
| RESEARCH ARTICLE

Additive Manufacturing of Lightweight, Fire-Resistant Alloys for Automotive and Aerospace Applications

Md Arman Hossain¹, Shipon Chandra Barman² and S M Tarikul Islam³

¹ Mechanical Engineering, University of New Haven, West Haven, Connecticut, United States

² Industrial Engineering, University of New Haven, West Haven, Connecticut, United States

³ School of Aeronautic Science and Engineering, Beihang University, Beijing, 100191, China

Corresponding Author: Md Arman Hossain, **E-mail:** mhoss15@unh.newhaven.edu

| ABSTRACT

The current review has critically discussed the industrial preparedness of additive manufacturing (AM) in lightweight, fire-resistant alloys, and it is found that its so-called transformative potential is oversold in recent literature. Empirical research has pointed out continuous mechanical unreliability, anisotropy, and defect fragility, which have compromised operational reliability in aerospace and automotive systems. Long-term performance has also been limited by thermal instability, phase heterogeneity, and narrow process windows, and scalability is limited by the fact that post-processing is extensively dependent. Successes in methods like selective laser melting (SLM), electron beam melting (EBM), and directed energy deposition at the laboratory scale have scarcely been translated into reproducible industrial results and residual stresses, irregular microstructures, and quality assurance gaps remain. Alloy progression techniques such as alloy modification and coating on surfaces have not been fully tested to be accepted by regulations as fire resistant, indicating how difficult it has been to balance the mechanical, thermal and safety needs. Regulatory, certification and standardisation have also been found to hinder adoption of the industry, as well as high energy consumption and lifecycle inefficiencies. To mitigate these shortcomings, studies have laid more and more stress on scalable process optimisation, enhanced in-situ monitoring, predictive modelling and stringent life-cycle testing in real conditions. The cooperation of the manufacturers and regulators with the certification bodies has been confirmed to be critical towards creating standard qualification routes. Altogether, AM has shown conditional capability to form lightweight, fire-resistant alloy, but has not yet been able to become industrialised and thus is limited to niche or experimental use instead of providing the radicalising effect that is often advertised.

| KEYWORDS

Additive manufacturing, lightweight alloys, fire-resistant alloys, aerospace, automotive, mechanical reliability, thermal stability, process reproducibility, certification, industrial adoption

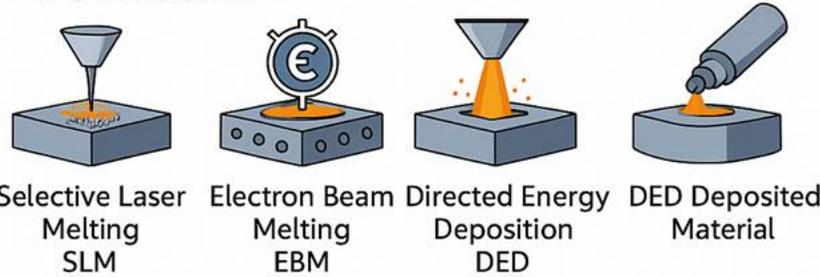
| ARTICLE INFORMATION

ACCEPTED: 01 March 2026

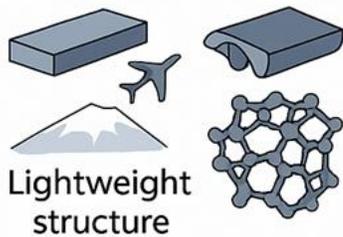
PUBLISHED: 09 March 2026

DOI: 10.32996/jmci.2026.7.3.2

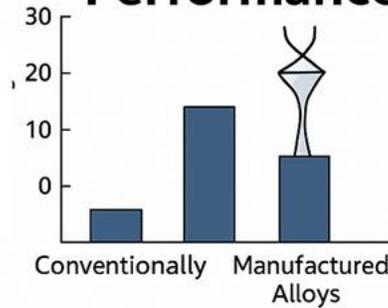
Processes



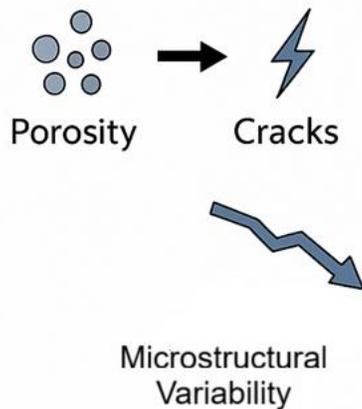
Materials



Performance



Common defects



Challenges

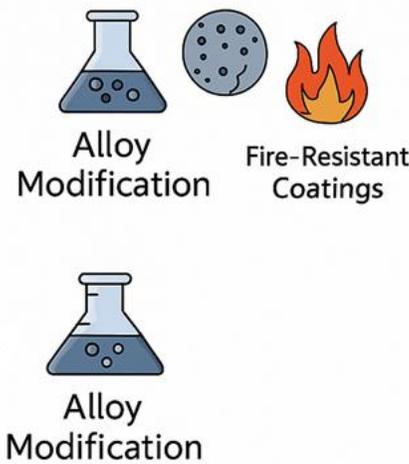


Figure 1. Graphical Abstract

1. Introduction

Despite the fact that additive manufacturing (AM) is continuously presented as disruptive technology in the automotive, aerospace, and high-technology engineering world, recent publications have shown that most of them are hyperbolic, conflicting, or not sufficiently supported by evidence. Although AM is often framed as a disruptive alternative to subtractive and formative processes [1], [2]. Much of the research remains a regurgitation of optimistic stories without paying due attention to the systemic technical and operational limitations hampering industrial adoption. As an example, even though the capacity of AM to produce complex geometries and minimise waste has been well documented, empirical evidence continues to demonstrate irregular mechanical behaviour, unrealised anisotropy and significant post-processing needs that cancel most of its claimed efficiencies [3]; [4]. These inconsistencies point to a worrying disconnect between the theoretical capabilities AM had and its actual capabilities regarding large-scale, safety-critical production.

