Romanian Journal of Civil Engineering, Volume 17 (2026), Number 3

Perspectives and challenges of integrating high-entropy alloys into the HVAC industry through 3D printing

Perspective și provocări ale integrării aliajelor cu entropie ridicată în industria HVAC prin intermediul printării 3D

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DOI: 10.37789/rjce.2026.17.3.16

Abstract. *This study analyses the benefits of integrating high-entropy alloys (HEAs) into HVAC systems using 3D printing technologies. The results indicate high performance in corrosive environments and under thermal stress, optimizing critical components such as fans and heat exchangers. The paper introduces cost-effective repair methods and advocates for the standardization of additive manufacturing processes to maximize the impact of HEAs in high-performance industrial applications.*

Key words: 3D printing, High-Entropy Alloys, HVAC system, additive manufacturing

The article was received on 07.04.2026, accepted on 11.09.2026 and published on 22.09.2026

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are integral to providing comfortable and healthy indoor environments across a diverse range of building types, from residential homes to large industrial complexes. Beyond maintaining optimal temperature and air quality, modern HVAC installations are expected to meet increasingly stringent standards for energy efficiency, environmental compliance, and long-term durability. As concerns about global energy consumption and climate change intensify, these systems have come under growing pressure to operate more sustainably and cost-effectively.

In parallel with these evolving requirements, the field of materials science has witnessed remarkable developments that directly impact HVAC performance. HEAs - compositions characterized by multiple principal elements in near-equimolar proportions - have emerged as a powerful alternative to conventional alloys. These novel alloys often exhibit superior mechanical, thermal, and chemical properties, including enhanced corrosion resistance and improved thermal stability [1, 2]. Such characteristics are particularly relevant for HVAC applications, where components must withstand corrosive environments, frequent thermal cycles, and mechanical wear over extended operating lifespans.

Compounding the appeal of HEAs is the rapid rise of additive manufacturing (AM), commonly known as 3D printing, as a cost-effective and material-efficient production technology. By building components layer-by-layer, AM processes facilitate complex geometrical designs, minimal material waste, and rapid prototyping. Consequently, 3D printing of HEAs represents a valuable avenue for addressing critical HVAC challenges: it enables the fabrication of intricate, custom-tailored parts with enhanced properties while simultaneously reducing maintenance costs and downtime through advanced repair methods. In particular, directed energy deposition (DED) has garnered attention as a means to efficiently restore worn or damaged HEA components, extending their useful life and curbing material wastage [3].

2. Background on HEAs

HEAs represent a novel class of materials in which multiple principal metallic elements, typically with atomic fractions ranging from 5% to 35%, coexist in near-equiatomic proportions. By comparison, conventional alloys are usually based on one primary element which dictates the bulk of the alloy's properties. The distributive nature of elemental constituents in HEAs leads to unconventional microstructures and confers multiple structural advantages, such as enhanced mechanical robustness and excellent thermal stability. This chapter provides an overview of the composition and microstructural characteristics of HEAs, referencing seminal studies that have shaped current understanding and applications of these innovative materials.

Fig.1 provides a visual overview of the concept of high-entropy alloys (HEAs), highlighting the balanced distribution of elements, the differences compared to conventional alloys, and the superior structural properties that make them suitable for advanced applications.

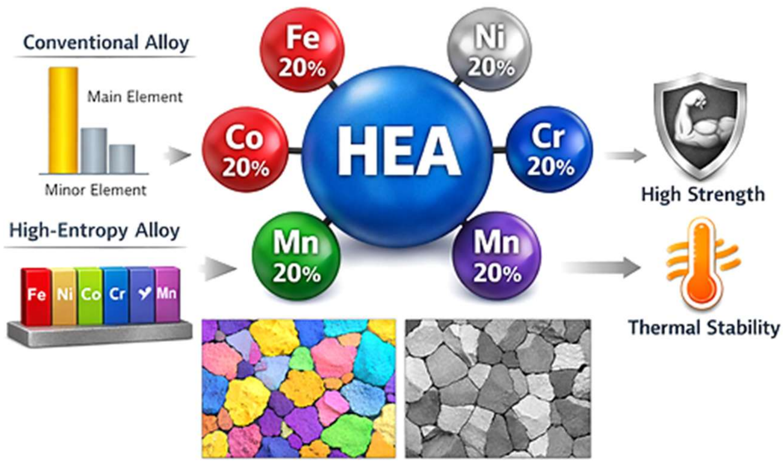


Fig. 1. Overview of the composition and microstructure of high-entropy alloys (HEAs)

