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Role of additive manufacturing in developing functionally graded materials for nuclear applications

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The global acceptance of additive manufacturing has evolved with time and has proven to provide promising solutions to varied critical requirements of the nuclear industry. The components of a nuclear reactor, when built using additive manufacturing techniques, offer high microstructural control, making them versatile for a range of properties. These properties can be made easily achievable and tailorable by using functionally graded materials. The nuclear components with a wide range of properties are essential, as the environment inside and outside the reactor varies drastically. This study reviews the current progress in additive manufacturing techniques used for manufacturing functionally graded materials for nuclear applications, highlighting the gradient design methodologies and processing techniques. Additive Manufacturing techniques such as selective laser melting uses multiple powder feeders, and mechanical pre-mixing of powders along with controlled process parameters for effectively fabricating functionally graded materials. These materials possess superior mechanical properties (such as microhardness ranging up to 890 $H0_{0.5}$ and compressive strength up to 2040 MPa for $FeCrCoNiMo_{0.5}W_{0.75}$), thermal conductivity and thermal properties compared to monolithic counterparts. A comparative analysis of the manufacturing capabilities of the additive manufacturing techniques, along with the usage of advanced computational techniques such as AI in optimising process parameters for desirable strength and low defect generation, is also presented. The study emphasises on the need for strategies such as process parameters optimisation and data-driven design to fully utilise the potential of additively manufactured functionally graded materials in the nuclear sector.

KEYWORDS

additive manufacturing, functionally graded material, nuclear component, gradient microstructure, machine learning

1 Introduction

Additive manufacturing (AM), commonly known as 3D printing, is revolutionising various industries, including the nuclear sector. It supports digital design and computer-controlled manufacturing of intricate geometries that were challenging to achieve using conventional techniques. This advanced manufacturing technique offers several advantages over conventional manufacturing techniques, including rapid production time, minimized wastage, and enhanced precision (Huang et al., 2015a; Huang et al., 2015b). More importantly, reducing the impact of structural design significantly contributes to the

weight reduction of the components. These qualities not only increase production efficiency but also provide an economical method for large-scale manufacturing. In the nuclear sector, this technology has created specialized, durable, and precise parts critical for nature safety. It also facilitates the synthesis of radiation-resistant materials and equipment for maintenance and repair in radioactive environments by using various materials such as metals, polymers, ceramics, and composites. AM plays a significant role in the production of reactor components, fuel assemblies, and maintenance tools (Lou and Gandy, 2019). AM is expected to become a routine manufacturing, certification, and deployment method over a decade (Mondal et al., 2023; Nelson, 2023).

From an energy point of view, AM supports the advancement of next-generation nuclear reactors by enabling the fabrication of high-performance materials capable of withstanding extreme temperatures and radiation environments. In the major industrial landscape, companies such as GE in aircraft engines and SpaceX in rocket components are already using 3D printing for manufacturing high-precision components (How Additive Manufacturing Helped Launch SpaceX | Kingsbury, https://kingsburyuk.com/how-additive-manufacturing-helped-launch-spacex/.; NASA and Aerojet Rocketdyne Partner to Test AM Hardware - 3Dnatives, https://www.nasa.gov/centers-and-facilities/marshall/3d-printed-rocket-launched-using-innovative-nasa-alloy/.; SpaceX debuts Raptor three engine, further enhanced with metal AM, https://www.3dnatives.com/en/nasa-and-aerojet-rocketdyne-partner-to-test-am-hardware-180520215/#; Through the doors: Inside the AM strategy at GE Aerospace - TCT Magazine, https://www.tctmagazine.com/additive-manufacturing-3d-printing-industry-insights/technology-insights/through-the-doors-inside-the-am-strategy-at-ge-aerospace/). AM has the potential to revolutionize nuclear industries by manufacturing high-performance components efficiently and cost-effectively. Hence, components for the nuclear sector that have higher performance can be manufactured efficiently.

Traditional large light-water nuclear reactors, such as boiling water reactors (BWR) and pressurized water reactors (PWR), have been the strength of nuclear power generation since the late 1950s. However, the global construction of new reactors has been hindered since the 1990s, primarily because of the competition with alternative energy resources. To maintain the nuclear share in the energy portfolio, there is strong interest in smaller, simpler, and more efficient nuclear reactor designs. Several advanced reactor concepts, including small modular reactors (SMR) and GEN IV advanced reactors (e.g., sodium metal fast reactors, molten salt reactors, and gas-cooled reactors), are actively being explored for next-generation solutions for electricity generation (Thompson et al., 2015).
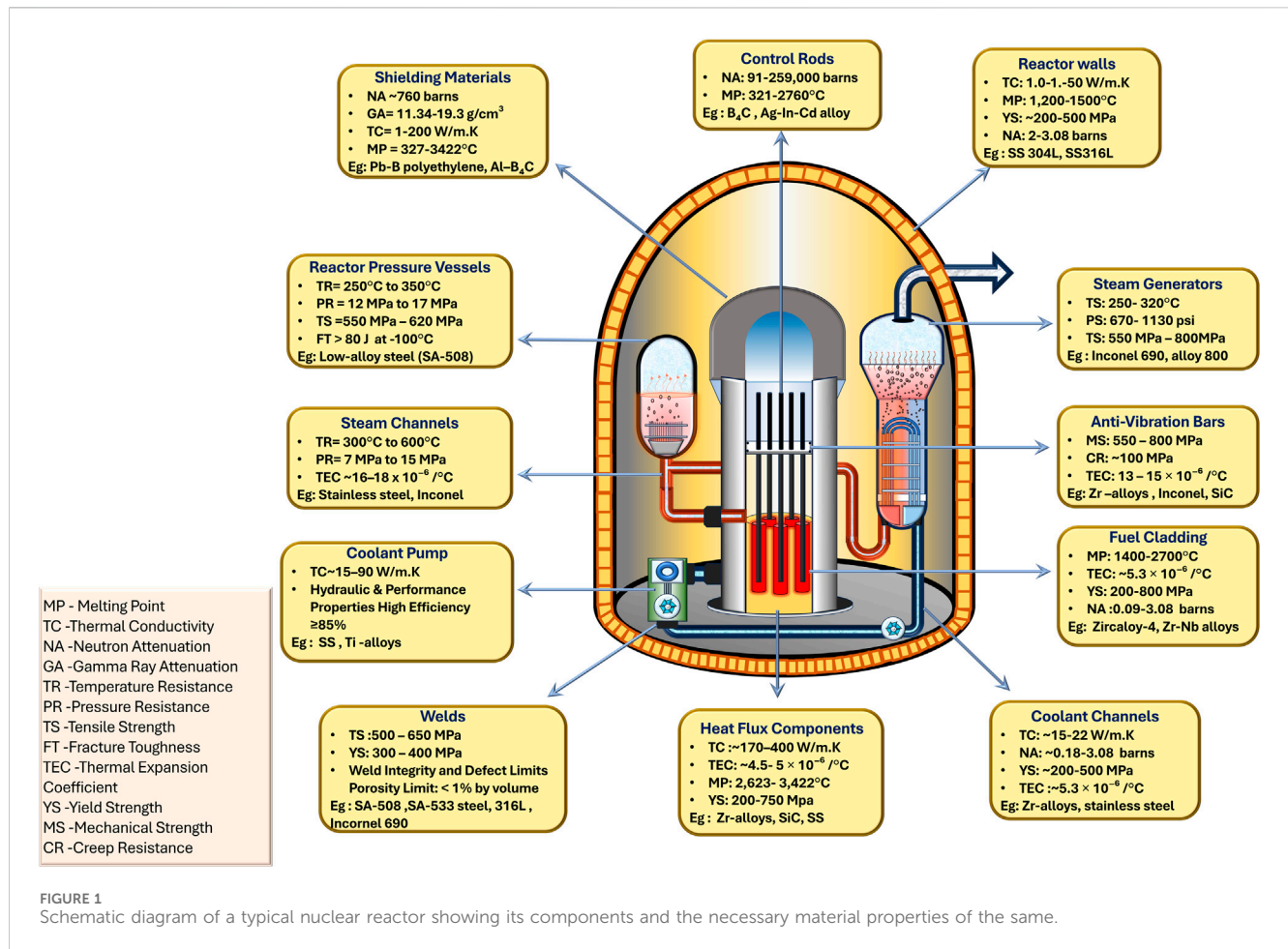
The evolution from conventional materials (steel, aluminum, copper, brass, bronze, and cast iron) and traditional manufacturing methods to AM and, eventually, advancing towards the development of functionally graded materials (FGMs) marks a significant advancement. Initially, manufacturing depended on processes such as casting, forging, and machining, which worked best for producing components from uniform materials with limited design flexibility (Singh et al., 2017; Wohlers et al., 2022). The traditional methods failed to synthesise complex geometries, and component customisation was inadequately met by these approaches, leading to more advanced methods of material

