

High-Entropy Materials for Aerospace Applications: A Path to Enhanced Performance

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Abstract. With the thriving of aerospace engineering, human beings are pursuing materials with higher standard properties that could be applied in this certain field. High-entropy materials (HEMs) are known for their special qualities that make them perfect for use in aircraft. The main topics of this study include fatigue resistance, fracture toughness, and severe lattice distortion. It also investigates the basic principles underlying these improved mechanical properties of HEMs. Because of these characteristics, HEMs can function in harsh situations with high temperatures, mechanical stress, and corrosive substances. The study focuses on particular aerospace applications where HEMs perform better than conventional alloys in terms of strength, hardness, and durability. These applications include turbine blades, structural parts, and thermal protection systems for re-entry vehicles. Furthermore, HEMs are especially well-suited for high-temperature applications in jet engines and spacecraft due to their inherent oxidation and creep resistance. Notwithstanding the benefits, scaling up production for industrial applications still presents difficulties. Ongoing research in alloy design and additive manufacturing holds promise for overcoming these barriers, paving the way for HEMs to play a crucial role in the future of aerospace technology.

Keywords: High-entropy material; aerospace application; lattice distortion; fatigue resistance; oxidation resistance.

1. Introduction

Metallic materials play an important role in all aspects of life, these materials have long been used in the aspect of aerospace. Modern components for aerospace use have to withstand extreme temperatures, fracture, and creep under movements of high speed, other materials are applied for long-term reliability considering safety issues. What has long been used in this industry were alloys of titanium, nickel or aluminum, as the cornerstone of aerospace engineering for decades. They did offer a balance between the properties needed for this industry. Balancing and trading off between strength, weight and durability, alloys based on these metals fulfilled their mission well. However, certain limitations of these materials make it difficult to go further, particularly at elevated temperatures where their mechanical properties may degrade and in environments where corrosion resistance becomes critical.

The reason why titanium and its alloys are widely used in aerospace applications is due to their high strength-to-weight ratio and excellent corrosion resistance. These materials are commonly employed in engine components and airframes, where their performance at moderate temperatures is highly valued. Titanium exhibits two key phases: α -titanium, which is stable up to 882 °C, and β -titanium, stable from 882 °C to its melting point at 1670 °C [1]. As temperature increases, it is approaching the upper limit which will limit the usage of titanium in high-temperature areas of an aircraft. Though the material is suitable for many parts of an aerospace craft, the phase change and loss of structural integrity will largely affect the performance of the material. Still, considering the balance between performance and weight reduction in spite of these difficulties, titanium is a vital material for aerospace applications. Despite their toughness, components made with these materials will still be thick and add a large amount of weight to the aeronautical parts. For nickel superalloys, the pricey components of nickel and cobalt reduced the cost to a considerable range. Aluminum, in spite of being lightweight and easy to produce, lacks the high-temperature strength and corrosion resistance that are crucial for aerospace applications.

For pursuing better materials for aerospace use, HEMs have emerged in recent years to be a promising alternative to traditional superalloys. The most obvious difference between these materials is that, unlike conventional alloys, which are usually composed of one or two principal elements, HEMs consist of five or more elements with a near-equiatomic proportion. The multi-element configuration results in a high degree of configurational entropy and largely helps to stabilize the materials' structure even at extremely high temperatures [2]. HEMs are known for their extraordinary oxidation and corrosion resistance, as well as their capacity to retain mechanical strength and ductility at temperatures that might cause them to fail. While performance and fuel efficiency depend on decreasing weight while optimizing strength, strength-to-weight ratios would be a key consideration, and that is also a reason why HEMs are especially desirable for aeronautical applications.

As HEMs are being studied, human beings have also made great strides in the direction of aerospace. These materials might be applied in place of or in addition to current materials in high-stress, high-temperature applications, such as heat shields, turbine engines, and structural elements. HEMs can help extend the life of important components, thus save maintenance costs, and improve overall performance by enhancing the strength, thermal stability, and corrosion resistance of aerospace materials. As the aerospace industry continues to push the boundaries of flight and space exploration, HEMs in the future will absolutely play a pivotal role in enabling the next generation of high-performance industries in our lives.