2.1. Composition and microstructure

The key defining feature of HEAs is their high configurational entropy, derived from the presence of several principal elements in near-equiatomic ratios. This elevated entropy can stabilize simple solid-solution phases (i.e., face-centred cubic (FCC), body-centred cubic (BCC), or mixed phases) rather than complex intermetallic structures, thus contributing to outstanding strength, ductility, and thermal stability [4, 5]. For instance, Miracle and Senkov [4] underscore that the absence of dominant single-element phases in HEAs promotes equilibrium structures that are notably resistant to phase transformations. Such stability is especially critical for applications requiring extended service life at elevated temperatures or in highly corrosive environments.

Moreover, the characteristic multi-principal-element composition introduces several phenomena often referred to as the “core effects” of HEAs:

- High entropy effect: stabilizes simple solid-solution phases by increasing the overall entropy and lowering free energy;
- Sluggish diffusion effect: slows the rate of atomic diffusion, potentially improving creep resistance and dimensional stability;
- Severe lattice distortion: the presence of different atomic radii causes localized strain fields and can hinder dislocation movement, enhancing mechanical strength;
- Cocktail/ensemble effect: different elements can exert synergistic strengthening effects, collectively improving corrosion resistance, wear behavior, and other functional properties.

In practice, alloy design strategies for producing HEAs often rely on computational tools such as CALPHAD (CALculation of PHAse Diagrams) to predict stable phases and optimize compositions prior to experimental validation. As a result, manufacturers can systematically explore countless multi-component systems to tailor specific properties (e.g., hardness, ductility, corrosion resistance) to meet application requirements in high-demand sectors.

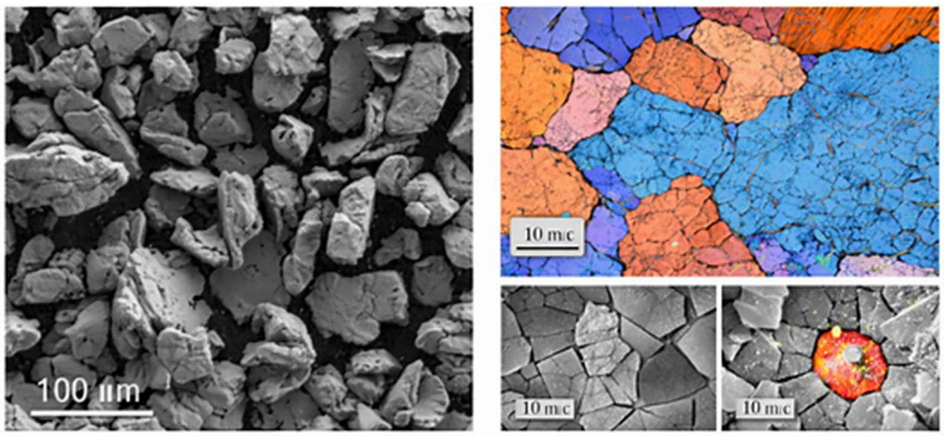


Fig. 2. Microstructure of CoCrFeMnNi HEA powder observed via scanning electron microscopy (SEM)

Representative examples of microstructural features

- FCC-dominant HEAs: commonly observed in systems such as CoCrFeMnNi (figure 2), the FCC structure lends excellent ductility and moderate strength. Zhu et al. [5] have demonstrated that tuning the relative ratios of elements can lead to substantial improvements in tensile strength without sacrificing elongation, making these alloys ideal for structural applications;
- BCC-dominant HEAs: BCC-based HEAs often exhibit higher strength than their FCC counterparts, though sometimes at the expense of ductility. Despite this trade-off, BCC structures can be favourable in applications where superior yield strength and hardness are prioritized (e.g., cutting tools or high-stress environments);
- Mixed FCC/BCC structures: some HEAs adopt dual-phase microstructures, combining the toughness of FCC phases with the high strength of BCC phases. This composite-like configuration can yield a unique balance of mechanical properties suitable for demanding environments, such as turbines and heat exchangers in energy systems.