synthesis. AM, first with stereolithography and then with fused deposition modelling (FDM) and selective laser sintering (SLS), allowed for direct layer-by-layer fabrication from digital designs, reduced material waste, and increased design options (Singh et al., 2017). Further studies in the optimisation process parameters (layer thickness, printing speed, nozzle or laser power, scan speed, etc.) and computer-aided design modelling (CAD) led to the development of FGM materials with spatially varying properties (NASA, 2016).

FGMs in AM offer significant benefits for nuclear applications, addressing many of the unique challenges posed by extreme operational environments (Reichardt et al., 2021). FGMs enable the creation of components with spatially tailored properties, such as radiation resistance, thermal conductivity, and mechanical strength, which are critical for nuclear reactors, shielding, and waste containment systems. By gradually varying material composition and microstructure, FGMs can optimise performance in specific regions of a component, for example, providing a radiation-resistant surface while maintaining ductility in the core (Zhang et al., 2019; Yoon and Kim, 2024). AM further enhances this capability by allowing precise, layer-by-layer fabrication of complex geometries and material gradients that are difficult or impossible to achieve with traditional methods. This combination reduces material waste, improves design flexibility, and enhances the overall efficiency and safety of nuclear systems. Additionally, AM-enabled FGMs can lead to lighter, more durable components, reducing costs and extending the lifespan of nuclear infrastructure (Li et al., 2020).

The development of FGMs for nuclear and other high-performance applications has been greatly accelerated by recent developments in AM. Complex FGM structure with controlled compositional gradient can be achieved by various AM techniques such as selective laser melting (SLM), wire arc additive manufacturing (WAAM), and laser engineered net shaping (LENS) (Zhang et al., 2019; Sanjeeviprakash et al., 2023; Kumar et al., 2022). These techniques provide high precision, design flexibility, and the ability to locally customise material properties, which are of significance in nuclear reactors that are subjected to hostile environments. However, with these advancements, there is still scope for improvement regarding the reliable production of metal–ceramic and ceramic–ceramic FGMs under nuclear-relevant environments. Thermal mismatch, residual stresses, and microstructural heterogeneity compromise the structural integrity of FGMs when exposed to radiation and high temperatures. Moreover, reproducibility and lack of standardised protocols for testing FGMs in nuclear environments must be addressed (Kumar et al., 2022).

The ability to produce parts quickly and domestically, reduces dependence on complex supply chains, and further improves sustainability and reduces the carbon footprint associated with transportation and logistics. The development of next-generation reactors, including small modular reactors (SMRs) and advanced fission reactors, requires new innovative manufacturing approaches such as gradient based AM (Sun et al., 2021; Liao et al., 2024). AM has the potential for rapid prototyping and repeated testing, accelerating the design and development of advanced reactors. The flexibility of AM also allows engineers to experiment with new materials and design concepts, which can lead to innovation in reactor technology with high safety concerns. The major components of a nuclear reactor include the reactor core, fuel rods and assemblies, moderator, control rods, pressure vessel, steam generator, and cooling system, demonstrated in Figure 1,

FIGURE 1
Schematic diagram of a typical nuclear reactor showing its components and the necessary material properties of the same.

along with specific properties of each component. AM enables the incorporation of high-performance materials and design elements, such as optimized cooling channels, improved radiation shielding, and long-lasting protective coatings, which are major components of nuclear reactors. These innovations improve the overall safety and lifespan of nuclear reactors, addressing critical concerns such as design flexibility, safety features, production time, cost-effectiveness, strengthened structural integrity, localized and on-demand manufacturing, reactor lifespan, and sustainability and waste reduction with traditional manufacturing methods (Kang et al., 2021; Bergeron and Crigger, 2018). Nuclear projects are often associated with high costs and extended lifetimes, but by incorporating AM, production costs and time can be reduced, making nuclear energy projects more economically viable. Additionally, the ability to manufacture components locally saves on delays associated with long supply chains and logistics, further lowering costs and project timelines (Thomas, 2016).

2 Economics of AM and current market

The global additive manufacturing market size was valued at USD 20.37 billion in 2023 and is expected to grow at a CAGR of 23.3% from 2023 to 2030. A total of 2.2 million units of 3D printers were shipped globally in 2021, and the unit shipments are expected to reach

21.5 million units by 2030. Figures 2a,b illustrates the global AM market and parts production. The growing demand for prototyping applications in healthcare, automotive, aerospace and defence industries have encouraged aggressive research and development in AM and thereby drove the growth of the market (Hensley et al., 2021).

Innovation in materials, precision engineering, and applications in critical industries underpins the market's growth. In the nuclear sector, these innovations are unlocking new possibilities for component design, efficiency, and sustainability. The integration of AM in nuclear applications is expected to grow as the technology evolves and regulatory frameworks adapt. AM plays a pivotal role in advancing small modular reactors (SMRs). SMRs (Liao et al., 2024) fusion energy systems, and next-generation reactor designs. In conclusion, the synergy between the expanding global AM market and the nuclear sector highlights its potential to revolutionise the industry by enhancing efficiency, safety, and sustainability while contributing to the broader growth of advanced manufacturing technologies (Bergeron and Crigger, 2018; Kang et al., 2021; Liao et al., 2024).

3 AM processes for nuclear applications

AM has emerged as an advanced manufacturing technique that offers precise control over spatial resolution and enables layer-by-
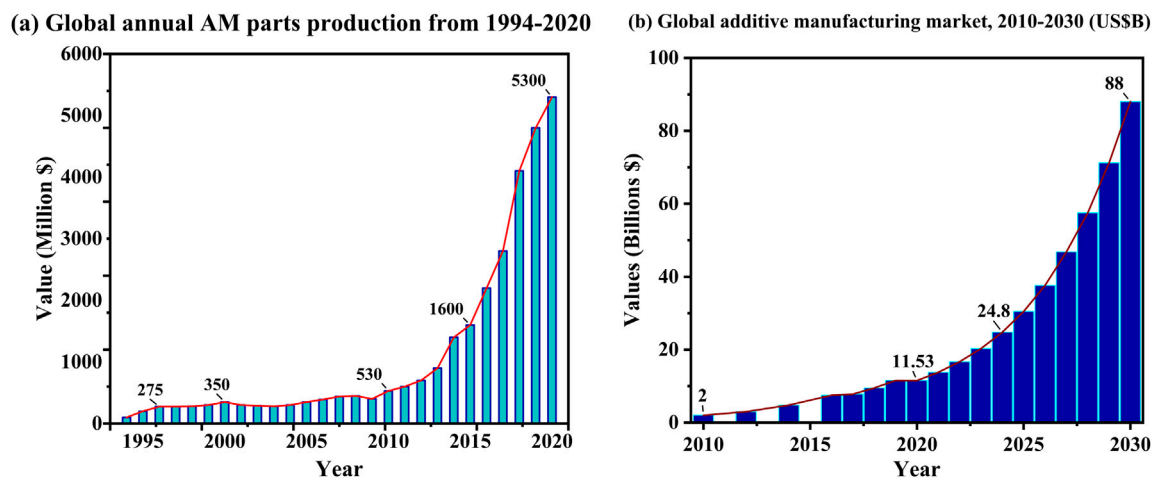
FIGURE 2
(a) Global annual AM parts production from 1993 to 2020, **(b)** Global AM market from 2010 to 2030.

layer deposition of multi-materials. It provides control over the compositional and microstructural features in localised regions across different dimensions. These characteristics of AM make it suitable for the fabrication of FGM, whose properties can be tailored for various extreme condition environments such as nuclear reactors. As the nuclear reactor components have to withstand mechanical stresses, high temperatures, and radiation exposure, the strategic control over the AM process parameters can lead to the formation of multi-dimensional gradient structures. Such advancements in AM can enable the next-generation systems for nuclear applications in terms of efficiency, longevity, and safety of the components. A range of AM techniques that can be deployed for the development of materials for the nuclear reactor have been shown in Figure 3.

