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A REVIEW ON POLYMER ADDITIVE MANUFACTURING

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ABSTRACT

Additive manufacturing, or 3D printing, creates objects by building them layer by layer from a digital model, unlike traditional methods that remove material. This technique allows for the precise production of complex, customized shapes using materials like plastics, metals, and ceramics. Polymer additive manufacturing, a subset of 3D printing, uses polymer-based materials to fabricate objects, offering versatility in mechanical properties. Its advantages include reduced waste, shorter lead times, and lightweight, high-strength components, making it ideal for industries like aerospace, automotive, and healthcare. This technology enhances design freedom, supports rapid innovation, and promotes sustainability by minimizing waste and enabling on-demand production

Keywords:
3D printing , Additive manufacturing , polymer

I. Introduction

Polymer additive manufacturing (PAM), or 3D printing, has transformed the manufacturing industry by enabling the production of complex, customized components and functional prototypes with high speed and flexibility. Originally a prototyping tool, PAM now produces end-use parts for industries such as aerospace, automotive, healthcare, and consumer goods. The technology deposits polymer materials layer by layer from digital models, reducing material waste and enabling the creation of intricate structures not achievable with traditional methods. Recent advancements in high-performance polymers like PEEK and PPS, along with multi-material and continuous fiber reinforcement techniques, have expanded PAM's capabilities, making it suitable for producing parts with excellent mechanical, chemical, and thermal properties

II. Literature

S Raja A., [1] Polymer additive manufacturing (PAM), or 3D printing, has revolutionized manufacturing by enabling the rapid creation of complex, customized components and functional prototypes. Evolving from a prototyping tool, PAM now produces end-use parts in industries such as aerospace, automotive, and healthcare. By selectively depositing polymer materials layer by layer, PAM minimizes waste and allows for the creation of intricate structures. Recent advancements in high-performance polymers, multi-material techniques, and post-processing have expanded PAM's capabilities. However, challenges remain in process control, material optimization, surface finish, scalability for mass production, and sustainability.

Ans Al Rashid et al., [2] Polymer nanocomposites, known for their high strength-to-weight ratio and customizable features, are gaining attention in research, especially with the integration of additive manufacturing (AM) techniques like fused deposition modeling (FDM) and selective laser sintering (SLS). AM allows for complex geometries and precise material control, combining nanotechnology's benefits with advanced manufacturing. However, challenges remain in uniformly dispersing nanoparticles, essential for optimizing properties like mechanical strength and thermal stability.

Researchers are exploring various nanofillers to enhance these materials, focusing on optimizing compositions, processing parameters, and structural properties. This review highlights the potential of AM in advancing polymer nanocomposites, despite challenges in synthesis and processing.

Alianna Maguire et al., [3] Extrusion-based additive manufacturing (AM), including Fused Filament Fabrication (FFF) and Direct Ink Writing (DIW), is crucial for creating complex, high-performance structures in industries like aerospace, medical, automotive, and electronics. These techniques enable precise layer-by-layer deposition of polymers and composites, allowing for customized mechanical properties and the incorporation of various fillers. While advancements have been made, challenges remain in optimizing material properties, improving adhesion, and enhancing print quality. Future research will focus on reducing waste, developing novel composites, and improving sustainability, positioning extrusion-based AM as a key player in innovative manufacturing processes.

Saad Saleh Alghamdi et al., [4] Polymer additive manufacturing (AM) has advanced from prototyping to a versatile manufacturing method, capable of transforming traditional production processes. By building objects layer by layer from digital models, AM offers exceptional design flexibility and minimal material waste. Techniques like Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) are prominent for producing a wide range of parts, from prototypes to functional components, across various industries. The development of advanced materials, including composites, nanocomposites, and shape memory polymers, further enhances AM's versatility. As research progresses, polymer AM is poised to become more integrated into mainstream production, offering flexible, efficient, and sustainable manufacturing solutions. Future advancements will focus on overcoming challenges and expanding the applications of polymer AM in modern manufacturing.

