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Progress and Prospects of 3D-Printed Steel Structures

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Abstract. Additive Manufacturing (AM), also known as 3D printing, is gradually being adopted in the field of construction engineering due to its advantages of high customization, rapid prototyping, and environmental sustainability. Steel, with its high strength, good toughness, excellent workability, and cost-effectiveness, is a critical material for modern structural engineering. The integration of AM technology with steel offers enormous potential for future construction applications. AM processes—particularly Laser Powder Bed Fusion (LPBF) and Wire Arc Additive Manufacturing (WAAM)—can produce unique microstructural features such as hierarchical (sub)grains, fine precipitates, and nanoscale inclusions, which significantly affect the material's mechanical, corrosion, and wear properties . This paper first reviews commonly used metal additive manufacturing technologies and their current applications; second, it systematically summarizes key research findings on additively manufactured structural steels for construction; and finally, it offers a perspective on the technology itself, the performance of 3D-printed steels, and the importance and prospects of this approach.

Keywords: Metal Additive Manufacturing, 3D-Printed Steel, Mechanical Properties, Wire Arc Additive Manufacturing (WAAM), Hybrid Structures

1. Introduction

Steel, with its high strength, good toughness, ease of fabrication, and cost-effectiveness, has become an indispensable engineering material in modern industry. Its properties can be further optimized to meet specific engineering requirements through careful control of alloy composition, manufacturing processes, and heat treatments. However, traditional manufacturing methods for structural steel components—such as casting and forging—face numerous challenges. These include the tendency to form internal defects such as porosity and shrinkage cavities, as well as rough surfaces that often require subsequent finishing; difficulties in producing complex geometries with high mold costs; low material utilization and significant waste; reliance on large-scale equipment and molds leading to persistently high costs; high energy consumption and low efficiency in processing; and limited ability to meet increasingly complex architectural design demands.

Additive Manufacturing (AM) technology, which builds complex geometries layer by layer directly from material feedstock, offers a new approach to overcoming these limitations. By the end of 2020, the market value of AM had reached $21 billion, attracting widespread attention from both academia and industry. The concept of forming metal powder with a high-energy beam (e.g., laser)

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was first proposed in 1973 by Pierre Ciraud. Laser Powder Bed Fusion (LPBF) technology originated from a research project at the Fraunhofer Institute for Laser Technology in 1996. Over more than three decades of development, AM has achieved significant advances in processing innovations and in understanding the "process–microstructure–property" relationships. A deep understanding of microstructural evolution during AM will enable systematic optimization of process parameters, ultimately leading to superior component performance. The intense thermal cycling inherent to AM (characterized by high temperature gradients and rapid cooling rates) results in the formation of non-equilibrium microstructures, such as extremely fine cellular structures, elemental segregation, unique grain morphologies (including columnar grains and epitaxial growth), and high dislocation densities—all of which have decisive effects on the properties of AM-produced steels.

This paper aims to systematically explore the progress and future directions of additive manufacturing technology for structural steel applications in the construction sector.

2. Metal additive manufacturing technologies

Metal additive manufacturing technologies are primarily classified based on the form of raw materials (powder or wire) and the type of energy input (laser, electron beam, etc.). This section provides an overview of mainstream metal AM technologies with application potential in the construction industry.

2.1. Powder-based additive manufacturing technologies

2.1.1. Powder Bed Fusion (PBF) technology

Powder Bed Fusion [1]is one of the most widely used metal additive manufacturing technologies. Its process principle involves spreading a thin layer of metal powder in the build chamber and selectively melting powder particles using a laser beam or electron beam to form a single cross-sectional layer. A new powder layer is then spread, and the melting process is repeated layer by layer to build a three-dimensional solid component. PBF offers several advantages: no need for additional support structures (the unfused powder acts as support), high material utilization (unfused powder can be recycled), and the capability for multi-material printing. However, the technology also has limitations, such as relatively low production efficiency and potential anisotropy in the mechanical properties of printed components. The rapid solidification in the PBF process (especially in LPBF, with cooling rates up to 10^3–10^8 K/s) is key to forming fine microstructures, such as submicron-scale cellular structures.

Mainstream metal PBF technologies include:

Selective Laser Melting (SLM): Invented in Germany in 2002, this technology has expanded to process a wide range of metals (such as tungsten, copper, and aluminum alloys) thanks to advances in high-power lasers, and it produces parts with good density. SLM-manufactured components typically exhibit high dimensional accuracy and good surface finish (relative to other AM technologies) but suffer from significant residual stress and anisotropy.