Table 1 summarizes the AM based techniques for nuclear sector materials. Laser DED and PBF are the most commonly used AM techniques in nuclear applications due to their superior advantages, such as being capable of fabricating large and complex parts with graded material compositions, high-resolution and near-net-shape production with minimal post-processing (Xie et al., 2021; Downey, 2023). These two methods address the key challenges, such as porosity, residual stresses, and anisotropic mechanical properties. In the case of DED, it offers high accuracy and the capability for repair, rebuild, and fabrication of complex components. Its capability to deposit material layer by layer ensures effective utilization of material and part customization necessary for utilisation of material and part customisation necessary for the rigorous demands of nuclear systems. On the other hand, PBF provides unmatched detail and homogeneity, making it ideal for producing components with complex geometries and excellent mechanical properties (Uribe-lam et al., 2021; Singh and Singh, 2018). The precise control over the fusion process ensures high-quality and defect-free parts, which is crucial for reliability in nuclear environments. The dominance of laser DED and PBF lies in their ability to meet the demands of the nuclear industry, including durability, resistance to aggressive environments, and consistent performance over time, which is essential for maintaining the reliability and safety of nuclear reactors.

Several other AM techniques available are Laser Chemical Vapour Deposition (LCVD) (Miyagishi et al., 2025), Wire Arc Additive Manufacturing (WAAM) (Chen et al., 2021), etc., are not preferred in nuclear applications due to limitations in scalability, precision, or material compatibility when compared to L-DED and PBF.

Various studies related to the printing of compositionally graded FGMs using primarily Laser DED, also known as laser engineered net shaping (LENS) technique, have been reported. This technique uses a laser heat source for melting the powders and the substrate, along with a coaxial nozzle for printing the 3D component. Yoon and Kim (2024) developed an approach to replace the dissimilar metal welds in the nuclear reactors with FGM fabricated through the DED technique. The work focuses on utilising the potential of FGM to reduce the primary water stress corrosion cracking, which is the major concern in nuclear reactors due to the residual stress caused by the dissimilar welds. The study analyses the potential of FGM comprising low alloy steel and stainless steel in terms of mechanical performance and its behaviour under temperature variations. The DED fabricated FGM showed enhanced mechanical and thermal performance, which is essential for the structural integrity and safety of the nuclear reactors. However, the optimum compositional ratio and impact on the material under a corrosive environment for long-term application can further explore the possibilities of achieving tailored microstructures and mechanical properties. Jinoop et al. (2019) explored the process window for fabricating thin-walled Inconel 718 structures using the DED technique, established an optimum range of laser energy per unit length (105 kJ/m to 210 kJ/m) and powder feed rates per unit length (4 g/m to 12.5 g/m) for structural integrity. A significant effect of the post-heat treatment on the mechanical performance of the fabricated structures was reported in terms of reduction in tensile residual stress (50%) and enhancement in ductility (62.5%) and energy storage capacity (2.4 times). The study suggested the potential of DED for fabricating lightweight, durable components with tailored characteristics for nuclear applications. However, a few concerns remain unaddressed. With further exploration of the process and

FIGURE 3
Additive manufacturing processes in nuclear materials engineering.
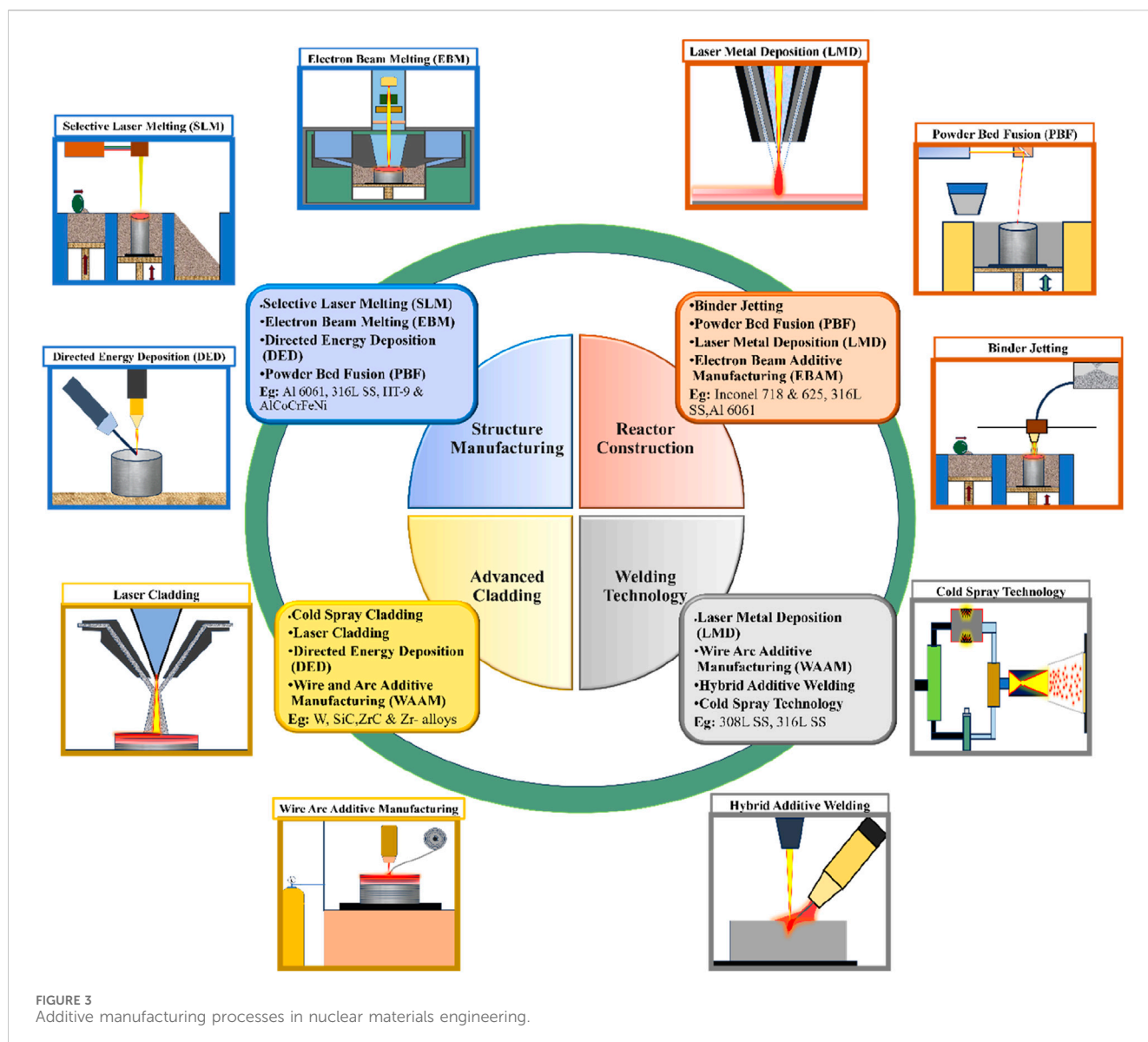
property relationship, the behaviour of these components under cyclical loading conditions and the influence of the variable microstructure along the layers for long-term application can be examined to determine the optimum manufacturing conditions. Mcmurtrey et al. (2019) compared the irradiation damage and irradiation-assisted stress corrosion cracking (IASCC) susceptibility of AM 316L stainless steel and wrought 316L stainless steel. The work demonstrates a lower susceptibility of AM 316L stainless steel to IASCC than wrought 316L, which is essential for nuclear applications. It also explores the microstructural features of AM 316L, which depicts a lower density of voids in AM 316L as compared to wrought 316L, resulting in reduced localised deformation. This work establishes the initial understanding of the relation between microstructures and AM materials' performance. However, exploring the post-processing treatments of AM components can further lead to improving the safety and performance of the nuclear reactor components. Moorehead et al. (2021) worked on developing

