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A REVIEW OF PERFORMANCE METRICS FOR ADDITIVE MANUFACTURING - FUNCTIONALLY GRADED MATERIALS

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Abstract
Additive Manufacturing (AM) combines several material properties into a single component, giving Functionally Graded Materials (FGMs) design freedom. Managing the challenges posed by material incompatibilities during production is critical to the practical application and efficacy of FGMs. In order to describe the performance landscapes of various additively manufactured dissimilar metal FGM combinations, this work synthesizes and investigates the available literature with a focus on important components such as interface integrity, densification, residual stress management, and mechanical properties.
By graphically articulating the relative performance results of different FGM systems, the study's output is a generic framework for material selection accelerating their rational design and broader acceptance.

Key words: Additive Manufacturing (AM), Functionally Graded Materials (FGMs), Mechanical properties, Performance metrics.

Introduction
Additive Manufacturing (AM), often referred to as 3D printing, has emerged as a disruptive technology capable of transforming conventional material processing and design. Unlike traditional subtractive methods, AM builds components layer by layer directly from digital models, offering design flexibility, reduced material wastage, and the ability to fabricate intricate geometries. This capability has opened the door to innovative material concepts such as Functionally Graded Materials (FGMs)**,** which combine multiple materials within a single structure to achieve spatially varying properties.
FGMs provide a gradual transition in composition and microstructure, eliminating the sharp interfaces typically observed in conventional composites. This continuous gradation improves structural integrity, minimizes stress concentrations, and enables the combination of contrasting properties such as toughness and thermal resistance within one component. Such unique attributes make FGMs highly attractive for demanding applications in aerospace, biomedical implants, automotive engineering, and energy systems, where materials are subjected to extreme environments and multifunctional performance is essential.
A key aspect of advancing AM-based FGMs lies in the evaluation of performance metrics**.** Parameters such as mechanical strength, ductility, wear resistance, thermal conductivity, and corrosion resistance are critical in determining their suitability for industrial use. By systematically reviewing these performance indicators, researchers can better understand the strengths, limitations, and potential of FGMs in additive manufacturing. This knowledge not only aids in optimizing material design but also accelerates the adoption of FGMs for real-world applications, driving in novation in next-generation engineering solutions.

Problem definition
Functionally Graded Materials (FGMs) fabricated through Additive Manufacturing (AM) promise tailored property distributions and enhanced performance across diverse applications. However, their practical implementation faces critical barriers. Material incompatibilities during deposition often lead to weak interfaces, residual stress accumulation, and porosity, compromising structural integrity and

reliability. The absence of standardized performance metrics further limits comparative evaluation across studies, hindering optimized material selection and process design. Moreover, the complexity of simultaneously balancing mechanical strength, thermal resistance, and microstructural stability poses challenges for reproducibility and scalability. Thus, a systematic assessment framework is required to establish reliable performance metrics for AM-based FGMs

Methodology
This study adopts a structured literature review methodology to evaluate performance metrics of Functionally Graded Materials (FGMs) fabricated through Additive Manufacturing (AM). The following steps were undertaken:

1. Literature Collection – Research articles, conference papers, and reviews published between 2015–2025 were collected from databases such as Scopus, Web of Science, Science Direct, and IEEE explore. Selection criteria focused on studies reporting performance parameters of AM-produced FGMs.
2. Screening and Classification – The papers were screened based on relevance to dissimilar material combinations, mechanical characterization, and process–property relationships. The selected works were then classified into categories such as *interface integrity, densification, residual stress management, microstructure evolution, and mechanical properties*.
3. Data Extraction – Quantitative and qualitative data were extracted, including reported values of tensile strength, hardness, thermal conductivity, corrosion resistance, and stress–strain behavior. Graphical data were digitized where necessary to ensure comparability.
4. Comparative Analysis – The extracted data were normalized and compared across different FGM systems. Performance trends were analyzed with respect to AM techniques such as Selective Laser Melting (SLM), Directed Energy Deposition (DED), and Powder Bed Fusion (PBF).
5. Framework Development – A generic framework was developed to map the performance metrics of FGMs, graphically illustrating their suitability for different industrial applications. This framework supports material selection and design optimization for advanced AM components.

Literature review
1. **Dr.C. NAGA BHASKAR et.al. This** paper investigates the performance and thermal analysis of disc brakes using **functionally Graded Materials (FGMs)** compared with conventional cast iron. Three materials were studied: cast iron, **FGM 1 (Al_2O_3–Al),** and **FGM 2 (Zr–Al).** Disc brake models with 40, 50, and 60 holes were designed in **Pro/Engineer** and analyzed using **ANSYS** under structural pressure (1.2 N/mm²) and thermal load (373 K). Results show FGMs outperform cast iron in stress resistance and heat dissipation. **FGM 2 (Zr–Al)** exhibited lower stress and higher thermal flux than FGM 1, making it the most suitable material for disc brake applications.

2. **D .RAMBABU, R. VIJAY KRISHNA** .This paper presents the modeling and thermal analysis of disc brake rotors using different designs and materials, comparing conventional cast iron with Functionally Graded Materials (FGMs). Disc brakes face high stresses and thermal loads, so the study evaluates FGMs to improve performance. Three materials were considered: **cast iron**, **FGM 1 (Al_2O_3–Al)**, and **FGM 2 (Zr–Al)**. Models of disc brakes with 40 and 50 holes were designed in **Pro/Engineer** and analyzed using **ANSYS** under a structural load of 1.2 N/mm² and thermal load of 373 K. FGMs were analyzed with material variation parameters **k = 2, 4, 6**. Results showed that FGMs outperform cast iron in stress and thermal analysis. **FGM 1** displayed higher stress and displacement due to its high elastic modulus, while **FGM 2** showed lower stress and higher thermal flux, enhancing heat dissipation. Overall, **FGM 2 (Zr–Al)** proved to be the most suitable material for disc brake rotors.