Electron Beam Melting (EBM): Similar to SLM but uses an electron beam as the heat source. EBM offers higher build speeds and is particularly suited for printing titanium and its alloys, with widespread use in aerospace, medical, and automotive sectors. EBM is typically performed in a vacuum at elevated temperatures (preheated substrate), which helps reduce residual stress but may lead to grain coarsening.

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Direct Metal Laser Sintering (DMLS): A process similar to SLM but primarily focused on titanium alloy printing. DMLS helps reduce inter-layer porosity issues. The term DMLS is sometimes used interchangeably with metal powder bed fusion, and there is some overlap in how these terms are applied .

2.1.2. Directed Energy Deposition (DED) technology

Directed Energy Deposition [2] uses a nozzle to feed metal powder directly into the focal point of a laser (or other high-energy beam), creating a molten pool. As the heat source moves, the molten pool solidifies, forming the component layer by layer. DED technology offers advantages such as high deposition efficiency, the ability to produce large-scale components, and the capability to achieve multi-material or functionally graded material manufacturing by controlling powder feed. However, its limitations include lower dimensional accuracy and surface finish compared to PBF technologies. DED processes (such as Laser Metal Deposition, LMD) allow for larger build volumes and the repair of existing parts, but generally result in higher surface roughness .

2.2. Wire-based additive manufacturing technologies

The principle of metal wire-based additive manufacturing is similar to Directed Energy Deposition (DED) [3] , but it uses metal wire instead of powder as the feedstock, with energy sources such as electric arc, laser, or electron beam. Compared with powder-based technologies, wire-based additive manufacturing (particularly when using an electric arc as the energy source) offers several advantages: it requires less stringent environmental controls, achieves near-100% material utilization, delivers higher deposition rates, lowers production costs, and can yield better surface quality.

Among these, Wire Arc Additive Manufacturing (WAAM) is widely regarded as the most suitable metal additive manufacturing technology for structural applications in construction, thanks to its high deposition rate, large build size, low cost, good mechanical properties, reasonable geometric resolution, and easy availability of raw materials (welding wire). WAAM is especially well-suited for producing large, near-net-shape structural components or nodes. Its deposition rate is significantly higher than that of PBF technologies (reaching several kilograms per hour), while equipment and material costs remain low, with a wide selection of welding wires available—including grades commonly used in construction. However, WAAM has limitations: its surface finish is relatively poor, and its geometric accuracy and resolution are lower than those of LPBF. The high heat input also makes the control of residual stresses and distortion a key challenge . A process variant, pointwise WAAM (depositing material point by point rather than using continuous welding), has been developed to reduce distortion, but this comes at the cost of lower efficiency .

3. Additively manufactured steels and their properties

The steels most widely used in additive manufacturing for structural applications in construction are primarily austenitic stainless steels and martensitic aging/precipitation-hardening (PH) stainless steels [4].

3.1. Austenitic stainless steels

Austenitic stainless steels are currently the most widely used steel type in additive manufacturing. LPBF-produced austenitic stainless steels (such as 316L) typically exhibit columnar grain structures

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delineated by melt pool boundaries, with extremely fine submicron-scale cellular substructures within the grains. Alloying elements such as Cr and Mo often segregate at cell walls, accompanied by the formation of nanoscale oxide inclusions rich in O, Mn, and Si . Additively manufactured austenitic stainless steels often demonstrate an excellent combination of strength and ductility due to the presence of these nanoscale inclusions and low-angle boundaries in the cellular substructure that impede dislocation motion . Such microstructural features also confer good wear resistance, fatigue resistance, and hydrogen embrittlement resistance, making their properties comparable to those of forged materials .

Advantages: The inherently rapid solidification in AM processes limits the formation of MnS inclusions, thereby enhancing pitting corrosion resistance . AM 316L typically shows superior pitting resistance compared to conventionally forged counterparts, primarily because rapid solidification suppresses the formation of detrimental MnS inclusions [5] .

Challenges: Key challenges include residual stresses, mechanical property anisotropy, and the formation of porosity . Property anisotropy mainly arises from the columnar grain structure and melt pool boundaries, leading to differences in properties parallel and perpendicular to the build direction (BD) .

