Technical Article

High-Entropy Alloys as Bond Coats in Thermal Barrier Coatings

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Abstract

Thermal barrier coatings (TBCs) are vital for boosting the performance and longevity of high-temperature components in gas turbines and jet engines, offering thermal insulation and oxidation resistance. Traditional MCrAlY bond coats, though effective, suffer from drawbacks such as rapid oxidation above 1100°C, substrate interdiffusion, and limited high-temperature strength. High-entropy alloys (HEAs), featuring multiple principal elements in near-equimolar proportions, present a promising alternative due to their high configurational entropy, sluggish diffusion, lattice distortion, and synergistic effects, resulting in enhanced oxidation resistance, thermal stability, and mechanical properties. This review consolidates recent progress in HEAs as bond coats, emphasizing compositions like NiCoCrAlY-based alloys, AlCrFeCoNi, and refractory variants applied via thermal spray methods such as high-velocity oxy-fuel (HVOF), atmospheric plasma spray (APS), and high-velocity air-fuel (HVAF). Notable outcomes include improved oxidation resistance via stable alumina scales, reduced interdiffusion, and extended TBC durability under thermal cycling. Issues like in-flight oxidation and phase changes are explored, alongside future strategies for optimizing HEA compositions with reactive elements such as Y and Hf. This study underscores HEAs' potential to push TBC operating temperatures beyond current thresholds, benefiting aerospace and power generation sectors.

Keywords: HEA, TBC, Bond Coats, Oxidation Resistance, Thermal Spray.

1. Introduction

Thermal barrier coatings (TBCs) are a cornerstone technology in modern high-performance engines, including aerospace propulsion and ground-based gas turbines, enabling higher operating temperatures to enhance efficiency and lower fuel use [1]. A standard TBC system includes a metallic bond coat for oxidation protection, a thermally grown oxide (TGO) layer (mainly α-Al_2O_3), and a ceramic top coat (e.g., yttria-stabilized zirconia, YSZ) for insulation [2]. The bond coat is crucial, forming a protective oxide layer that reduces environmental damage, improves adhesion between the substrate and top coat, and manages thermal expansion differences [3]. However, conventional MCrAlY bond coats (where M is Ni, Co, or both) face challenges like accelerated oxidation above 1050–1100°C, significant interdiffusion with Ni-based superalloys, and insufficient strength at high temperatures, leading to failures such as rumpling, cavitation, and spallation [4, 5]. These limitations become particularly pronounced in next-generation engines demanding service temperatures exceeding 1200°C, where traditional bond coats fail to maintain structural integrity, resulting in reduced engine lifespan and increased maintenance costs [6].

The search for advanced bond coats capable of enduring temperatures beyond 1100°C has spotlighted high-entropy alloys (HEAs). Introduced in 2004 by Yeh et al. [7] and Cantor et al. [8], HEAs are multi-principal-element alloys (typically five or more elements in equimolar or near-equimolar ratios) that stabilize simple solid-solution phases (e.g., FCC or BCC) due to high configurational entropy ($\Delta S\_conf > 1.5R$, where R is the gas constant) [9]. Their stability, coupled with effects like sluggish diffusion (which slows elemental migration and interdiffusion), severe lattice distortion (increasing yield strength and hardness), and cocktail effects (combining properties from multiple elements for synergistic enhancements), makes them ideal for high-temperature use [10]. Unlike traditional alloys reliant on one or two base elements, HEAs allow customizable compositions with oxidation-resistant elements (e.g., Al, Cr) while preserving phase stability and mechanical integrity [11]. This flexibility enables tailoring for specific applications, such as incorporating refractory elements for elevated melting points or reactive elements for improved oxide adhesion [12]. Recent research has highlighted HEAs' superior oxidation resistance, corrosion protection, and thermal cycling performance compared to MCrAlY [3]. Examples include AlCrFeCoNi and NiCoCrAlY variants, which exhibit slower oxide growth and better adhesion in TBC systems [11]. This review analyzes

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HEA bond coat literature, covering materials, deposition techniques, microstructures, and properties. It identifies research gaps, such as the need for reactive element doping and extended cyclic testing under realistic engine conditions, and shows how HEAs can overcome traditional limitations, potentially enabling ultra-high-temperature TBCs for nuclear reactors, turbine blades, and combustion chambers [2]. Integrating computational modeling (e.g., CALPHAD) with experiments, this review offers a pathway for advancing HEA bond coat development, emphasizing the role of entropy in phase stabilization and the potential for cost-effective manufacturing through scalable thermal spray processes [3].