3. **G. BHARGAV SAI et.al**. This paper reviews advancements in **additive manufacturing with a focus on 4D printing**, an evolution of 3D printing that incorporates time as the fourth dimension,

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enabling objects to self-transform when exposed to stimuli like heat, light, water, or electricity. Unlike traditional materials, 4D printing uses **smart materials** such as shape memory polymers, alloys, hydro gels, photo- and electro-responsive materials. Various additive manufacturing techniques, including SLA, FDM, SLS, and EBM, support this technology. Applications span **medicine, tissue regeneration, stents, soft robotics, aerospace, and automotive industries**. The paper concludes that 4D printing reduces energy use, enhances adaptability, and represents the future of manufacturing.

4. **U. SAI KRISHNA et.al.** The paper reviews the applications of Additive Manufacturing (AM) in the aerospace industry, emphasizing its role as a transformative technology. AM, also known as 3D printing, enables the creation of lightweight, complex, and optimized components while reducing material waste and production costs. Materials such as titanium alloys, nickel alloys, polymers like PEEK and PLA, and advanced composites are widely used. Various methods, including FDM, SLA, SLS, DMLS/SLM, and EBM, are applied for aerospace parts. The study concludes that AM improves efficiency, performance, and sustainability, while also enhancing structural health monitoring, making it a promising technology for future aerospace development.

5. **K. YASHWANTH et.al**. This paper reviews Metal Additive Manufacturing (MAM), a layer-by-layer process of creating complex 3D metal parts using advanced technologies. Common methods include Selective Laser Melting (SLM), Electron Beam Melting (EBM), Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Wire and Arc Additive Manufacturing (WAAM). Materials such as aluminum alloys, titanium alloys, stainless steel, and nickel-based alloys are widely used. MAM offers significant advantages like reduced waste, lightweight structures, high precision, and design flexibility, making it valuable in aerospace, automotive, and medical sectors. Despite challenges like cost, defects, and standardization, MAM is rapidly advancing and revolutionizing modern manufacturing.

6. **M.JAGADEESH et.al**. This paper reviews Polymer Additive Manufacturing (PAM), an important branch of 3D printing that enables lightweight, complex, and customized structures with minimal material waste. Common materials include thermoplastics (ABS, PLA, Nylon, and PEEK), elastomers, thermosets, biopolymers, and polymer composites reinforced with fibre or nano particles. Key PAM methods discussed are Fused Deposition Modeling (FDM), Stereo lithography (SLA), Selective Laser Sintering (SLS), Direct Ink Writing (DIW), and PolyJet printing. The paper concludes that PAM provides cost-effectiveness, design flexibility, and sustainability; though challenges like limited material properties and surface quality remain. Future advancements in composites, nanomaterials, and AI-driven control will further expand PAM applications.

7. **K. YASHWANTH et.al**. This paper presents the design and fabrication of a low-cost, portable 3D printer based on Fused Deposition Modeling (FDM) . The printer uses thermoplastic filaments such as PLA and ABS, extruded layer by layer under computer control through Arduino Mega 2560 with RAMPS 1.4, stepper motors, and G-code instructions. CAD models are converted into STL and sliced with Slic3r software for printing. The developed “Solid Modeler” printer achieved high precision with a 55-micron resolution, lightweight design (7 kg), and affordability (₹24,000). Compared to commercial printers, it offers better resolution, portability, and cost-effectiveness, making it suitable for rapid prototyping applications.

8. **CHEIBAS et.al.** This paper reviews 3D printing, a fast-growing additive manufacturing technology that enables lightweight, complex, and cost-effective designs with rapid prototyping. Materials include polymers, metals, ceramics, and biomaterials, while key processes involve FDM, SLA, SLS, DMLS, and EBM. It concludes that 3D printing is a versatile and transformative technology with wide applications in aerospace, medical, automotive, and consumer industries, though challenges like scalability and material limitations persist.

9. **GISELLE HSIANG LOH, EUJIN PEI** This paper reviews 3D printing technology, also known as additive manufacturing, which fabricates objects layer by layer from digital models. It highlights the advantages of 3D printing such as reduced material waste, cost-effectiveness, rapid prototyping, and the ability to create complex geometries. The paper discusses common materials like

polymers (ABS, PLA, PEEK), metals (titanium, aluminum, stainless steel), ceramics, and composites. Key methods include Fused Deposition Modeling (FDM), Stereo lithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS). Concluding, the study emphasizes 3D printing's vast applications in aerospace, medical, automotive, and consumer industries, despite challenges in scalability and material performance.

10. **CHOY, S. Y.SUN, C. N. LEONG** This paper reviews the development of functionally graded materials (FGMs) using additive manufacturing, emphasizing their advantages over conventional fabrication methods. FGMs feature gradual variations in structure or composition, offering improved performance in biomedical, aerospace, and industrial applications. Materials discussed include titanium alloys (Ti-6Al-4V), polymers, ceramics, metals, and composites. Methods covered are Selective Laser Melting (SLM), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Laser Engineered Net Shaping (LENS), and Electron Beam Melting (EBM). The study demonstrates successful SLM fabrication of a Ti-6Al-4V lattice with smooth gradients, concluding that additive manufacturing provides design flexibility while addressing challenges like thermal stress and fine feature resolution.