The elevated configurational entropy derived from the balanced distribution of multiple elements explains why HEAs exhibit properties rarely found in traditional alloys. It is precisely this unique synergy - coupled with emerging manufacturing techniques like additive manufacturing - that positions HEAs as promising candidates for advanced structural and functional components in various industries, including the realms of heating, ventilation, and air conditioning (HVAC) discussed in subsequent chapters.

2.2. Properties relevant to HVAC applications

The unique composition and microstructure of high-entropy alloys provide a range of functional properties especially pertinent to the demanding conditions found in heating, ventilation, and air conditioning (HVAC) systems. By combining multiple principal elements with high configurational entropy, HEAs often outperform conventional alloys (e.g., aluminium, steel, copper) in areas critical to HVAC performance and longevity. This section details three key properties - corrosion resistance, thermal fatigue performance, and wear resistance - and highlights their relevance to HVAC applications.

Several material properties make HEAs attractive for HVAC applications:

2.2.1. Corrosion resistance

HVAC components frequently operate in environments where moisture, chemicals, or pollutants threaten the integrity of metallic parts (e.g., heat exchangers, piping, and condensing units). Many HEAs exhibit superior corrosion resistance due to their highly stable surface oxide layers and optimized chemical compositions. For instance, Shi et al. [6] point out that the multi-element nature of HEAs can promote uniform passivation, effectively slowing down corrosion-induced degradation. Additionally, the sluggish diffusion effect inherent in HEAs may further protect surfaces by limiting the transport of corrosive agents throughout the material.

In practical HVAC settings, improved corrosion resistance translates to:

- longer service life for components exposed to harsh conditions;
- reduced maintenance, as protective coatings or frequent replacements become less necessary;
- improved reliability, beneficial in large-scale installations (e.g., industrial cooling towers or district heating systems).

2.2.2. Thermal fatigue performance

Thermal fatigue arises when materials are subjected to regular heating and cooling cycles, causing repeated thermal expansion and contraction. Over time, these cycles can lead to crack initiation and propagation, reducing the component’s service lifespan. HEAs, however, often exhibit excellent high-temperature strength and phase stability, making them well-suited to handle frequent temperature swings in HVAC equipment [7].

Schuh et al. [7] have shown that certain HEA compositions, especially FCC-dominated alloys, maintain their ductility and toughness at elevated temperatures. This characteristic is crucial in heat exchangers, compressors, and furnace systems, where components undergo cyclical thermal stresses. By incorporating thermally robust HEAs, HVAC systems can:

- minimize crack formation and fatigue-induced failures;
- operate more reliably for extended periods under fluctuating temperatures;
- reduce downtime associated with unplanned maintenance or part replacements.

2.2.3. Wear resistance

Moving components within HVAC systems - such as fan blades, valves, and pumps - are subject to frictional forces and mechanical wear, especially when handling dusty or corrosive airflows and water streams. The mechanical robustness of HEAs makes these alloys particularly advantageous for combating wear. Miao and Tsai [8] reported that the presence of multiple principal elements in HEAs induces a range of solid-solution or intermetallic phases, contributing to hardness, reduced friction, and lower wear rates.

From an industrial perspective, leveraging the wear resistance of HEAs in HVAC systems can:

- enhance operational efficiency by maintaining smoother surfaces;
- lower maintenance costs via elongated service intervals;
- improve overall system reliability, reducing the likelihood of critical failures in moving parts.

2.2.4. Comparison with conventional alloys

Although aluminium, steel, and copper have long been used in HVAC due to their availability, cost, and familiarity, HEAs offer a compelling alternative in environments where standard metals may rapidly corrode, fail under cyclic stress, or wear out prematurely. While some HEAs can be more expensive initially, their enhanced durability and improved operational efficiency have the potential to offset these costs over the long term. Moreover, the advent of additive manufacturing has made it more feasible to produce complex HEA geometries in a cost-effective and material-efficient manner, further bolstering their appeal for HVAC applications.

