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Post-Treatment Methods in Additive Manufacturing: A Review of Mechanical, Thermal, Chemical, and Hybrid Approaches

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Abstract

Additive manufacturing, particularly Fused Deposition Modeling (FDM), has become a cornerstone of rapid prototyping and functional part production due to its accessibility and material versatility. However, the inherent layer-by-layer nature of FDM introduces surface roughness, reduced mechanical strength, and anisotropic behavior, which limit its industrial applications. This literature review investigates the impact of chemical post-processing treatments such as solvent vapor smoothing, immersion, and hybrid chemical-thermal methods on the surface quality and mechanical performance of FDM-printed components made from commonly used thermoplastics like PLA, ABS, and PETG. A comprehensive analysis of recent experimental studies reveals significant improvements in surface finish, tensile strength, and fracture resistance following controlled chemical treatment. The review also highlights the material-specific behavior, solvent compatibility, safety considerations, and potential drawbacks such as dimensional distortion and reduced ductility. The insights gained serve as a foundation for optimizing post-processing protocols, enabling the broader use of FDM parts in end-use, load bearing, and visually demanding applications. Mechanical methods such as machining, abrasive finishing, and shot peening improve dimensional accuracy and surface finish; thermal treatments like annealing, laser remelting, and hot isostatic pressing (HIP) relieve internal stresses and reduce defects; and chemical processes, including electrochemical polishing and solvent vapor smoothing, provide superior surface uniformity. Hybrid post-treatment techniques that combine multiple methods are gaining prominence for achieving optimized performance and efficiency. The paper also discusses current challenges, recent advancements, and future research directions aimed at integrating automated and energy-efficient post-processing within the AM workflow. Overall, this review underscores the critical role of post-treatment in bridging the gap between as-built and application-ready AM parts, enabling their broader adoption in high-performance industrial sectors.

Keywords: Fused deposition modeling (FDM), chemical post-processing, solvent vapor smoothing, surface roughness, mechanical properties, dimensional accuracy, PLA, ABS, PETG

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INTRODUCTION

Additive Manufacturing (AM), commonly referred to as 3D printing, has transformed modern manufacturing by enabling rapid prototyping, complex geometries, and customizable part production across industries. Among the various AM techniques, Fused Deposition Modeling (FDM) is widely used due to its cost-effectiveness, material availability, and ease of use. However, despite its advantages, FDM suffers from limitations such as poor surface finish, visible layer lines, reduced mechanical properties, and anisotropy in the build direction. These shortcomings necessitate effective post-processing treatments to improve the quality

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and functionality of printed components.

Post-processing methods in AM can broadly be categorized into mechanical, thermal, chemical, and hybrid techniques, each addressing specific deficiencies of as-printed parts:

- Mechanical post-treatment involves abrasive methods like sanding, bead blasting, and tumbling. These approaches are typically used to improve surface smoothness but are often labor-intensive and may not access intricate geometries.
- Thermal Treatment includes annealing and heat treatment processes designed to relieve internal stress, improve crystallinity, and enhance mechanical properties. However, thermal processes require precise control to prevent warping or distortion.
- Chemical Treatment is a highly effective method to smooth the surface and, in some cases, modify mechanical behavior. This includes vapor smoothing, solvent immersion, and chemical polishing, using agents such as acetone (for ABS), dichloromethane (for PLA), and others compatible with specific polymers.
- Hybrid Methods combine chemical and thermal or mechanical actions, for instance, chemical vapor exposure followed by thermal curing or nanoparticle embedment via solvent swelling and heat consolidation. These techniques aim to improve both aesthetic and structural attributes of the printed parts.

The selection of post-treatment techniques depends on factors such as material type, desired surface quality, functional requirements, and application environment. For functional and end-use applications, especially in automotive, aerospace, and biomedical fields, the enhancement of surface integrity and mechanical reliability through optimized post-processing is critical.

This study focuses specifically on chemical post-processing techniques applied to FDM-printed polymers, and reviews recent literature to assess their impact on surface finish, mechanical strength, and overall part performance. By comparing various studies and treatment methods, the review aims to provide comprehensive insights into the effectiveness, limitations, and applicability of chemical treatments across different materials.

LITERATURE REVIEW

This section provides a detailed review of the literature, establishing theoretical foundation for the experimental work. It begins with a comparative analysis of the chemical, mechanical, and thermal properties of the three thermoplastic filaments central to this study: Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyethylene Terephthalate Glycol (PETG). It then explores common surface finishing strategies for FDM parts, with a specific focus on the principles of chemical vapor smoothing. Finally, it delves into the specific solvent-polymer interactions between acetone and the selected materials, synthesizing existing knowledge to frame the hypotheses for this research.