2. Research Background

The development of bond coats in thermal barrier coatings (TBCs) has undergone a significant evolution, transitioning from early diffusion aluminides—simple aluminum-rich layers formed through pack cementation processes—to more sophisticated MCrAlY overlays (where M represents Ni, Co, or a combination of both), which incorporate chromium and yttrium to enhance oxidation resistance and adhesion [11]. These advancements marked a substantial improvement over aluminides by providing a more robust protective layer against high-temperature oxidation and thermal cycling stresses, particularly in gas turbine and jet engine applications where operating temperatures often exceed 1000°C. However, despite these improvements, persistent high-temperature challenges remain, including rapid oxide scale growth above 1100°C, significant interdiffusion with Ni-based superalloy substrates leading to phase instability, and insufficient mechanical strength under prolonged thermal exposure, which can result in failures such as rumpling, cavitation, and spallation [6]. These limitations have driven the exploration and adoption of high-entropy alloys (HEAs) as a next-generation solution, leveraging their unique multi-principal-element composition to address the shortcomings of conventional materials. HEAs, characterized by the presence of five or more elements in near-equimolar or equimolar ratios, derive their transformative potential from high configurational entropy ($\Delta S\_conf > 1.5R$, where R is the gas constant), which stabilizes simple solid-solution phases such as face-centered cubic (FCC) or body-centered cubic (BCC) structures, minimizing the formation of brittle intermetallics [9]. This multi-component design not only enhances thermal stability and oxidation resistance but also introduces synergistic effects like sluggish diffusion, severe lattice distortion, and the "cocktail effect," where the combined properties of constituent elements exceed those of individual components [10]. Extensive studies have supported this shift, with research focusing on deposition techniques such as high-velocity oxy-fuel (HVOF), atmospheric plasma spray (APS), and high-velocity air-fuel (HVAF), which enable the production of dense, adherent HEA coatings with tailored microstructures [2]. Performance evaluations have revealed superior properties, including slower TGO growth, improved cyclic durability, and enhanced mechanical strength, making HEAs a promising candidate for extending the operational lifespan of TBCs in ultra-high-temperature environments [3]. Detailed analyses of microstructural evolution have further underscored the advantages of HEAs, with techniques like scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) providing insights into phase stability and oxide formation under thermal stress [3]. For instance, the sluggish diffusion effect in HEAs reduces elemental intermixing with the substrate, preserving the integrity of the bond coat-substrate interface, while lattice distortion increases hardness and wear resistance, critical for components exposed to erosive conditions [10]. Property enhancements, such as improved oxidation resistance through the formation of protective alumina scales and enhanced thermal cycling performance, have been documented across various HEA compositions, including NiCoCrAlSi, AlCrFeCoNi, and refractory variants like TiZrNbWMo [1, 4, 3]. These findings are complemented by computational modeling approaches like CALPHAD, which predict phase diagrams and guide the optimization of HEA formulations for specific applications [9]. Collectively, this body of research highlights the transformative impact of HEAs, positioning them as a cornerstone for future advancements in TBC technology, with potential applications extending to nuclear reactors, advanced turbine blades, and combustion chambers operating beyond current temperature limits [2].

2.1. HEA Compositions for Bond Coats

HEA bond coats typically rely on 3d transition metals (e.g., Ni, Co, Cr, Fe, Al) or refractory elements (e.g., Mo, Nb, Ta), designed for oxidation resistance and compatibility with Ni-superalloy substrates [10]. Ma et al. [1] developed NiCoCrAlSi HEAs using HVOF and APS, noting a BCC-dominant phase in HVOF coatings that resisted failure after 100 cycles at 1150°C despite internal oxidation. Al enhances α-Al_2O_3 formation, vital for TGO stability, by promoting selective oxidation and reducing transient oxide phases [12]. Zhao et al. [2] studied Y/Hf-doped NiCoCrAlFe HEAs, reporting improved oxidation and hot corrosion resistance due to sluggish diffusion, reducing substrate interdiffusion and preventing deleterious phase formations like spinels [13].

Table. 1. Summary of HEA Compositions as Bond Coats in TBCs.

