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Additive Manufacturing of Refractory Alloy-based Multi-Material Structures: A Review

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내화 합금 기반 다중 소재 구조의 적층제조: 종설

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ABSTRACT

Refractory alloys exhibit exceptional high-temperature strength and stability, but their high melting points and limited ductility restrict the fabrication of complex structures through conventional manufacturing methods. Additive manufacturing (AM) provides new opportunities by enabling geometric freedom, near net-shape capability, and the fabrication of multi-material structures. These attributes allow fabrication of compositionally graded interfaces, improved thermal stress management, and integration of diverse functionalities. However, AM of refractory alloy-based multi-material systems remains challenging due to non-uniform thermal gradients, oxidation, cracking susceptibility, vaporization of elements, and formation of brittle intermetallic compounds. Understanding the process-structure-property-performance relationship is therefore essential for predicting material behavior and optimizing process parameters. This review summarizes major AM processes for refractory alloys, examines strategies for multi-material design, and analyzes the microstructure-property relationships that govern mechanical performance. Key challenges and future research directions are highlighted, emphasizing the need for design rule establishment to enable reliable, next-generation high-temperature materials fabricated through additive manufacturing.

Keywords : Additive Manufacturing(적층제조), Refractory Alloys(내화합금), Multi-material(다중소재), Intermetallic Compound

1. Introduction

Refractory metals such as tungsten (W), molybdenum (Mo), tantalum (Ta), niobium (Nb), zirconium (Zr) exhibit exceptional melting temperatures, high-temperature strength, and environmental stability, making them suitable for aerospace propulsion, nuclear systems, and other extreme-environment applications [1]. However, intrinsic brittleness, high thermal conductivity, and limited ductility limit the fabrication of complex geometries by conventional manufacturing processes

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and hinder their broader industrial implementation [2].

Additive manufacturing (AM) provides a promising alternative to overcome these limitations by leveraging localized melting and rapid solidification to directly fabricate near-net-shape components with tailored microstructure [3]. Nonetheless, challenges such as severe thermal gradients, cracking, oxidation, and porosity formation remain significant obstacles to produce defect-free refractory alloy parts.

AM offers distinct advantages of fabricating multi-material structures with spatially controlled composition and microstructure. The ability to deposit dissimilar alloys within a single build enables the formation of functionally graded structures, development of tailored thermo-mechanical properties, nearly impossible by traditional process [4]. For refractory alloys, such capabilities could unlock new design spaces for high-temperature systems.

Despite these opportunities, critical knowledge gaps persist regarding melt pool behavior, interdiffusion mechanisms, formation of intermetallic compounds, and the long-term in-service performance of multi-material refractory structures [5]. The underlying physics governing these phenomena remains only partially understood, since the extreme thermal gradients and rapid solidification inherent to AM introduce significant complexity and uncertainty in predicting microstructural evolution and corresponding mechanical properties. As a result, the process-structure-property-performance relationship is not yet fully established, and generalized design rules or processing guidelines for refractory multi-material systems remain underdeveloped.

This review provides an overview of current advances in the additive manufacturing of refractory alloy-based multi-material structures, with emphasis on processing strategies, microstructural evolution, and property development. Key challenges and future research needs are highlighted to support the establishment of design principles for fabrication of next-generation high-temperature components.

2. AM Processes for Refractory Alloys

Several metal additive manufacturing techniques have been applied to fabricate refractory alloys, each offering distinct processing characteristics, advantages, and limitations. The primary AM processes investigated for refractory alloy fabrication are summarized below, and their specific benefits and drawbacks are discussed in the following subsections.

2.1 Laser Powder Bed Fusion (L-PBF)

Laser Powder Bed Fusion (L-PBF) is a powder-bed-based AM technique in which a focused laser selectively melts thin layers of metal powder according to sliced digital data. The process is known for its high resolution, precise thermal control, and ability to produce complex geometries with fine microstructural features. Rapid solidification and localized heat input make L-PBF attractive for advanced engineering materials that benefit from microstructure refinement.

Due to outstanding properties of W, different studies have investigated its fabricability by LPBF [6]. However, the fabricated W commonly exhibits multi-scale porosity throughout the microstructure. W has a high oxygen affinity, forming oxides. Due to higher thermal conductivity, faster cooling is achieved, and metal oxides are trapped as the pores. Beyond porosity, a more critical issue is the prevalence of extensive microcracking. This is attributed to tungsten’s intrinsically high Ductile-to-Brittle Transition Temperature (DBTT). During cooling from the melt, the accumulated thermal residual stresses rapidly exceed the material's fracture strength, leading to intergranular cracking [7]. Similar challenges have been reported for LPBF-processed Mo, where cracks and porosity are present in the microstructure [8]. These defects are formed due to Mo’s thermo-physical properties, particularly DBTT and strong oxygen affinity, closely matching W. In LPBF Ta and Nb,

Fig. 1 NASA Marshall Space Flight Center manufactured C103 Green Propulsion Thruster and Stand-off [11]

conservable porosity and cracks are not present [9, 10]. This might be due to their lower DBTT and affinity for metal oxide formation which contribute to more stable melt pool dynamics and superior microstructural integrity. Fig. 1 shows C103 propulsion thruster and Stand-off fabricated by NASA Marshall Space Flight Center utilizing LPBF technique without considerable defects [11].