TahaminaNasrin et al., [5] Integrating machine learning (ML) into additive manufacturing (AM) optimizes the production of complex polymer structures by addressing challenges like quality control and defect management. ML algorithms analyze AM process data to predict and set optimal conditions, minimizing defects and improving efficiency. ML-driven design optimization explores design spaces to create innovative, manufacturable geometries, with real-time adjustments ensuring consistent quality. Additionally, ML aids predictive maintenance by monitoring equipment performance and detecting anomalies. In polymer AM, particularly Fused Filament Fabrication (FFF), artificial neural networks (ANNs) are crucial for predicting material properties and optimizing processes. Future research will focus on refining these methodologies to enhance material adaptation, design innovation, and production efficiency.

Taha Sheikh et al., [6] This study focuses on enhancing the mechanical properties of Fused Filament Fabrication (FFF) printed objects by incorporating carbon nanotube (CNT) composites. A novel three-scale computational model, combined with a water-quenching technique, improved CNT-infused filaments. Results showed that CNTs significantly increased bonding and the elastic modulus of 3D-printed parts compared to pure ABS, though higher CNT content (above 10 wt%) increased brittleness. The water-quenching technique improved nanotube dispersion, leading to uniform properties in the polymer matrix. The computational model aligned closely with experimental data, offering a valuable tool for optimizing FFF processes and part performance with CNTs. This research highlights the potential of nanocomposite materials to enhance FFF, enabling stronger, more reliable 3D-printed components.

Abinesh Ravi et al., [7] Advancements in material extrusion-based 3D printing, particularly Fused Deposition Modeling (FDM), are addressing anisotropic mechanical properties with techniques like near-IR laser-based pre-deposition heating. This method improves inter-layer bond strength by heating existing layers before adding new material, enhancing bond strength by 50% and improving isotropy. Unlike traditional heating methods, laser heating offers precise, localized heating, boosting intermolecular interactions for stronger bonds. Tests with a LulzBot Mini 3D printer and ABS filament showed improved mechanical performance, and real-time temperature monitoring further enhances control over printed part properties. This innovation overcomes FDM limitations, promising high-strength, reliable components for engineering applications and broader industry adoption.

Kartikeya Walia et al., [8] Polymer-based additive manufacturing (AM) is transforming industrial robotics by offering design flexibility, customization, and cost-effectiveness. It enables rapid prototyping and development of robots tailored to specific tasks, reducing risks and costs. Techniques like material extrusion and powder bed fusion produce lightweight, customized components with specific mechanical and thermal properties. Despite challenges with dimensional accuracy and material limitations, AM's ability to iterate designs quickly minimizes waste and lowers costs. AM is especially valuable in sectors like food processing and plastics, where affordable automation is sought. Optimizing AM involves selecting suitable processes, meeting application requirements, and iterative design and testing, making AM essential for advancing cost-effective, high-performance robotics.

Soheila Shabaniverki., [9] In additive manufacturing (AM), integrating micro- or nanoparticles into polymer matrices creates advanced composites with enhanced mechanical, electrical, thermal, and optical properties. Applying external fields like electric, magnetic, or acoustic forces aligns these particles, resulting in functionally graded materials with tailored characteristics. This approach is vital for applications in wearable sensors, energy storage, and soft robotics. Controlling particle distribution and alignment improves the mechanical properties of the composites, enabling the creation of high-performance, multifunctional materials. As these techniques advance, they promise to revolutionize AM by developing next-generation materials with exceptional performance for specific applications.

Miryam Criado-Gonzalez et al., [10] Additive manufacturing (AM) has advanced the fabrication of conducting polymers (CPs), enabling the creation of complex, three-dimensional structures with high spatial resolution. This overcomes the limitations of traditional methods like solvent casting and spin-coating, allowing for shape-conformable, multifunctional electronic devices. AM techniques such as inkjet printing, extrusion, and stereolithography are adapted to handle the insoluble and infusible nature of CPs, expanding their use in wearable electronics, sensors, and health monitoring. Materials like PEDOT, PPY, and PANI show promise, with ongoing research into other CPs like P3HT and PPV. Optimizing CP formulations and printing parameters could revolutionize the production of high-performance, bespoke wearable bioelectronics.