HEA Composition	Deposition Process	Dominant Phases	Test Temperature (°C)	Key Properties	Reference
NiCoCrAlSi	HVOF/APS	BCC (HVOF), $L1_2$ + BCC/B2 (APS)	1050–1150	Oxidation resistance, thermal cycling (100 cycles)	[1]
Y/Hf-NiCoCrAlFe	Sintering	FCC + BCC	1100	Low oxidation rate, hot corrosion resistance	[2]
AlCrFeCoNi	HVAF	FCC + BCC	1100	Thermal stability, oxidation resistance	[4]
AlTiCrNiTa	Magnetron Sputtering	FCC/Amorphous	330	High hardness, corrosion resistance	[5]
$(CoCrFeMnNi)_{0.85}Ti_{0.15}$	Plasma Cladding	FCC + BCC + Sigma	400	High wear resistance	[3]
$RE_2(Ce_{0.2}Zr_{0.2}Hf_{0.2}Sn_{0.2}Ti_{0.2})_2O_7$	APS	Fluorite	1200	Low thermal conductivity	[12]

Refractory HEAs, as reviewed by Nair et al. [3], include elements like Ti, Zr, and Nb for high melting points and strength, offering superior creep resistance at temperatures above 1200°C. Arshad et al. [5] categorized HEAs into metallic, ceramic, and composite types, highlighting AlTiCrNiTa coatings via magnetron sputtering for high hardness and corrosion resistance up to 330°C, where the amorphous structure impedes ion diffusion [9]. Ceramic HEAs, such as rare-earth zirconates (e.g., $(La_{0.2}Nd_{0.2}Sm_{0.2}Eu_{0.2}Gd_{0.2})_2Zr_2O_7$), provide low thermal conductivity for top coats and are considered for bond coat enhancements to further lower heat transfer [12]. As observed in Table 1, the diversity of HEA compositions highlights their versatility in bond coat applications, where metallic types dominate due to their ductility and oxidation protection, while refractory types are more suitable for higher thermal stability [3].

2.2. Deposition Processes for HEA Bond Coats

Thermal spray techniques dominate HEA bond coat application, enabling dense, adherent layers with controlled microstructures [2]. HVOF, used by Ma et al. [1], reduces in-flight oxidation (IFO) with lower temperatures and air-fuel mixtures, producing BCC phases with minimal oxide stringers, which enhances coating cohesion and reduces defect sites for oxygen ingress. APS, applied by Zhao et al. [2], involves higher heat, forming dual-phase ($L1_2$ + BCC/B2) structures but increasing IFO and reducing Al content, potentially compromising long-term oxidation resistance [3]. HVAF, as noted by Ossiansson et al. [4], employs compressed air for lower oxidation, yielding denser AlCrFeCoNi coatings with slower oxide growth than CrFeCoNi, due to higher particle velocities that minimize melting and preserve composition. Laser and plasma cladding, explored by Nair et al. [3], allow in-situ alloying of refractory HEAs like TiZrNbWMo, achieving BCC + HCP phases with high hardness up to 800°C, ideal for applications requiring both thermal and mechanical robustness [2]. Fig. 1. Shows the Thermal spray processes such as HVOF and HVAF.

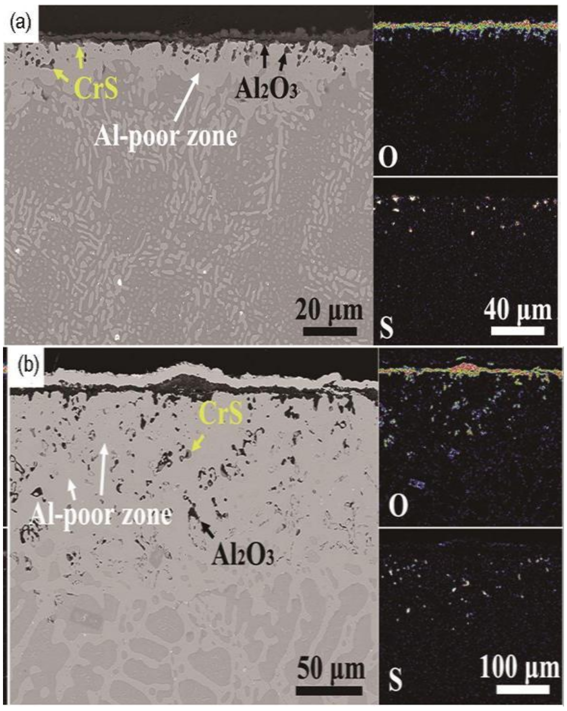

Fig. 1. thermal spray processes such as HVOF and HVAF [2].