11. **LI, Yan et.al**. This paper reviews the applications of Metal Additive Manufacturing (MAM) in the aerospace industry, emphasizing its advantages over conventional methods. MAM enables lightweight, complex, and customized structures while reducing material waste and production costs. Materials commonly used include titanium alloys (Ti-6Al-4V), aluminum alloys (Al-Si10-Mg), nickel-based super alloys (Inconel 718, Hastelloy-X), stainless steels, and cobalt-chrome alloys. Key processes discussed are Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), LENS, WAAM, and Powder Bed Fusion. The study concludes that MAM is transforming aerospace by improving efficiency and sustainability, though challenges like high cost, defects, and certification remain.

12. **MAJIDMOHAMMADI, MASOUDRAJABI** This paper presents a detailed review of functionally graded materials (FGMs), focusing on their classifications, fabrication methods, and wide-ranging applications. FGMs are unique because their properties change gradually across their structure, overcoming the sharp interfaces and weaknesses often seen in traditional composites. The review highlights different material systems, including metal–metal, metal–ceramic, ceramic–ceramic, and polymer-based FGMs, as well as natural examples such as bones and bamboo that inspire engineering solutions. Various fabrication techniques are discussed and categorized into solid-based methods like powder metallurgy and spark plasma sintering, gas-based methods such as chemical or physical vapor deposition and thermal spraying, and liquid-based methods including centrifugal casting, slip casting, gel casting, electrophoretic deposition, chemical solution deposition, laser deposition, and combustion synthesis. The paper concludes that FGMs hold significant promise in fields like aerospace, energy, medicine, defense, and manufacturing. However, challenges in scalability, cost, and defect control remain, requiring further innovation and process optimization for wider industrial adoption.

13. **Silvia MARZAVAN et.al.** This paper reviews mathematical models used to study Functionally Graded Materials (FGMs), a class of advanced composites where properties vary gradually across thickness to improve performance and reduce stress concentrations. Typical FGMs combine ceramics (e.g., Al_2O_3, zirconia) with metals (aluminum, steel, titanium) or other material pairs. The study evaluates several models, including Reuss, Voigt, LRVE, Tamura, Mori-Tanaka, Exponential, Power, and Sigmoid, which describe variations in elastic and physical properties. Results show that models like Power and Voigt are widely used for accuracy. The paper concludes that refining and developing models is essential for advancing FGM design and applications.

14. **Burak Ikinci.** The paper reviews Functionally Graded Materials (FGMs) in dentistry, focusing on their ability to mimic the natural composition of teeth and bone. FGMs are developed using ceramics, metals, polymers, and composite combinations to improve strength, toughness, and biocompatibility. Fabrication techniques include powder metallurgy, centrifugal casting, hot pressing,

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plasma spraying, additive manufacturing, and vapor deposition. Applications include dental implants, crowns, bridges, restorations, and prosthetics, where FGMs provide superior stress distribution and durability compared to conventional materials. The paper concludes that FGMs are highly promising for future dental use, though further research on cost efficiency, manufacturability, and long-term clinical performance is needed.

15. **Jiahao Zhanag et.al.** This paper investigates the fabrication of TiC/Ti6Al4V functionally graded materials (FGMs) using Directed Energy Deposition (DED). Ti6Al4V titanium alloy and TiC ceramic powders were used to achieve gradients up to 50 wt.% TiC. Microstructure analysis (OM, SEM, EBSD, TEM, XRD) and finite element thermal simulations revealed that TiC morphology evolved from eutectic to dendritic with increasing content. The best mechanical properties occurred at 5 wt.% TiC, showing high tensile strength (1296 MPa) and good ductility (7.17%) due to grain boundary and solid-solution strengthening. Higher TiC contents increased hardness but caused brittleness, reducing tensile properties.

16. **Suhas Alkunte et.al**. This paper reviews advancements and challenges in Functionally Graded Materials (FGMs) produced byAdditive Manufacturing (AM). FGMs enable tailored properties across a part, overcoming limitations of traditional materials. Common materials include metals (Ti, Al, steel, Cu, Nb), ceramics (Al_2O_3, ZrO_2), polymers, composites, and CNT-reinforced systems**.** Manufacturing methods discussed are PVD, CVD, powder metallurgy, solid freeform fabrication, laser/electron beam deposition, WAAM, hybrid AM, and AI-driven approaches**.** Applications spanaerospace, automotive, biomedical, robotics, electronics, and 4D printing**.** The study concludes that FGMs have transformative industrial potential but face challenges in defects, cost, scalability, and software limitations, requiring further innovation.

17. **Mohammad Karimzadeh et.al.** This paper reviews the role of Machine Learning (ML) in improving the additive manufacturing of functionally graded materials (FGMs), which are advanced composites with gradual property transitions between dissimilar materials. While FGMs hold great promise for aerospace, biomedical, and energy applications, their fabrication is highly complex due to challenges in process optimization, defect control, and quality assurance. The review highlights how ML techniques can address these issues by optimizing process parameters, predicting thermal histories, detecting defects like porosity or cracks, and even classifying microstructures in real time. It discusses applications across several material systems, including SS316L/Inconel 718, Cu/SS, Ni/Al_2O_3, YSZ/Ni-based superalloys, and Co–Cr alloys, using additive methods such as Directed Energy Deposition and Laser Powder Bed Fusion. The study concludes that ML greatly reduces trial-and-error experimentation and accelerates design, though challenges with data availability and model generalization remain. Integrating ML with physics-based models is identified as a key future direction.