2. Working Mechanism of HEMs in Aerospace

One of the main ways HEMs accomplish better mechanical performance is through solid solution strengthening. Traditional alloys have a restricted degree of lattice deformation due to the dispersion of one or two solute components within a solvent matrix. Compared to HEMs, it would be a quite different situation, they have many primary elements at appreciable concentrations. In this case, it allows them to have different atomic radii and sets of characteristics. These multi-element compositions, compared to those of conventional alloys, will have significantly bigger lattice distortions.

The varying atomic sizes in HEMs are the reason why it has significant irregularities in the crystal lattice and that will lead to severe lattice distortions. These distortions generate local stress fields, which act as barriers to dislocation motion, a key mechanism behind plastic deformation in materials [3]. When a material is under stress, dislocations will allow for easier deformation. However, in HEMs, the random distribution of components and the associated lattice distortions make it more difficult for dislocations to move freely. Because the energy needed to move a dislocation varies throughout the lattice due to the random nature of these distortions, that will make it even more difficult to move. As a result of the dislocation slides, the material hardness or yield strength will also improve.

Conventional alloys tend to weaken at high temperatures due to the increase in dislocation mobility, that is the reason why solid solution strengthening works so well in HEMs. HEMs, being different, remain strong at high temperatures because the lattice distortions still prevent dislocation migration. Furthermore, the complex and irregular atomic arrangement of HEMs helps suppress grain boundary sliding. This makes HEMs ideal for aerospace applications, where components are subjected to extreme mechanical loads and thermal conditions. For example, for building a turbine blade or any structural component in a spacecraft, we need material to have a high strength-to-weight ratio and resistance to fatigue. After solid solution strengthening, HEMs will be able to offer superior durability and stability compared to traditional alloys and thus ensure the integrity of the structure for aerospace components for long-term usage.

3. Feasibility and Application Principles of HEMs in Aerospace

The successful integration of HEMs into aerospace technology is grounded in several key principles, which include thermal stability, weight efficiency, environmental resistance, and enhanced mechanical properties. These principles enable HEMs to outperform traditional alloys in the demanding environments found in aerospace applications.

3.1. High-Temperature Stability

One of the key features that make HEMs stand out from all the alloys is their exceptional heat stability. For example, turbine blades and jet engine elements will frequently be exposed to extremely high temperatures. Long-time exposure to high temperatures can lead to phase transitions or mechanical strength loss for alloys, the conventionally used nickel-based alloys included. However, HEMs with high configurational entropy, could be able to preserve a stable single-phase solid solution [4]. The high entropy mixing of several elements in about equiatomic proportions results in a disordered atomic structure, and that is primarily responsible for its stability. This disorder prevents second-phase precipitates or brittle intermetallic phases from forming, somehow weakening the material when it is subjected to heat stress.

On the other hand, the behavior of sluggish diffusion of atoms in HEMs will further strengthen the resistance to high-temperature deterioration. For traditional alloys, creep and grain coarsening will be likely to be postponed by reduced atomic mobility at high temperatures. Nevertheless, HEMs will be perfect for high-performance applications like turbine blades or combustion chambers, which need to be operated under extremely high temperatures. As a result they can also preserve their mechanical integrity and show long-term stability.

3.2. Weight Reduction

Aerospace engineering places weight reduction at high priority since lighter materials result in higher payload capacities and better fuel economy. Because HEMs have a high strength-to-weight ratio, they offer an appealing alternative. By lowering the density by fine-tuning the compositions, researchers will be able to balance the mechanical qualities of HEMs. This will make them more competitive substitutes compared with conventional alloys like titanium or aluminum alloys.

When it comes to the application on airframes or wings, when even a single kilogram of weight saving can result in a considerable reduction in fuel composition and improve operating efficiency, the operation of fine-tuning capability turns out to be extremely important [5]. Furthermore, HEMs' structural integrity and toughness make them ideal for use in load-bearing components, where strength maintenance is crucial even in the face of mechanical stress and temperature fluctuations. Aerospace engineers have a tremendous tool to optimize materials for specific performance requirements, from propulsion systems to structural elements, thanks to the flexibility in building robust, lightweight, and thermally stable HEMs.

3.3. Corrosion and Oxidation Resistance

Ranging from high-altitude, low-pressure environments to the intense heat experienced during re-entry into Earth's atmosphere, this aerospace environment puts materials under extreme conditions. To cope with this certain situation, High-entropy alloy (HEA) coatings exhibit excellent corrosion and oxidation resistance due to their multi-elemental composition since they can promote the formation of stable, protective oxide layers and thus further protect the inner part of the material. These layers act as effective barriers, preventing the penetration of oxygen, moisture, and other corrosive elements that could degrade the material's integrity.