Magnetron sputtering, per Arshad et al. [5], suits thin films, producing amorphous structures for corrosion resistance but limited thickness for TBCs, often requiring multilayer designs for thickness buildup. Cold spray preserves feedstock composition, as seen in AlCoCrFeNi coatings with FCC + BCC phases [9]. Challenges include optimizing parameters to minimize porosity and ensure adhesion, where improper settings can lead to unbounded particles and reduced performance [11]. CALPHAD, used by Ma et al. [1], predicts phase diagrams for $Al_x(Co,Cr,Ni)_{88-x}Si_2$ systems, guiding composition design to avoid detrimental transformations during service [9]. As illustrated in Figure 1, thermal spray processes such as HVOF and HVAF, characterized by higher particle velocities, result in denser coatings with reduced oxidation, which is critical for the stability of HEA bond coats [2].

2.3. Microstructural and Phase Analysis

HEA bond coats feature solid-solution phases stabilized by high entropy, contrasting with intermetallics in traditional alloys, which often lead to brittleness at high temperatures [11]. NiCoCrAlSi HEAs [1] show BCC phases post-HVOF vacuum treatment at 1080°C, while APS yields $L1_2$ + BCC/B2 due to rapid solidification, where the dual-phase structure provides a balance of ductility and strength. Lattice distortion boosts strength, with Al favoring BCC for oxidation resistance by increasing the energy barrier for dislocation movement [12]. Fig. 2. shows the XRD patterns of as-sprayed and heat-treated HEA bond coats [1].

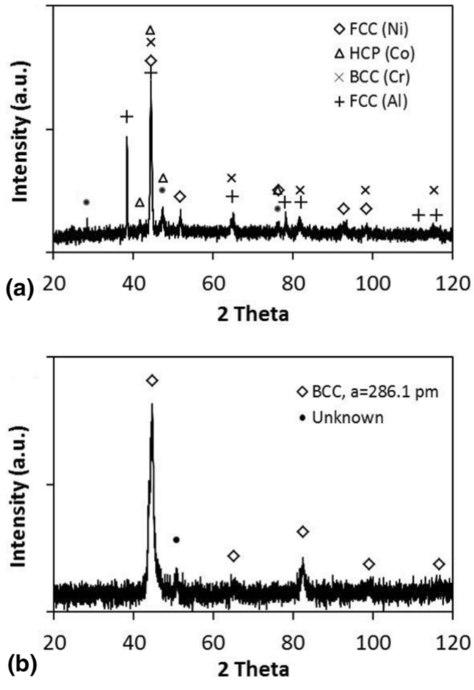

Fig. 2. XRD patterns of (a) as-sprayed (b) heat-treated HEA bond coats[1].

Y/Hf doping in NiCoCrAlFe [2] produces FCC + BCC, with sluggish diffusion limiting decomposition and maintaining phase homogeneity over prolonged exposures. Refractory HEAs like MoFeCrTiWAlNb [3] exhibit BCC + HCP, offering thermal stability through high melting points and reduced thermal conductivity. Microstructures include splats in thermal sprays, with HVAF porosities <1% [4], reducing oxygen ingress paths and enhancing lifespan. SEM/EDS and XRD reveal oxide subscales (e.g., SiO_2 in Si-doped HEAs) stabilizing Al_2O_3, preventing mixed oxides that accelerate failure [2].

Aging-induced phase changes, as in Huang et al.'s $AlSiTiCrFeCoNiMo_{0.5}$ [9], enhance hardness via precipitation, but must be controlled to avoid embrittlement. As depicted in Figure 2, the XRD patterns of HEA coatings after heat treatment reveal the stability of solid-solution phases, which, due to high entropy, delays phase transformations and enhances long-term performance [1].

3. Results and Discussion

3.1. Oxidation and Corrosion Resistance

The exceptional oxidation resistance of HEAs is fundamentally attributed to high configurational entropy, sluggish diffusion, and the resultant formation of stable, protective oxide scales, primarily α-Al_2O_3 and Cr_2O_3 [10]. These characteristics collectively decelerate the growth of the thermally grown oxide (TGO) layer and enhance its adhesion to the underlying alloy, which is critical for the longevity of TBCs. Traditional MCrAlY bond coats, while effective, exhibit accelerated oxidation and scale spallation above 1100°C [4,5]. In contrast, HEA compositions demonstrate a paradigm shift in high-temperature stability. For instance, NiCoCrAlSi coatings applied via HVOF showed significantly slower TGO growth rates at 1050°C compared to MCrAlY, a performance linked to entropy-stabilized phases that inhibit Al diffusion and promote the formation of a more compact alumina scale [1].