Rajesh *et al*. conducted an experimental study to define the mechanical characteristics of specimens, 3D printed with ABS, PLA, and PETG via fused deposition modeling. This research addresses the need for reliable, comparative data on how these widely used filaments perform under mechanical stress. The study likely involved standardized tensile and impact testing to provide an empirical basis for material selection in functional applications [1]. The work is a valuable resource for engineers needing to make informed choices based on the load-bearing requirements of a part.

Ekrem *et al.* investigated the mechanical properties of PLA, PETG, and ABS samples when printed on a high-speed 3D printer. This research is timely, as it explores whether material performance is compromised by the accelerated deposition and cooling rates of modern, faster printing technologies. The findings offer crucial insights for manufacturers adopting high-speed printing, clarifying the trade-offs between production speed and the final structural integrity of the components. This study helps ensure that parts made with these advanced systems meet necessary safety and performance standards [2].

Dinița *et al*. provided a comprehensive overview of additive manufacturing post-processing treatments, with a clear emphasis on their effect on mechanical characteristics. The paper synthesizes a wide range of information, analyzing how treatments like thermal annealing or chemical smoothing alter a component's strength, ductility, and fatigue life. It serves as a consolidated resource that categorizes different methods and their material-specific effects. This work is invaluable for engineers aiming to produce functional, end-use parts capable of withstanding demanding operational loads [3].

Bolat *et al*. presented a comparative analysis of how post-production treatments and layer thickness jointly affect the tensile and impact properties of additively manufactured polymers. The research recognizes that these factors are not independent and explores their interactive effects on final part quality. By using a systematic experimental design, the study provides a holistic understanding of process optimization for achieving a desired balance of strength and durability. The findings are directly applicable in industrial settings for developing integrated strategies for printing and post-processing [4].

Barrios *et al*. focused on improving the surface roughness and hydrophobicity of PETG parts made via Fused Deposition Modeling (FDM). The research demonstrates a practical outcome by applying these surface enhancements to create 3D printed self-cleaning parts. This work bridges the gap between material science and product design, showing how post-processing can impart advanced functionalities to printed objects. It serves as a compelling case study on value addition, opening up new application areas for FDM technology [5].

Kopar *et al*. conducted an experimental investigation into the mechanical properties of PLA, ABS, and PETG, contributing further comparative data on these common 3D printing materials. The research utilized fused deposition modeling and likely followed standardized testing protocols to ensure the results are both reproducible and reliable for engineering use [6].

Francis *et al*. detailed an innovative post-processing method involving a combination of chemical and heat treatment to embed nanoparticles into 3D printed parts. This approach moves beyond simple surface smoothing to actively modify the part's surface region, potentially enhancing properties like wear resistance or UV stability. The study represents a step towards creating multifunctional components where the surface provides specialized properties distinct from the bulk material. This work opens new possibilities for customizing part characteristics in a targeted manner after the printing process is complete [7].

Khosravani *et al*. focused their research on the post-processing of 3D-printed parts made from ABS, a popular engineering thermoplastic. Given the material's use in functional parts, this study provides important insights into finishing techniques suitable for ABS, with a likely focus on acetone vapor smoothing. The research probably investigates how such treatments affect dimensional accuracy and mechanical integrity, not just surface finish. The paper is a valuable resource for users looking to optimize the finishing process for one of the cornerstone materials of FDM 3D printing [8].

Tamasag *et al*. offered targeted insights on the chemical treatment of 3D printed parts, a key area of post-processing. The paper likely analyzes the compatibility of various solvents with different printing polymers and the resulting changes in surface quality. It probably also discusses the practical aspects of these treatments, such as process control and safety considerations. This type of study is beneficial for practitioners seeking to implement chemical post-processing methods safely and effectively [9].

Heikkinen *et al*. addressed a critical industrial application by evaluating the chemical compatibility of FFF-based 3D printed components. It specifically tests their resilience against aggressive solutions commonly used in semiconductor wet processing, a demanding environment [10]. The research is vital for qualifying low-cost, rapidly produced 3D printed parts for use in high-tech industries where material inertness is essential. The findings provide evidence-based guidelines on which 3D printing materials can withstand such specialized applications.

Khosravani *et al*. investigate how post-processing affects the fracture behavior of surface-treated 3D-printed parts. This research explores how surface treatments can alter crack initiation and propagation, a critical aspect of mechanical reliability. Understanding these effects is crucial for safety-critical applications, where predicting and preventing catastrophic failure is a primary design driver. The work provides deep insights into the structural integrity of post-processed parts, offering a more complete picture than standard strength tests alone [11].