In addition, the development of AM is commonly depicted as one that follows a linear evolution and is inevitable; however, historical and technological studies show disproportionate development. Although initial reviews cite quick diversification of AM techniques from fused deposition modelling to powder bed fusion to directed energy deposition, most of the industrial applications still stay in prototyping, tooling, or low-volume parts [1]. Arguments of mature manufacturing power are thus premature when the literature also admits high defects, stress retention and dissimilarity in the build of the microstructure in metal and alloy prints, especially within the aerospace qualification criteria [5]. Equally, even though AM can boast of the lightweight production of structures. According to Ramos et al. (2025), design optimisation and microarchitectural patterning are still considered in a highly experimental stage, and not much evidence is provided to prove their long durability under operational loads [2].

The drawbacks of the existing AM technologies become even more apparent in aerospace and automotive engineering, in which structural reliability, thermal stability, and fire resistance are a must. According to Georgantzinis et al. (2025), the much-hyped in-space manufacturing is still limited by defects due to microgravity, unstable printing, and limited material variety [3]. Meanwhile, Alami et al. (2023) suggest that AM has often been overstated according to environmental and sustainability advantages, as life-cycle assessments always show that there is a significant amount of energy consumption in the production of powders, the work of lasers, and their subsequent processing [4]. Such discrepancies defy the common understanding of AM as a necessarily more environmentally friendly option and the necessity to have more rational evaluations.

In the case of AM, which is most actively advertised, like aerospace, it is prevented by strict qualification, certification, and quality control standards. Industry standards, as they were set up, are hardly met by AM parts unless much rework is done, which poses a technical maturity gap that most review articles fail to acknowledge [5]. Although new alloys, reinforced composite and hybrid materials have spread, there is little agreement on printability, long-term performance or fire-resistant behaviour under actual service conditions. Taken together, the literature indicates that although AM is growing in scope and ambition, its industrial acceptability is now less of theoretical potential and more of addressing long-standing deficiencies in the material consistency, process control, defect mitigation and certification preparedness. Instead of strengthening the optimistic narrative that much of the AM discourse upholds, a more critical analysis is required, one which anticipates unresolved issues, questions the overreach of the capabilities of AM, and rethinks its actual role in high-performance manufacturing in the automotive and aerospace sectors. This review takes a critical approach towards claiming progress in AM in the field of lightweight and fire-resistant alloy work and evaluates whether the existing technologies are truly up to the challenge of the next-generation engineering system.

2. Literature Review

2.1 Additive Manufacturing Technologies for Metallic Alloys

Despite the fact that the additive manufacturing (AM) of metallic alloys is commonly discussed as a breakthrough technology, recent literature suggests a more troubled and volatile situation. Anang et al. (2024) state that manipulation of parameters in processes like SLM and EBM makes predictable microstructural tuning, but their review provides little evidence that these correlations can be replicated across machines, alloys, and environments [6].

Volumetric Energy Density:

$$E_v = \frac{P}{v \cdot h \cdot t} \quad \text{(equation 1)}$$

Where:

P = laser power

v = scan speed

h = hatch spacing

t = layer thickness

This controllability assumption seems to be excessively high, particularly when the melt pools are unstable, and the sensitivity of defects in experiments is a highly sensitive matter that is widely recognised in empirical literature. The assertions of excellent mechanical ability in AM alloys are also disputed by the corrosion-based studies like Verma et al. (2024/2025). They found that AM alloys of SS316L, Inconel 718, and AlSi10Mg often contain higher surface roughness, microgalvanic coupling, and residual stresses, which contribute to higher levels of corrosion [7]. These weaknesses are a direct contradiction of the story of the consistently improved performance and point to the fact that AM is inclined to exchange mechanical improvements with chemical weaknesses.

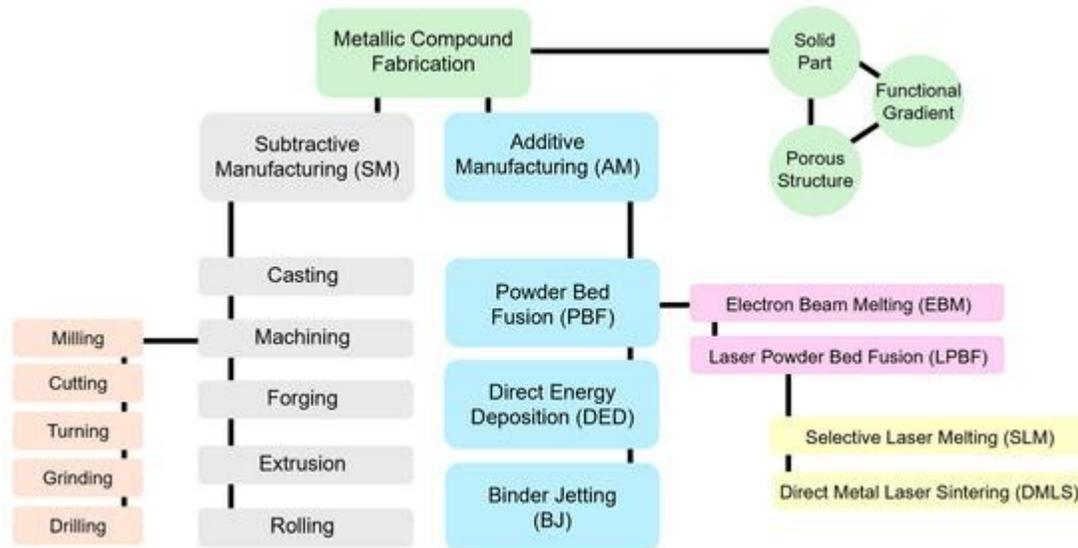


Figure 2. Schematic of metallic component fabrication routes, contrasting conventional subtractive manufacturing and additive manufacturing [8]