The beneficial role of reactive elements is highlighted in Y/Hf-doped NiCoCrAlFe HEAs, which achieved oxidation rates as low as 0.01–0.03 mg/cm^2/h at 1100°C. The presence of Hf was found to promote the development of a columnar Al_2O_3 microstructure, thereby improving scale adhesion and mitigating spallation under thermal cycling [2]. Recent research has significantly broadened the understanding of composition-property relationships and processing effects on HEA oxidation behavior:

- Silicon as a Potent Alloying Element: Minor additions of Si (1-2 at. %) to Ti-bearing high-entropy superalloys (HESAs), such as $(Ni_2Co_2FeCr)_{92-x}Ti_4Al_4Si_x$, have been shown to simultaneously mitigate intermediate-temperature

(700°C) intergranular embrittlement and dramatically improve oxidation resistance. Silicon promotes the formation of a continuous, protective Al_2O_3 layer and facilitates the precipitation of intergranular G-phase particles, which act as barriers to oxygen diffusion along grain boundaries. This dual mechanism reduced the oxide scale growth rate to a quarter of that observed in the Si-free alloy [17].

- Advantages of Additive Manufacturing: High-entropy alloys fabricated via advanced manufacturing techniques exhibit unique microstructures that confer superior oxidation resistance. A fine-grained CrMnFeCoNi HEA produced by Laser Powder Bed Fusion (LPBF) demonstrated significantly lower mass gain and a ~60% thinner internal oxide scale after exposure at 1000°C compared to its conventionally processed counterpart. The refined microstructure promotes the rapid formation of a dense, continuous Cr_2O_3 scale while suppressing the development of non-protective spinel phases [18]. Furthermore, post-processing treatments like Laser Shock Peening (LSP) on LPBF-fabricated AlCoCrCuFeNi HEA can convert surface tensile stress to compressive stress, induce grain refinement, and create high-density dislocations. This modified surface layer promotes the formation of a denser protective oxide scale, significantly inhibiting inward oxygen diffusion and enhancing high-temperature oxidation resistance [19].
- Synergistic Effects of Composite and Refractory Additions: The strategic incorporation of ceramic phases and refractory elements can tailor HEA properties. In $AlCoCrFeNiMox(TiC)_{2-x}$ coatings fabricated by laser cladding, the combined addition of Mo and in-situ TiC particles was investigated. An optimum composition (x=1) was found to provide the best balance, offering high-temperature oxidation resistance 5–12 times better than other variants in the series. Mo aids in forming a stable protective oxide layer, while the ceramic phase contributes to mechanical robustness [20]. Similarly, in refractory HEAs (RHEAs), copper alloying in systems like $(Ti_{40}Nb_{40}Ta_{10}Zr_{10})_{100-x}Cu_x$ was found to enhance oxidation resistance at 800°C. The added Cu refines the dendritic structure and forms dispersed (Cu,Zr)-rich precipitates, which alter the oxidation morphology and reduce the overall area of the oxide layer [21].
- Critical Role of Specific Elements: The oxidation behavior of HEAs is highly sensitive to the presence of certain elements. A foundational study on the CoCrFeMnNi system established that while Cr is essential for forming protective Cr_2O_3, Mn has a markedly detrimental effect on oxidation resistance, even outweighing the benefits of Cr at elevated temperatures (e.g., 750°C). Alloys without Cr (e.g., CoFeMnNi) suffered catastrophic oxidation, underscoring the indispensable role of chromium [22]. This is directly corroborated by a comparative study between FeCoNi Medium-Entropy Alloy (MEA) and CoCrFeNi HEA. The Cr-containing HEA formed a thin, dense, and adherent Cr_2O_3 layer, providing excellent protection in simulated marine environments at 900°C. In contrast, the Cr-free MEA developed a thick, porous, and cracked bilayer oxide of CoO and Fe_3O_4, leading to poor oxidation and corrosion resistance [23].
- Design of Oxidation-Resistant Compositions: Targeted compositional design can yield HEAs with exceptional oxidation resistance. For example, $Al_{0.45}CoCrFeNiSi_{0.45}$ HEA demonstrated outstanding performance, gaining only about 0.1 mg/cm² after 10 hours at 900°C. This was attributed to the formation of a protective, complex oxide layer rich in Al_2O_3–SiO_2. In contrast, a Mn-containing variant ($Al_{0.25}CoCrFeNiMn$) showed an order of magnitude higher weight gain under the same conditions, forming a non-protective oxide scale [24]. The efficacy of Al and Cr in synergy is further demonstrated in laser-clad FeCrNiMnAl coating, which formed protective Al_2O_3 and Mn_3O_4 gradient films, granting impressive oxidation resistance on ferritic/martensitic steel at 550°C [25].