Existing standard heat treatment processes may not be fully applicable to additively manufactured stainless steels , making the optimization of post-processing heat treatments crucial. High-temperature solution treatments (>1000 °C) can reduce pitting resistance, due to possible MnS re-precipitation or the release of compressive residual stresses .

Furthermore, the erosion–corrosion and intergranular corrosion behavior of AM-produced stainless steels under service conditions still requires in-depth study. Some research indicates that AM 316L may exhibit worse corrosion resistance than conventional materials in media containing solid particles, attributed to weaker repassivation ability and microstructural heterogeneity . Studies on intergranular corrosion (IGC) sensitivity have shown conflicting results, potentially due to differences in sensitization conditions and testing methodologies .

3.2. Martensitic aging steels / Precipitation-Hardening (PH) stainless steels

Among PH stainless steels, 17-4 PH is currently the most commonly used grade in additive manufacturing due to its good printability and broad range of applications . The AM process itself can be seen as an “intrinsic heat treatment” that may induce in situ phase transformations (such as tempering and precipitation), offering the possibility of reducing or even replacing some conventional heat treatment steps for certain steels (such as PH steels and tool steels) . However, regions containing retained austenite may lack precipitation strengthening .

Strength and Ductility: Additively manufactured 17-4 PH, 15-5 PH, and 18Ni 300 maraging steels typically exhibit high strength owing to their refined microstructures . However, the presence of porosity can reduce ductility. AM processes (such as LPBF) often introduce pores (gas porosity, lack-of-fusion defects), which significantly degrade fatigue performance . Compared with forged components, additively manufactured 15-5 and 17-4 PH steels tend to have inferior fatigue properties, primarily due to the poorer surface finish resulting from AM . Notably, incompletely transformed austenite can exhibit a Transformation-Induced Plasticity (TRIP) effect under stress, giving AM 17-4 PH steels a promising combination of strength and ductility . AM-produced 17-4 PH often contains a significant volume fraction of retained austenite (up to 36%), which can undergo TRIP during deformation. This improves ductility and work-hardening capacity but may also suppress age-hardening responses .

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Wear Resistance: The wear performance of additively manufactured PH steels depends on their wear mechanisms. Under dry friction conditions, their finer microstructures and higher hardness typically yield better wear resistance. However, under lubricated conditions, factors such as porosity can increase wear rates by shifting the dominant wear mechanisms from adhesive wear to surface fatigue and abrasive wear . This mechanism dependence must be considered in design [1].

Corrosion Resistance: The relatively high austenite content in as-built AM PH steels (due to the more noble surface potential of austenite) can enhance corrosion resistance . However, the higher porosity in LPBF-produced PH steels—particularly pores larger than 50 µm that can act as sites for localized corrosion—can reduce overall corrosion resistance [6]. Porosity is therefore a critical factor influencing the corrosion performance of AM PH steels .

Heat Treatment: Aging treatment of AM PH steels can significantly increase strength (for example, 18Ni 300 can reach an ultimate tensile strength of 2200 MPa after aging at 482 °C), but high retained austenite content may result in lower peak hardness than that of conventionally produced materials . Optimizing heat treatment protocols is therefore essential to achieve the best possible properties.

3.3. Other construction-relevant steels

Duplex Stainless Steels: These are primarily processed using LPBF and DED technologies. The rapid cooling in LPBF typically results in a ferrite-dominated microstructure (high strength but poor ductility), requiring subsequent heat treatment (~1100 °C) to restore the austenite/ferrite balance . DED-produced parts tend to contain more austenite (offering better ductility but somewhat lower strength) . Annealing can improve elongation and pitting resistance but reduces strength [7] . Increasing nitrogen content can enhance austenite fraction and hardness . Achieving the desired duplex microstructure and properties demands precise control of both processing parameters and heat treatment .

Ferritic/Martensitic Steels: Various ferritic and martensitic steels have been successfully processed using additive manufacturing. Substrate temperature and post-processing heat treatments significantly affect their microstructure and properties . For example, LPBF-produced Reduced Activation Ferritic-Martensitic (RAFM) steels show excellent tensile properties (YS ~900 MPa, UTS ~1050 MPa, El ~18%) thanks to grain refinement .

Silicon Steels: AM has successfully produced silicon steels with silicon content up to 6.9 wt%, demonstrating promising magnetic properties. Achieving excellent soft magnetic performance requires post-printing annealing to reduce lattice defect density . This highlights AM's potential for manufacturing complex-shaped electrical steels (e.g., customized motor cores) .