J.M. Jaffer son et al., [11] Polymers are central to additive manufacturing (AM), providing versatility, cost-effectiveness, and ease of processing. AM uses polymers to create complex, customized components with specific mechanical properties for various applications. Key materials include Shape Memory Polymers (SMPs), thermoplastics, elastomers, thermosets, and bio-polymers, each selected for traits like strength, elasticity, and thermal stability. For example, Polybutylene terephthalate and Polypropylene are valued for their durability. Techniques such as SLA, DLP, and CLIP enable high-precision, complex geometries. Advanced materials like PA12 and BASF’s Ultrasint TPU 90A highlight the focus on high-performance polymers for sectors like automotive, aerospace, and healthcare. As AM evolves, innovations in polymer technology will drive further growth and the creation of efficient, functional, and sustainable products.

Kirstie R et al., [12] Additive manufacturing (AM) has greatly enhanced the creation of complex geometries with high precision by integrating electrically conductive polymers (CPs) and polymer nanocomposites. AM allows for the layer-by-layer fabrication of low-density, cost-effective conductive parts, offering flexibility and customization not possible with traditional methods. Techniques such as FDM, DIW, and SLS provide various benefits in processing CPs and nanocomposites, while vat polymerization and inkjet printing methods offer smooth, precise results. This integration opens new possibilities for wearable technology, smart materials, and advanced electronics. As research advances, AM combined with conductive polymers is set to transform electronics design and manufacturing, providing lightweight, customizable solutions.

Sagar D Kapil et al., [13] Additive manufacturing (AM) of polymer composites offers cost-effectiveness, waste reduction, and design flexibility, enabling rapid prototyping and production of complex geometries. Techniques like FDM, binder jetting (BJ), and direct energy deposition (DED) each have unique benefits and challenges. FDM is cost-effective but struggles with filler distribution, while BJ provides precise deposition but requires careful handling of materials. Despite advancements, challenges remain in material performance and technique-specific limitations. Ongoing research and interdisciplinary collaboration are needed to address these issues and fully harness AM's potential in creating strong, flexible, and functional composites for various industries, including aerospace and biomedical engineering.

Antonio Dominguez-Alfaro et al., [14] The development of PLA-based composite filaments for fused filament fabrication (FFF), incorporating gas-atomized maraging steel particles, enhances magnetic properties in 3D-printed components. The spherical particles reduce filament viscosity, allowing for lower extrusion temperatures and improved printability, while decreasing energy consumption. Rheological characterization helps optimize printing conditions, and X-ray tomography shows a log-normal distribution of particles, improving flow properties. This innovation addresses traditional FFF limitations by offering custom filaments with magnetic functionality, enabling efficient applications in electronics, sensors, and actuators, and reducing environmental impact and energy costs.

Md Aminul Islam et al., [15] Additive manufacturing (AM) has revolutionized polymer research by offering unmatched design flexibility and material efficiency while minimizing waste. Unlike traditional methods, AM enables the rapid creation of intricate, customizable structures with minimal environmental impact. Techniques such as Poly Jet and stereolithography (SLA) have advanced, allowing for high-resolution, multi-material, and multicolor prints. Poly Jet uses inkjet heads and UV light to produce detailed, flexible parts, while SLA has evolved with methods like Continuous Liquid Interface Production (CLIP) for faster, large-scale printing. Quality evaluation methods such as SEM, DMA, TGA, and DSC ensure the performance of printed polymers. AM continues to transform industries by addressing complex manufacturing challenges and enabling innovative polymer applications.

Arthur Lepoivrea et al., [16] Additive manufacturing (AM), particularly Fused Filament Fabrication (FFF), enables complex geometry creation but often results in lower mechanical properties compared to traditional methods like thermoplastic injection molding. To address this, a modified CR-10 printer with advanced thermal controls, including a 500W heating plate and an insulated chamber, was developed to study heat exchanges during printing. Thermal characterization using an infrared camera and pyrometer revealed that vertical heat transfer is key for layer adhesion. A numerical model predicted cooling rates and adhesion, showing that interlayer adhesion, or "degree of healing," is quickly achieved within 0.5 seconds. For ABS, an extrusion temperature of 255°C was optimal, while PEKK required even higher temperatures, highlighting the need for precise thermal management. This research enhances understanding of thermal dynamics in FFF, leading to better control and improved mechanical properties in 3D-printed parts.