Kenzari et al. (2014) provide a history that supports the fact that the diversification of materials is a slow process. Although progress has been made over the last ten years, they found that alloy availability was limited by problems they saw with binder reliance and lack of microstructural reliability, especially with novel alloys like quasicrystalline Al alloys. This implies that the material flexibility of AM is much more limited than it is normally alleged [9]. More modern efforts to honour AM-enabled heterogeneous microstructures, including those discussed by Chen et al. (2024), are based on demonstrations of HDI hardening and the gradient microstructure effect on a laboratory scale. However, these have not been demonstrated on an industrial level in any large scale yet, and certification, reproducibility, and affordability are the major factors there [10]. On the same note, Su et al. (2024) endorse AM as the basis of space-based manufacturing, alongside admitting harsh uncertainties in microgravity-based thermal behaviour, radiation interactions and solidification processes [11]. Altogether, the literature introduces a technology that has significant theoretical capabilities yet remains constrained by operational limitations. In all literature, AM is depicted less as a developed manufacturing solution and more as a developing, unstable process, the advantages of which are alloy-specific, situation-dependent and often exaggerated.

2.2 Lightweight Alloys in AM: Aluminium, Titanium, and Magnesium

Lightweight alloys and, in particular, aluminium (Al), titanium (Ti), and magnesium (Mg) are systematically placed among the promising materials for additive manufacturing (AM) in both aerospace and automobile domains. Nonetheless, there exists a consistent discrepancy between laboratory functionality and industrial reliability as per the literature. Aboulkhair et al. (2019) admit that there is a rapid development of selective laser melting (SLM) of aluminium alloys, but the range of alloys that have been worked with reliable fidelity is extremely small. Defects, such as porosity, absence of fusion and microstructural heterogeneity, remain a result of high reflectivity, oxidation sensitivity, and unstable melt pool dynamics, which compromise repeatability and fatigue performance.

porosity-strength reduction rule:

$$\sigma = \sigma_0(1 - \sqrt{P}) \tag{equation 2}$$

where:

σ is the effective (reduced) strength of the porous AM alloy (e.g. yield strength or UTS),
 σ_0 is the strength of the corresponding fully dense (pore-free) alloy,
 P is the **porosity fraction** (0–1), i.e. the volume fraction of pores in the material.

Although the process control has been improved, successful prints are often very narrow parameter parameter-sensitive and system-specific, and also have low scalability. The value proposition of AM alloys is worsened by the fact that it depends on post-processing [12]. Ghio and Cerri (2022) reveal that the mechanical behaviour of most frequently printed alloys, including AlSi10Mg and Ti6Al4V, is highly contingent on the use of complex heating regimens. Although the treatments improve the strength and ductility, they also increase cost, the process time, and variability, which negates the argument that AM offers almost net-shape efficiency. Also, residual stresses and cellular microstructures that result as part of laser powder bed fusion usually worsen corrosion resistance, which supports the argument that AM benefits are realised by secondary intervention as opposed to inherent process stability [13].

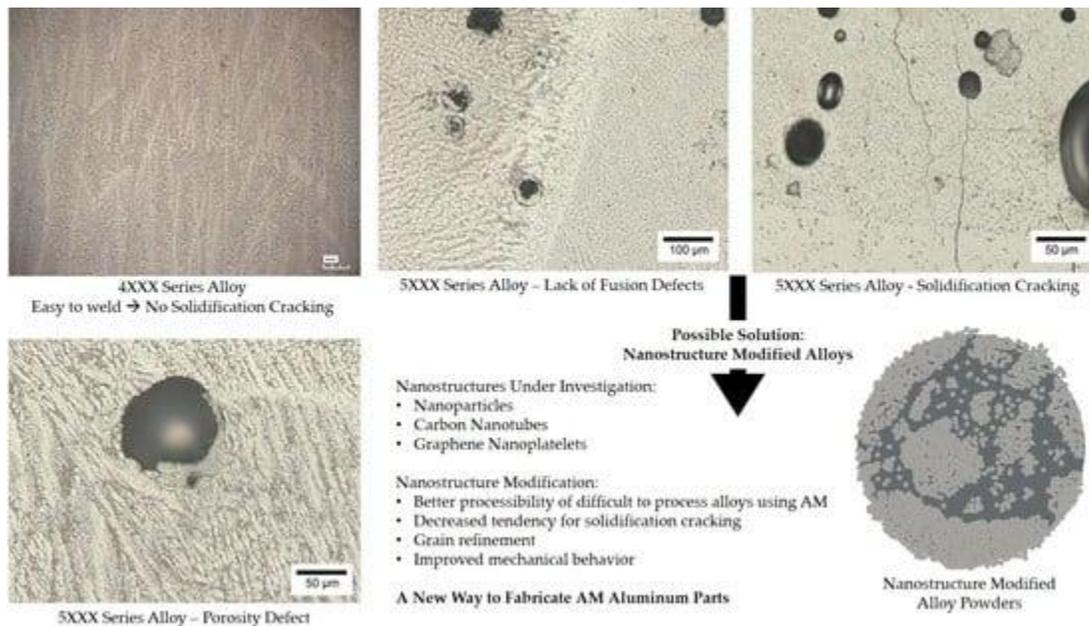


Figure 3. Representative examples of AM aluminium alloy defects [14]

In a broader sustainability context, Blanco et al. (2022) demonstrate that although there are strong policy drivers in terms of lightweight materials in transport decarbonisation strategies, additive manufacturing has only 18 percent of the interest in such manufacturing-related studies than conventional forming and machining processes [15]. This implies that AM is still auxiliary, not transformative, in lightweight alloy manufacturing. Li and Feng (2023) also warn that cost barrier, especially to titanium alloys, remains a limiting factor to their extensive use, although they have great mechanical properties. Lastly, the mechanisms of quality deterioration are not well addressed [16]. Although they deal with casting, Olofsson et al. (2024) emphasise the extent to which discrete entrainment flaws (oxide bifilms) severely diminish ductility and fatigue life and avoid conventional inspection tools. These results have a lot of applicability in AM research, where characterisation of the pore is the leading factor in quality assurance, whereas subsurface cracking initiators are under-investigated [17]. Taken together, the evidence makes AM of lightweight alloys appear technically attractive but industrially weak, whereby adoption has been hindered by defect sensitivity, post-processing sensitivity, lack of quality assurance concerns and cost-efficiency.