Tool Steels: High-carbon tool steels pose challenges in additive manufacturing due to their low toughness, poor melt pool wettability, and high thermal gradients that promote cracking . Printing high-carbon tool steels (such as H13) requires preheating the substrate (>300 °C) to reduce cracking risk . AM can simplify heat treatment processes for high-carbon tool steels, with tempering alone sufficient to achieve mechanical properties superior to those of conventional processes . H13 is the most common tool steel in AM. LPBF and DED-produced H13 typically exhibit a martensite + retained austenite microstructure . The strong intrinsic heat treatment during DED can lead to in-situ tempering of martensite . Substrate preheating is critical for successful printing of tool steels . Major challenges include surface and internal defects (pores, lack-of-fusion defects) that degrade wear and fatigue performance, as well as property heterogeneity . Compared to forged parts, AM-produced components often have higher defect densities, a more pronounced layered structure, and higher

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oxygen content. Their fatigue performance typically lags behind conventional materials, primarily due to surface roughness and internal defects .

TRIP/TWIP Effects: AM processes—especially due to the ability to locally vary chemical composition—can promote Transformation-Induced Plasticity (TRIP) and Twinning-Induced Plasticity (TWIP) effects in tool steels, PH steels/maraging steels , and even high-manganese steels , thereby improving tensile properties [8]. This is mainly because AM enables control over stacking fault energy (SFE) . In DED-produced high-manganese steels, local chemical inhomogeneity can lead to position-dependent heterogeneous TRIP/TWIP effects, offering new opportunities to design high-performance steels with tailored deformation behavior .

4. Application examples of additively manufactured metals in building structures

WAAM technology has demonstrated enormous potential in the field of structural engineering. Several landmark projects have validated its feasibility for producing large-scale structural components with complex geometries, for example:

• MX3D Bridge in Amsterdam, the Netherlands (see Figure 1). This project represents the first real-world application of a full-scale, metal 3D-printed pedestrian bridge. WAAM technology was used to fabricate the complex spatially curved steel structure, which underwent comprehensive load testing and numerical simulation validation .

• On-site printed pedestrian bridge at TU Darmstadt . This project demonstrated the feasibility of in-situ WAAM printing on-site, although the robot still operated within a protective enclosure .

• A series of optimized truss structures . Research has shown that combining topology optimization with WAAM manufacturing can significantly reduce truss weight, as exemplified by the optimized truss designs studied by Kyvelou et al. .

• Optimized Garden Bridge in London (in design) . Such projects represent cutting-edge explorations that combine advanced optimization design with AM manufacturing.

Figure 1. WAAM technology [9]

In addition, experimental research on WAAM-produced components with traditional geometries —including cross-sections , bars , and joints —is increasingly common. Results indicate that their structural performance is broadly comparable to conventionally manufactured counterparts. This

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highlights the enormous potential of additive manufacturing to improve material utilization efficiency by fully leveraging its geometric design freedom through structural optimization.

Despite rapid progress, WAAM technology is unlikely to fully replace conventional manufacturing methods for producing entire buildings or bridges in the short term, due to issues of production scale, energy consumption, and cost. Against this backdrop, the concept of Hybrid Structures has emerged [10] . The core idea of this concept is that the main structural elements are produced using efficient traditional methods (such as hot-rolling or cold-bending), while strategically incorporating a limited number of WAAM components at critical or complex locations (such as optimized nodes, bespoke connections, or locally reinforced regions) . This approach takes advantage of WAAM's geometric flexibility (enabling topology-optimized designs, customized connections, and targeted reinforcement) while retaining the efficiency and cost benefits of conventional manufacturing. It strikes a balance among structural efficiency, productivity, and economic viability. The hybrid structure concept can be seen as an adaptation of the broader "hybrid manufacturing" philosophy to the construction engineering domain, offering a practical pathway for widespread WAAM adoption in structural engineering [11]. For example, WAAM can be used to add optimized stiffening ribs to the flanges of conventional I-section steel columns, significantly improving their weak-axis flexural buckling capacity with relatively little additional material , or to fabricate complex nodes that connect multiple conventional tubular members .