Dizon *et al*. provide an overview of the post-processing of 3D-printed polymers. The work is positioned to give a broad summary of the various techniques available to enhance polymer-based parts, from simple mechanical sanding to more advanced chemical treatments. The authors likely discuss the purpose of these different methods, whether for improving aesthetics, strength, or functionality. This paper serves as an excellent entry point for understanding the importance of this final manufacturing step in producing a finished product [12].

Lavecchia *et al*. present a focused study on using chemical vapor treatment to improve the surface finish of 3D printed Polylactic Acid (PLA) parts. Finding effective and safe smoothing agents for PLA is challenging, making this research particularly valuable. The study demonstrates a viable method for achieving a high-quality, smooth finish on PLA, which is significant for consumer products and visual prototypes. The work contributes a practical, solutions-oriented approach to a common problem in FDM printing [13].

Mathew *et al*. provide an extensive examination of vapor polishing for Fused Deposition Modelling (FDM) parts. The paper surveys different techniques and critically assesses their impact on both surface finish and subsequent mechanical properties. This dual focus is crucial, as solvent vapors can alter a part's structural integrity. The review synthesizes data from numerous studies to guide researchers toward best practices and highlight the trade-offs involved in vapor polishing [14].

Sawant *et al*. uniquely combine a state-of-the-art literature review with original experimental work on FDM post-processing techniques. This hybrid approach grounds a broad survey of existing knowledge in tangible, empirical data from their own experiments. The paper serves a dual function, acting as both an introductory guide and a source of novel findings in the field. It emphasizes the practical application of methods to improve the quality of FDM parts [15].

Wickramasinghe *et al*. offer a holistic review of FDM-based 3D printing of polymers and composites. The work is structured around three interconnected themes: mechanical properties, common defects, and post-processing treatments used to mitigate them. This perspective acknowledges that final part quality results from the interplay between material, process, and finishing steps. The review serves as a comprehensive resource for understanding the entire FDM workflow and the strategies for optimizing its output [16].

Karakurt *et al*. provide a high-level overview of 3D printing technologies from a chemical engineering perspective. It systematically covers the main printing techniques, the diverse materials used, and the essential role of post-processing. As a "current opinion" piece, it likely highlights recent advancements and future trends, such as the development of new functional polymers. The paper acts as a concise but authoritative summary of the state of the art in the field [17].

Markovic *et al*. focus on maximizing the mechanical performance of 3D printed parts by optimizing the printing process parameters themselves. This research emphasizes that superior strength can be engineered during the printing stage, not just through post-processing. The study likely investigates key parameters like layer height, infill, and speed to identify the optimal settings for performance. This work is highly valuable as it provides a clear path to producing stronger, more reliable parts directly from the printer [18].

The study by Amza *et al*. is dedicated to enhancing the mechanical properties of polymer 3D printed parts. The paper likely investigates various strategies to improve structural performance, from process optimization to the use of advanced composites and post-processing treatments. The central goal is to overcome inherent weaknesses associated with 3D printing, such as anisotropy. This contribution aims at pushing the boundaries of polymer 3D printing for use in more demanding, load-bearing applications [19].

Guduru *et al*. investigate how post-treatment affects the tensile properties of a carbon-reinforced PLA composite made by 3D printing. The study focuses on the intersection of advanced composite materials and post-processing. It likely explores how thermal or chemical treatments affect the fiber-matrix interface and the overall strength of the composite part [20]. This work is important for high-performance applications where lightweight yet strong components are in high demand.

An *et al*. explored a high-tech post-processing method: using laser surface treatment to improve the surface quality of 3D-printed parts. This non-contact technique can melt and reflow a thin surface layer to eliminate layer lines and create a smooth finish. The study would focus on optimizing laser parameters to achieve a high-quality surface without damaging the part's underlying structure. This work represents the cutting edge of post-processing, pointing towards more automated and precise finishing solutions [21].

Kantaros *et al*. provide a broad survey of the various post-production finishing processes utilized in 3D printing technologies. This review likely categorizes and compares a wide array of processes applicable to different materials and printing methods. It covers the purpose and mechanism of finishing steps like support removal, polishing, coating, and coloring. The paper serves as a valuable reference for understanding the full spectrum of available finishing options to create a final product [22].