2.3 Fire-Resistant Alloys for Aerospace and Automotive Applications

Fire resistance is an absolute need in the materials used in aerospace, automobile applications, but the literature has consistently shown that no extant lightweight alloy system offers a completely satisfactory balance of flame retardancy, mechanical performance, manufacturability and cost efficiency. Although Titanium alloys offer a good strength-to-weight ratio, they are susceptible to high-temperature ignition events termed as titanium fire. It is demonstrated by Liang et al. (2023) that alloy design methods, including Ti-V-Cr or Ti-Cu systems, enhance the burn resistance but have lowered specific strength, complicated processing requirements and unacceptable material prices, which restrict their wide-scale applications. These inadequacies have changed the work on research to surface-level engineering solutions instead of bulk alloy development. But traditional coating processes like laser cladding cause thermal distortion and the creation of defects in thin-walled components, which corrode structural integrity. Even though cold spray deposition is a promising low-temperature alternative, Liang et al. report that coating adhesion durability and long-term oxidation resistance have not been sufficiently confirmed so far on safety-critical components [18].

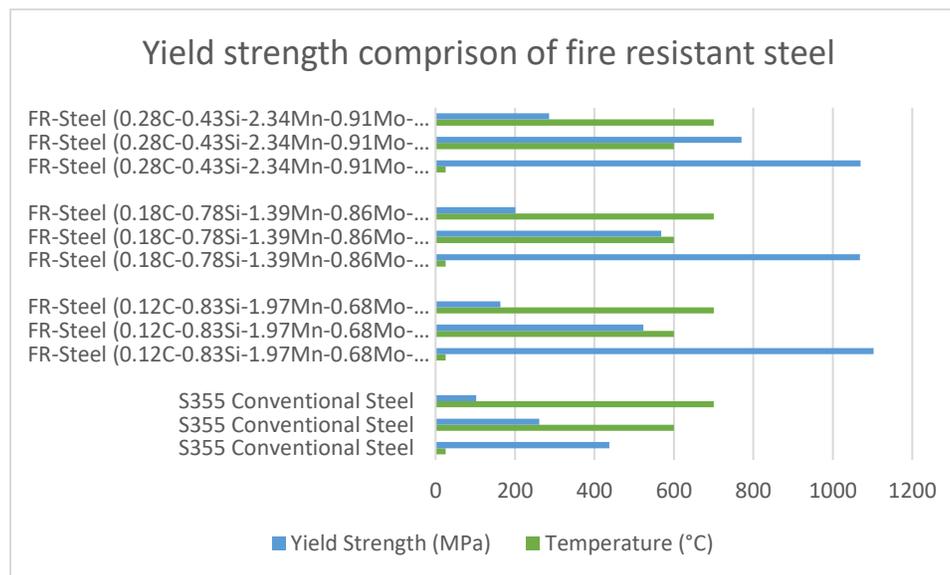


Figure 4. Comparison of yield strength of commercial S355 steel and novel fire-resistant steel compositions at room temperature, 600 °C, and 700 °C (data from [19]).

Even bigger weight reduction is assured to be achieved by magnesium alloys, but with much worse flammability issues. According to Chen et al. (2025), alloying and nanoparticle reinforcements are making progress to increase ignition points and enhance strength; however, low ductility, low corrosion resistance, and low melting points continue to compromise safety margins. Regulatory acceptance is still weak, and aviation acceptance is limited to non-structural interior elements and not primary load-bearing systems [20]. This highlights the fact that material development has not succeeded in addressing the essential incompatibility of the density benefit of magnesium with its exposure to fire. Regarding a systems perspective, Williams and Boyer (2020) highlight that even titanium already in aerospace that is commercially available still commands an outrageous cost to production and processing complications that limit its application to non-high-value components. TiAl compound additive manufacturing is promising, and its current application is a niche, with qualification challenges being significant [21].

Other fire-resistant options are more and more based on polymer-coated or hybrid surfaces [22]. Although the development of halogen-free and bio-based retardants helps to improve environmental performance, there are still apprehensions regarding the performance of the coating in terms of longevity, stability during thermal degradation, and testing standardisation. Carvalho et al. (2025) also mention that sustainable new materials encounter sluggish regulatory routes and unclear lifecycle performance unknowns [23]. In general, literature indicates that fire-resistant alloy initiatives have been technologically disjointed and rely on coated layers, limited application settings, and cost-limited production pathways as opposed to scalable and resilient material interventions.

2.4 Mechanical and Thermal Performance of AM Alloys

Although the metallic additive manufacturing (AM) is rapidly growing in its scope, the mechanical reliability and thermal stability of AM alloys remain among the list of the most resolute impediments to be adopted in a structural form. Daiy et al. (2023) point out that, as much as high cooling rates and steeper thermal gradients can create refined microstructures with high room-temperature strength, thermal conditions that cause microstructural instability, phase inhomogeneity, and residual stresses in materials are the basic factors that undermine performance over time at high temperatures.

Thermal stress buildup in AM:

$$\sigma = E\alpha\Delta T$$

where:

σ is the thermally induced (residual) stress in the AM part,

E is the Young’s modulus of the alloy,

α is the coefficient of thermal expansion,

ΔT is the temperature change between the processing temperature and the reference condition (typically room temperature).