compositionally complex alloys (Cr-Fe-Mn-Ni) for nuclear applications by utilising high-throughput methodology in combination with AM. This study addresses the limitations of the ASME-qualified materials codes for advanced nuclear reactor design. The AM-DED technique was employed to fabricate the compositional array of unary, binary, ternary, and quaternary alloys (Cr-Fe-Mn-Ni). With further implementation of synthesis, irradiation, and characterisation methodology, a significant reduction in fabrication time was observed in comparison to conventional methods. In addition, some studies also reported the wire-DED technique, i.e., the combination of wire and powder-fed DED for printing larger FGM components.

In PBF, different types of heat sources are used to fuse the powdered raw material and form a 3D component. Based on these heat sources (laser, electron), PBF can build 3D components with different types of fusion techniques, such as laser fusion and electron beam fusion. The laser fusion technique can further be classified as selective laser melting (SLM) and selective laser sintering (SLS).

TABLE 1 AM techniques used in nuclear applications for various parts.

AM techniques properties	Materials/ Components	Improved/ Unique	Significance & performance	Applications in nuclear systems	Energy application	References
DED	Inconel 718	Mechanical properties and energy storage capacity	* Maintains mechanical integrity up to ~700 °C * Resists corrosion in both aqueous and high-temperature environments, including exposure to coolants like water, steam, or molten salts * Good resistance to neutron irradiation-induced embrittlement, swelling, and stress corrosion cracking	- Reactor Internals - Steam Generators and Heat Exchangers - Fuel Assembly Components	Nuclear energy, Oil and gas	Jinoop et al. (2019)
	316L stainless steel	Enhanced resistance to IASCC	* Suitable for operating temperatures up to ~500 °C * Resists corrosion in water, steam, and reactor coolant systems, especially against chlorides and acidic environments * Tolerates moderate neutron irradiation without significant embrittlement or swelling, making it suitable for out-of-core applications (not directly in the fuel zone) * Easily formed, machined, and welded, which is crucial for maintenance and replacement operations in nuclear systems	- Piping and Tubing - Reactor Internals (non-core) - Heat Exchangers and Condensers - Storage Containers	Nuclear energy	Mcmurtrey et al. (2019)
	High-entropy alloy AlCoCrFeNi	Resistance to void swelling	* Exhibits exceptional resistance to irradiation damage, including low void swelling, minimal radiation-induced segregation, and stable microstructures under high neutron flux * high strength and wear resistance, even at elevated temperatures (up to ~1,000 °C) * Resistant to oxidation and corrosion in aggressive environments, including coolants, molten salts, and supercritical water, depending on the specific phase composition and processing	- Core Structural Materials - Radiation-Resistant Barriers	Nuclear energy	Wang et al. (2017)
	Oxide dispersion strengthened (ODS)14Cr stainless steel	Resistance to creep	* ODS steels demonstrate excellent resistance to radiation-induced swelling, creep, and embrittlement * Maintains mechanical strength and creep resistance up to ~700 °C–800 °C, far beyond conventional stainless steels * Exhibits minimal void swelling and embrittlement even at doses exceeding 100 dpa (displacements per atom) * Retains microstructural stability and mechanical integrity during long-term exposure to reactor operating temperatures	- Fuel Cladding and Core Structures - Reactor Pressure Boundary Components	Nuclear energy	Arkhurst et al. (2017)
	17.8% Cr, 12.8% Ni, 2.36% Mo, with small		* Prevents carbide precipitation during welding or high-temperature exposure, significantly	- Primary and Secondary Piping Systems - Steam Generators and Condensers	Manufacturing of the body, the bonnet and the	Kang et al. (2021)

(Continued on following page)

TABLE 1 *(Continued)* AM techniques used in nuclear applications for various parts.

AM techniques properties	Materials/ Components	Improved/ Unique	Significance & performance	Applications in nuclear systems	Energy application	References
	amounts of additional elements such as Mn, Si, P, S, N and Fe, C<0.02%		reducing the risk of intergranular corrosion * Maintains good mechanical properties under neutron irradiation, especially in out-of-core regions	- Welded Components - Spent Fuel Storage and Waste Containers	cage parts of a 3-inch nuclear safety class 1 valve	
	Cr-Fe-Mn-Ni	radiation-tolerant materials	* Alloys show good resistance to radiation-induced swelling	- Reactor Internal Components (non-core) - Heat Exchanger Tubing - Coolant System Components	cladding material	Moorehead et al. (2021)
	316LN SS		* Performs well up to ~550 °C, beyond which creep becomes a limiting factor * Well-suited for welding and forming into complex shapes	- Primary and Secondary Piping - Pressure Boundary Components - Steam Generators and Heat Exchangers - Spent Fuel and Waste Containers		Shang et al. (2021)
	WR316L SS		* Excellent resistance to pitting, crevice, and general corrosion in high-humidity, borated water, and radioactive liquid environments * Easily welded and fabricated into complex shapes and large containment structures, which is critical for waste canisters and shielding assemblies	- Spent Nuclear Fuel Storage Canisters - Radioactive Waste Containers - Shielding Components - Waste Transfer and Processing Equipment		McMurtrey et al. (2021)
	316L SS		* Excellent resistance to oxidation, pitting, and stress corrosion cracking, especially in high-purity water, borated water, and humid environments * Prevents carbide precipitation at grain boundaries during welding, preserving corrosion resistance and structural integrity in high-radiation and high-temperature areas	- Coolant and Feedwater Systems - Heat Exchangers and Condensers - Spent Fuel and Waste Storage		Hu et al. (2021), Zhang et al. (2021)
PBF	Aluminum 6,061	Crack-free	* Good resistance to corrosion in air and water, including moderately radioactive water environments, making it suitable for peripheral systems and coolant-exposed surfaces in low-radiation zones * Efficient heat transfer makes it suitable for non-core heat exchangers, cooling channels, and thermal shields * Light Weight & High Strength-to-Weight Ratio	- Support Structures and Frames - Neutron Beamline Components - Radiation Shielding Backing - Non-Core Cooling Components	Nuclear energy, Oil and gas	Uddin et al. (2018)
	Inconel 718	Average heat capacities are greater when irradiated	* Maintains excellent mechanical properties at temperatures up to 700 °C * Demonstrates good tolerance to neutron irradiation, with minimal swelling, embrittlement, or radiation-induced degradation	- Reactor Internals (Non-Core) - Steam Generators and Heat Exchangers - Control Rod Drive Mechanisms - Fuel Assembly Hardware		Graham et al. (2021)

TABLE 1 (*Continued*) AM techniques used in nuclear applications for various parts.