3. Additive manufacturing of HEAs

Additive manufacturing (AM), or 3D printing, has rapidly gained importance in the production of metallic components, offering the potential to reduce material waste, shorten lead times, and enable customized designs. In the context of high-entropy alloys (HEAs), AM methods amplify these benefits by providing precise control over microstructure, chemistry, and geometry - factors that can significantly impact an HEA's mechanical and thermal properties.

3.1. 3D printing techniques

The feasibility of 3D printing HEAs has been demonstrated using a range of powder-based and wire-based techniques, each with unique strengths and limitations regarding cost, build rate, part geometry, and mechanical properties [9, 10].

❖ Selective laser melting (SLM) (figure 2a):

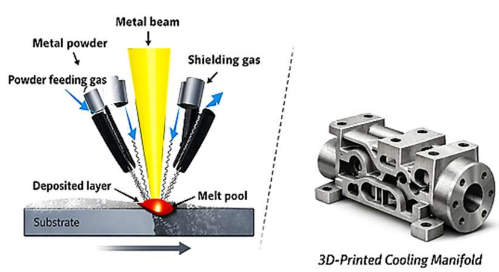
- process overview: a laser selectively fuses regions of a powder bed in a layer-by-layer fashion;

- advantages: high dimensional accuracy and surface finish; suitable for complex, intricate parts [10];
- limitations: slower build rate than some deposition-based methods due to the layer-by-layer powder bed approach, and strict powder specifications to ensure part quality.

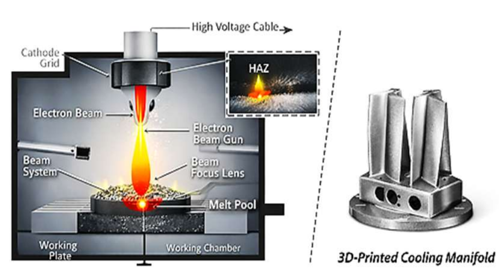
❖ Electron Beam Melting (EBM) (figure 2b):
- process overview: similar to SLM but employs an electron beam in a controlled vacuum environment;
- advantages: faster build rates compared to SLM, lower residual stresses due to vacuum operation, and good consolidation for reactive materials (e.g., titanium alloys and certain HEA compositions) [11];
- limitations: more expensive equipment, requirement for vacuum conditions, and potential challenges in controlling powder charging during the process.

❖ Laser Metal Deposition (LMD) (figure 2c):
- process overview: also known as Laser Cladding or Laser Direct Metal Deposition, this process delivers powder coaxially into a melt pool generated by a high-power laser scanning over a substrate [12];
- advantages: suited for near-net-shape builds, gradient materials creation, or application of coatings. Often used in aerospace and energy industries for larger structural parts;
- limitations: less precise than SLM for fine geometrical features, potentially leading to larger feature sizes and higher surface roughness.

❖ Directed Energy Deposition (DED) (figure 2d):
- process overview: a technique in which a heat source (laser beam, electron beam, or plasma arc) fuses material (either blown powder or fed wire) delivered through a nozzle mounted on a multi-axis system [9];
- advantages: selective repair: DED can rebuild worn or damaged sections of a part, making it highly appealing for HVAC components requiring maintenance and retrofits; versatile: able to deposit material in any 3D path, enabling designs with internal channels or complex geometries; high deposition rates relative to powder-bed processes.
- limitations: may yield coarser microstructures and require post-processing (e.g., machining, heat treatment) to achieve final desired tolerances and properties.



(a)



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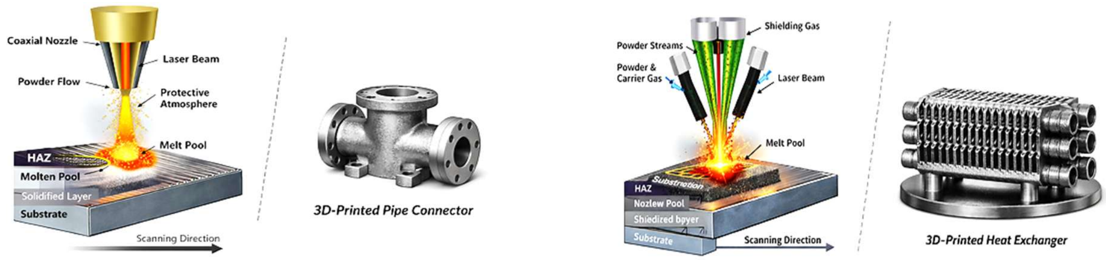