Elements such as chromium and aluminum are often incorporated into HEA coatings to enhance their resistance to oxidation. Chromium helps form hard phases, such as Cr_3Si , which improves hardness and wear resistance, while aluminum promotes the development of a dense oxide layer that preserves the coating's structural integrity at high temperatures. For instance, HEA coatings have

demonstrated superior performance compared to traditional coatings, with oxidation rates up to nine times lower than those of the base material (Ti-6Al-4V alloy) at 600 °C [6]. These coatings offer excellent resistance to oxidation and corrosion, making them ideal for aerospace components exposed to extreme conditions. The multi-element matrix, combined with advanced surface technologies, allows HEA coatings to provide outstanding performance in harsh environments, significantly improving wear resistance and durability. As a result, substrates like stainless steel experience prolonged service life, even in high-temperature erosive conditions.

The ability of HEMs to withstand extended periods of oxidation plays a crucial role in increasing the operational life of aerospace components, such as engine parts, which are frequently exposed to hot gases and oxidizing environments. HEMs also offer a reliable solution for spacecraft and re-entry vehicles, ensuring that heat shields and thermal protection systems maintain their integrity and functionality when re-entering the Earth's atmosphere despite the intense heat and oxidative stress encountered. Moreover, HEMs exhibit exceptional resistance to corrosion in harsh conditions, including seawater and humid environments, which are common during aerospace operations over oceans or in coastal regions. This resistance to environmental degradation makes HEMs highly valuable across a broad range of aerospace applications, from propulsion systems to structural components, where long-term durability is essential for safety and reliability.

3.4. Other Key Factors: Fatigue and Creep Resistance

Aside from the advantages of weight reduction, environmental resistance, and thermal stability, HEMs also have great resistance to fatigue and creep. Aerospace components that are repeatedly loaded and unloaded are particularly vulnerable to fatigue, which can lead to fracture formation and eventual failure. Because of their improved solid solution strengthening and intrinsically disordered atomic architectures, HEMs contribute to a more uniform distribution of stresses throughout the material, reducing the stress concentrations that usually cause fatigue failure [7].

Similarly, the slow atomic diffusion in HEMs significantly reduces creep, which is the gradual deformation of materials under constant stress at high temperatures. Due to the presence of multiple elements in HEMs, the atoms within the lattice have limited mobility, which delays the onset of creep deformation. This property makes HEMs particularly well-suited for high-temperature aerospace applications, where preserving structural integrity and functionality over extended service periods is essential.

3.5. Conclusion on Key Principles for Application

The combination of high-temperature stability, weight efficiency, environmental resistance, and resistance to fatigue and creep gives HEMs a significant advantage in aerospace technology. These materials can be tailored to meet the specific requirements of aerospace applications, offering not only enhanced performance but also longer operational life and reduced maintenance costs. Furthermore, their compatibility with existing manufacturing techniques improves their feasibility for large-scale industrial production, positioning HEMs as a promising solution for next-generation aerospace components.

4. Mechanical Properties of HEMs

HEMs excel in delivering outstanding mechanical properties, particularly in terms of strength, hardness, and fracture toughness, which are essential attributes for aerospace components that must withstand extreme mechanical stresses. The superior performance of HEMs in these areas can be attributed to their unique solid solution strengthening mechanisms and severe lattice distortion, which arise from their multi-elemental alloying design.

4.1. Solid Solution Strengthening

Solid solution strengthening is one of the primary mechanisms that makes the exceptional strength of HEMs. Unlike conventional alloys that typically consist of one or two primary elements, HEMs are composed of multiple elements, each present in near-equal atomic concentrations. This multi-elemental composition leads to significant atomic size mismatches, resulting in severe lattice distortions within the crystal structure. These distortions create internal stresses and impede the motion of dislocations, which are defects in the crystal lattice responsible for plastic deformation [8].

In a typical metallic alloy, dislocations move relatively easily through the crystal lattice, allowing the material to deform under stress. However, in HEMs, the presence of multiple alloying elements with different atomic radii disrupts the regularity of the crystal lattice. The dislocations encounter numerous obstacles as they attempt to move, making it much more difficult for the material to deform. This phenomenon leads to a marked increase in both yield strength and ultimate tensile strength. As a result, HEMs exhibit a much higher strength level than that of conventional material.