18. **J.B. Marques et.al.** This paper reviews functionally graded adhesives (FGAs**)**, designed to reduce stress concentrations in bonded joints and enhance strength, toughness, and durability. Materials used include epoxy and acrylic adhesives with reinforcements like microparticles, nanoparticles, and metallic fibres. Manufacturing methods involve mixed adhesives, graded curing, variable ratios, and 3D printing. Results show major improvements in strength, toughness, and stress distribution, though challenges remain in reproducibility, particle dispersion, and long-term durability for industrial applications.

19. **REZA GHANAVATI et.al.** This study focuses on optimizing functionally graded materials (FGMs) of AISI 316L stainless steel and IN718 superalloy using laser-directed energy deposition (L-DED). Gas-atomized powders of both alloys were deposited with various gradient designs (multi-material, 50%, 25%). Micro structural analysis (SEM, EDS, EBSD, X-ray CT) and mechanical testing were performed. Results showed the 75% AISI 316L–25% IN718 region was highly susceptible to liquation cracking due to eutectic compounds, oxides, and crystallographic texture. In contrast, the 50% gradient design minimized residual stresses, prevented cracking, and achieved superior tensile

strength (540 MPa), elongation (52%), and toughness (24 kJ/mm³), proving most suitable for defect-free fabrication.

20. **VALMIK BHAVAR et.al.** This paper reviews Functionally Graded Materials (FGMs), highlighting their evolution, manufacturing methods, applications, and challenges. FGMs overcome the weaknesses of conventional composites by providing smooth property transitions, reducing residual stresses and delamination. Materials include combinations of metals, ceramics, polymers, and composites, tailored for aerospace, defense, biomedical, and energy sectors. Manufacturing methods discussed are vapor deposition, powder metallurgy, centrifugal casting, and advanced additive manufacturing techniques such as laser metal deposition, selective laser melting, and electron beam methods. FGMs show superior performance in turbine blades, cutting tools, thermal barriers, implants, and armor systems. Challenges remain in cost, testing, and large-scale adoption.

21. **Lei Yan et.al.** This paper reviews the progress in fabricating metallic functionally graded materials (FGMs) using Laser Metal Deposition (LMD), a promising additive manufacturing technique. Unlike traditional composites, which often fail at sharp interfaces due to stress concentrations, FGMs allow gradual transitions between materials, enhancing performance and durability. The review highlights various material systems studied through LMD, including stainless steels with nickel-based alloys (SS316L/Inconel 718), titanium alloys with AlSi10Mg, Invar or Mo, copper-based alloys with Ni or Inconel, and even magnetic stainless steels (SS316/SS430). Two main fabrication strategies are discussed: the gradient path method, where powder feed ratios are varied gradually, and the intermediate section method, where a third material such as NiCr, vanadium, or VC is inserted to prevent brittle phase formation and cracking. Overall, the paper concludes that LMD is highly effective for producing metallic FGMs with tailored properties, though challenges like crack control, intermetallic suppression, and process optimization remain for large-scale industrial adoption.

22. **Yingchun Fang et.al.** This paper addresses the long-standing challenge of improving the mechanical properties of commercially pure titanium (CP-Ti), which, despite its excellent corrosion resistance and biocompatibility, has limited structural use due to low strength and poor ductility. To overcome this, the researchers explored multi-element alloying during additive manufacturing by blending CP-Ti with 316L stainless steel powder, which introduces Fe, Cr, Ni, and Mo into the titanium matrix. Using laser melting deposition, they fabricated novel alloys and studied their phase evolution, microstructure, and mechanical performance through XRD, SEM, EBSD, TEM, tensile testing, and hardness measurements. Results revealed that the alloying refined α-laths, stabilized β-phases, and suppressed brittle inter metallics, leading to significant property improvements. Notably, the Ti-1.35Fe-0.36Cr-0.24Ni-0.05Mo alloy achieved a strong balance of ~635 MPa tensile strength with 12% uniform ductility, far better than pure titanium. Although higher alloying increased strength further (~920 MPa), it reduced ductility, highlighting the effectiveness of controlled multi-element alloying for designing high-performance titanium alloys.

23. **Garcia collado et.al.** This paper presents a comprehensive review of advances in polymer-based Multi-Material Additive Manufacturing (MMAM), a field that is gaining increasing importance as industries move toward multifunctional, lightweight, and customized products. While additive manufacturing has transformed prototyping and production, producing multi-material components in a single step still poses challenges such as weak bonding at material interfaces, hardware and software limitations, and lack of standardized testing methods. The review highlights the wide variety of polymers used in MMAM, including ABS, PLA, PC, PA6, PA12, TPU, PCL, PET, and ASA, as well as fibre-reinforced composites with glass or carbon fibres. Several techniques are discussed, ranging from Fused Filament Fabrication (FFF) and Stereolithography (SLA/DLP) to Direct Ink Writing (DIW), PolyJet printing, and hybrid polymer–metal approaches. The study concludes that MMAM offers great potential in sectors like biomedical, aerospace, automotive, and electronics, but emphasizes the need to improve interfacial bonding, hardware integration, and standardization for broader industrial adoption.