(c) (d)

Fig. 2. 3D printing techniques
(a). Selective laser melting (SLM); (b). Electron Beam Melting (EBM); (c). Laser Metal Deposition (LMD); (d). Directed Energy Deposition (DED)

Among these techniques, Directed Energy Deposition has garnered particular interest for repair strategies in HVAC systems, due to its capability to pinpoint locations on worn or corroded components and rebuild them in situ. This localized approach minimizes material waste and reduces downtime, enabling a more cost-effective lifecycle for HEA-based HVAC parts [9].

Relevance to HVAC applications

HVAC systems often contain numerous custom metal parts (e.g., specialized fan blades, cones, ducts) that suffer from corrosion, thermal stress, or mechanical wear. In such scenarios:

- SLM or EBM may be beneficial for fabricating entirely new, complex HEA components, particularly where fitness-for-service depends on precise geometries or lightweight, lattice-like structures;
- DED or LMD become extremely valuable for on-site repairs or the remanufacture of critical sections, reducing the need to discard an entire part.

By selecting an appropriate AM method, engineers and technicians can tailor the build process to meet specific performance requirements - be it surface finish, dimensional accuracy, or throughput - while capitalizing on the robust material properties inherent in HEAs. In turn, such adaptability paves the way for longer service lives, enhanced efficiency, and lower maintenance costs in high-demand HVAC environments.

3.2. Advantages of 3D-printed HEAs

The process of additive manufacturing (AM), when applied to high-entropy alloys (HEAs), offers a host of benefits that extend well beyond those of conventional metal-forming methods. This is largely attributed to the synergy between the unique properties of HEAs - such as superior corrosion resistance, enhanced thermal fatigue strength, and robust wear behaviour - and the design freedoms enabled by AM. Figure 2 provides a conceptual illustration of the core advantages of 3D-printed HEAs for HVAC and other high-demand applications.

3.2.1. Geometrical complexity

One of the most significant benefits of additive manufacturing lies in its ability to produce complex geometries that are difficult - if not impossible - to achieve through traditional subtractive or casting-based processes. This is particularly valuable for HVAC systems, which may involve intricate heat exchanger designs, custom conduits, or optimized fan blade profiles.

- improved heat transfer: complex internal channels or cellular/lattice structures can be designed to increase surface area and optimize fluid flow, thereby improving thermal efficiency;
- design freedom for consolidation: AM enables part consolidation, reducing the total number of components and simplifying assembly [13].

Case example:

Using 3D-printed HEA heat exchangers featuring internal coolant channels optimized for convective transfer has been shown to reduce the system's overall weight and thermal resistance, expanding design possibilities in space-constrained areas like data centres and aircraft cabins.