AM techniques properties	Materials/ Components	Improved/ Unique	Significance & performance	Applications in nuclear systems	Energy application	References
			* High resistance to creep, stress relaxation, and thermal fatigue, making it well-suited for cyclic thermal conditions			
	Inconel 625	Average heat capacities are greater when irradiated	* Resistant to a wide range of corrosive environments, including chlorides, acids, steam (~980 ℃), and radiation-induced environments * Retains mechanical strength and structural integrity at 980 ℃	- Heat Exchangers and Steam Generator Tubing - Reactor Core Bypass Systems - Control Rod Drive and Sealing Mechanisms - Nuclear Waste Processing and Storage Systems		Graham et al. (2021)
	ODS-FeCrAl steel		* Excellent High-Temperature Oxidation resistance and layer stability up to ~1,200 ℃ * Outstanding; low swelling and good dimensional stability under neutron flux	- Accident-Tolerant Fuel (ATF) Cladding - Core Structural Components		Li et al. (2025)
Direct ink writing Stereolithography Direct ink writing Gel casting using 3D-printed polymer skeleton Selective laser sintering (SLS) Binder jet print Direct ink writing Laser chemical vapour deposition (LCVD) Laminated objective manufacturing	SiC	A crystalline SiC system with minimal secondary phases is suggested to minimise irradiation-induced strength degradation and dimensional instability at high neutron doses	* SiC can operate at temperatures above 1,000 ℃, maintaining mechanical strength and dimensional stability, ideal for high-temperature reactor environments like gas-cooled or molten salt reactors * Exhibits minimal swelling, low gas production, and good structural integrity under neutron irradiation * Highly resistant to oxidation, chemical attack, and coolant corrosion (such as molten salts, helium gas, and liquid metals)	- Accident-Tolerant Fuel (ATF) Cladding - Composite Fuel Cladding (SiC/SiC) - Structural Materials -		Koyanagi et al. (2021b)
Binderjet	SiC					Terrani et al. (2021)
Combination of binder jet printing and densification via chemical vapour infiltration (CVI)	SiC				Sensor protection in a nuclear reactor	Petrie et al. (2021)
	316L SS				reactor core and coolant system components	Byun et al. (2021)
Wire arc additive manufacturing (WAAM	308 L SS		* Minimises carbide precipitation at grain boundaries during welding, preventing sensitisation and extending the service life of nuclear components * High resistance to oxidation, aqueous corrosion, and chloride stress corrosion cracking	- Welding Filler Metal - Piping and Support Structures - Waste Management and Storage	Pipeline of the primary circuit, the surge tube of the stabiliser, and the inner lining of the reactor vessel	Li et al. (2021)

TABLE 1 (*Continued*) AM techniques used in nuclear applications for various parts.

AM techniques properties	Materials/ Components	Improved/ Unique	Significance & performance	Applications in nuclear systems	Energy application	References
	Nano-structured high-Mn 9Cr ferritic-martensitic (FM) steel		* Absorb radiation-induced defects (e.g., voids and dislocation loops), excellent resistance to swelling, embrittlement, and hardening * The ferritic-martensitic microstructure offers excellent creep strength and thermal fatigue resistance up to ~600 °C–650 °C	- High-Burnup Fuel Designs - Core Structures	first-wall, cladding, tube components, primary and secondary circuits, vessels	Zhong et al. (2021)
Hot-isostatic pressed (HIP)	316L SS				structural materials for core internals in light water reactors (LWRs)	Jiang et al. (2021)
Laser powder-bed Electro Optical Systems (EOS)	HT-9 and Grade 91	Higher strength at 25 °C–600 °C	* High creep strength for long-term service at high temperature * Good oxidation and corrosion resistance in high-temperature steam and gas environments * Better fabrication properties and weldability	- Fuel cladding, spacer grids, and core support structures - Reactor pressure vessels - Steam generator tubing - Heat exchangers and secondary loop piping		Eftink et al. (2021)
Electron beam melting	Tungsten (W)		* Withstands temperatures >3,000 °C without melting, making it ideal for plasma-facing surfaces in fusion reactors * Withstands temperatures >3,000 °C without melting, making it ideal for plasma-facing surfaces in fusion reactors * Produces relatively low levels of long-lived radioactive isotopes when irradiated	- Used in divertors, first wall panels, and blanket modules, where materials face intense plasma heat and neutron flux - High-Heat-Flux Components - Thermal Shields and Liners		Ellis et al. (2021)
Ultrasonic additive manufacturing	aluminium alloy 6,061		* Low Neutron Absorption Cross-Section * Offers protection against moisture, deionised water, and mild radioactive environments * Lightweight and Strong * Excellent Machinability and Weldability * Good Thermal Conductivity	- Support Structures and Frames - Radiation Shielding Support	complex geometry parts with internal channels, fibres or sensors	Gussev et al. (2021)
	Al 6,061				Control plate construction	Hehr et al. (2017)
	Zircaloy-4		* Resist oxidation in high-pressure, high-temperature water and steam environments * Maintains structural integrity under high pressures and temperatures over long periods of operation, even after neutron irradiation	- Fuel Cladding - Spacer Grids and Guide Tubes - Structural Components		Ridley et al. (2024)
Chemical vapour deposition (CVD)	zirconium carbide (ZrC)		* Highest melting points (~3,550 °C) * Provides efficient heat transfer from the nuclear fuel to the coolant, reducing the risk of hot spots and thermal fatigue * ZrC has good resistance to radiation-induced damage, maintaining mechanical integrity under high neutron flux and long-term exposure	- Tri-structural Isotropic Fuel Particles - Advanced Fuel Cladding and Matrices -	Nuclear fuel cell structures	Yang et al. (2024)

During the process, the laser scans the X-Y plane along the uniformly distributed powdered bed, which is fitted with a roller over a construction griddle. The interaction of the laser beam with the powdered material layer allows the beam to melt or sinter the particles together to form a solid layer. After the printing of the first layer, the powder bed steps down, and the roller spreads the powder uniformly over the bed for the next laser scan. SLS and SLM are the two commonly used PBF techniques used to manufacture FGM (Uribe-lam et al., 2021; Singh and Singh, 2018; Uddin et al., 2018). AA6061 components by laser-based PBF technique with assisted high-temperature powder bed heating. The cracking due to the solidification was eliminated by the optimised process parameters and preheating, which altered the thermodynamic conditions. This laser PBF technique for manufacturing AA6061 showed enhanced mechanical performance as compared to the conventionally manufactured material. The yield strength of the heated AA6061 was increased up to 280 MPa as compared to the as-fabricated AA6061 samples. The ultimate strength was recorded as 310 MPa in preheated AA6061 samples as compared to the as-built AA6061, which was recorded as 130 MPa (Uddin et al., 2018).

Unlike DED, where multiple hoppers for feedstock are provided, the fabrication of the gradient structure in SLM requires alternate strategies. Various studies reported different strategies for achieving a gradient microstructure. Demir and Previtali (2017) used a multiple powder feeder system for the fabrication of Fe/Al-12Si multi-material, where two separate material hoppers and a lower mixing hopper were used. The upper hopper was operated during single-material processing, and the lower hopper was used for mixing the materials. Though the approach was not standard, it allowed for achieving a similar composition as in DED. Similarly, C. Han et al. (Han et al., 2018) adopted the strategy of mixing the powder of different compositions (Ti/HA powder mixtures with varying HA content) using mechanical mixing by a planetary ball milling apparatus. After mixing, each composition was fed to the powder feeder, and a layer of 2 mm thickness was formed. Additionally, PBF processes can also manufacture gradient materials by gradually controlling the thermal cycles, cooling rates, or laser parameters during the SLM process (Parhizkar et al., 2023).