David Macerates et.al., [17] Conducting polymers (CPs) such as PEDOT, polypyrrole (PPY), and polyaniline (PANI) are increasingly used in additive manufacturing (AM) for bioelectronic and energy devices due to their flexibility and improved performance over traditional rigid electronics. The shift from 2D films to 3D structures necessitates advanced AM techniques like inkjet, extrusion-based, electrohydrodynamic, and light-based printing. PEDOT:PSS, in particular, is valued for its high conductivity, optical transparency, and stability. Inkjet printing has successfully created stretchable, multilayer electrodes with PEDOT:PSS, preserving its properties in complex 3D forms. However, challenges in processability often require additional polymers or nano-additives to maintain conductivity. As research progresses, 3D-printed CPs are poised to advance bioelectronics, including wearable devices, sensors, and soft robotics.

Mathias Wiese et.al., [18] This review examines the compatibility of polymer additive manufacturing (AM) processes and materials for automotive series production, guided by the VDA 232-201 standard. It traces AM's evolution from stereolithography to various commercial processes and rapid manufacturing (RM) for end-use parts. The study analyzed 129 materials and 47 AM machines across four categories—PBF, ME, VP, and MJ—using data from eight OEMs, creating material selection charts and a compatibility index. The findings suggest that this system can assist in material selection across different AM technologies, although data inconsistencies and varied testing methods present challenges. The methodology is relevant for other industries, such as aerospace and medical, aiming to enhance AM adoption and decision-making.

Md Aminul Islam et.al., [19] Additive manufacturing (AM) is advancing drug delivery by enabling complex geometries and programmed release profiles. Integrating AM with polymers allows for optimized drug delivery systems that enhance safety, efficacy, and patient compliance. Systems include matrix (simple production, based on drug-polymer interactions), reservoir (constant release with a polymeric membrane), and conjugated (drugs attached to polymers for controlled release). Advanced 3D printing techniques offer precise control over pore size and architecture. Despite the conservative stance of the pharmaceutical industry, AM shows promise for personalized medicine and improved clinical outcomes in drug delivery.

Thomas Hofstetter et.al., [20] Additive manufacturing (AM) is increasingly used for producing functional parts, with a focus on enhancing mechanical properties by integrating fibers into plastic composites. Fiber-reinforced composites improve tensile strength and Young's modulus, but challenges like proper fiber placement and material handling remain. This research examines fiber-reinforcement in AM using vat polymerization (VP) and material extrusion (ME). VP allows for fine features and cost-effective production, while ME extrudes fiber-filled filaments at high temperatures. The study produced fiber-reinforced injection molding (IM) inserts with carbon fibers in HTM 140 photopolymer, analyzing fiber-matrix interactions through imaging and tensile testing. Results showed increased mechanical strength but also fiber segregation issues, with suggestions for process adjustments to improve outcomes. Overall, the research highlights the potential of AM with fiber reinforcement as a sustainable and cost-effective alternative for rapid prototyping and pilot production in IM technology.

Haihong Huang et.al., [21] A novel recycling approach combines carbon fiber reclamation and composite additive manufacturing to transform Carbon Fiber Reinforced Polymer (CFRP) waste into new 3D parts. The process involves recycling CFRP with supercritical n-butanol, grinding the reclaimed fibers, and mixing them with PEEK powder. This mixture is then extruded into a composite filament for additive manufacturing. The method offers a sustainable solution by reducing the environmental impact and production costs of virgin carbon fiber, known for its high energy consumption. Supercritical fluid technology ensures high-strength, clean recycled fibers, while 3D printing enables the creation of complex, customized parts with minimal waste. This integrated approach presents a viable way to convert CFRP waste into valuable products, promoting sustainability in industries reliant on carbon fiber composites. Future research will focus on optimizing the recycling process and scaling production.

M.S Islama et.al., [22] This study explores enhancing interlaminar shear strength (ILSS) of multi-directional prepreg laminates using polymer additive manufacturing (PAM) with fused deposition modeling (FDM). Reinforcement patterns are imprinted onto carbon prepregs to fabricate laminates. Numerical simulations identify delamination-prone regions for targeted reinforcement. Two laminate types, A and B, with 40 layers each, are tested under three conditions: pristine, FDM-printed interfaces, and FDM-printed interfaces with additional resin to address voids. Using carbon fiber prepregs, Epon 862 resin, EPIKURE 9553 hardener, and PLA filament at 215°C, the method aims to improve ILSS values and mitigate delamination, despite potential epoxy-PLA compatibility issues.