24. **Phuangphagadaram et.al.** This paper focuses on developing functionally graded Ni–Ti alloys using the Laser Powder Bed Fusion (L-PBF) process, aiming to overcome the difficulties of joining nickel- and titanium-based alloys, which often suffer from cracking and brittle intermetallic formation due to their chemical and physical mismatches. Pure Ni and pure Ti powders were blended in controlled ratios and deposited layer by layer to create smooth compositional gradients. The fabricated samples were examined using SEM, EDS, XRD, EBSD, hardness testing, and thermodynamic simulations to study phase evolution and microstructural changes. Results showed a sequence of transformations, from γ-Ni to Ni_3Ti, NiTi phases, $NiTi_2$, and finally α/β-Ti. Cracks appeared mostly in regions rich in Ni_3Ti and $NiTi_2$, where brittleness was highest, while hardness peaked at around 685 HV in the 30% Ti region before stabilizing near 520 HV in Ti-rich areas. Overall, the study demonstrated L-PBF's potential for producing advanced Ni–Ti FGMs, though minimizing cracking remains a key challenge.

25. **Srinivasan Chandrasekaran et.al.** This paper addresses the critical issue of corrosion and strength loss in marine risers, which are essential for transporting crude oil and gas in harsh offshore environments. Conventional carbon-manganese steels, like X52, are vulnerable to corrosion and mechanical failures, so the study proposes a functionally graded material (FGM) riser combining duplex stainless steel and carbon-manganese steel. Using Wire Arc Additive Manufacturing (WAAM) with Cold Metal Transfer (CMT)–Gas Metal Arc Welding, the researchers fabricated graded layers of both materials and evaluated their structural and corrosion performance. Advanced testing methods, including X-ray computed tomography, tensile tests, microstructural analysis, hardness measurements, and corrosion studies, confirmed the integrity of the build. Results showed that the FGM achieved yield strength comparable to X52 steel with a 6% higher ultimate strength, while the interface remained defect-free and highly bonded due to martensite formation. Importantly, corrosion resistance improved twelve-fold compared to carbon-manganese steel, making the proposed FGM a strong candidate for reliable marine riser applications.

26. **Seymur Hasanov et.al.** This paper explores the development of functionally graded materials (FGMs) using fused filament fabrication (FFF) to overcome the common problem of weak interfaces and stress concentrations in multi-material additive manufacturing. Instead of abrupt transitions, the study focuses on creating smooth gradients between materials to enhance bonding and performance. The materials used were neat Acrylonitrile Butadiene Styrene (ABS) and short carbon fibre reinforced ABS (CF/ABS), chosen to investigate how gradual reinforcement transitions affect strength. To achieve this, researchers applied a voxelization-based design approach, followed by FFF multi-material 3D printing with both direct and graded transitions. Mechanical evaluation was carried out through tensile testing in line with ASTM D638, supported by microstructural analysis and hierarchical homogenization with finite element modeling to predict behavior across scales. The findings showed that gradual transitions greatly improved interface strength, with tensile strength increases of up to 84% over sharp transitions. Experimental and computational results aligned closely, proving FFF's effectiveness in producing stronger, reliable FGMs.

27. **Bassiouy Saleh et.al.** This paper provides a broad review of thirty years of progress in the field of functionally graded materials (FGMs), highlighting their growing importance in industries such as aerospace, automotive, biomedical, and defense. Unlike traditional homogeneous materials, FGMs are designed with gradual variations in composition and structure, enabling them to meet demanding requirements like thermal resistance, strength, and wear protection in a single component. The review does not focus on one specific material but discusses a wide range of systems, including metal–metal, metal–ceramic, ceramic–ceramic, and ceramic–polymer composites such as Al–SiC, ZrO_2–NiCr, TiO_2–HA, Ni/YSZ, and SS316L–hydroxyapatite. It examines multiple processing methods, ranging from deposition-based techniques like PVD, CVD, and thermal spraying to solid-state routes like powder metallurgy and modern additive manufacturing technologies. The paper concludes that while FGMs have shown remarkable advancements, future research must address cost efficiency, large-scale production, and better process control to fully unlock their industrial potential.

28. **Shuwei ji et.al.** This study focuses on developing a high-temperature resistant functionally graded material (FGM) coating made of Ti-6Al-4V and Inconel 718, aimed at meeting the demanding needs of aerospace and turbine applications. Traditional fabrication methods struggle to achieve both structural stability and desired composition, so the researchers employed Directed Energy Deposition – Laser (DED-L) to gradually deposit Ti-6Al-4V and Inconel 718 powders in controlled layers. The process began with a Ti-6Al-4V substrate, followed by gradient layers with increasing Inconel 718 content, and finally pure Inconel 718 layers at the top. The resulting coating was analyzed using microscopy, XRD, TEM, hardness testing, and computational phase diagram calculations. Findings showed a smooth transformation of microstructure and phases, with grain refinement and precipitation of strengthening compounds like Ti_2Ni and TiNi. Microhardness improved significantly, peaking at 1030 HV1 in the Inconel 718 layer, while the coating demonstrated strong thermal stability up to 900 °C, proving its reliability for extreme environments.