To mitigate porosity and crack in W and Mo, different approaches have been investigated such as remelting, increasing laser power, and minimizing impurities. However, the extreme melting temperatures, high thermal conductivity, and DBTT present significant challenges. Despite ongoing research involving process modification, achieving fully dense and crack-free refractory alloy parts remains difficult by LPBF process.

2.2 Electron Beam PBF

Electron Beam Powder Bed Fusion (EB-PBF) is an AM process that employs a high-energy electron beam as the heat source, operating under vacuum conditions. The electron beam provides deeper penetration and higher energy efficiency compared to laser-based methods. The inert environment also prevents oxidation, which is advantageous for fabricating reactive or high-melting-point metals.

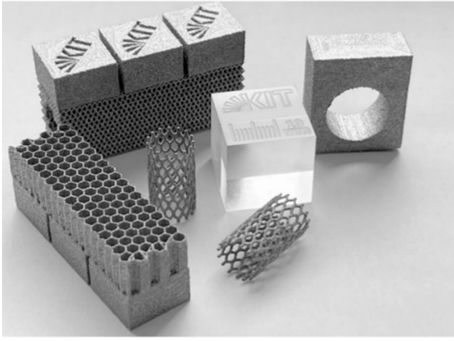

Fig. 2 Different shaped tungsten samples printed via EBM [12]

EB-PBF has been investigated to fabricate refractory alloys. Fig. 2 shows that different tungsten samples printed by the EB-PBF [12]. Ledford et al. [13] established a process window for fabricating defect free pure W, demonstrating that the EB-PBF could generate crack-free, high-density structures with mechanical properties comparable to conventional manufactured components. Sturco et al. [14] successfully fabricated Mo specimens using the EB-PBF. The study reported the presence of microstructural porosity; however, no evidence of large-scale cracking was found. The formation of porosity was attributed to the entrapment of MoO_3 during melting and solidification of EB-PBF process.

Literature suggests that EB-PBF demonstrates improved printability relative to L-PBF, with higher densities and fewer defects. The high preheating temperatures common in EB-PBF help reduce thermal gradients across the build, thereby decreasing the risk of cracking [15]. The vacuum environment additionally minimizes oxidation-sensitive degradation, which is crucial for refractory systems.

Despite these benefits, EB-PBF processing of refractory alloys still faces substantial challenges. The high energy density inherent to the electron beam can promote evaporation of volatile alloying elements, resulting in compositional deviations and microstructural heterogeneity within the as-built material. Powder charging effects may destabilize the beam and affect melt pool control. Moreover, EB-PBF typically produces lower surface quality and coarser features than L-PBF because of partial powder sintering and reduced process resolution. These limitations restrict the precision and reproducibility of EB-PBF builds for refractory alloys.

2.3 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) employs a focused thermal energy source to melt powder or wire feedstock and deposit layer-by-layer to fabricate final components. The process supports large build volumes, high deposition rates, and flexible control of composition by adjusting feedstock inputs [16]. DED is widely used for repair, cladding, and the production of large metallic components due to its scalability.

Refractory alloys have been deposited using both powder-fed and wire-fed DED systems [17]. The slower cooling rates and larger melt pools relative to PBF processes can reduce the tendency for cracking, enabling fabrication of W, Mo, Nb, Ta in bulk geometries. DED also enables in-situ alloying and graded compositions, making it particularly relevant for multi-material structures involving refractory metals.

Xie et al. [18] successfully deposited tungsten using a laser-based DED process, achieving a relative density of 99.78 wt.%. Although the material exhibited numerous pores and microcracks, no wide or catastrophic cracks were observed across the deposited layers. Notably, cracking tended to localize in the upper regions of the build and propagated preferentially between adjacent pores, indicating a pore-assisted cracking mechanism. Fig. 3 illustrates powder-blown laser beam DED of Mo incorporating lanthanum oxide as an additive to mitigate porosity [19]. Pure Mo deposits exhibited substantial porosity; however, increasing the lanthanum oxide content markedly reduced pore formation. With optimized lanthanum additions, a relative density of approximately 99% was achieved, demonstrating the effectiveness of

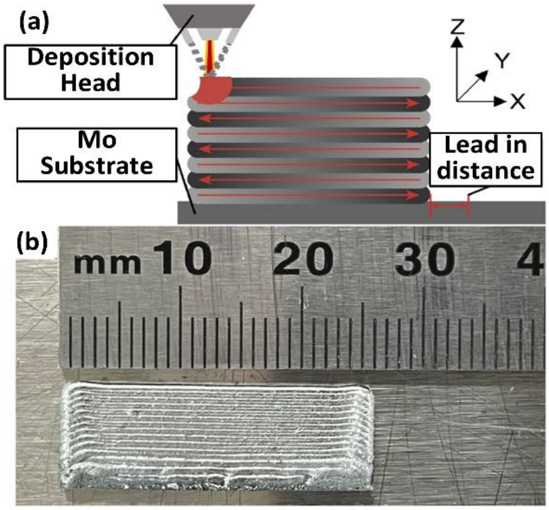

Fig. 3 (a) DED-LB-BP schematic showing scan strategy and lead in/out distance, (b) representative print geometry used for this work, 25.4 mm long and 7.5 mm high [19]

oxide dispersion in stabilizing melt pool dynamics, and improving densification.