As a result, AM-made alloys often exhibit mechanical degradation in long-term thermal applications, compromising their ability to serve in the aerospace and automotive service applications (where temperatures are often above 200–450 °C) [24]. This concern is backed by the empirical evidence. Moreno et al. (2025) show that Co–Cr–Mo superalloys produced by AM have sharp declines in ultimate tensile strength with a rise in temperature and non-monotonic yield behaviour due to unstable phase changes. The regaining of the ϵ -HCP phase at intermediate temperatures (around 800 o C) with strong ductility loss discloses underlying unpredictability in deformation mechanisms in AM microstructures. Although these alloys have oxidation resistance and corrosion stability, which are desirable in turbine environments, the alloys show metallurgical responses that are sensitive to temperature, and this poses serious qualification challenges to safety-critical deployment [25].

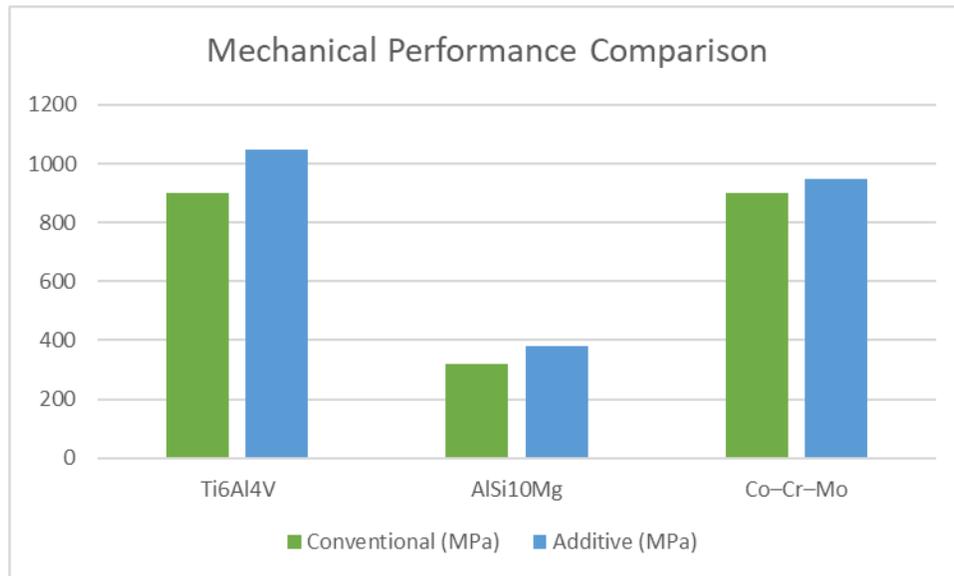


Figure 5. Mechanical performance comparison chart

Table 1. Mechanical and thermal properties of common AM aluminium alloys

Alloy system	Representative composition (wt.%)	AM process	RT yield strength, YS (MPa)	RT UTS (MPa)	RT elongation (%)	High-T test temperature(s) (°C)	YS at high T (MPa)	Reference
Al-Mn-Cr-Zr high-temperature alloy family	Al-Mn-Cr-Zr based (three variants; Mn ≈ 4.7–5.0, Cr ≈ 0.8–0.9, Zr ≈ 0.6–1.2, small Mg/Fe/Si)	PBF-LB (laser powder bed fusion)	250–500	≈ 550	5–25	Up to 573 K (~300 °C)	up to ≈170 at 573 K	[26]
Al-Ce-Mg near-eutectic AM alloy	Al-11Ce-7Mg (near-eutectic w.r.t. L→Al+Al ₁₁ Ce ₃)	LPBF (laser powder bed fusion)	not fully specified (reported higher than AM Al-10Si-Mg)	not fully specified	not specified	Up to 350 °C	not explicitly tabulated; reported higher YS than AM Al-10Si-Mg up to 350 °C	[27]
Al-Ce-Mg hypereutectic AM alloy	Al-15Ce-9Mg (hypereutectic w.r.t. L→Al+Al ₁₁ Ce ₃)	LPBF (laser powder bed fusion)	not fully specified (RT strength above AM Al-10Si-Mg)	not fully specified	not specified	Up to 350 °C	not explicitly tabulated; good high-T strength retention above 200–350 °C	[27]
Micro-alloyed 2219 Al-Cu (MA2219, Sc/Zr/Ti/Er-modified)	2219 Al-Cu with minor Sc, Zr, Ti, Er + trace Mg/Zn/Mn, etc.	Wire-arc DED	RT YS not numerically specified in excerpt (reported superior to wrought micro-alloyed 2219 after HT6)	RT UTS not numerically specified (reported “promising combination of strength and ductility”)	not specified	250–350 °C (thermal-exposure tests)	not explicitly tabulated; hardness/strength shown to be stable under exposure at 250–350 °C	[28]

The process of trying to fix performance shortages via the development of aluminium alloys depicts more drawbacks. According to Sisco et al. (2021), near-eutectic AM aluminium systems (e.g., Al-Si-Mg) are easy to process, although with low retention of strength at high temperatures, and recently designed Al-Ce-Mg alloys have higher yield strength at temperatures up to 350 on the cost of increased processing sensitivity and reduced scalability [29]. Michi et al. (2021) find that there is much microstructural characterisation and a severe absence of high-temperature fatigue, creep, corrosion, and lifecycle performance data metrics needed to engineer-validated [30]. Adding to these inherent material problems, Govindarajan et al. (2025) single out thermal distortion, residual stress volume, defect formation, and the lack of solutions to manufacturability challenges as a direct and indirect threat to mechanical durability. Modelling, in-situ monitoring and process optimisation are more advanced, but their conversion to regular, error-free and thermally stable production has not been achieved yet [31]. Taken together, the evidence shows that although AM alloys have competitive short-term mechanical performance, they are not thermally stable, their phase evolution is highly unpredictable, and they are still susceptible to defects, preventing them from being used in high-temperature structures on a mass basis but as a niche or non-critical material instead.