29. **Ioan Milosan et.al.** This paper investigates the significance of additive manufacturing (AM) in industrial engineering, emphasizing its ability to create lightweight designs, shorten production times, and provide greater design freedom compared to traditional methods. It reviews several materials commonly used in AM, including titanium alloys like Ti-6Al-4V, nickel-based alloys such as Inconel, aluminum alloys, stainless steels, and composites, which broaden its industrial applications. The study also outlines a range of AM processes—Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer—each with its own strengths and challenges. In its conclusion, the paper identifies AM as a transformative technology with strong potential to enhance efficiency, material utilization, and design flexibility in industry. However, it also highlights that for AM to achieve broader adoption, key challenges such as defects, anisotropy, fatigue performance, and the lack of proper certification and standardization must be resolved.

30. **Y.Y. SU et.al.** Additive manufacturing (AM) is transforming industrial fields by enabling the production of lightweight structures, optimized designs, and complex shapes that traditional methods can't match. This technology utilizes a diverse range of materials, including titanium alloys, nickel-based alloys, aluminum alloys, stainless steels, and composites, each offering unique benefits for specific applications. Various AM processes, such as Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer, are being explored for their potential and limitations. While AM holds the key to revolutionizing industry through enhanced efficiency, material utilization, and design flexibility, challenges like defects, anisotropy, fatigue strength, and the need for reliable certification and standardization must be addressed to unlock its full potential and achieve widespread adoption.

31. **Islan M.EI-Galy et.al.** This paper examines the expanding role of additive manufacturing (AM) in modern industries, highlighting its ability to create lightweight structures, speed up production, and provide greater design flexibility compared to traditional methods. It reviews a range of materials commonly used in AM, including titanium alloys such as Ti-6Al-4V, nickel-based alloys like Inconel, aluminum alloys, stainless steels, and advanced composites, each chosen for their suitability in different applications. The study also discusses several important AM processes, including Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer, outlining their unique benefits and challenges. In conclusion, the paper recognizes AM as a transformative industrial technology with the potential to improve efficiency, save materials, and enable innovative designs. However, it stresses that for AM to achieve widespread adoption, issues such as defects, anisotropy, fatigue resistance, and the lack of standardized certification must be addressed.

32. **Magda silva et.al.** This paper explores the significance of additive manufacturing (AM) in engineering, emphasizing its ability to produce lightweight structures, reduce production time, and enable complex designs that traditional methods cannot easily achieve. It reviews a variety of materials commonly used in AM, such as titanium alloys like Ti-6Al-4V, nickel-based alloys such as Inconel,

aluminum alloys, stainless steels, and composite materials, each suited to different industrial needs. The study also examines key AM processes, including Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer, highlighting their unique advantages and challenges. In conclusion, the paper identifies AM as a transformative technology capable of enhancing efficiency, material utilization, and design flexibility in industry. However, it also underlines that widespread adoption requires solving persistent issues such as defects, anisotropy, fatigue performance, and the lack of established certification and standardization frameworks.

33. **Cahi Zhang et.al.** This paper explores the role of additive manufacturing (AM) in engineering, showing how it can revolutionize production by enabling lightweight designs, reducing manufacturing time, and allowing the creation of complex geometries that are difficult to achieve with conventional methods. It highlights the wide range of materials used in AM, including titanium alloys like Ti-6Al-4V, nickel-based alloys such as Inconel, aluminum alloys, stainless steels, and composites, all of which expand its applications across different industries. The study also reviews several important AM processes, including Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer, each offering specific advantages and limitations. In conclusion, the paper identifies AM as a transformative technology that improves efficiency, saves materials, and enhances design flexibility, while emphasizing that issues such as defects, anisotropy, fatigue performance, and the lack of proper certification and standardization must be addressed for broader industrial adoption.

34. **S.M. Banait et.al.** This paper looks at how additive manufacturing (AM) is changing industrial and mechanical engineering by making it possible to create lighter, more efficient designs, speed up production, and build complex shapes that traditional methods can’t easily achieve. It highlights the wide range of materials used in AM, including titanium alloys like Ti-6Al-4V, nickel-based alloys such as Inconel, aluminum alloys, stainless steels, and advanced composites, all of which expand its usefulness across industries. The study also explains key AM processes—Powder Bed Fusion, Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer—showing how each has its own advantages and challenges. Ultimately, the paper concludes that AM is a game-changing technology with the potential to boost efficiency, reduce weight, and save material. However, it also stresses that for AM to reach its full potential, issues such as defects, fatigue performance, anisotropy, and the need for certification and standards must be addressed.

35. **Rajkumar Velu et.al.** The paper investigates the role of additive manufacturing (AM) in engineering industries, emphasizing its ability to reduce weight, optimize designs, shorten production times, and enable complex geometries, while also acknowledging challenges such as defects, fatigue life, anisotropy, and the need for standardization. It reviews a wide range of materials commonly used in AM, including titanium alloys like Ti-6Al-4V, nickel-based superalloys such as Inconel, aluminum alloys, stainless steels, and various composite materials. The study also highlights several AM processes, including Powder Bed Fusion (both laser and electron beam), Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer, each offering unique benefits and limitations for industrial applications. In conclusion, the paper identifies AM as a transformative technology with significant potential to revolutionize industry by improving efficiency, material utilization, and design flexibility, but stresses that addressing current limitations and establishing certification and standardization are essential for its broader adoption.