Skorski *et al*. investigate the properties of a novel TiO_2-ABS nanocomposite material for 3D printing. This research delves into creating functional materials that go beyond simple structural performance. The inclusion of TiO_2 nanoparticles could impart functionalities like photocatalytic activity or enhanced UV resistance. The study provides a thorough chemical, mechanical, and physical characterization of this advanced composite filament [23].

Kumbhar *et al*. focused on post-processing methods used to improve the surface finish of additively manufactured products. The review consolidates information on mechanical, chemical, and thermal techniques whose primary goal is aesthetic or functional surface enhancement. It likely compares the effectiveness, cost, and complexity of different methods. The review helps guide users in selecting the most appropriate surface finishing technique for their specific product needs [24].

Peng *et al*. present a review of post-processing technologies across the broad field of additive manufacturing. The paper provides a comprehensive survey of the state of the art in finishing 3D printed parts, covering processes applicable to polymers, metals, and ceramics. It likely categorizes the technologies and discusses their advantages and limitations, creating a useful decision-making framework. The review highlights the critical role post-processing plays in determining the final performance and economic viability of a printed part [25].

Mahmood *et al*. specifically focused on post-processing techniques for enhancing the quality of metallic parts from additive manufacturing. The finishing of metal AM parts presents unique challenges, such as high hardness and internal residual stresses. The paper would review pertinent techniques like stress relief, heat treatment, and hot isostatic pressing (HIP) to close internal porosity. This work serves as a specialized guide for engineers working with metal additive manufacturing technologies [26].

Ge *et al*. offer a comprehensive review of post-process treatments for additive-manufactured metallic structures. This paper provides an in-depth survey of the field, covering thermal, mechanical, and chemical processes. The review details how these treatments are used to control microstructure, reduce residual stress, and enhance mechanical properties like fatigue life. It stands as a cornerstone reference for material scientists and engineers in the metal AM sector [27].

Wong *et al*. is a foundational review of the additive manufacturing field. Published when technology was moving towards the mainstream, it provides a historical perspective on the state of the art at the time. It serves as a benchmark for understanding the rapid innovation that has occurred in the subsequent years [28].

Sames *et al*. provide a significant review focused on the metallurgy and processing science of metal additive manufacturing. The work examines the core physics of layer-by-layer fusion processes and their effect on the metal's resulting microstructure and defect formation. It explains how process parameters control metallurgical outcomes, which in turn dictate the final mechanical properties. This paper is essential for metallurgists needing to understand the science behind metal AM process development and quality control [29].

Huang *et al*. presented a literature review that explores the societal impact of additive manufacturing. The paper steps back from purely technical aspects to consider broader implications like distributed manufacturing, mass customization, and supply chain disruption. It synthesizes early literature on how AM could change the way products are designed, made, and distributed. Work is important for understanding the "big picture" of technology’s potential to drive significant social and economic change [30].

Gu *et al*. published a comprehensive review on the laser additive manufacturing (LAM) of metallic components. This paper provides a deep dive into processes like Selective Laser Melting (SLM), which use a laser to fuse metal powder. The review systematically covers the materials, the complex physical processes, and the underlying mechanisms that govern microstructure formation [31]. This foundational review is a key resource for understanding the science behind laser-based metal AM.

Alexander *et al.* address the critical need for standardized terminology in 3D printing, particularly within biomedical research. The paper advocates for adopting formal ISO/ASTM standards to prevent confusion and ensure clear, consistent communication of research findings. This is paramount in the biomedical field for reproducibility, regulatory approval, and clinical application. The work is an essential reference for researchers to ensure their work is understood correctly and aligns with international standards [32].

Abdulhameed *et al*. provide a broad overview of additive manufacturing, covering its challenges, trends, and applications. As a review, it synthesizes the state of the art, offering a snapshot of the technology's capabilities and limitations. The discussion of trends would highlight emerging areas like multi-material printing and the integration of AI for process control [33]. This work serves as a comprehensive introduction for those interested in the overall landscape of additive manufacturing.

Chockalingam *et al*. focus on enhancing the anisotropic strength of FDM-printed ABS parts using a genetic algorithm. FDM parts are notoriously weaker in the build direction, and this research uses a computational approach to find printing parameters that mitigate this weakness. The use of a genetic algorithm allows for an efficient search of the complex design space to optimize part strength. This work is a great example of applying computational intelligence to solve a fundamental problem in 3D printing [34].

Mazzanti *et al*. provide a review focused on the FDM 3D printing of polymers containing natural fillers like wood flour or plant fibers. This research area is driven by interests in sustainability and creating materials with unique aesthetics. The review synthesizes literature on the mechanical properties of these composites, discussing how fillers affect strength and stiffness. This work is a key reference for designers interested in using these more sustainable or unique filaments [35].