Nonetheless, the DED process undergoes repeated non-equilibrium thermal cycles and melting of previous layers, resulting in coarse microstructures with significant residual stresses, which can lead to cracking upon solidification. Powder-based DED also suffers from low powder capture efficiency, while wire-based DED is constrained by the brittleness and feeding difficulty of refractory wires. Furthermore, porosity, lack-of-fusion defects, and strong texture formation are frequently observed, posing major obstacles in achieving consistent mechanical performance.

2.4 Wire Arc AM (WAAM)

Wire Arc Additive Manufacturing (WAAM) uses an electric arc to melt metal wire feedstock and deposit layer wise to fabricate final components. The technique offers exceptionally high deposition rates and cost-effective production of large metal structures, making it attractive for applications requiring substantial component size. The use of wire feedstock also simplifies material handling compared to powder-based systems. Although WAAM is often used for steel, titanium, and nickel alloys, it has gained increasing attention for refractory materials.

Since WAAM employs a high-intensity heat source capable of melting refractory wire feedstocks and operates at a high build rate, it facilitates the fabrication of large tungsten or tantalum structures. Marinelli et al. [20] fabricated large WAAM fabricated W component at high deposition rates, as shown in Fig. 4. No cracks were present, but microporosity was found. Wang et al. [21] processed unalloyed molybdenum using WAAM and achieved crack-free parts with a relative density of approximately 99%. Marinelli et al. [22] also deposited tantalum via WAAM, obtaining components with no significant cracking or porosity. The components achieved tensile strength of 261 MPa with 36% elongation, indicating high ductility.

Comparing all the AM processes, it is evident that WAAM provides better opportunities for fabrication of refractory metals. However, the high heat input inherent in WAAM generates wide heat-affected zones and coarse columnar grains, which degrade their properties. Severe residual stresses arise due to the uneven cooling associated with arc-based melting, and oxidation becomes a concern unless well-controlled inert atmospheric conditions are maintained. Additionally, refractory wires are prone to cracking and feeding instability, limiting process reliability. These challenges need to be solved for large-scale industrial applications.

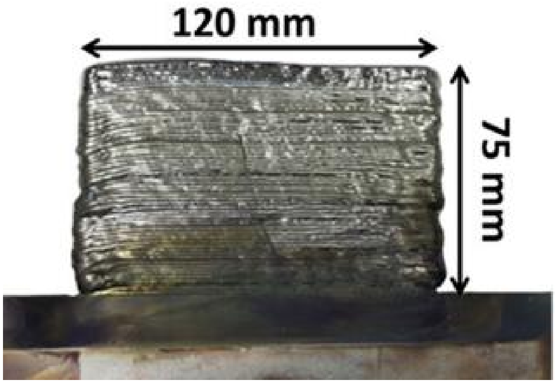

Fig. 4 Large-scale unalloyed tungsten linear structure deposited via Wire + Arc Additive Manufacturing process [20]

3. Multi-Material Design and Process Considerations

The fabrication of multi-material refractory structures through AM introduces a new paradigm beyond monolithic alloys. By integrating multiple materials into a single component, it is possible to harness the distinct advantages of individual materials. Bimetallic structures have a broad range of applications, spanning the automotive, aerospace, energy, nuclear, transportation, and medical sectors. However, designing such components requires an understanding of compositional transitions, metallurgical compatibility, and the influence of processing conditions on the resulting microstructure and properties. The following subsections discuss key considerations in multi-material AM of refractory alloys, including functionally graded materials, the process-structure-property-performance relationship, and the requirement for establishing robust design rules.

3.1 Multi-Material Design

Functionally graded materials (FGMs) and bimetallic structures offer two common approaches for combining distinct metals within a single component. FGMs provide gradual variations in composition or properties, reducing abrupt transitions, whereas bimetallic structures involve discrete interfaces between two metals [23]. AM enables both concepts by allowing controlled feedstock modulation, precise thermal management, and the creation of engineered interfaces that conventional joining techniques cannot achieve [24].

In refractory alloy systems, FGMs and bimetallic structures are particularly valuable since they can combine high-temperature strength with improved

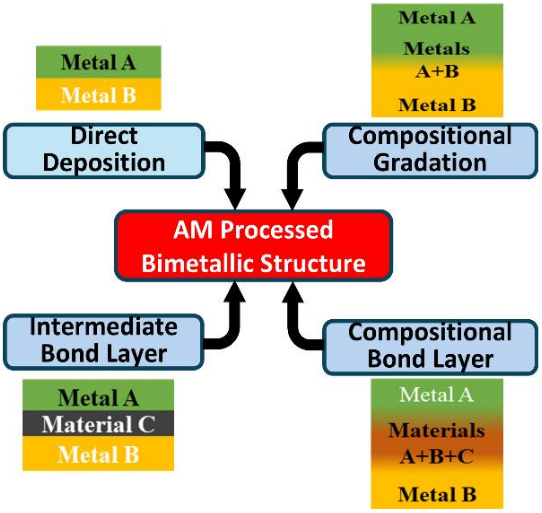

Fig. 5 Bimetallic structure processing strategies [23]

ductility or manufacturability. For example, joining tungsten with tantalum or niobium can enhance ductility and reduce component weight without compromising thermal performance. Moreover, gradual compositional or property transitions can mitigate the effects of mismatches in thermophysical properties, such as differences in thermal expansion coefficients.