In addition to oxidation, HEAs exhibit remarkable resistance to hot corrosion and wear in aggressive environments. Their performance in sulfate-rich atmospheres surpasses that of MCrAlY, as elements like Cr and Al synergistically form stable protective layers [3]. The incorporation of sigma phases, as seen in $(CoCrFeMnNi)_{0.85}Ti_{0.15}$, enhances wear resistance at elevated temperatures (400°C) [3]. Coatings like AlCrFeCoNi applied via HVAF form thinner oxides than their CrFeCoNi counterparts, though the addition of reactive elements (e.g., Y, Hf) is suggested to further suppress transient oxide formation and optimize performance [4]. The sluggish diffusion intrinsic to HEAs remains a cornerstone of their durability, as it drastically reduces deleterious interdiffusion with the substrate, preserving interface integrity and preventing the formation of brittle secondary phases [12].

Table. 2. Oxidation Rates of Bond Coats at High Temperatures.

Bond Coat Type	Composition	Oxidation Rate (mg/cm²/h at 1100°C)	TGO Thickness After 100 h (μm)	Reference
Traditional	NiCrAlY	0.05–0.10	5–10	[4]
HEA	NiCoCrAlSi	0.02–0.05	3–6	[1]
HEA	Y/Hf-NiCoCrAlFe	0.01–0.03	2–4	[2]
HEA	AlCrFeCoNi	0.03–0.06	4–7	[4]
Refractory HEA	TiZrNbWMo	0.04–0.08	5–8	[3]

Fig. 3. Cross-sectional SEM of TGO growth on HEA bond coat [4]. As observed in Fig. 3, the SEM cross-sectional image of TGO growth on the HEA bond coat reveals a thin and uniform oxide layer, attributed to sluggish diffusion, which limits oxygen penetration [4].

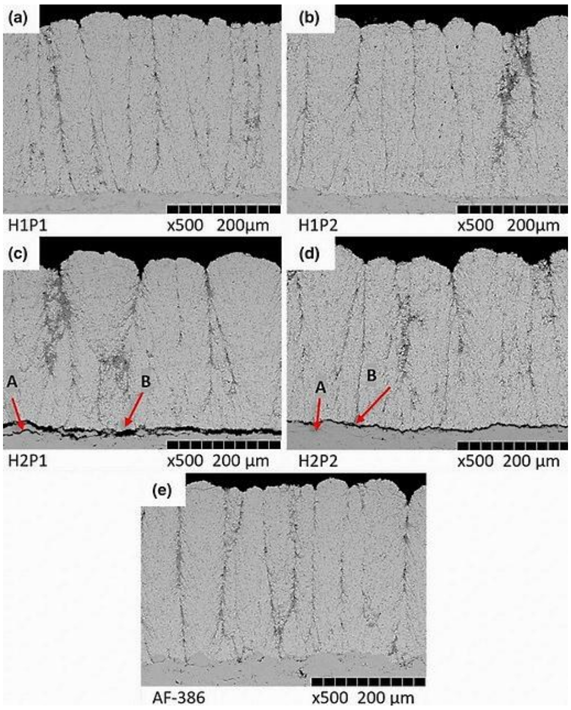

Fig. 3. Cross-sectional SEM of TGO growth on HEA bond coat [4].

3.2. Thermal Cycling and Mechanical Performance

TBCs with HEA bond coats withstand more cycles before spallation, owing to better strain tolerance and reduced residual stresses [15]. Ma et al. [1] reported no failure in HVOF NiCoCrAlSi + 8YSZ after 100 cycles at 1150°C, due to elastic TGO and reduced rumpling, where the multi-element composition distributes stresses evenly. Ossiansson et al. [4] found AlCrFeCoNi HVAF coatings match MCrAlY cycling life but form faster oxide scales without reactive elements, highlighting the need for dopants to enhance interface toughness. HEA hardness reaches 400–700 HV from lattice distortion, as in AlTiCrNiTa [5], providing wear resistance in erosive environments like turbine blades. Wear resistance improves with Ti precipitates [3], forming hard phases that deflect cracks. Refractory HEAs remain stable up to 1200°C [12], with fluorite phases maintaining low conductivity and preventing thermal fatigue. Challenges include APS IFO reducing Al [3] and phase instability in non-equimolar compositions [16]. Y/Hf doping improves adhesion [2], and CALPHAD refines designs [1], allowing prediction of optimal compositions for specific service conditions. Fig. 4. Thermal cycling performance of HEA vs. MCrAlY bond coats [1]. As depicted in Fig.4 the thermal cycling performance of HEA bond coats, compared to MCrAlY, demonstrates a higher number of cycles without failure, attributed to greater phase stability and reduced rumpling [1].