In the binder jetting (BJ) process, the powder particles are fused by selectively depositing the liquid bonding agent onto the powder bed (Koyanagi et al., 2021a; She et al., 2024). The print head drops the bonding agent onto the powder platform, and the particles are bonded together through the process of adhesion or chemical reaction. The support structures for the printed objects are facilitated by the surrounding powder materials, which are removed on the completion of the printing process. The required level of printing quality is achieved through post-processing processes such as sintering, infiltration, and hot-isostatic processing. The major advantages of BJ include large build volume, high printing speed, and low printing cost. In view of this, Zhao et al. (2023) fabricated 316L-toughened porous Al_2O_3-based functionally graded ceramic using a binder jetting technique. The printed parts were further subjected to sintering from 1,200 °C to 1,450 °C for 2 h at a heating rate of 5 °C/min in a vacuum atmosphere. This approach leads to achieving tailored properties of the material for complex applications such as high-temperature and nuclear reactors. The work explores a low-temperature toughening

mechanism by utilising 1% CuO and 4% TiO_2 as sintering aids and 0%–40% Al_2O_3, which enhances the densification process and mechanical properties of the component. However, further exploring the incorporation of metal alloys as toughening phases could lead to the development of materials with enhanced performance for various applications (Srivastava et al., 2024). The printed parts using BJ techniques are typically porous and require certain post-processing, such as sintering or infiltration, to enhance their mechanical properties and functional performance. The post-infiltration of the printed or sintered parts involves the filling of the porous structure with molten alloys, epoxy or precursors to enhance the sintered density of the structure (Chen et al., 2022). However, the extent and spatial distribution of infiltration can be varied by changing the orientation, capillarity and the time of infiltration, which is responsible for achieving gradient structures. Chen et al. (2022) studied the effect of multi-infiltration operations in alumina parts. It was observed that the ceramic suspension infiltrated the skeleton under the effect of gravity, which resulted in density heterogeneities of the parts. Therefore, BJ can offer the flexibility of fabricating graded structures through the post-infiltration technique.

Stainless steel alloys like 316LN, 308L SS, and WR316L are well known for their excellent mechanical strength, corrosion resistance, and ability to withstand high temperatures and radiation. Their durability and reliability make them essential for critical components like reactor pressure vessels, piping, and core structures. Similarly, zirconium carbide (ZrC) has outstanding thermal conductivity, a high melting point, and resistance to neutron irradiation. These properties make ZrC a key material in fuel cladding and protective coatings. These properties help improve reactor efficiency while enhancing safety by preventing fuel degradation and reducing radiation exposure. By combining these advanced materials, the nuclear industry ensures the structural integrity and longevity of reactors, meeting the demanding performance and safety requirements.

Combining AM techniques to fabricate FGM demonstrates significant potential in nuclear sector. Superalloys such as Inconel 718 and 625 are already AM-compatible for complex reactor components and provide exceptional resistance to corrosion and high temperatures (Jinoop et al., 2019; Graham et al., 2021). Well-known in AM, austenitic stainless steels like 316L and 316LN are perfect for graded structures with improved surface qualities (Shang et al., 2021; Mcmurtrey et al., 2019). Although ODS variants present processing challenges, HEAs (like AlCoCrFeNi) and ODS steels (like 14Cr and ODS-FeCrAl) offer radiation and creep resistance appropriate for fuel cladding and structural internals (Li et al., 2025; Wang et al., 2017). For core applications that demand corrosion and radiation tolerance, ferritic-martensitic steels such as HT-9 and Grade 91 benefit from FGMs (Eftink et al., 2021). Despite the fabrication challenges, ceramics like SiC and ZrC are being incorporated into AM and FGM processes because they are perfect for components that face plasma and are related to fuel (Petrie et al., 2021; Yang et al., 2024). For accident-tolerant designs, FGMs can improve zirconium-based alloys, such as Zircaloy-4, which are essential in Light Water Reactors (LWRs) (Ridley et al., 2024). Aluminium 6,061 is perfect for non-core and instrumentation roles because of its low neutron absorption and ease of AM fabrication, particularly using ultrasonic AM (Gussev

et al., 2021). While tungsten is challenging to process, it is necessary for fusion applications when graded with steels to manage thermal mismatch (Ellis et al., 2021). Specialised stainless alloys, such as Cr-Fe-Mn-Ni variants, support containment and reprocessing applications (Moorehead et al., 2021). When combined with AM and FGM methods, these materials mark a substantial improvement in nuclear system performance and design.

4 Properties of nuclear reactor materials

Nuclear reactor materials are specifically engineered to withstand extreme conditions, such as high temperatures, radiation exposure, oxidation, and corrosive environments, ensuring the safety and efficiency of the nuclear reactor (Was, 2007). Figure 4 shows the structural and functional property requirements of nuclear reactor materials. These materials are exceptionally strong, with yield strengths ranging from 250 to 800 MPa and ultimate tensile strengths between 450 and 800 MPa. They also have high fracture toughness (50–200 MPa) and hardness (150–400 HV), making them highly resistant against mechanical stresses with delayed failure (Hehr et al., 2017; Lou and Gandy, 2019). The resistance to radiation is a key property, as these materials must maintain their structural integrity under high levels of neutron irradiation ($\sim 10^{25}$ n/m^2). They must resist swelling, with volume increasing typically limited to less than 1%. The materials need to be resistant to radiation damage up to $\sim$100 displacements per atom (dpa). Corrosion rates in high-temperature water are limited below 5 μm/year and oxide layer growth rates below 2 μm/year. The thermal properties optimised for reactor conditions, with thermal conductivity ranging from 10 to 30 W/mK and specific heat capacities between 400 and 500 J/kg·K. These materials also have high melting points (1,327 °C–1,577 °C) and low thermal expansion coefficients ($5\text{-}17 \times 10^{-6}$/K), ensuring stability under thermal cycling. Furthermore, they exhibit excellent creep strength, resisting deformation under stresses of 100–300 MPa at 300 °C–600 °C for over 10,000 h (Frost and Ashby, 1982) (*Thermophysical Properties of Materials for Nuclear Engineering: A Tutorial and Collection of Data*, 2009). Combined, these set of critical properties make nuclear reactor materials highly durable and reliable, essential for the safe and efficient operation of nuclear power plants.

5 Materials for nuclear applications

Nuclear materials should be able to sustain harsh conditions like high temperatures, neutron radiation, corrosive media, and mechanical stress. Inconel 718 and 625 are two examples of alloys that have high mechanical strength and are resistant to corrosion at temperatures up to 980 °C. They also have strong resistance to radiation, which makes them perfect for use in interior components of the reactor, heat exchangers, and steam generator tubing (Jinoop et al., 2019; Graham et al., 2021). Stainless steels such as 316L and 316LN SS are also common in non-core reactor parts because they can be shaped and welded easily and can withstand moderate amounts of radiation. They find applications starting from piping systems to containers for spent fuel (Shang et al., 2021;

Mcmurtrey et al., 2019). Advanced stainless steels like ODS 14Cr are highly resistant to creep and swelling up to 800 °C. This is important in high-radiation areas like fuel cladding and core structures (Li et al., 2025; Arkhurst et al., 2017).

High-entropy alloys (like AlCoCrFeNi) and ceramics, SiC and ZrC, are new types of materials that are pushing the boundaries of nuclear material science. High-entropy alloys are capable of resisting void swelling and damage caused by radiation, making them potential materials for core structural parts that are exposed to high neutron flux (Wang et al., 2017). Both SiC and ZrC are excellent options for accident-tolerant fuel cladding and gas-cooled reactor applications because they can work at temperatures over 1,000 °C and have excellent thermal stability and resistance to oxidation (Koyanagi et al., 2021a; Yang et al., 2024; Petrie et al., 2021; Terrani et al., 2021). Refractory materials are crucial for nuclear reactor applications because they can keep their shape even when exposed to very high temperatures and radiation. Tungsten, as well as Zr-4 alloys, are key materials in plasma-facing components as they can withstand temperatures over 3,000 °C and have low long-term radioactivity (Ridley et al., 2024; Ellis et al., 2021).

6 Functionally graded materials: role of properties and microstructures

Functionally graded materials exhibit a hierarchical arrangement at the microstructural level, which caters to the nuclear sector prominently. Due to the demand for graded properties in nuclear materials, FGM is a popular choice for the above. Properties of FGM in the nuclear industry, grouped under various requirements, include dissimilar welds in components such as nuclear walls. The additive manufacturing industry is instrumental in meeting the demands of the graded property arrangement in FGMs (Mahamood and Akinlabi, 2017). Ti-6Al-4V/Ni-20Cr FGM has been shown to have combined effects of heat and corrosion resistance of both alloys, which is appropriate for the nuclear wall developed using DED (Yakovlev et al., 2005). The laser power optimisation during DED led to a crack-free interface. The nuclear wall has a high demand for versatile and dynamic properties, wherein tungsten is an integral part of the former as it helps in providing superior thermal protection to the stainless-steel wall. The above FGM is achieved using cold gas spraying, where the coarser tungsten particles show efficient peening, rendering it an efficient thermal barrier. The diffusivity and conductivity properties exhibited by the W/316L FGM are an average of both systems, which were engineered using a radio frequency inductively coupled system (Kim et al., 2019). The hierarchical microstructure rendered by the virtue of FGM can be attributed to the robust nature of additive manufacturing, which provides an avenue for optimizing process parameters selectively to obtain the former (Dash et al., 2020).