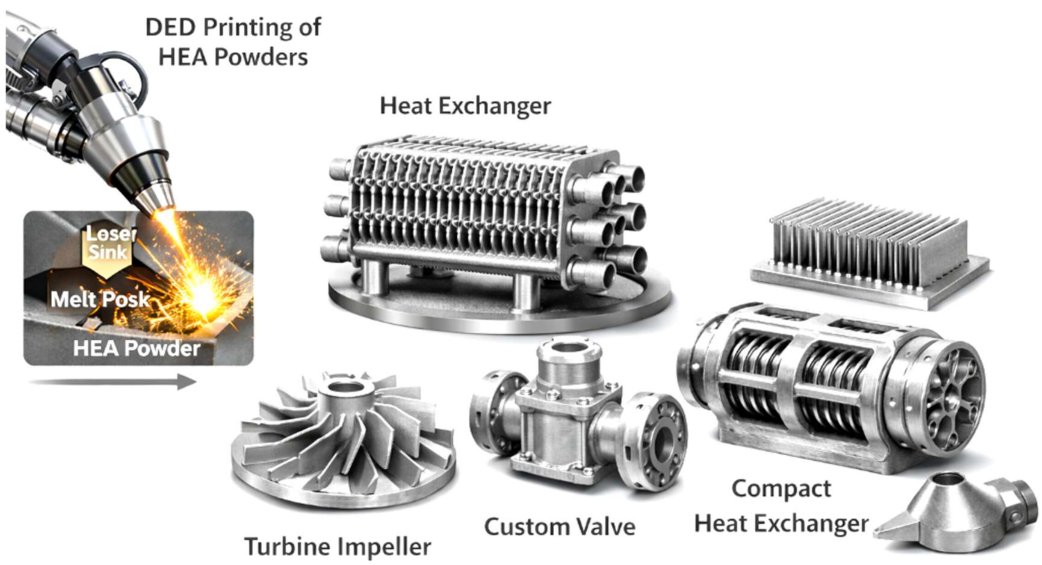

Fig. 6. 3D printed heat exchangers

3.2.2. Material savings

Additive manufacturing builds components layer by layer, maximizing the usage of raw materials and significantly reducing scrap compared to subtractive machining. For HEAs, which can be more expensive than conventional alloys, minimizing material waste becomes a critical economic advantage.

- near-net-shape production: by depositing or fusing only the required amount of HEA powder or wire, manufacturers avoid the large-scale removal of material inherent in milling or turning;

- reduced stock requirements: complex parts no longer need to start from bulky forgings or cast billets, leading to lower inventory and logistical costs [14].

This approach is especially helpful in HVAC, where customization (e.g., specialized fan blades or custom duct adaptors) often results in significant scrap if produced via traditional methods.

3.2.3. Enhanced mechanical properties

During many powder-bed or directed energy deposition processes, the rapid solidification of metal feedstock can yield fine-grained microstructures, resulting in enhanced mechanical performance [15]. In the context of HEAs, which already exhibit high strength and excellent durability, this phenomenon can further improve:

- tensile strength: HEA components fabricated via selective laser melting (SLM) or electron beam melting (EBM) have shown increased yield and ultimate tensile strength due to grain refinement [16];
- fatigue resistance: the fine microstructure may also limit the propagation of microcracks, translating to superior fatigue life under repeated loading conditions often encountered in HVAC fans and compressors;
- thermal stability: many HEAs maintain phase stability and structural integrity at elevated temperatures, further enhanced by the uniform as-built microstructure formed during rapid cooling [17].

4. Benefits and challenges in HVAC applications

HEAs have garnered significant attention in heating, ventilation, and air conditioning (HVAC) systems due to their formidable mechanical properties, corrosion resistance, and thermal stability. When paired with additive manufacturing (AM) methods (e.g., selective laser melting (SLM), directed energy deposition (DED)), these alloys promise longer service lives, improved performance, and cost-saving advantages. Figure 3 provides a conceptual illustration of the synergistic benefits HEAs and 3D printing offer for HVAC applications.

4.1. Benefits

4.1.1. Extended lifespan

One of the most significant advantages offered by HEAs in HVAC is extended component lifespan. These alloys owe their longevity to:

- intrinsic corrosion resistance: HEAs often develop protective oxide layers that inhibit corrosion processes, especially in moist or chemically aggressive HVAC environments [9, 13];
- thermal fatigue resistance: high configurational entropy helps stabilize microstructures against temperature fluctuations, reducing the likelihood of cracks and failures over repeated cycles [6, 7];

- additive design optimization: with AM, engineers can tailor part geometries - e.g., lattice structures or reinforced ribs - to distribute stress more evenly, thus minimizing structural weaknesses and extending service life [14].

By leveraging these attributes, HVAC components (e.g., fan casings, heat exchanger tubes, rotating shafts) stand to benefit from longer operational intervals and decreased failure rates.

4.1.2. Improved performance

In HVAC systems, overall efficiency and throughput can hinge on factors such as heat transfer and energy consumption. 3D-printed HEAs address these areas in multiple ways:

- customized heat exchanger designs: complex internal channels and intricate fins created via SLM or EBM maximize heat transfer surface area, resulting in improved thermal efficiency [15];
- lightweight and robust fan blades: advanced topology optimization combined with the high strength-to-weight ratio of HEAs fosters lighter, stronger rotating components. Lighter fans consume less energy and can reduce vibration, extending bearing life and improving reliability [16];
- enhanced flow dynamics: by incorporating streamlined contours or integrated fluid guides in conduits and ducts, airflow can be optimized, decreasing energy loses and improving overall handling capacity.