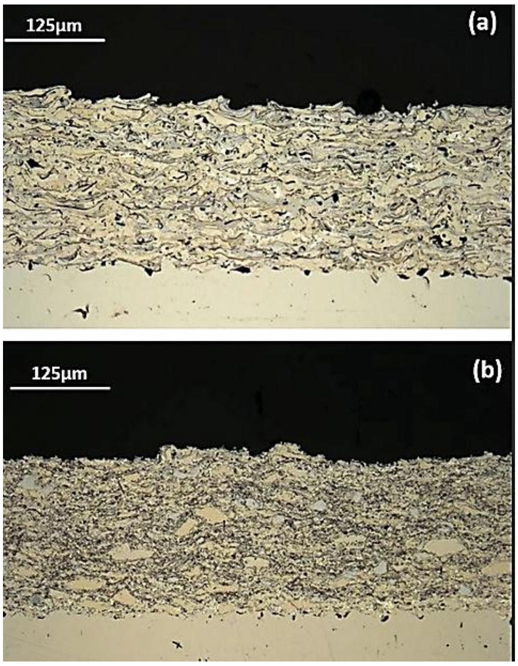

Fig. 4. Thermal cycling performance of the (a) HEA (b) MCrAlY bond coats [1].

As illustrated in Fig 5, the proposed HEA-SPS hybrid system for TBC exhibits a layered structure comprising an HEA bond coat and a columnar SPS top coat, enhancing strain tolerance and suitability for ultra-high-temperature applications [11,15].

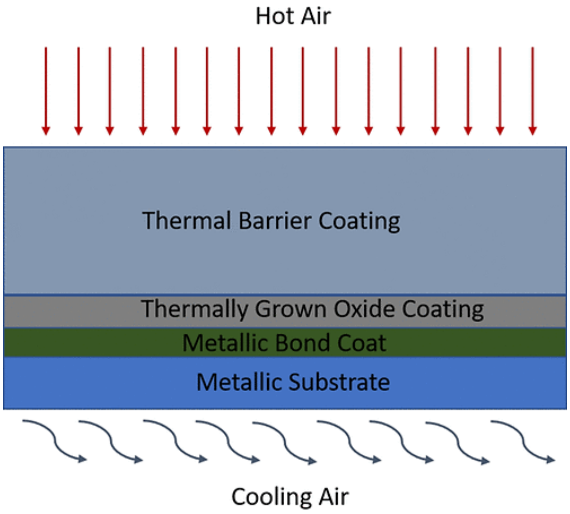

Fig. 5. Proposed HEA-SPS hybrid TBC system[15]

3.3. Future Perspectives

Combining HEAs with advanced processes like SPS for columnar top coats [10] could improve strain tolerance and reduce thermal conductivity further. Nair et al. [3] advocate tribological testing in extreme conditions, including erosion and corrosion simulations, while Arshad et al. [5] propose ceramic HEAs for hybrid bond coats to achieve multifunctional properties like self-healing oxides. As shown in Fig. 6, the microstructural comparison of HEA and MCrAlY bond coats highlights a more uniform phase distribution and lower porosity in HEAs, contributing to superior performance in harsh environments [11].

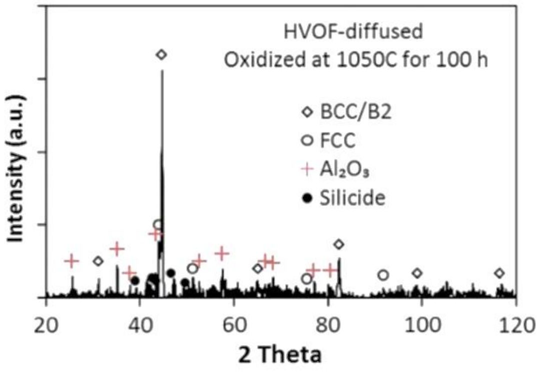

Fig. 6. Microstructural comparison of HEA and MCrAlY bond coats [11].