Nonetheless, fabricating FGMs and bimetallic structures with refractory alloys remains challenging. Large differences in melting temperature, thermal conductivity, and chemical reactivity can destabilize melt pools and promote brittle intermetallic formation. Residual stresses may still accumulate even in graded regions, and controlling interfacial morphology requires precise process optimization. These issues highlight the need for better understanding of interfacial phase formation and the development of design guidelines tailored to refractory FGMs and bimetallic structures.

3.2 Process-Structure-Property-Performance Relationship

The process-structure-property-performance (P-S-P-P) relationship provides a systematic framework for understanding how AM processing conditions influence microstructural evolution, material properties, and ultimately the functional performance of multi-material components. In AM, process parameters such as heat input, deposition rate, and scan strategy directly affect melt pool dynamics, thermal gradients, solute redistribution, grain morphology, and phase formation. These microstructural characteristics determine local mechanical behavior, thermal conductivity, oxidation resistance, and other key properties [25].

In the context of refractory multi-material systems, the P-S-P-P relationship becomes particularly important because sharp microstructural transition occurs at the interface, influencing mechanical properties. For example, a tungsten-molybdenum gradient may exhibit fine cellular structures in tungsten-rich regions and coarse grains in molybdenum-rich regions. Understanding these transitions is essential for ensuring predictable performance under extreme thermal or mechanical loading. Establishing the P-S-P-P linkage allows researchers to identify process windows that minimize the formation of defects and intermetallic components.

However, establishing comprehensive P-S-P-P relationships for refractory multi-materials remains challenging due to the complexity of melt pool interactions, strong thermophysical mismatches, and limited experimental data. The high melting temperatures and rapid cooling rates typical of AM complicate in-situ observation of microstructure evolution. Furthermore, characterizing the interdependence of processing variables requires advanced characterization techniques, not extensively investigated for refractory alloys. As a result, development predictive models remain challenging due to unavailability of material property databases, and process optimization often relies on empirical approaches.

3.3 Design Rule Establishment

Since additive manufacturing of multi-material refractory alloys is gaining importance, the establishment of robust design rule is essential to ensure reliable fabrication and consistent performance. Design rules encompass guidelines for identifying material compatibility, thermal gradient management strategies, and process parameter windows tailored specifically for multi-material structures. For AM, such rules must integrate both geometric constraints and metallurgical considerations, including phase stability and residual stress control.

For refractory alloy systems, design rules must consider their unique thermo-physical behaviors (e.g., high-melting point) during deposition. This includes identifying compatible material combinations and identifying interfaces that inhibit brittle phase formation. By establishing these rules, functionally graded refractory components can be fabricated which provide enhanced thermal shock resistance, improved mechanical performance, and predictable long-term stability. As AM enables unprecedented compositional flexibility, design guidelines are crucial for preventing undesirable intermetallic compounds or microstructural defects.

Despite the clear need, design rule establishment is still in its early stages due to the lack of systematic experimental data and validated computational models for refractory multi-material AM. Most current practices depend on trial-and-error approaches rather than quantitative frameworks. The development of standardized rules will require integrated efforts involving materials characterization, in-situ monitoring, thermodynamic modeling, and machine-learning-based prediction tools. Without establishing these design rules, the transition of refractory multi-material AM from laboratory research to industrial application remains limited.

4. AM-Fabricated Refractory Multi-Materials

In this section, the microstructural characteristics and mechanical properties of three representative categories, such as refractory-to-refractory combinations, refractory-to-high-performance alloys, and refractory-to-typical engineering materials, are examined.

4.1 Refractory to Refractory Materials

Multi-material structures composed exclusively of refractory alloys, such as W-Mo, Ta-Nb, or combinations within the W-Mo-Ta-Nb quaternary family, exhibit relatively favorable metallurgical compatibility due to similarities in melting temperature, crystal structure, and thermophysical behavior. During AM processing, these alloys tend to form coherent or semi-coherent interfacial regions with limited formation of brittle intermetallic compounds, enabling smoother transitions in microstructure across the interface [26]. The diffusion behavior between refractory metals is generally slow because of their high melting points, but the extreme thermal gradients and localized overheating inherent to AM can accelerate interdiffusion, producing narrow reaction zones or solid-solution gradients. Fig. 6 shows the bimetallic structure of TZM and NbZr1 fabricated by the WAAM process. The study indicated that no intermetallic compounds are formed at the interface [26].