3. Analysis

The literature review has shown that there is a great gap between the theoretical potential of additive manufacturing (AM) and its proven industrial capability in lightweight and fire-resistant alloy usage in the automotive and aerospace sectors. Although AM has been repeatedly stated to be a revolutionary substitute for traditional manufacturing [32]; [33]; [34] suggests that these statements are often exaggerated or undermassively proved. In a variety of studies, the mechanical unpredictability, the unresolved anisotropy, and reliance on massive post-processing are recurrently cited as the ongoing limitations, compromising

the alleged efficiency and reliability of AM processes [35]; [36]. This implies that AM is a strong player in the manufacture of complex geometries, although its operational capability is very inconsistent, particularly in components of critical safety.

One of the patterns is the underdevelopment of AM technologies. SLM, EBM, and directed energy deposition are among the techniques that appear to be promising under controlled laboratory conditions, but at the industrial scale, consistent reproducibility is still lacking [37]. Possible high defect rates, stress retention, and non-homogeneous microstructures, especially when it comes to metal and alloy prints, do not bode well with the idea that AM is already at the stage of maturity to be adopted at a large scale [5]. Microarchitectural patterning, even with sophisticated design optimisation, is still an extremely experimental concept yet to be validated over operational loads, even in the long term [2]. As a result, the positive outlook on AM as an almost ready-to-use industrial technology seems premature.

AM is also limited in its applicability to the industry by material-specific challenges. Light alloys such as aluminium, titanium and magnesium have high susceptibility to defects, post-processing and lack of consistency in mechanical as well as corrosion behaviour [11]; [12]. On the same note, fire-resistant alloy plans, particularly titanium and magnesium, are still fragmented. Enhancements in alloy designs tend to negatively affect either strength or ease of manufacture, and methods based on coating solutions have not completely solved the issue of durability and bonding [16]; [17]. This points out that after specific research work, AM has not been able to come up with alloys that can suitably fit the mechanical, thermal, and fire-resistance behaviour in aerospace or automobile applications.

One more theme is the industrial legitimacy and standardisation. The fact that it is used by many individuals is not only obstructed by inherent material and process constraints but also by regulatory and certification barriers. The gap between the AM laboratory promise and its contribution in the industry practice is enhanced by high power use, large post-processing, and low consensus on the long-term performance [4]; [5]. It is always pointed out in the current literature that until issues related to the control of the process, mitigation of defects, and certification preparedness are addressed, AM is, as of now, not a fully reliable manufacturing solution to high-performance structural components.

4. Discussion

A review of additive manufacturing (AM) of lightweight, fire-resistant alloys indicates that there is an ongoing gap between theory and practice. Whereas AM is often placed as a disruptive technology that can revolutionise the aerospace and automotive production, the data indicate that its implementation is limited by the basic technological, material and regulatory issues. Repeatedly mentioned in the literature, mechanical unpredictability, anisotropy, and dependence on extensive post-processing, these aspects prove that operational reliability is an impeding factor. All these findings point to the fact that the main strengths of AM complex geometry production and design flexibility are yet to be converted into the regular industrial performance, especially in the case of safety-related components [3]; [4].

One of the major conclusions made during the review is that AM technologies are relatively immature. Although demonstrations of processes like SLM, EBM, and directed energy deposition have been shown at laboratory scale, demonstrations at industrial scale have not been demonstrated to be reproducible [6]; [9]. The premise that AM can be an easy replacement for classic production methods is confronted by high defect rates, stress retention, and microstructure variation. Additionally, the experimental achievements in design optimisation and microarchitectural patterning have not been successfully tested in the operational field, implying that the credibility of the technology in industry is being overrated in the existing literature [2].

Material-specific limitations are also mentioned in the discussion. The lightweight alloys aluminium, titanium and magnesium have long-term defect sensitivity problems, post-processing reliance and inconsistent mechanical and corrosion performance [11]; [12]. The use of fire-resistant alloys and, more so, titanium and magnesium-based alloys also depicts the trade-offs involved in current AM approaches. It is possible to enhance fire resistance by alloy modifications and surface coatings; however, they tend to reduce manufacturability, strength or long-term functionality, and their effectiveness has not been well verified to industrial certification [16]; [17]. This highlights the fact that AM has not produced materials that meet at the same time the rigid structural, thermal and fire-resistance specifications of aerospace and the automotive application. Such technical difficulties are augmented by industrial and regulatory barriers. AM parts are also not scalable because certification, the qualification criteria and quality control requirements are still tough. The large amount of energy used in manufacturing, large post-processing, and the absence of an agreed-upon long-term performance lead to further decreased practical feasibility of AM [4]; [5]. All of these combine to indicate that the present role of AM in the automotive and aerospace manufacturing is not transformative.

5. Conclusion

As evidenced by this review, additive manufacturing (AM) of lightweight alloys capable of being fire-resistant is a technology of conditional potential, not a fully developed industrial solution. Despite the hypothetical benefits of AM that include complex geometries and reduction of weight and possibly better fire-resistance, its practical implementation is limited by the continued technical, material, and regulatory constraints. Mechanical unreliability, anisotropy, and sensitivity of defects destroy operational reliability, especially in aerospace and automotive usage, and thermal instability and phase heterogeneity limit long-term operation in sustained service environments, limiting large-scale usage. A gap that is critical gap is the industrial reproducibility. Scale: SLM, EBM, and directed energy deposition have failed to consistently produce results at the laboratory level, with residual stress still, high defect rates, and inconsistent microstructures all to be overcome. The limitations are additionally complicated by material-specific issues: the processing windows of aluminium, titanium, and magnesium alloys are narrow, they are highly dependent on the post-processing, and their corrosion or fire resistance is poor, and coating-based and alloy-based fire mitigation methods have not been adequately proven to be regulatory-acceptable.