These features collectively contribute to reduced power consumption, lower operational costs, and fewer system downtimes, all of which are crucial in large-scale installations like data centres, hospital HVAC systems, or manufacturing plants.

4.1.3 Cost savings

While initial investments in 3D printing systems, HEA powders, and process development can be significant, the long-term economic benefits often justify these expenditures [9, 14]. Key cost-saving mechanisms include:

- reduced maintenance: DED is particularly valuable for repairing worn or damaged HEA components. Rather than scrapping an entire unit (e.g., a corroded fan hub or damaged heat exchanger plate), targeted deposition allows in-situ restoration [9, 17]. This practice can dramatically lower lifecycle costs and extended the useful life of essential HVAC hardware;
- minimized downtime: less frequent component failures translate to fewer unplanned shutdowns, which can be enormously costly in critical facilities;
- optimal material utilization: additive processes inherently minimize waste by depositing material only where it is needed, proving especially beneficial for expensive HEA feedstocks [14].

Together, these factors can significantly offset the higher upfront costs of implementing 3D-printed HEAs in HVAC, culminating in greater overall economic viability - particularly for mission-critical systems where reliability and efficiency are paramount.

4.2. Challenges

Despite the promising benefits of 3D-printed high-entropy alloys (HEAs) in HVAC systems, several challenges must be addressed before these advanced materials can be widely adopted. These obstacles range from supply-chain issues and cost considerations to process control and standards development. The following subsections detail the most common hurdles and provide insights into ongoing research and industry efforts aimed at overcoming them.

4.2.1. Material cost and availability

Although HEAs are gaining momentum in aerospace, energy, and other high-demand markets, cost and availability remain significant barriers:

- powdered feedstock: high-quality HEA powders tailored for specific AM processes (e.g. SLM, DED) can be expensive due to complex production routes (e.g., gas atomization) and limited-scale supplies [14];
- economies of scale: the relatively low demand for HEA powders - compared to conventional metals like stainless steel or aluminium - means they are not yet produced in large volumes, which inflates costs further;
- supplier network: a robust supply chain featuring multiple powder producers is needed to drive down prices and standardize quality. Many HVAC manufacturers, however, lack established procurement channels for high-entropy alloy materials [9].

Over time, as AM use cases continue to expand and HEA compositions are optimized for specific applications, economies of scale may reduce costs, enhancing feasibility for the HVAC sector.

4.2.2. Complex process parameters

Additive manufacturing of HEAs requires precise control of multiple process variables - a challenge that intensifies when dealing with highly reactive or multi-component metals:

- laser power and energy density: if power levels are too low, lack of fusion or porosity may result; if too high, spatter or excessive vaporization can occur [10];
- scanning speed and hatch distance: subtle changes in scan strategy can shift the thermal history and microstructural evolution of the alloy;
- build temperature: maintaining a uniform build environment is crucial to minimize thermal gradients that can lead to cracking or distortion.

Failure to optimize these parameters can yield undesirable phases, residual stress, or inconsistent microstructure, thus compromising mechanical strength, ductility, and corrosion resistance.

Modelling tools and in-situ monitoring systems are increasingly used to adjust process settings in real time, improving overall build quality and repeatability [15, 16].

5. Prospective developments and future directions

The integration of high-entropy alloys and additive manufacturing in HVAC applications opens up exciting possibilities for advanced materials and innovative engineering solutions. As research in this area expands, the next phase of developments will likely address design optimization, standardization, cost reduction, smart monitoring, and multi-functional materials. Below are the primary future directions that promise to enhance the viability and performance of 3D-printed HEAs in the HVAC industry.

5.1. Design optimization tools

Recent progress in computational modelling and topology optimization aims to exploit the unique mechanical and thermal properties of HEAs:

- advanced simulation: techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD) allow precise prediction of heat transfer, stress distribution, and flow patterns in material designs [18];
- AI-assisted optimization: machine learning algorithms can rapidly evaluate microstructure – property relationships, suggesting ideal compositions or fabrication parameters for custom HVAC parts [19];
- generative design: tools like Autodesk Generative Design and Siemens NX offer capabilities for lightweighting, lattice structures, and complex geometries, building on HEA mechanical robustness to develop novel part designs with unprecedented performance.