4.2. Severe Lattice Distortion

Another key factor that improves the strength of HEMs is their high lattice distortion. This means the arrangement of atoms in the material is uneven because the atoms are of different sizes. This unevenness makes it harder for dislocations to move through the material, which helps "lock" them in place. As a result, HEMs can handle more stress before they break or bend.

The hardness of HEMs, which makes them very resistant to wear and abrasion, is also due to this lattice distortion [3]. For aerospace parts like engine components and turbine blades, which face tough conditions and high pressures, resistance to mechanical wear is crucial. The natural hardness of HEMs ensures these parts last longer without major damage, reducing the need for frequent repairs or replacements.

4.3. Fracture Toughness

HEMs have excellent fracture toughness, which is the ability of a material to resist crack growth and absorb energy before breaking. This property, along with their strength and hardness, makes HEMs ideal for aerospace applications. In these applications, parts must handle not only constant loads but also changing pressures, impacts, and fatigue from repeated use. Fracture toughness is especially important in such conditions.

The multi-element composition of HEMs gives them a unique advantage. In regular materials, cracks can quickly spread, leading to failure. However, in HEMs, the complex microstructure created by the random mix of different atoms makes it harder for cracks to grow. When a crack forms, it is forced to take a more complicated path through the material, which uses up energy and slows down the crack's progress. This ability to stop or slow down cracks greatly improves the fracture toughness of HEMs.

Moreover, in high-temperature aerospace applications, HEMs also resist creep, which is the slow deformation of a material under long-term stress at high temperatures. Regular alloys can develop microcracks due to creep, which may eventually lead to fracture, especially in high-stress parts like turbine blades. HEMs, on the other hand, have a strong lattice structure and slow atomic movement, which helps prevent creep and keeps the material stable even under extreme conditions.

4.4. Durability and Fatigue Resistance

HEMs also provide excellent fatigue resistance and durability, making them ideal for high-stress, load-bearing aerospace applications. Components like aircraft fuselages, landing gear, and wing structures need to be highly resistant to fatigue [7]. Over time, repeated mechanical stress can cause tiny cracks to form and spread, eventually leading to fatigue failure. However, the unique microstructure of HEMs, with their significant lattice distortions and strong atomic bonds, helps evenly distribute mechanical loads, reducing the risk of fatigue cracks forming.

Additionally, the disordered structure of HEMs plays a key role in preventing the growth of fatigue cracks. The random arrangement of atoms acts as a natural barrier to crack propagation, allowing HEMs to handle more load cycles compared to traditional alloys. This increased fatigue life is especially important in aerospace, where the durability of components is critical for safety and helps lower operational costs by reducing the need for frequent part replacements.

4.5. Applications in Critical Aerospace Components

The combination of high strength, hardness, fracture toughness, and fatigue resistance makes HEMs ideal for various aerospace applications. In high-performance jet engines, for example, HEMs can be used in turbine blades, combustion chamber liners, and other parts that face extreme mechanical stress and high temperatures. Their resistance to deformation and cracking under these conditions ensures reliable performance and reduces the risk of catastrophic failure.

In structural applications, like airframes, fuselage panels, and landing gear, HEMs provide the durability needed to handle the high-impact forces and repeated stresses experienced during flight. Their excellent fatigue resistance and toughness make them a great choice for components where long service life and minimal maintenance are crucial.

5. Specific Aerospace Applications of HEMs

5.1. Engines and Turbines

High-performance jet engines and gas turbines, which operate under extreme conditions like high temperatures, oxidative environments, and mechanical stress, are perfect candidates for HEMs. These materials provide a significant advantage over traditional nickel-based superalloys, as they can maintain mechanical strength and resist deterioration at temperatures above 1100°C. The naturally high configurational entropy of HEMs prevents performance-limiting issues such as phase separation or the formation of brittle intermetallic compounds. This makes them ideal for components like turbine blades and vanes, which face intense heat, rotational forces, and corrosive conditions that challenge the durability of conventional materials [10].

By enduring these extreme conditions, HEMs allow engines to operate at higher temperatures, enhancing combustion cycle efficiency. This leads to better fuel efficiency, higher thrust-to-weight ratios, and lower emissions—key factors in the development of next-generation aircraft propulsion systems.