Future studies can therefore be focused on those gaps and should focus on scalable, repeatable process optimisation, comprehensive in-situ monitoring, and predictive modelling to minimise defects and stabilise microstructures. The alloys to develop materials with should be based on alloys that inherently trade between mechanical, thermal and fire-resistant properties, backed by stringent life-cycle testing under realistic operational conditions. Besides, the cooperation of manufacturers, regulatory bodies, and certification agencies is needed to form standardised qualification routes, allowing for meeting the aerospace and automotive standards. To sum up, although AM has a significant potential in lightweight and fire-resistant alloys production, technical, material, and regulatory issues that remain unresolved make it currently applicable only in niche or experimental applications, which inhibits its transformative power in industrial practice.

References

- [1] L. Zhou *et al.*, 'Additive Manufacturing: A Comprehensive Review', *Sensors*, vol. 24, no. 9, p. 2668, Apr. 2024, doi: 10.3390/s24092668.
- [2] A. Ramos, V. G. Angel, M. Siqueiros, T. Sahagun, L. Gonzalez, and R. Ballesteros, 'Reviewing Additive Manufacturing Techniques: Material Trends and Weight Optimization Possibilities Through Innovative Printing Patterns', *Materials*, vol. 18, no. 6, p. 1377, Mar. 2025, doi: 10.3390/ma18061377.
- [3] S. K. Georgantzinis *et al.*, 'A Comprehensive Review of Additive Manufacturing for Space Applications: Materials, Advances, Challenges, and Future Directions', *Adv. Eng. Mater.*, vol. 27, no. 22, p. e202501082, Nov. 2025, doi: 10.1002/adem.202501082.
- [4] A. H. Alami *et al.*, 'Additive manufacturing in the aerospace and automotive industries: Recent trends and role in achieving sustainable development goals', *Ain Shams Eng. J.*, vol. 14, no. 11, p. 102516, Nov. 2023, doi: 10.1016/j.asej.2023.102516.
- [5] R. C. R. Shanmugam, M. Ramoni, and G. Bk, 'A review on additive manufacturing for aerospace application', *Mater. Res. Express*, vol. 11, no. 2, p. 022001, Feb. 2024, doi: 10.1088/2053-1591/ad21ad.
- [6] A. N. Anang, B. Alade, and R. Olabi, 'Additive Manufacturing of Metal Alloys: Exploring Microstructural Evolution and Mechanical Properties', *Int. J. Res. Publ. Rev.*, vol. 5, no. 10, pp. 2373–2388, Oct. 2024, doi: 10.55248/gengpi.5.1024.2827.
- [7] C. Verma, A. Alameri, I. Barsoum, and A. Alfantazi, 'Review on corrosion-related aspects of metallic alloys additive manufactured with laser powder bed-fusion (LPBF) technology', *Prog. Addit. Manuf.*, vol. 10, no. 5, pp. 3195–3223, May 2025, doi: 10.1007/s40964-024-00810-x.
- [8] R. Rahmani, B. Bashiri, S. I. Lopes, A. Hussain, H. S. Maurya, and R. Vilu, 'Sustainable Additive Manufacturing: An Overview on Life Cycle Impacts and Cost Efficiency of Laser Powder Bed Fusion', *J. Manuf. Mater. Process.*, vol. 9, no. 1, p. 18, Jan. 2025, doi: 10.3390/jmmp9010018.
- [9] S. Kenzari, D. Bonina, J. Marie Dubois, and V. Fournée, 'Complex metallic alloys as new materials for additive manufacturing', *Sci. Technol. Adv. Mater.*, vol. 15, no. 2, p. 024802, Apr. 2014, doi: 10.1088/1468-6996/15/2/024802.
- [10] H. Chen, Y. He, S. S. Dash, and Y. Zou, 'Additive manufacturing of metals and alloys to achieve heterogeneous microstructures for exceptional mechanical properties', *Mater. Res. Lett.*, vol. 12, no. 3, pp. 149–171, Mar. 2024, doi: 10.1080/21663831.2024.2305261.
- [11] X. Su, P. Zhang, and Y. Huang, 'Research Progress of Metal Additive Manufacturing Technology and Application in Space: A Review', *Metals*, vol. 14, no. 12, p. 1373, Dec. 2024, doi: 10.3390/met14121373.
- [12] N. T. Aboulkhair, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, and R. Hague, '3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting', *Prog. Mater. Sci.*, vol. 106, p. 100578, Dec. 2019, doi: 10.1016/j.pmatsci.2019.100578.
- [13] E. Ghio and E. Cerri, 'Additive Manufacturing of AlSi10Mg and Ti6Al4V Lightweight Alloys via Laser Powder Bed Fusion: A Review of Heat Treatments Effects', *Materials*, vol. 15, no. 6, p. 2047, Mar. 2022, doi: 10.3390/ma15062047.
- [14] R. Boillat, S. P. Isanaka, and F. Liou, 'The Effect of Nanostructures in Aluminum Alloys Processed Using Additive Manufacturing on Microstructural Evolution and Mechanical Performance Behavior', *Crystals*, vol. 11, no. 5, p. 524, May 2021, doi: 10.3390/cryst11050524.
- [15] D. Blanco, E. M. Rubio, R. M. Lorente-Pedreille, and M. A. Sáenz-Nuño, 'Sustainable Processes in Aluminium, Magnesium, and Titanium Alloys Applied to the Transport Sector: A Review', *Metals*, vol. 12, no. 1, p. 9, Dec. 2021, doi: 10.3390/met12010009.
- [16] C. Li and Q. Feng, 'Light Alloys and Their Applications', *Metals*, vol. 13, no. 3, p. 561, Mar. 2023, doi: 10.3390/met13030561.
- [17] J. Olofsson, T. Bogdanoff, and M. Tiryakioğlu, 'On the Competition between Pores and Hidden Entrainment Damage during In Situ Tensile Testing of Cast Aluminum Alloy Components', *Metals*, vol. 14, no. 10, p. 1175, Oct. 2024, doi: 10.3390/met14101175.
- [18] S. Liang, J. Tang, Y. Wang, T. Duan, B. Normand, and T. Chen, 'Perspectives on Developing Burn Resistant Titanium Based Coatings—An Opportunity for Cold Spraying', *Materials*, vol. 16, no. 19, p. 6495, Sept. 2023, doi: 10.3390/ma16196495.