The microstructure in these systems is often dominated by coarse columnar grains that follow the direction of temperature gradient, although refined or

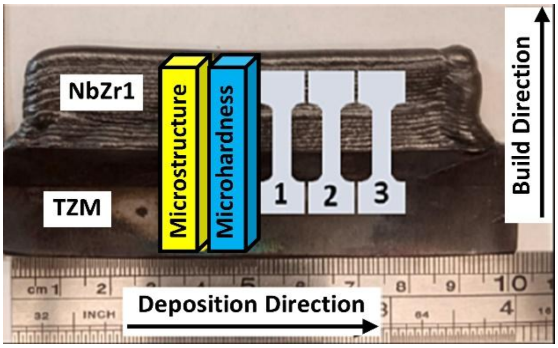

Fig. 6 Bimetallic structure of TZM and NbZr1 fabricated by wire-based directed energy deposition [26]

equiaxed grains can be observed in regions where melt pool turbulence or temperature fluctuations promote heterogeneous nucleation. Mechanical properties across the interface tend to vary gradually, and the combined structure typically exhibits strong high-temperature strength, creep resistance, and thermal stability. However, residual stresses remain a major concern, especially when properties vary significantly between the two refractory alloys or compositionally graded transitions are not sufficiently smooth.

Despite their compatibility, fabrication of refractory-refractory combination presents significant challenges. High melting temperatures require large heat inputs, which can result in excessive grain growth, porosity, and residual stress [27]. Differences in thermal conductivity and elastic modulus may still cause localized stress concentrations, while slow diffusion kinetics may limit the homogenization of functionally graded regions. Consequently, achieving predictable microstructural transitions requires careful control of melt pool dynamics and application of post-processing techniques such as heat treatments.

4.2 Refractory to High Performance Materials

Combining refractory alloys with high-performance materials such as titanium alloys or nickel-based superalloys offers unique opportunities for tailoring thermal-mechanical performance [28][29]. Refractory metals provide exceptional high-temperature capability, while Ti-6Al-4V or Inconel 718 contribute improved toughness, oxidation resistance, or reduced density [30]. AM enables the fabrication of such hybrid structures by creating controlled compositional or microstructural transitions between the materials. Fig. 7 shows SEM images consisting of W7Ni3Fe, W7Ni3Fe-Inconel 718 bimetallic interface, and Inconel 718 [28].

However, the microstructure at the interface between refractory and high-performance alloys can be significantly complex. Large differences in melting temperature, thermal expansion coefficients, and chemical reactivity often drive the formation of intermetallic phases or brittle reaction layers during AM processing. For example, joining tungsten and titanium tends to form W-Ti intermetallic compounds with poor ductility, while tungsten-Inconel transitions may generate carbides, Laves phases, or segregation-induced brittle zones [31]. The rapid solidification of AM may partially suppress some equilibrium intermetallic formation but often introduces metastable phases.

These microstructural complexities strongly influence mechanical properties. While graded compositions can enhance stress distribution, improperly controlled interfaces exhibit limited ductility, reduced tensile strength, and high susceptibility to cracking. Furthermore, the large mismatch in thermal conductivity between refractory metals and titanium or nickel alloys can produce steep thermal gradients during deposition, further amplifying residual stress accumulation. Despite these challenges, well-designed transitions-typically involving intermediate or buffer layers-can significantly improve performance, demonstrating the promise of such hybrid combinations.

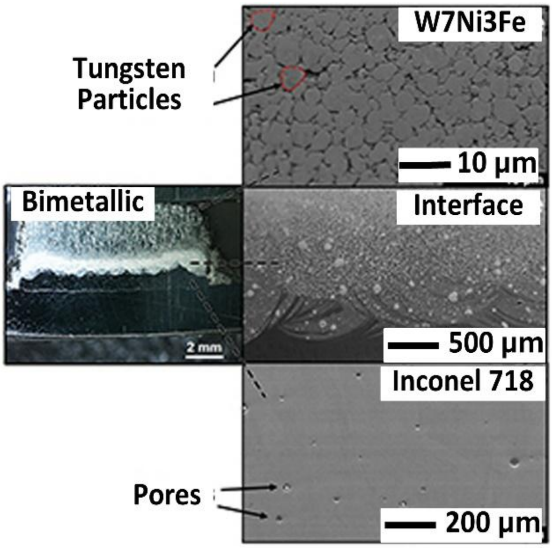

Fig. 7 SEM images show W7Ni3Fe, bimetallic interface, and Inconel 718 [28]

4.3 Refractory to Typical Materials

Refractory alloys have also been combined with more conventional engineering materials such as steels, copper alloys, or aluminum alloys in an effort to produce components with local high-temperature reinforcement or specialized thermal management capabilities [32], [33]. These hybrid configurations are made possible by the geometric flexibility of AM, which enables refractory materials to be deposited precisely in regions subjected to severe thermal or mechanical loading while lower-cost conventional alloys are utilized throughout the remaining structure.

Fig. 8 shows Cu10Sn-W composite fabricated by LPBF process [34]. Since the temperature difference is too large between the alloys, SS316L has been utilized as an interlayer for better bonding. Microstructural interactions in these systems are generally dominated by severe thermo-physical mismatches. Refractory alloys exhibit melting temperatures several times higher than those of steels or aluminum alloys, causing asymmetric melting behavior and unstable melt pool boundaries during deposition. This often leads to incomplete fusion, excessive dilution, or uncontrolled mixing. The chemical incompatibility between refractory metals and typical structural alloys can also result in persistent intermetallic compounds or brittle eutectic phases at the interface, severely limiting structural integrity. For example, W-Fe combinations typically form Fe-rich brittle phases [32], while W-Cu interfaces exhibit limited mutual solubility that produces mechanically weak boundaries [35].