Microstructure plays a vital role in enhancing prosperities of FGMs such as mechanical strength, tensile strength, ductility, wear resistance, thermal stability and resistance to extreme corrosion environment and other characteristics (Chen et al., 2022). FGMs can achieve high mechanical strength by controlling the distributions and morphology of grains and tuning of phases. For instance, grain refinement and phase distribution gradients can make the material
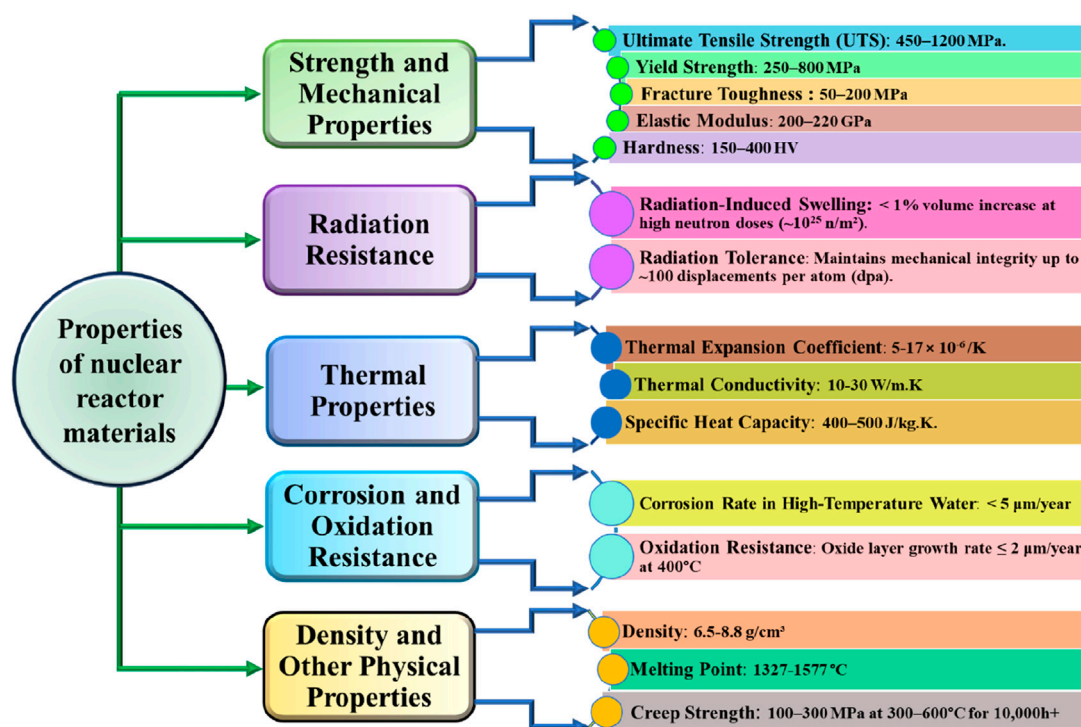
FIGURE 4
Properties of nuclear reactor materials.

vulnerable to dislocations formation which renders the material with high strength and fracture toughness. Microstructural gradients can aid in formation of passive oxide layers or lowering the susceptibility localised galvanic reactions, which makes the material more resistant to corrosion. Also, the controlled change in microstructure can lower residual stresses and stop cracks from spreading (Chen et al., 2022).

Conventional materials such as metals, alloys, polymers, and ceramics have uniform or homogeneous compositions. Therefore, their physical, mechanical, thermal, and chemical properties are the same throughout the structure. In the case of FGMs, properties are varied in a gradient manner through the thickness of the material. In terms of mechanical properties, Ti-based alloys possess tensile strength ranging from 210 MPa to 1,380 MPa and Young's modulus of 120 GPa. Compared to the homogenous Ti-alloys, their FGM counterpart exhibits higher range of tensile strength and Young's modulus (Yin et al., 2018; Hu et al., 2021; Alarifi, 2024). FGM made of stainless steel has tensile strengths between 515 and 625 MPa and a higher Young's modulus of 190 GPa. The tailored FGM counterpart material gradient makes these materials less stress-concentrated and improves the resistance against crack formation and propagation under load conditions. Alternatively, standard wrought Ti6Al4V alloys usually have a uniform tensile strength of around 950 MPa and a Young's modulus of about 110 GPa (Yin et al., 2018; Alarifi, 2024). Similarly, Al_2O_3–ZrO_2 systems, can combine the 260 MPa strength of alumina with the enhanced fracture toughness of zirconia (ZrO_2). Homogeneous alumina alone has a Young's modulus of up to 413 GPa but is prone to brittle failure (Wu et al., 2022).

The thermal property of FGM have the ability to create a thermal gradient in bulk material for efficient heat management. For instance, Al-based FGMs can work at melting temperatures of about 660 °C, and their thermal conductivities can be altered depending on the gradient composition, which is not possible in non-FGM Al alloys (Zhang et al., 2021; Su et al., 2023). Ceramic-based FGMs, like alumina/zirconia systems, show a range of Vickers hardness values, from 18.4 GPa (pure alumina) to 15.0 GPa with a 50% zirconia blend (Li et al., 2020; Li et al., 2021; Zhang et al., 2021). As the porosity in the gradient FGMs move from a dense core to a porous outer layer, their thermal conductivities drop from typical metal values (~20–50 W/m·K) to insulating ceramic values (<5 W/m·K). Homogeneous ceramics often suffer from thermal shock and brittleness. FGMs mitigate these by gradually changing from an area with high thermal conductivity to low thermal conductivity. This makes them more durable in high-temperature environments (Zhang et al., 2021).

7 Microstructural gradient in FGMs

FGMs can be classified into three main types based on their gradient characteristics. Chemical Composition Gradient FGMs, where the material composition gradually transitions, optimise properties such as corrosion resistance, thermal conductivity, and mechanical strength for applications in aerospace and biomedical implants. Porosity Gradient FGMs, where porosity varies throughout the material to enhance thermal insulation, reduce weight, or improve bone integration in medical implants.
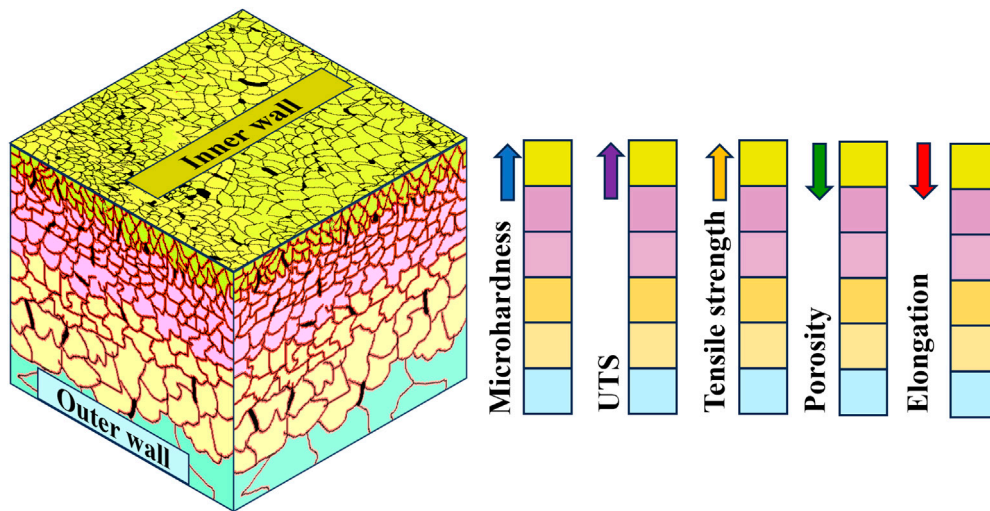
FIGURE 5
Graded microstructures showing the variation of properties from one surface to the other.