- [19] A. Zargarani *et al.*, 'Integrated Computational Materials Engineering of Fire-Resistant Steels', *Mater. Des.*, vol. 251, p. 113721, Mar. 2025, doi: 10.1016/j.matdes.2025.113721.
- [20] X.-W. Chen *et al.*, 'The development of high-strength flame-retardant magnesium alloys', *J. Mater. Res. Technol.*, vol. 36, pp. 5797–5823, May 2025, doi: 10.1016/j.jmrt.2025.04.076.
- [21] J. C. Williams and R. R. Boyer, 'Opportunities and Issues in the Application of Titanium Alloys for Aerospace Components', *Metals*, vol. 10, no. 6, p. 705, May 2020, doi: 10.3390/met10060705.
- [22] R. Patel, M. L. Chaudhary, Y. N. Patel, K. Chaudhari, and R. K. Gupta, 'Fire-Resistant Coatings: Advances in Flame-Retardant Technologies, Sustainable Approaches, and Industrial Implementation', *Polymers*, vol. 17, no. 13, p. 1814, June 2025, doi: 10.3390/polym17131814.
- [23] P. Carvalho, J. Aguiar-Branco, and R. M. Guedes, 'Emerging Materials for Durable and Sustainable Design of Aeronautic Structures', *Materials*, vol. 18, no. 21, p. 4922, Oct. 2025, doi: 10.3390/ma18214922.
- [24] H. Daiy, Y. Najafi, Z. D. Ragheb, and H. R. Abedi, 'A review study on thermal stability of powder-based additively manufactured alloys', *J. Alloys Compd.*, vol. 965, p. 171384, Nov. 2023, doi: 10.1016/j.jallcom.2023.171384.
- [25] D. Moreno *et al.*, 'High Temperature Mechanical Properties of Additive Manufacturing CoCr F75 Alloy', *J. Miner. Mater. Charact. Eng.*, vol. 13, no. 02, pp. 31–43, 2025, doi: 10.4236/jmmce.2025.132003.
- [26] B. Mehta *et al.*, 'Mechanical properties and microstructural characterisation including high-temperature performance of Al-Mn-Cr-Zr-based alloys tailored for additive manufacturing', *Mater. Des.*, vol. 244, p. 113160, Aug. 2024, doi: 10.1016/j.matdes.2024.113160.
- [27] K. Sisco *et al.*, 'Microstructure and properties of additively manufactured Al-Ce-Mg alloys', *Sci. Rep.*, vol. 11, no. 1, p. 6953, Mar. 2021, doi: 10.1038/s41598-021-86370-4.
- [28] Y. Zhou, T. Chang, X. Fang, R. Chen, Y. Li, and K. Huang, 'Tailoring the mechanical properties and thermal stability of additive manufactured micro-alloyed Al-Cu alloy via multi-stage heat treatment', *Mater. Des.*, vol. 233, p. 112287, Sept. 2023, doi: 10.1016/j.matdes.2023.112287.
- [29] K. Sisco *et al.*, 'Microstructure and properties of additively manufactured Al-Ce-Mg alloys', *Sci. Rep.*, vol. 11, no. 1, p. 6953, Mar. 2021, doi: 10.1038/s41598-021-86370-4.
- [30] R. A. Michi, A. Plotkowski, A. Shyam, R. R. Dehoff, and S. S. Babu, 'Towards high-temperature applications of aluminium alloys enabled by additive manufacturing', *Int. Mater. Rev.*, vol. 67, no. 3, pp. 298–345, Apr. 2022, doi: 10.1080/09506608.2021.1951580.
- [31] G. Boopathy, V. Srinivasan, A. Krasnikovs, and B. Ganesan, 'Thermal and Mechanical Analysis of Materials in Additive Manufacturing'; in *Modeling, Analysis, and Control of 3D Printing Processes*, R. Ben Khalifa, Ed., IGI Global, 2025, pp. 193–236. doi: 10.4018/979-8-3373-0533-2.ch008.
- [32] S. Jung, L. B. Kara, Z. Nie, T. W. Simpson, and K. S. Whitefoot, 'Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production?', *Environ. Sci. Technol.*, vol. 57, no. 16, pp. 6373–6386, Apr. 2023, doi: 10.1021/acs.est.2c04927.
- [33] O. J. Oladunni, C. K. M. Lee, I. D. Ibrahim, and O. A. Olanrewaju, 'Advances in sustainable additive manufacturing: a systematic review for construction industry to mitigate greenhouse gas emissions', *Front. Built Environ.*, vol. 11, p. 1535626, Mar. 2025, doi: 10.3389/fbuil.2025.1535626.
- [34] L. Ben Said, B. Ayadi, S. Alharbi, and F. Dammak, 'Recent Advances in Additive Manufacturing: A Review of Current Developments and Future Directions', *Machines*, vol. 13, no. 9, p. 813, Sept. 2025, doi: 10.3390/machines13090813.
- [35] T. C. Dzogbewu and D. J. De Beer, 'Additive manufacturing of NiTi shape memory alloy and its industrial applications', *Heliyon*, vol. 10, no. 1, p. e23369, Jan. 2024, doi: 10.1016/j.heliyon.2023.e23369.
- [36] M. Maroszek, I. Hager, K. Mróz, M. Sitarz, and M. Hebda, 'Anisotropy of Mechanical Properties of 3D-Printed Materials—Influence of Application Time of Subsequent Layers', *Materials*, vol. 18, no. 16, p. 3845, Aug. 2025, doi: 10.3390/ma18163845.
- [37] M. Soori and B. Arezoo, 'Smart materials and alloys for additive manufacturing integration: A review', *Addit. Manuf. Front.*, vol. 4, no. 4, p. 200242, Dec. 2025, doi: 10.1016/j.amf.2025.200242.