36. **Alexander SCHMIDT et.al.** The paper analyzes the impact of additive manufacturing (AM) technologies in mechanical engineering and industrial applications, emphasizing their ability to enable lightweight structures, reduce production time, and provide design freedom, while also noting challenges such as structural integrity, defects, and fatigue behavior. It reviews a range of materials used in AM, including titanium alloys (particularly Ti-6Al-4V), nickel-based alloys like Inconel, aluminum alloys, stainless steels, and polymer composites, especially for structural and automotive applications. Various AM methods are discussed, such as Powder Bed Fusion (laser-based and electron

beam melting), Directed Energy Deposition, Wire Arc Additive Manufacturing, Binder Jetting, and Cold Metal Transfer. The paper concludes that AM represents a transformative technology for industry, offering benefits in lightweighting, material efficiency, and design flexibility, but stresses that issues of fatigue resistance, anisotropy, defects, and the need for certification and standardization must be resolved for its widespread industrial adoption

37. **Yoshinari Miyamoto.** The paper reviews the applications of Functionally Graded Materials (FGMs) in Japan, highlighting their unique ability to integrate dissimilar materials and optimize properties such as toughness, hardness, and thermal resistance. Key applications include aerospace components like reusable rocket engine combustion chambers, high-performance cutting tools, and biomaterials such as hip prostheses and dental implants. FGMs are also being explored for energy systems, nuclear reactors, and electronic devices. While commercialization is still limited, successful uses in cutting tools and biomedical implants demonstrate their potential. Future progress depends on improving reliability, cost-effectiveness, and developing advanced manufacturing processes.

38. **Roberto Citarella et.al.** Additive manufacturing is changing the game in industrial applications, and this editorial shines a spotlight on its growing importance. By allowing for new design possibilities, weight reduction, and simplified production, AM is opening doors to innovative solutions. However, it's not without its challenges - issues like residual stresses, anisotropy, and surface roughness need to be addressed. Researchers are exploring various materials and techniques, from polyamide and titanium alloys to advanced methods like Laser Powder Bed Fusion and Wire Arc Additive Manufacturing. While AM has tremendous potential for creating high-performance products, it's crucial to overcome hurdles like fatigue, fracture, and standardization. Despite these challenges, the future of AM looks bright, and this Special Issue aims to inspire further research and innovation in the field.

39. **Byron Blaker – Milner, Paul Gradl** - This paper reviews the state-of-the-art of metal additive manufacturing (AM) in the aerospace industry, highlighting its potential, limitations, and future opportunities. The review covers commonly used aerospace materials, including Titanium alloys, Nickel-based superalloys, Aluminum alloys, Stainless steels, and Cobalt-chromium alloys, which are valued for their strength, heat resistance, and lightweight properties. The paper discusses major AM techniques, such as Powder Bed Fusion, Directed Energy Deposition, Binder Jetting, and Sheet Lamination, and their advantages and challenges in aerospace applications. The conclusion is that metal AM has significant potential for creating lightweight, complex, and high-performance components, but challenges like material defects, process variability, and certification issues need to be addressed. Despite these challenges, the outlook is optimistic, with ongoing research and improved reliability expected to play a transformative role in aerospace manufacturing. Metal AM is poised to reduce weight, cost, and lead time while enabling design freedom.

40. **Chenyang Wang et. al.** This paper focused on defect-free bimetallic structure composed of Titanium alloy (TC4) and Nickel-based alloy (IN718) was successfully fabricated using Laser Additive Manufacturing (LAM) with a Tantalum/Copper (Ta/Cu) multi-interlayer. This approach effectively suppressed the formation of brittle inter metallic compounds (IMCs) that typically cause cracks when joining these alloys directly. The LAM process utilized a 6000 W fibre laser and Argon-purged chamber, with a CNC and coaxial powder delivery system. Characterization methods included SEM, EDS, XRD, Vickers hardness testing, and tensile testing. The results showed a good metallurgical bond between the two alloys, with a phase evolution from α-Ti to γ-Ni + laves. The Vickers hardness values remained close to those of the pure materials, and the ultimate tensile strength (UTS) was 369.32 MPa at room temperature. Fracture occurred in the Ta region near the Ta/Cu interface, exhibiting quasi-cleavage fracture. The Ta/Cu interlayer proved effective in improving bonding and preventing cracks, making it a promising method for aerospace bimetallic structures. This development has significant potential for enhancing the performance and durability of aerospace components.

41.

Results

The following graph shows the comparison of strength for different materials

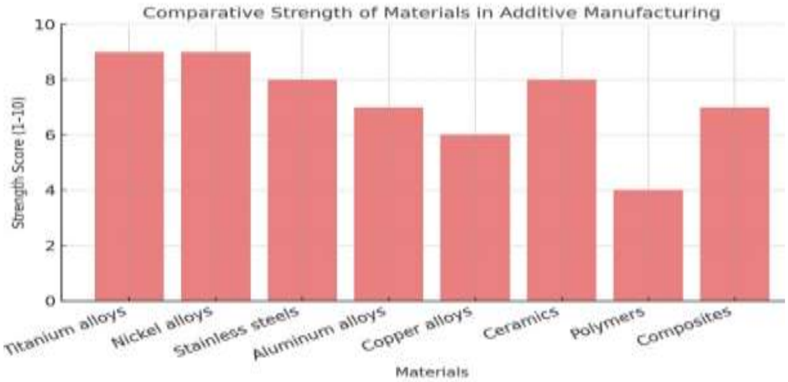


Fig:1 Comparative strength of materials in additive manufacturing

The following graph shows the comparison of corrosion resistance for different materials