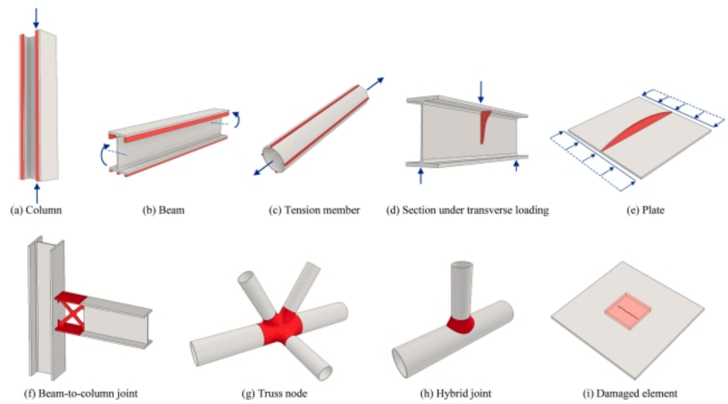

Figure 2. Compound structure

5. Conclusion

Steel has long been the dominant structural engineering material, owing to its ability to achieve diverse microstructural designs through precise control of solid-state phase transformations during heat treatment. The steep temperature gradients, extremely high cooling rates, and inherent chemical inhomogeneity of additive manufacturing (AM) processes provide unprecedented potential to generate unique microstructures in steel. AM technologies—especially LPBF and WAAM—can produce hierarchical microstructures that are difficult or impossible to achieve via conventional methods (e.g., cellular sub-grains, fine grains, elemental segregation, nanoscale precipitates/inclusions). These features significantly enhance steel's strength, hardness, wear resistance, and, under certain conditions, corrosion resistance (for example, by suppressing MnS inclusion formation) . However, these distinctive microstructural evolutions also demand the development of new post-processing heat-treatment strategies that differ from traditional paths. At present, steel additive manufacturing still faces challenges such as residual stress, surface quality, microstructural inhomogeneity, and anisotropy, while the underlying mechanisms for certain

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properties remain under investigation. AM steels often exhibit lower fatigue performance and ductility than their conventional counterparts, with porosity, surface roughness, and anisotropy being key limiting factors . Although it will take time before additive manufacturing can broadly replace traditional steel fabrication across all sectors, its most promising avenue lies in enabling microstructural designs unattainable by conventional processes. This underscores the potential for developing AM-specific steel grades designed to exploit the distinctive thermal cycling inherent in AM, thereby maximizing performance benefits.

Future Challenges and Directions:

Development of Dedicated Materials: Focus on designing high-performance steels for construction applications that are optimized for AM thermal histories, fully leveraging effects such as TRIP and TWIP. Alloy compositions must be developed to exploit the advantages of rapid solidification and non-equilibrium conditions .

Optimization of Post-Processing: Develop tailored heat-treatment and surface-treatment processes for various AM steels and techniques to relieve residual stress, improve microstructural uniformity, and enhance fatigue and corrosion performance. Establish dedicated heat-treatment databases for AM steels .

Expansion of Hybrid Structure Applications: Advance research and practice in applying WAAM to critical nodes, bespoke components, and functionally graded structures. Focus on connection design and technology, residual stress and deformation control (e.g., path optimization, substrate preheating, fixture design), and the economic viability of large-scale applications .

Process Robustness and Standardization: Improve the stability, repeatability, and dimensional accuracy control of AM processes—particularly WAAM—and promote the establishment of relevant material, design, manufacturing, and acceptance standards. Address challenges in surface roughness, geometric accuracy, and anisotropy, and develop efficient post-processing technologies .

Cost-Effectiveness Improvements: Continue improving machine efficiency, material utilization (e.g., powder recycling), and automation to reduce overall costs and increase market competitiveness. Key areas include boosting WAAM deposition rates and developing adaptive path planning and parameter control (using AI and in-situ monitoring) to handle complex geometries and compensate for deformation .

Multiscale Simulation and Intelligent Optimization: Deepen multiscale simulation studies of the process–microstructure–property relationships, combining them with AI to optimize process parameters and component design. Develop predictive models spanning from melt-pool dynamics to macroscopic performance .

Lifecycle Assessment: Systematically evaluate the full lifecycle environmental and economic impacts of additively manufactured steel structures in construction. Quantify the actual benefits of hybrid strategies for carbon reduction and cost savings .

Expansion of On-Site Applications: Develop mobile WAAM equipment and processes suitable for on-site environments to enable strengthening, repair, and retrofitting of existing structures, thereby expanding application scenarios .