These microstructural challenges translate into limited mechanical performance. The interfaces often show low fracture toughness, poor fatigue resistance, and limited thermal cycling stability due to stress concentration and poor mechanical bonding. As a result, refractory-typical material combinations remain largely experimental, and successful integration generally requires the use of buffer layers, intermediate alloys, or functionally graded architectures to mediate incompatibility.

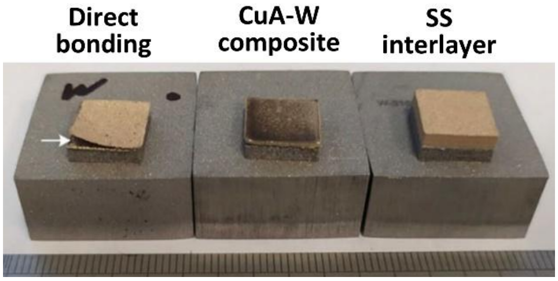

Fig. 8 Direct bonded Cu10Sn-W square sample, Cu10Sn-W composite fabricated by LPBF, and Cu10Sn-SS-W composite fabricated by LPBF [34]

5. Challenges and Future Perspectives

Additive manufacturing of refractory alloy-based bimetallic and graded structures remains a highly promising but technically challenging research area. Although AM enables unprecedented freedom in material selection, the extreme thermophysical properties of refractory alloys introduce significant obstacles in achieving consistent quality, stable interfacial behavior, and reproducible mechanical properties. The following subsections outline the major challenges that limit current progress, followed by future research directions and technological prospects that may help overcome these limitations.

5.1 Technical Challenges

The AM of refractory alloy-based bimetallic and graded structures faces a series of interconnected challenges arising from the extreme thermophysical properties of refractory metals and mismatch between the properties. Key issues include material incompatibility, intermetallic compound (IMC) formation, microstructural heterogeneity, residual stress accumulation, defect generation, and the difficulty of optimizing and standardizing processing parameters. Together, these factors significantly constrain the reliability and performance of AM-fabricated refractory components. Fig. 9 shows different defect formation during the AM of refractory multi-material structures.

Material incompatibility remains one of the most fundamental challenges in these systems. Refractory alloys often exhibit strong chemical interactions with adjacent metals during high-temperature AM processing, leading to the formation of brittle intermetallic layers. When two metals with significantly different melting points or thermodynamic properties are joined, the interface becomes susceptible to undesirable metallurgical reactions. In many cases, the inherent incompatibility between the paired materials manifests as weak bonding, phase segregation, or excessive dilution during deposition.

Closely linked to compatibility issues is the formation of intermetallic compounds and microstructural heterogeneity at the interface. Under the rapid, non-equilibrium thermal cycles characteristic of AM, IMCs can form more abundantly compared to conventional processing conditions. These phases are typically hard and brittle, reducing fracture toughness and increasing susceptibility to cracking. Even if the IMC formation is partially suppressed, heterogeneous microstructures marked by abrupt changes in grain morphology, composition, or mechanical properties are often found, creating localized weak regions. Fig. 9(a-c) shows the formation of IMC in WAAM fabricated W7Ni3Fe and SS316L interface.

Residual stress formation presents another considerable challenge. The large thermal gradients imposed during AM, combined with the distinct thermal conductivity and coefficients of thermal expansion of the two metals, generate intense stress concentrations within the interfacial zone. Refractory alloys, with their high modulus and limited ductility, have little tendency to accommodate these stresses, leading to distortion, interlayer delamination, or immediate cracking during solidification. Fig. 9(d) shows formation of cracks due to the presence of residual stress in WAAM W7Ni3Fe/SS316L and TZM-NbZr1 bimetallic structure. These stresses can also compromise performance under service conditions, especially in cyclic thermal environments.

Defect formation is another persistent obstacle that degrades the structural integrity of refractory alloy components. Porosity commonly arises from inadequate fusion, trapped gases, or keyhole instability, while microvoids and unmelted particles reflect insufficient or uneven energy delivery to high-melting-point feedstock. Fig. 9(e) shows formation of porosity at the interface of WAAM fabricated TZM-NbZr1 structure. Cracking is especially prevalent due to the intrinsic brittleness of refractory alloys and the amplified thermal stresses at bimetallic interfaces. Each of these defects undermines mechanical strength, fatigue resistance, and thermal transport performance.

In addition, the inherent complexity and uncertainty of multi-material AM further hinder process repeatability and part reproducibility. The underlying physics of melt pool dynamics, interfacial diffusion, and phase evolution involves nonlinear and highly coupled thermal, mechanical, and chemical phenomena that are difficult to predict or control. Small variations in process conditions or material properties can lead to unpredictable microstructural outcomes, making it difficult to establish deterministic control or reliable design guidelines. This fundamental uncertainty highlights the need for physics-informed modeling, advanced in-situ characterization, and data-driven approaches to improve reproducibility and build confidence in refractory multi-material AM.