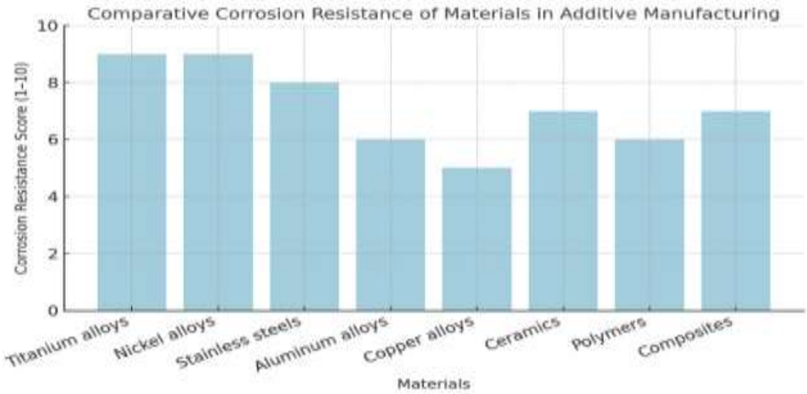
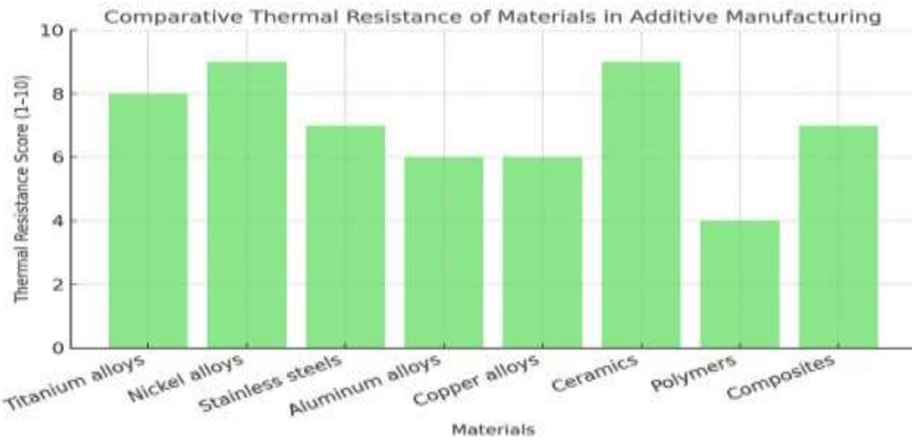


Fig:2 Comparative corrosive resistance of materials in additive manufacturing

The following graph shows the comparison of thermal resistance for different materials



Fig;3 Comparative thermal resistance of materials in additive manufacturing

The following shows the overall graph representation of three parameters (strength , termal resistance , corrosion resistence)

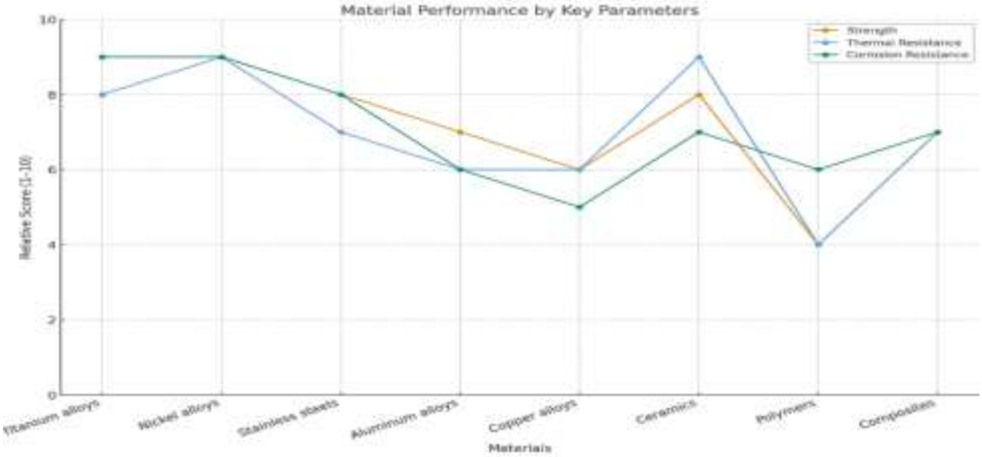


Fig-4 : Material Performance Comparison: Strength, Thermal Resistance, and Corrosion Resistance

Dicussion

Titanium and nickel alloys emerge as the most reliable materials, offering superior strength, corrosion, and thermal resistance with balanced ductility. Stainless steels provide a good compromise, while ceramics excel only in heat resistance. Polymers and copper remain less effective, making titanium and nickel the best overall performers.

Conclusion

Based on the comparative analysis of strength, thermal resistance, and corrosion resistance, Titanium alloys and Nickel alloys consistently outperform other materials. Titanium alloys (Ti-6Al-4V, TC4) offer an excellent balance of high strength, lightweight nature, superior corrosion resistance, and good thermal stability, making them highly versatile for aerospace, biomedical, and automotive applications. Nickel alloys (Inconel 718, Hastelloy) exhibit exceptional strength and outstanding thermal resistance at extreme temperatures, making them ideal for turbines, aerospace engines, and high-heat environments, though they are heavier and costlier. Overall, Titanium alloys are the best all-round performers, while Nickel alloys are superior for extreme thermal conditions.

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