage and load-input characteristics were systematically quantified, and their effects on material removal and damage evolution in two columnar ceramic topcoats (YSZ and modified GZO) were elucidated. The regulating role of a 1 mm/3 mm multi-scale abrasive size distribution on machining uniformity and surface integrity was further validated. Based on these results, the following conclusions are drawn:

1. DEM simulations indicate that, under the superposed dual-rotation kinematics, abrasives in the contact zone exhibit quasi-directional rolling/sliding, with both tangential and normal components contributing non-negligibly to the contact loading. When particles become locally closely packed, the intrinsic geometric gaps between neighboring abrasives project onto the workpiece surface as persistent low-contact-probability regions, leading to spatially non-uniform material removal and providing a mechanistic explanation for the localized “unreached/under-processed” areas.

2. Under the monodisperse alumina media condition with a particle diameter of 3 mm, both the YSZ and modified GZO coatings exhibit an overall capability for roughness reduction; however, their finishing uniformity and damage-evolution pathways differ markedly. For YSZ, the dominant features after finishing are the flattening of column tips and the formation of local cutting facets, while certain regions remain insufficiently processed and no pronounced inter-column cracking is observed in cross-section. In contrast, the modified GZO surface shows more complete areal coverage but a substantially larger material removal, and inter-column cracks together with local fracture/pull-out pits emerge in the near-surface region at approximately 12–16 min, indicating an earlier transition to a brittle-damage-dominated regime, consistent with its lower fracture toughness.

3. Introducing 1 mm particles into the 3 mm media to form a multiscale mixed-abrasive system provides an effective degree of freedom for tailoring the relative contributions of “cutting” and “impact.” Owing to the interstitial filling effect, the smaller abrasives increase the contact-point density and access micro-regions where the large spheres cannot act stably, thereby mitigating the shadowing effect and markedly activating fine-scale tangential scratching. Notably, the cutting-related traces that are inconspicuous for the modified GZO under the 3 mm monodisperse condition become clearly discernible in the mixed system, demonstrating the enhancement of tangential cutting by the small-particle fraction. As the volume fraction of 1 mm abrasives increases, the relative contributions of long-range sliding and strong impacts dominated by the 3 mm spheres are progressively suppressed, and the resulting grooves become shorter and more dispersed. The roughness evolution further indicates that YSZ exhibits a more stable decay at the 6:4 ratio, whereas the roughness reduction rate of the modified GZO decreases with increasing 1 mm fraction.

In summary, this study establishes a transferable “contact coverage–load input–surface response” analytical framework and provides guidance for designing process windows for drag finishing of multi-material TBC systems. By optimizing the abrasive grading, a controllable balance and optimization can be achieved among removal efficiency, processing uniformity, and surface integrity.

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Abbreviations

The following abbreviations are used in this manuscript:

TBCs	Thermal Barrier Coatings
YSZ	Yttria-Stabilized Zirconia
GZO	Gallium Zinc Oxide
EB-PVD	Electron Beam Physical Vapor Deposition
SEM	Scanning Electron Microscopy
DEM	Discrete Element Method
AFM	Atomic Force Microscopy

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