Michael Borish et.al., [23] A novel recycling approach combines carbon fiber reclamation and composite additive manufacturing to transform Carbon Fiber Reinforced Polymer (CFRP) waste into new 3D parts. The process involves recycling CFRP with supercritical n-butanol, grinding the reclaimed fibers, and mixing them with PEEK powder. This mixture is then extruded into a composite filament for additive manufacturing. The method offers a sustainable solution by reducing the environmental impact and production costs of virgin carbon fiber, known for its high energy consumption. Supercritical fluid technology ensures high-strength, clean recycled fibers, while 3D printing enables the creation of complex, customized parts with minimal waste. This integrated approach presents a viable way to convert CFRP waste into valuable products, promoting sustainability in industries reliant on carbon fiber composites. Future research will focus on optimizing the recycling process and scaling production.

Alireza Nouri a et.al., [24] Additive manufacturing (AM), particularly laser powder bed fusion (L-PBF), has revolutionized the production of load-bearing prostheses and implants in hard-tissue engineering. L-PBF enables the precise fabrication of complex biomaterials with customized porosity, crucial for orthopedic, craniofacial, maxillofacial, and dental applications. This technology builds parts layer by layer using lasers, offering high accuracy and resolution, with typical layer thicknesses of 20-100 μm for metals and ceramics, and 100 μm for polymers. While L-PBF excels in creating intricate geometries and controlled microarchitecture, challenges like limited material compatibility, dimensional accuracy, and post-processing costs remain, necessitating further refinement to optimize its use in advanced biomaterial applications.

Claudio Favia et.al., [25] This study evaluates adhesive bonding as an alternative to traditional assembly methods such as screw fastening and riveting for engineering polymers. It examines four surface pre-treatments—mechanical, chemical, plasma, and laser activation—to enhance mechanical performance and sustainability. The research finds that laser and plasma treatments are particularly sustainable, significantly reducing product weight and environmental impact compared to conventional techniques. The Life Cycle Assessment (LCA) shows that these methods consume less energy and have lower environmental impacts than abrasion and primer methods, with primers having a higher environmental impact due to their by-products. Future research will explore end-of-life considerations and compare adhesive bonding with mechanical methods like bolted joints, which, despite using more materials, allow for disassembly and reuse.

Mauricio A et.al., [26] This review examines recent advancements in additive manufacturing (AM) of polymeric materials, emphasizing progress in material extrusion and VAT-photopolymerization techniques. Key innovations include improvements in part size, continuous production capabilities, reduced fabrication time, and the reduction of support structures, as well as the integration of multi-material components. The review also highlights advancements in reinforced polymers, high-temperature materials, and the use of polymers in fabricating metallic and ceramic parts. Additionally, it explores the development of smart and sustainable materials, enabling the creation of shape-changing 3D objects. These technological and material improvements enhance the functionality and efficiency of polymer-based AM, expanding its applications and contributing to more sustainable manufacturing practices.

Grzegorz Budziket.al., [27] This publication presents a quality control methodology for polymer additive manufacturing (AM), focusing on aligning products with their intended use. It distinguishes between models for visual presentation and functional needs, and proposes a control system based on Industry 4.0 standards. The methodology includes data control, manufacturing control, and post-processing control. The study evaluated materials like RGD 720 resin, ABS M30, and PLA, and AM methods such as Poly Jet, FDM, DLP, FFF, and MEM. Poly Jet was found to offer the highest accuracy, while MEM provided the least. The study highlights the importance of choosing materials and methods based on model specifics, purpose, and economic factors to ensure quality and suitability.

Md Hosne Mobarak b et.al., [28] This study examines how additive manufacturing (AM) has revolutionized polymer production over the past thirty years, addressing limitations of traditional methods and environmental concerns. AM offers significant advantages, including design flexibility, reduced material waste, and the capability to produce complex structures, benefiting industries such as consumer products, automotive, aerospace, and medical implants. The paper reviews advancements in AM techniques and polymer synthesis, highlighting innovations tailored for AM processes. It also evaluates methods for assessing polymer material quality and performance and discusses current challenges and future prospects. The integration of AM with automation, AI, and advanced materials science is poised to further enhance efficiency and create hybrid production systems that merge traditional and modern methods.