Although additive manufacturing has advanced rapidly in recent years, its widespread adoption in construction steel structures still faces multiple challenges, including technology, cost, and standardization. Hybrid structures currently represent the most feasible industrialization pathway, combining the geometric freedom and automation advantages of WAAM with the high efficiency and low cost of conventional manufacturing. This approach is a critical breakthrough for achieving more efficient material use, improved structural performance, and low-carbon transformation in the

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construction sector . Continued research and technological innovation are essential to unlocking AM's enormous potential in the built environment.

6. Outlook

Additive manufacturing (AM) technologies have already been successfully applied to a wide range of metallic systems, including titanium alloys, nickel-based superalloys, aluminum alloys, and steels. Currently, research on steel accounts for roughly one-third of all publications in the field of metal additive manufacturing. However, given that steel represents nearly 80% (by weight) of all engineering metal components, there remains enormous room for expansion of its use in AM. At present, the vast majority of steel components are still manufactured via traditional processes such as casting, forming, and machining.

Sustainability and Lightweighting: Although there is ongoing debate about the overall sustainability of additive manufacturing, producing geometrically complex steel components via AM can avoid many of the emissions associated with traditional energy-intensive processes, offering the potential to reduce greenhouse gas emissions. Studies have shown that through design optimization—which can reduce component weight by up to 50%—the carbon footprint of AM can be lower than that of conventional manufacturing . AM's unprecedented design freedom (e.g., complex geometries, hollow structures) enables significant weight reduction and performance improvements. The Hybrid Structures strategy—using AM components only in critical areas (such as complex nodes, high-stress regions, or localized reinforcements) while manufacturing the main structural elements with highly efficient conventional processes—offers an effective way to balance performance enhancement and material savings against the cost and energy consumption limitations of AM. This approach can substantially improve overall sustainability and economic viability .

Circular Economy: Steel is 100% recyclable. Additive manufacturing can play a crucial role in promoting the circular economy by enabling the reuse of recycled powder to produce high-value products and by reclaiming by-products. WAAM in particular shows promise for repairing damaged components (e.g., suppressing crack propagation, restoring corroded areas) and refurbishing recycled structural members (e.g., filling holes, extending service life). Such applications help prolong the lifespan of structures and enable the direct reuse of steel, thereby reducing the energy demands associated with remelting .

References

[1] Singh R. Powder bed fusion process in additive manufacturing: An overview. Materials Today: Proceedings, 2022, 26: 3058-3070.
[2] Gibson I. Directed energy deposition processes. Additive Manufacturing Technologies, 2015: 245-268.
[3] Bandyopadhyay A. Recent developments in metal additive manufacturing. Current Opinion in Chemical Engineering, 2020, 28: 96- 104.
[4] Haghdadi, Nima , et al. "Additive manufacturing of steels: a review of achievements and challenges." #i{Journal of Materials Science} 56.1(2021): 64-107.
[5] Laleh M, Hughes AE, Xu W, Cizek P, Tan MY (2019) Unanticipated drastic decline in pitting corrosion resistance of additively manufactured 316L stainless steel after hightemperature post-processing. Corros Sci 165: 108412
[6] Schaller RF, Taylor JM, Rodelas J, Schindelholz EJ (2017) Corrosion properties of powder bed fusion additively manufactured 17–4 PH stainless steel. Corrosion 73(7): 796–807
[7] Liu H, Feng X (2013) Effect of post-processing heat treatment on microstructure and microhardness of watersubmerged friction stir processed 2219-T6 aluminum alloy. Mater Des 47: 101–105
[8] Kies F, Ko¨hnen P, Wilms MB, Brasche F, Pradeep KG, Schwedt A, Richter S, Weisheit A, Schleifenbaum JH, Haase C (2018) Design of high-manganese steels for additive manufacturing applications with energy-absorption functionality. Mater Des 160: 1250–1264

DOI: 10.54254/2755-2721/2025.MH26032

[9] Meng, Xin , and L. Gardner . "Hybrid construction featuring wire arc additive manufacturing: review, concepts, challenges and opportunities." Engineering Structures 326.000(2025).
[10] Park JH, Kang Y (2017) Inclusions in stainless steels—a review. Steel Res Int 88(12): 1700130
[11] Saeidi, Kamran , et al. "Austenitic stainless steel strengthened by the in situ formation of oxide nanoinclusions." #i{Rsc Advances} 5(2015).