In addition to their thermal stability, HEMs provide excellent oxidation resistance. Oxidation can weaken engine parts over time, reducing their durability. However, HEMs, with their complex alloying of elements like chromium and aluminum, form durable protective oxide layers that prevent oxidation from spreading. This increases the lifespan of components and reduces maintenance needs. The integration of HEMs into engine and turbine applications is a promising step toward creating more robust, eco-friendly, and efficient aircraft propulsion systems.

5.2. Structural Components

Aerospace engineers consider weight reduction to be a crucial design objective since it has a direct impact on aircraft performance, cargo capacity, and fuel efficiency. Because HEMs offer a special blend of exceptional mechanical strength and lightweight characteristics, they are the best choice for structural parts, including landing gear, wing spars, and fuselage sections. By replacing traditional metals with HEMs, aircraft designers can achieve significant weight savings without sacrificing the mechanical integrity necessary for safety and performance.

Because of the exceptional toughness of HEMs, structural elements are guaranteed to be able to endure the high-impact forces and dynamic loads encountered during takeoff, flight, and landing. This is particularly crucial for components like landing gear, which have to withstand repeated landing stresses without wearing out or breaking. Another important benefit of HEMs in aeronautical structures is their resilience to fatigue. Cycle loading can cause fatigue and, eventually, material

failure in aircraft components. The intricate atomic structure of HEMs improves their resilience to fatigue and prolongs the operational life of crucial structural elements by preventing crack development.

HEMs not only provide great mechanical strength and endurance, but they also resist corrosion in harsh situations. Aircraft frequently operate in extremely corrosive situations, such as those where they are exposed to different air contaminants and saltwater when flying over the ocean. Because of their multi-element makeup, HEMs can generate surfaces resistant to corrosion and other environmental stresses, hence lowering the need for regular maintenance and early part replacement.

5.3. Heat Shields and Re-Entry Vehicles

When spacecraft re-enter Earth's atmosphere, they face extreme conditions that make material selection challenging. Re-entry vehicles and heat shields experience rapid temperature changes, thermal shocks, and exposure to highly reactive gases. This requires materials with excellent resistance to heat, shock, and oxidation. HEMs are well-suited for these conditions, making them ideal for thermal protection systems (TPS) in spacecraft. HEMs can withstand extremely high temperatures without losing their structure or strength, which is crucial for re-entry vehicles where temperatures can exceed 1500°C. Their unique structure helps maintain crystal stability at high temperatures, ensuring that they retain their strength during re-entry. HEMs also slow down atomic movement within the material, reducing the risk of creep or weakening over time.

In addition to thermal stability, HEMs are highly resistant to oxidation, a key factor in their effectiveness as heat shield materials. During re-entry, spacecraft encounter extreme heat and reactive oxygen species due to air friction. The special combination of metals in HEMs forms strong oxide layers on the surface, protecting the material from oxidation, which can weaken traditional heat shields.

HEMs also have high thermal shock resistance, allowing them to withstand the rapid heating and cooling cycles experienced during launch, space travel, and re-entry without cracking or spalling [11]. This ensures the spacecraft remains protected throughout the mission, minimizing the risk of material failure. As a result, HEMs are ideal for use in heat shields, spacecraft exteriors, and other TPS where temperature resilience and oxidative stability are critical. Incorporating HEMs into heat shields and re-entry vehicles can improve spacecraft reliability and durability, enhancing mission safety and reducing overall space exploration costs by using longer-lasting materials. Additionally, the lightweight nature of certain HEMs can further reduce the spacecraft's mass, enabling more efficient missions with greater payload capacity.

6. Conclusion

HEMs are a major improvement in aerospace materials technology. They offer a mix of heat resistance, strength, and durability that is better than traditional alloys. The special way HEMs are made, using multiple elements and high configurational entropy, helps them stay stable even in extreme conditions, like high temperatures and corrosive environments. This makes HEMs very good for use in aerospace, where long-term performance and reliability are very important. They are used in turbine blades, structural parts, and spacecraft heat shields.

However, there are still challenges in producing HEMs on a large scale. Some of these challenges include the cost, the availability of raw materials, and the need to improve the production process. Researchers are working on solving these issues through additive manufacturing, new alloy designs, and finding ways to lower costs. This research is crucial to unlocking the full potential of HEMs in aerospace.

In the future, research will focus on improving HEM compositions to make them even better for specific aerospace needs, such as making them stronger while keeping them light or improving their resistance to certain environmental factors. As manufacturing methods get better, HEMs will become

more important in next-generation aerospace technology, helping to make aircraft more efficient, durable, and safe.

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