Microstructure Gradient FGMs, where phase distribution, grain size, or crystallinity changes gradually, enhancing mechanical strength, wear resistance, porosity, and elongation (Mahamood and Akinlabi, 2017). Figure 5. shows the microstructure gradient FGM and the change in properties across the cross-section. This gradient in microstructure helps reduce defects caused by radiation exposure which minimises thermal stresses and enhance creep and corrosion resistance. As a result, these materials can withstand extreme nuclear environments, ensuring long-term performance and safety, making them suitable for nuclear applications (Duan et al., 2023). Microstructural gradation can be achieved during the solidification process by controlling the cooling rate and controlled heat treatment techniques. The microstructure gradient FGMs traditionally rely on conventional synthesis methods such as powder metallurgy, diffusion bonding, and plasma spraying, which often struggle with achieving precise gradients and complex geometries. However, 3D printing techniques, such as Direct Energy Deposition (DED), Selective Laser Melting (SLM), and Binder Jetting, offer significant advantages, including fine control over gradient transitions, complex shape fabrication, material efficiency, and reduced processing time (Singh et al., 2017). Compared to conventional methods, 3D printing enables superior customisation, better microstructural integrity, and optimised performance, making it a transformative approach for advanced FGM applications in the energy sector (Alarifi, 2024; Kumar et al., 2022).

8 Computational approaches

Artificial intelligence (AI) and machine learning (ML) are incorporated with AM, especially in the area of process optimisation, defect prediction, and property enhancement for FGMs. Artificial Neural Networks (ANNs), Decision Trees (DTs), Support Vector Machines (SVMs), and Convolutional Neural Networks (CNNs) are some of the most popular machine learning algorithms. Predicting mechanical defects such as surface morphology and dimensional accuracy, these models have helped minimise production errors and optimise process parameters. ANN has been used to predict surface roughness in BJ and to estimate build time in L-PBF. CNNs have successfully classified built quantity in L-PBF, achieving accuracy up to 89%. Meanwhile, CNNs in BJT applications showed ML's precision manufacturing capabilities by accurately predicting dimensional deviations in dental crowns (Jin et al., 2020; Raza et al., 2022; Babu et al., 2023; Ukwaththa et al., 2024).

Furthermore, the integration of explainable AI (XAI) methods into these ML models enhances transparency, interpretability, and user trust. A case study explained how design parameters, such as strut thickness and node radius, affect the Poisson ratio in hexachiral structure FGMs by combining Gaussian process regression (GPR) with SHapley Additive exPlanations (SHAP). Similarly, in L-PBF, SHAP analysis has been utilised to interpret how laser power and feed rate affect the geometry and porosity of Fe-Ni alloys, allowing more confident process optimisation (Ladani, 2021; Ukwaththa et al., 2024; Pancholi et al., 2025).

9 Limitations, challenges and considerations

FGM's synthesised through AM offer significant advantages due to their gradient composition and customizable properties. However, maintaining their structural integrity comes with challenges such as delamination, cracking, porosity, anisotropic behaviour, material inconsistencies, and thermal stress. It is vital to understand this process variation, since it could otherwise be a limiting factor in the use of AM in mission-critical components. One of the major issues of 3D printing is delamination, which occurs primarily at interface zones due to thermal fluctuation, poor interlayer bonding, thermal stresses, melt-pool behaviour, or differences in material properties. Delamination in AM can lead

to structural weaknesses, reduced mechanical properties, and potential failure of the printed component. Delamination is attributed to residual stresses and thermal gradients that occur during printing. However, optimising printing parameters can help mitigate this issue (Flavin et al., 1992; Negi et al., 2013; Frazier, 2014; Thompson et al., 2015; Lou and Gandy, 2019). Similarly, cracking is another common problem, primarily caused by the residual stresses that accumulate during the rapid heating and cooling cycles and post-processing stages. These stresses leads to differential expansion and contraction between the layers. To mitigate this issue, computational models have been developed to predict crack formation, while hybrid AM techniques, including ultrasonic additive manufacturing (UAM), preheating strategies, and heat treatments, are being used to reduce stress buildup and improve material stability. Porosity is another common issue, arising from incomplete fusion or gas entrapment, balling, and keyhole effects, reducing mechanical strength of the components. Studies suggest that optimising powder particle size, energy input, and scanning strategies can help minimise porosity and enhance material density (Zhang et al., 2019; Reichardt et al., 2021; Yoon and Kim, 2024).

Anisotropic behaviour is a major challenge in AM-based FGMs due to the layer-wise deposition process, which introduces mechanical and thermal property variations across different build directions. These microstructural differences affect the functional properties, such as fatigue resistance, mechanical strength, and material performance. Fibre-reinforced and metal matrix composites highlight the impact of material orientation and reinforcement distribution, emphasising the need for large-scale, optimised scanning patterns and post-processing treatments to address anisotropy. Material inhomogeneity is another issue arising from variations in composition and structural inconsistencies within individual layers (Li et al., 2020; Sun et al., 2021; Liao et al., 2024). Improper powder mixing and deposition irregularities can cause mechanical property variations, influencing hardness, ductility, and structural performance. There are some AM techniques, such as multi-material fused filament fabrication (FFF) and laser engineered net shaping (LENS), that have been explored to improve compositional grading and structural uniformity (Kang et al., 2021).

Challenges in AM of FGM material compatibility, process stability, and microstructural control differences in thermal expansion, bonding characteristics, and phase transformations can lead to defects such as cracks, delamination, or porosity. Process stability is another challenge, including optimising printing parameters to achieve consistent material gradients while ensuring defect-free strong layer adhesion and maintaining structural and mechanical integrity under varying conditions. Additionally, at the microscopic level, controlling the material's microstructure is equally important, since uneven phase distribution or internal voids can weaken performance. Research suggests that preheating or post-heat treatment processes, optimised laser parameters, and real-time thermal monitoring can significantly reduce thermal distortions, enhancing the stability and repeatability of AM processes. Addressing these structural issues through advanced manufacturing techniques, smarter process design, and process optimisations is crucial for the successful application of FGMs in engineering applications, from aerospace to biomedical devices (Thomas, 2016; Bergeron and Crigger, 2018).

10 Manufacturing of FGM using AM: future prospects

The future of FGMs manufactured using AM is influenced by emerging trends. One major prospect in hybrid manufacturing, which combines AM with conventional machining and heat treatment to enhance the structural performance. Currently, advanced materials like ceramics, polymers, and composites are being used in AM, thereby expanding their potential applications. Apart from that, AI and ML play a crucial role in optimising printing parameters and predicting material behaviour for improved performance. Sustainability initiatives focus on minimising material waste and developing recyclable FGMs. However, several challenges must be addressed, including material compatibility, process optimisation, cost-effectiveness, and the establishment of industry standards.

Advancements in FGMs using AM will require interdisciplinary collaboration, incorporating numerous fields such as metallurgy, material science, nanotechnology, computational modelling, and materials engineering. In AM, improvements in feedstock material development, process enhancements, and integration with smart materials and sensors will lead to stronger, more resilient, and adaptable FGMs. Improvements in process, such as real-time monitoring, AI-aided parameter control, and modifications, will increase the precision and quality. Through continued research and innovation, the next-generation of FGMs will offer superior performance, reliability, scalability, and adaptability, making them a valuable asset across various industries.

Author contributions

AS: Data curation, Writing – original draft, Writing – review and editing, Validation. MS: Conceptualization, Data curation, Investigation, Validation, Writing – original draft, Writing – review and editing. KD: Writing – review and editing, Conceptualization, Data curation, Writing – original draft.

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