Finally, the optimization and standardization of processing parameters remain underdeveloped for refractory AM systems. Stable bead geometry formation, consistent melt pool behavior, and controlled dilution are difficult to achieve due to extreme differences in thermal response between the two metals. Post-processing treatments such as heat treatment or HIP may help reduce porosity or residual stress [36], but they introduce new complexities and can alter the as-built microstructure. The absence of universally accepted processing guidelines limits reproducibility and hinders the broader industrial adoption of refractory alloy fabricated by additive manufacturing.

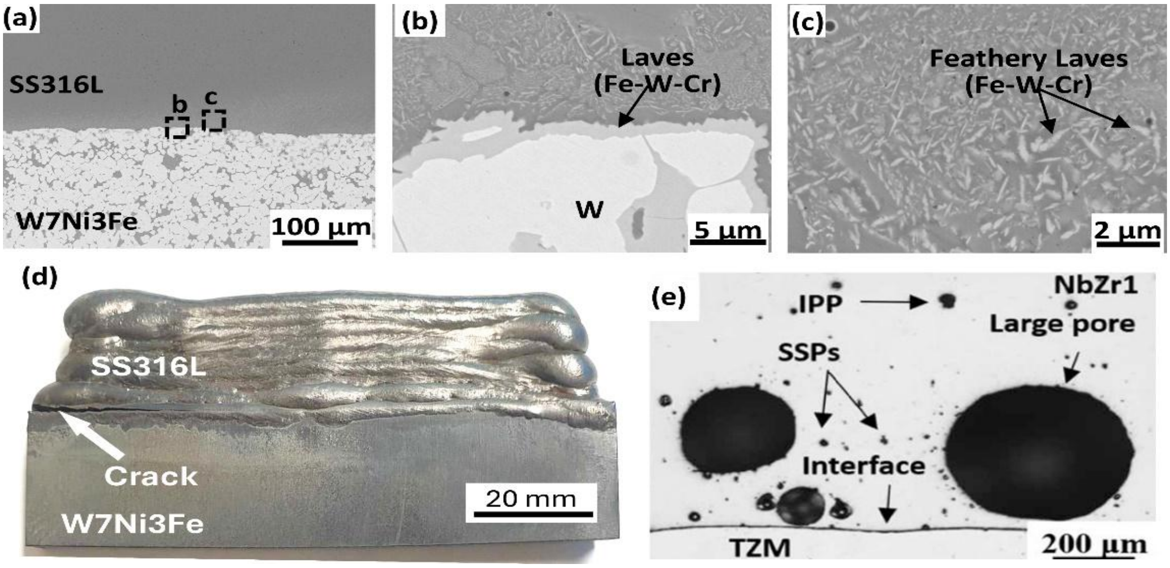

Fig. 9 (a-c) Intermetallic components are present as Laves phases in the W7Ni3Fe and SS316L interface [32], (d) f ormation of cracks due to residual tress in WAAM fabricated TZM/NbZr1 bimetallic structure [32], and (e) formation of porosity at the interface of WAAM fabricated TZM/NbZr1 Bimetallic structure [36]

5.2 Potential Ways for Remedy

Addressing the challenges associated with AM of refractory bimetallic and graded structures requires a comprehensive and integrative design framework. Integrated Computational Materials Engineering (ICME) provides such an approach by coupling experimental observations with computational modeling across multiple physical phenomena and length scales. Through this framework, multi-physics and multi-scale evaluation of melt pool behavior, interfacial reactions, thermal gradients, and defect formation becomes possible, enabling systematic optimization of alloy selection, interface design, and processing strategies [37].

Thermodynamic modeling tools offer an essential foundation for predicting intermetallic compound formation at interfaces. CALculation of PHAse Diagrams (CALPHAD)-based calculations allows researchers to assess equilibrium and nonequilibrium phase stability, identify potentially harmful reaction products, and design strategies to avoid brittle IMCs in refractory metal combinations. Fig. 10 shows equilibrium phase calculation using FactSageTM for W7Ni3Fe/SS316L structure. Such predictive capability is essential for guiding compositional design that minimizes interfacial instability [32]. Fig. 11 shows that Im625 interlayer mitigates crack and delamination in W7Ni3Fe/SS316L bimetallic structures [32].

Residual stress mitigation also benefits greatly from computational modeling. Thermo-mechanical numerical simulation of layer-by-layer deposition process can help predict stress accumulation and identify stress concentration zones. It can also evaluate the effects of preheating, post-heat treatment, scanning patterns, and deposition sequences on the residual stress formation. These simulation tools support the development of optimal deposition strategies that limit distortion and cracking, particularly in systems where thermal expansion mismatch is severe.

Microstructural evolution modeling plays a crucial role in designing reliable refractory structures by enabling direct simulation of phase transformation dynamics, grain growth, and texture development.

Methods such as phase-field modeling, cellular automata, and kinetic Monte Carlo allow researchers to simulate microstructure, solute redistribution, and precipitation behavior under rapid AM thermal cycling. When these mesoscale models are coupled with atomistic inputs from molecular dynamics or density functional theory (DFT)-including diffusivities, interfacial energies, and nucleation parameters, these models can elucidate oxidation mechanisms, interfacial reactions, and identify failure-susceptible regimes at the atomic scale, particularly in chemically heterogeneous interfaces.