As depicted in Fig. 7, the temperature-dependent hardness of HEA bond coats demonstrates high hardness retention at elevated temperatures, attributed to lattice distortion, which maintains mechanical strength and is ideal for long-term applications [10].

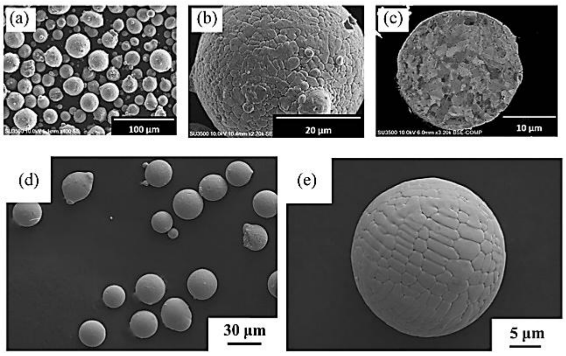

Fig. 7. Temperature-dependent hardness of HEA bond coats [10].

4. Conclusion

This review underscores the transformative potential of high-entropy alloys (HEAs) as bond coats in thermal barrier coatings (TBCs), offering significant advancements over conventional MCrAlY coatings through their unique entropy-driven properties. The key findings and implications are summarized as follows:

- **Enhanced Oxidation Resistance**: HEA compositions, such as NiCoCrAl-based and AlCrFeCoNi alloys, demonstrate superior oxidation resistance due to the formation of stable, compact alumina (α-Al_2O_3) scales. The high configurational entropy and sluggish diffusion effects minimize transient oxide formation and reduce thermally grown oxide (TGO) growth rates, with oxidation rates as low as 0.01–0.03 mg/cm^2/h at 1100°C compared to 0.05–0.1 mg/cm^2/h for traditional NiCrAlY coatings [1, 2, 4].
- **Improved Thermal Stability**: The multi-principal-element design of HEAs, stabilized by high entropy ($\Delta S\_conf > 1.5R$), promotes simple solid-solution phases (FCC or BCC) that resist phase decomposition at temperatures exceeding 1100°C. This stability, coupled with lattice distortion, enhances creep resistance and maintains mechanical integrity under prolonged thermal exposure [3, 9,19].
- **Superior Thermal Cycling Performance**: HEA bond coats, particularly those applied via high-velocity oxy-fuel (HVOF) and high-velocity air-fuel (HVAF), exhibit extended cyclic durability, with systems like NiCoCrAlSi + 8YSZ enduring 100 cycles at 1150°C without failure. This is attributed to reduced rumpling and improved strain tolerance due to uniform stress distribution across multi-element compositions [1, 4, 18].
- **Reduced Interdiffusion**: The sluggish diffusion effect in HEAs significantly lowers elemental intermixing with Ni-based superalloy substrates, mitigating deleterious phase formations such as spinels and preserving bond coat-substrate interface integrity, a critical factor in extending TBC lifespan [2, 12, 17].

. **Challenges and Optimization Needs**: Despite their advantages, challenges such as in-flight oxidation (IFO) during atmospheric plasma spray (APS) and phase instability in non-equimolar compositions persist. Incorporating reactive elements like Y and Hf enhances oxide scale adhesion and further suppresses transient oxides, but optimization of doping levels and spray parameters is essential [2, 3, 16-18].

. **Future Directions**: To fully realize HEAs' potential, future research should focus on:

- Long-term cyclic testing under realistic engine conditions to validate performance beyond 1200°C.
- Integration of computational tools like CALPHAD for predictive alloy design to optimize phase stability and oxidation resistance [1, 9, 20].
- Development of hybrid TBC systems combining HEA bond coats with advanced processes like suspension plasma spraying (SPS) for columnar top coats to enhance strain tolerance and reduce thermal conductivity [10-12, 21-23].
- Exploration of ceramic and composite HEAs for multifunctional properties, such as self-healing oxides, to further improve durability in extreme environments [5, 24, 25].

In summary, HEAs represent a paradigm shift in TBC bond coat technology, enabling operation at ultra-high temperatures critical for aerospace, power generation, and nuclear applications. By addressing current limitations through targeted doping and advanced deposition techniques, HEAs can significantly enhance TBC performance, paving the way for next-generation high-temperature systems.

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