Gloria Chyr et.al., [29] Additive manufacturing (AM), or 3D printing, has transformed manufacturing with rapid prototyping and customization. As environmental concerns rise, there is increasing emphasis on sustainability in AM processes and materials. This review explores recent advancements in high-performance sustainable polymers used in AM, assessing their properties, benefits, and applications across industries. It highlights eco-friendly aspects such as sustainable raw material sourcing, green synthesis methods, and recyclability. By examining case studies and practical applications, the review evaluates the performance and environmental impact of these polymers. Integrating sustainable practices in AM enhances technology versatility and performance while reducing its environmental footprint, contributing to a more sustainable manufacturing future.

Cheng Luo et.al., [30] This study examines the impact of bonding widths between polymer strands in additive manufacturing (AM) on the mechanical properties and structural integrity of 3D-printed objects. As AM evolves, understanding how deposition parameters affect bonding characteristics is crucial for optimizing component quality. The research provides analytical expressions for key parameters—flat width, compressed depth, and bonding width—based on various extrusion conditions and experimental data from ABS and PLA polymers. By analyzing how extrusion parameters influence bonding widths, the study offers insights into improving layer adhesion and reducing defects. Techniques like scanning electron microscopy (SEM) and image analysis software are used to measure and validate bonding widths. The findings emphasize the need to control bonding widths to enhance mechanical properties and durability, advancing AM technology.

R. Garcia et.al., [31] This paper investigates improving shear strength in adhesively bonded single lap joints using 3D printing technology. By incorporating structural reinforcements into carbon fiber woven epoxy laminates with fused deposition modeling (FDM), four models were developed. The results showed that 3D-printed adhesive (3D-PA) joints had higher peak loads and shear strengths compared to pure adhesive (PA) joints, with cohesive failure modes indicating better bond integrity. This research is relevant for automotive and aerospace industries, where fiber-reinforced polymer matrix composites (FRPCs) are used. 3D-printed reinforcements optimize stress distribution, reduce overdesign, and enhance joint performance, offering a promising alternative to mechanical fasteners.

Andrei Danut Mazurchevici et.al., [32] 3D printing, or rapid prototyping, is key in modern manufacturing for creating complex products layer by layer. Fused Deposition Modeling (FDM) stands out for its cost-effectiveness, quality, and efficiency, especially for scientific research and functional parts using biodegradable materials. The process involves analyzing a CAD model, converting it to an STL file, and slicing it for printing. Support materials are essential to address overhang issues, affecting the final product. FDM's use of biodegradable materials like polylactic acid (PLA) supports sustainable manufacturing. Research is focused on developing materials that are biodegradable, recyclable, and compostable to reduce environmental impact, with PLA highlighted as a leading biodegradable option in FDM.

Chao Zhanga et.al., [33] Functional fluid channels are essential in aerospace, robotics, and biomedical engineering for tasks like heat transfer and fluid transmission. Traditional manufacturing struggles with creating complex internal structures without adding weight. Additive Manufacturing (AM) addresses this by integrating intricate fluid channels directly into products, enabling lightweight, optimized designs. However, challenges such as controlling internal surface quality and variability in performance requirements remain. Advances in fluid topology optimization and multi-material AM are needed, but AM holds significant potential to revolutionize the design and manufacturing of products with functional fluid channels.

Alain Bernard et.al., [34] Additive Manufacturing (AM) has significantly impacted industries like aerospace, automotive, consumer products, and medicine. However, AM faces challenges such as complexity, slow processes, and high costs, complicating product design optimization. Design for Additive Manufacturing (DfAM) seeks to address these issues with specialized tools and methodologies, though comprehensive DfAM knowledge and tools are still lacking. This paper proposes a framework for DfAM, highlighting its importance for research and industry. Tools like topology optimization (TO), generative design (GD), lattice structures, and bio-inspired design offer benefits, but their mathematical complexity limits practical use. Improved TO methods and alignment of functional and economic demands with the AM process are crucial for maximizing AM's commercial potential.