For applications such as heat sinks and thermal protection systems, thermal conductivity and heat transfer performance must also be incorporated into the design framework since these properties dictate how efficiently a component can dissipate heat, moderate temperature gradients, and prevent localized thermal buildup during service. Interfacial IMCs, diffusion layers, and microstructural discontinuities can act as thermal barriers, creating local bottlenecks that limit heat dissipation and compromise system reliability. Therefore, dedicated investigation of thermal properties, including experimental thermal conductivity measurements and multi-physics heat transfer simulations, are needed to quantify interfacial thermal resistance and guide the design of thermally efficient multi-material architectures.

At the structural scale, crystal plasticity finite element modeling (CPFEM) and fast Fourier transformation-based approaches (CPFFT) provide powerful tools for evaluating anisotropic deformation, strain localization, and high-temperature mechanical response in refractory multi-material systems. Advanced computational frameworks such as Düsseldorf Advanced Material Simulation Kit (DAMASK) and Predictive Integrated Structural Materials Science (PRISMS) enable microstructure-sensitive simulations that explicitly incorporate crystallographic slip, phase and property heterogeneity, interfacial constraint effects, and thermo-mechanical coupling. These capabilities are

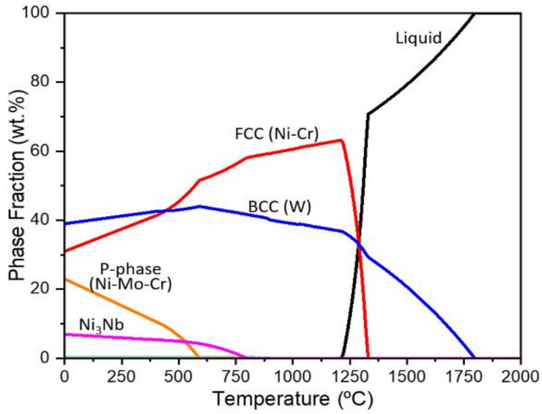

Fig. 10 equilibrium phase calculation using FactSage™ for W7Ni3Fe/SS316L structure [32]

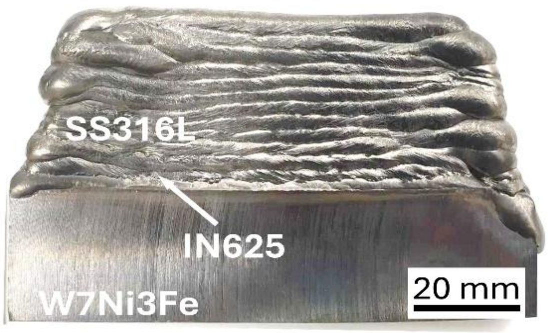

Fig. 11 In625 interlayer mitigating crack and delamination in W7Ni3Fe/SS316L bimetallic structures [32]

especially critical for understanding deformation behavior at dissimilar-metal interfaces, where gradients in elastic modulus, thermal expansion, and microstructure can drive localized stress concentrations, plastic incompatibility, and damage initiation. Under repeated thermal cycling and extreme temperature gradients, such interfaces become the most vulnerable sites for crack nucleation and propagation, making thermal fatigue prediction a key challenge. By capturing the evolution of microstructural defects such as pores, intermetallic layers, diffusion zones, and localized damage accumulation, these modeling approaches provide essential insight into interface-driven deformation modes and lifetime-limiting mechanisms in refractory multi-material components, forming the basis for performance-based design of next-generation high-temperature architectures.

In summary, these integrated experimental and computational methodologies create a pathway toward prediction of process-structure-property relationships for refractory alloy fabricated by AM. By enabling rational control of interfacial chemistry, microstructure, residual stress, and high temperature mechanical behavior, these approaches are expected to accelerate material development and significantly enhance the reliability and performance of next generation refractory metal architectures. However, the successful implementation of multistage and multi scale modeling frameworks ultimately depends on the availability of accurate physical and chemical property data, including thermodynamic, kinetic, mechanical, and transport parameters, which remain insufficient for many refractory alloy systems and their interfaces. This limitation highlights the need for continued fundamental research, including systematic property measurement, mechanistic studies, and atomistic to mesoscale modeling, in order to support the development of truly predictive and reliable computational tools for refractory multi material design and qualification.

6. Conclusion

AM offers a powerful platform for creating refractory alloy-based bimetallic and graded structures with tailored properties and enhanced high-temperature performance. The layer-wise nature of AM enables controlled interfacial design, allowing combinations of refractory metals that are difficult or impossible to achieve through conventional manufacturing processes.

However, issues such as intermetallic formation, chemical heterogeneity, residual stress accumulation, and defect generation continue to limit structural reliability. Advancing this field will require the establishment of predictive process-structure-property-performance relationships supported by integrated computational and experimental approaches. The combined use of ICME, CALPHAD modeling, residual stress simulations, and microstructure evolution tools is expected to guide the development of robust design rules and processing strategies, ultimately enabling reliable adoption of refractory alloy additive manufacturing in demanding high-temperature applications.

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