As these software tools gain maturity, they will rapidly accelerate the design – build – test cycles, enabling more efficient and innovative HVAC component solutions.

5.2. Cost reduction and supply chain improvements

Although HEA powders can be expensive, cost reduction and supply chain enhancements will likely expand the commercial viability of HEAs in HVAC:

- economies of scale: increased demand for HEAs in aerospace, energy, and automotive sectors enhances bulk production, leading to lower unit costs [14, 22];
- consolidated supply chains: collaboration between material suppliers, AM system manufacturers, and end-users in HVAC can coordinate R&D and production efforts, ensuring consistent powder availability and quality;
- new alloy development: research into lower-cost HEA ingredients (e.g., partially replacing expensive Co or Ni with abundant elements) can also reduce overall material expense without sacrificing core performance [19].

By addressing material economies, standardization, and logistics, HEAs will become increasingly attractive for HVAC applications requiring durable, high-performance alloys.

5.3. Smart monitoring and digital twins

Integrating Internet of Things (IoT) sensors and digital twin technologies offers real-time insights into component health and operational performance:

- predictive maintenance: sensor networks embedded in 3D-printed HEA parts can continuously monitor stress, temperature, vibration, and corrosion indicators. Advanced data analytics or machine learning can forecast failure modes, ensuring timely maintenance actions;
- digital twins: virtual replicas model physical HVAC systems through continuous data feeds, enabling simulation of how HEA components degrade or react under certain thermal or mechanical loads [23];
- targeted DED repair: based on sensor feedback, directed energy deposition can be initiated only where and when needed, minimizing downtime and extending service life.

These cyber-physical systems are the next level of proactive maintenance, offering cost-saving strategies while further enhancing the reliability of HEA-based HVAC systems.

5.4. Multi-functional materials

As the frontier of materials research expands, combining HEAs with other material systems may yield hybrid structures possessing unusual or next-level performance attributes:

- ceramic or polymer composites: embedding ceramic phases in HEA matrices could augment thermal insulation or wear resistance. Similarly, polymer over moulding might enable noise damping or vibration control in rotating assemblies [24];
- functional gradients: by additively blending multiple feedstock materials (e.g., metal-ceramic transitions), components can be graded to tailor thermal conductivity, stiffness, or coefficient of thermal expansion [25];
- surface coatings: functionally graded or co-deposited coatings may offer improved surface hardness, chemical barrier properties, or anti-fouling characteristics particularly beneficial in humid or chemically volatile HVAC conditions.

Such multi-functional combinations promise to deliver thermal, acoustic, and mechanical enhancements far beyond those of current single-alloy approaches, broadening the potential for HEAs in extreme or specialized HVAC environments.

6. Conclusions

3D-printed high-entropy alloys (HEAs) are rapidly emerging as a key enabling technology for the next generation of HVAC systems. By combining the intrinsic advantages of HEAs - such as superior corrosion resistance, thermal fatigue strength, and mechanical robustness - with the unprecedented design freedom of additive manufacturing (AM), engineers can produce highly optimized heat exchangers, fan blades, and airflow conduits that meet stringent energy efficiency and durability requirements [9, 14]. In addition, directed energy deposition (DED) offers cost-effective repair strategies, reducing material waste and maintenance downtime while extending the operational life of critical HVAC components [9].

However, realizing the full potential of 3D-printed HEAs in HVAC applications entails addressing several challenges. These include high powder costs driven by limited commercial production, complex process parameters requiring precise control, and the need for improved standardization to ensure consistent quality and regulatory acceptance [14, 21]. As the field progresses, collaborative efforts among material suppliers, research institutions, HVAC manufacturers, and standards organizations will be essential to drive down costs, streamline process control, and develop standardized testing and certification protocols [20, 21].

Looking to the future, sustained research and targeted investments are expected to accelerate advancements in computational modelling, topology optimization, powder production scalability, and real-time process monitoring. These developments will further enhance the mechanical, thermal, and economic viability of HEAs and spur broader adoption of AM-enabled solutions in high-demand HVAC environments. Ultimately, 3D-printed HEAs have the potential to revolutionize how HVAC systems are designed, manufactured, and maintained, ushering in an era of greater energy efficiency, longer service life, and reduced lifecycle costs for critical building infrastructure.

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