Marina A et al..[35]The study evaluates six key factors: volumetric error, support area, staircase effect, build time, surface roughness, and surface quality. It highlights the staircase effect as a major challenge, especially for parts with curved surfaces, leading to inaccuracies. The proposed solution uses an Electromagnetism-like algorithm for global optimization, identifying build orientations that reduce printing time, filament usage, and improve surface finish. The study also notes conflicting objectives among these factors and suggests a multi-objective optimization approach to balance these trade-offs. This framework offers valuable insights for enhancing AM precision and efficiency, particularly for complex 3D printing applications.

Hardikkumar Prajapati et.al., [36] This paper explores temperature distribution in the standoff region of polymer filaments during fused filament fabrication. An analytical model predicts an exponentially decaying temperature distribution, confirmed by infrared thermography under various conditions. The study identifies two key heat transfer regimes that influence filament bonding and final part properties. Insights gained are crucial for optimizing thermal performance in polymer-based AM, aiming to enhance filament bonding and part quality. The research contributes to better understanding and improving process parameters for high-quality 3D printed parts.

M.S. Islam et al.,[37] This paper introduces a novel method to enhance the interlaminar shear strength (ILSS) of multi-directional prepreg laminates using polymer additive manufacturing (PAM). The study utilizes fused deposition modeling (FDM) to create 3D-printed reinforcement patterns on carbon prepregs, incorporated into the laminate structure. These reinforcements aim to reroute delamination paths, improving ILSS and potentially enhancing the laminates' static and dynamic behavior. Short beam shear (SBS) tests show significant ILSS improvements: Type A laminates increased by 28.35%, and Type B by 11%, due to additional resin mitigating voids. The findings suggest PAM's precise design capabilities can significantly improve interlaminar properties, offering a promising alternative to traditional reinforcement methods like stitching and weaving.

Xiangfan Chen et.al., [38] This study introduces a novel piezoelectric photocurable resin called V-Ink, designed for additive manufacturing using projection micro stereolithography (PμSL). Composed of 35% polyvinylidene fluoride (PVDF) particles, V-Ink demonstrates a promising piezoelectric voltage coefficient of 105.12×10^{-3}, comparable to pure PVDF film. Unlike traditional planar deposition techniques that restrict piezoelectric structures to 2D or 2.5D, this resin enables the creation of complex 3D structures with high resolution. The development of V-Ink offers significant potential for fabricating flexible, functional devices, particularly in fields like biosensing and detection, where the piezoelectric effect is crucial. By leveraging 3D printing technology, this all-polymer-based material opens new avenues for innovative applications that require precise, geometrically complex piezoelectric components.

Camden A et.al., [39] This study investigates the use of thermosetting polymers in polymer laser powder bed fusion (PBF/L) technology, which has largely been applied to thermoplastics like nylon and PEKK. Unlike thermoplastics, thermosets undergo chemical crosslinking, affecting their performance. The research proposes a method to achieve complete crosslinking within individual layers while enabling secondary crosslinking during subsequent layers by carefully controlling temperature profiles. An expanded Energy Reaction Ratio (EXR) equation is introduced to address thermosetting polymers' unique properties and compare their behavior with thermoplastics. Future research aims to refine these parameters to improve processing and material development for PBF/L, expanding the range of materials for this additive manufacturing technique.

Aniket Jadhav et.al., [40] This paper provides an overview of 3D printing, a rapidly evolving digital fabrication technique used for mass customization and open-source design. It covers various 3D printing methods, materials (plastics, metals, and unconventional options like fruit), and the process from CAD models to STL formats, including the use of UV curable liquids and lasers. While highlighting advantages such as precision and customization, it also addresses challenges like material durability and adoption strategies. The paper emphasizes the need for ongoing research to enhance 3D printing technologies and infrastructure.

III. Conclusion

Polymer Additive Manufacturing (PAM) is a transformative 3D printing technology that offers significant benefits, including the creation of complex, customized, and lightweight structures with high precision. Techniques like Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS) enable rapid prototyping and reduced material waste. Despite challenges such as material limitations and surface finish quality, ongoing research is enhancing PAM's performance and versatility. As PAM evolves, it is expected to drive innovations in design, manufacturing processes, and end-use applications, cementing its role in modern manufacturing

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