Wojtyła *et al*. address the critical question of 3D printing safety by analyzing emissions from the thermal treatment of common thermoplastics. The research focuses on the release of volatile organic compounds (VOCs) and ultrafine particles (UFPs) when materials like ABS, PLA, and PET are melted. This work is of paramount importance for the health of users in non-industrial settings like offices and schools. The findings provide the scientific evidence needed to develop safety guidelines and ventilation recommendations [36].

Swetham *et al*. present a critical review of 3D printing materials, with a detailed focus on those used in Fused Deposition Modeling (FDM). The paper serves as a foundational guide to the wide palette of filaments available for FDM technology. It categorizes materials from standard plastics to engineering-grade polymers and composites, detailing their properties and applications. The work is an essential resource for newcomers to FDM and a useful reference for experienced users exploring new materials [37].

Nampoothiri *et al*. provide a broad overview of research developments concerning Polylactide (PLA), a cornerstone material for FDM 3D printing. The review covers the full spectrum of PLA research, including its synthesis from renewable resources, its material properties, and its biodegradation. While not exclusively about 3D printing, it provides a deep understanding of the fundamental nature of the material itself. This work is a key reference on the science of this environmentally significant polymer [38].

Wiberg *et al*. offer a review of Design for Additive Manufacturing (DFAM), a philosophy that encourages creating parts specifically optimized for 3D printing's unique capabilities. The paper surveys provide design methods, like topology optimization and lattice structure generation, that enable lightweight and strong structures. It also covers software tools that facilitate this design process. The review highlights that the greatest benefits of AM are unlocked at the design stage by fully exploiting its freedom [39].

Carolo *et al*. provide a review focused on how process variables influence the surface roughness of Ti-6Al-4V parts made by electron beam powder bed fusion (E-PBF). This is a specialized but critical topic in metal AM, as Ti-6Al-4V is a key aerospace and medical alloy. The review synthesizes literature on how parameters like beam power and scan speed affect the final surface topography. This understanding is fundamental to minimizing the need for costly post-processing to achieve a required surface finish [40].

RESULTS AND DISCUSSION

The literature reviewed in this study spans a diverse range of post-processing techniques used to improve the quality of FDM 3D printed parts, particularly focusing on surface finish and mechanical properties. The analysis highlights four primary methods: mechanical, thermal, chemical, and hybrid, each with varying degrees of effectiveness depending on the material and application.

SURFACE ROUGHNESS IMPROVEMENT

Among all methods, chemical post-processing, especially solvent vapor smoothing, has proven to be the most effective in enhancing surface finish. Studies by Khosravani *et al*. [8], Lavecchia *et al*. [13], and Mathew *et al*. [14] demonstrate significant reductions in surface roughness using acetone for ABS and dichloromethane or chloroform for PLA. These methods reduce visible layer lines and improve aesthetic and functional qualities. Mechanical methods like sanding or bead blasting were less effective in complex geometries and often required manual labor, making them less favorable for large-scale or intricate components.

MECHANICAL PROPERTY ENHANCEMENT

For mechanical strength, hybrid and thermal treatments showed notable improvements. Thermal annealing, as discussed by Ekrem *et al*. [2] and Guduru *et al*. [20], enhanced crystallinity and relieved internal stresses in PLA and PETG parts, leading to better tensile performance. Hybrid methods that combine chemical smoothing with thermal curing or nanoparticle infusion offered enhanced surface bonding and strength without compromising dimensional stability [7].

Interestingly, while chemical treatments primarily improve surface quality, their influence on mechanical properties is material-specific. Some solvents may weaken the structure due to excessive polymer swelling or over-smoothing, as noted by Dizon *et al*. Therefore, process control is critical to balancing aesthetic and functional requirements [12].

LIMITATIONS

- *Mechanical methods*: Economical and straightforward, but limited to external surfaces and risk of inconsistent finish.
- *Thermal methods*: Effective for strength but require precise temperature control to avoid warping.
- *Chemical methods*: Excellent for smoothing, especially on complex parts, but need controlled environments and solvent safety measures.
- *Hybrid methods*: Offer the best of both worlds but are often more complex and time-consuming to implement.

GRAPHICAL SUMMARY INTERPRETATION

Figure 1 illustrates the comparative effectiveness of different post-processing methods in Additive Manufacturing based on the literature. It shows that Chemical and Hybrid methods are most effective for improving surface roughness and mechanical properties. Thermal treatments follow closely, particularly for mechanical enhancement. Mechanical treatments are relatively less effective and best suited for basic surface refinement.

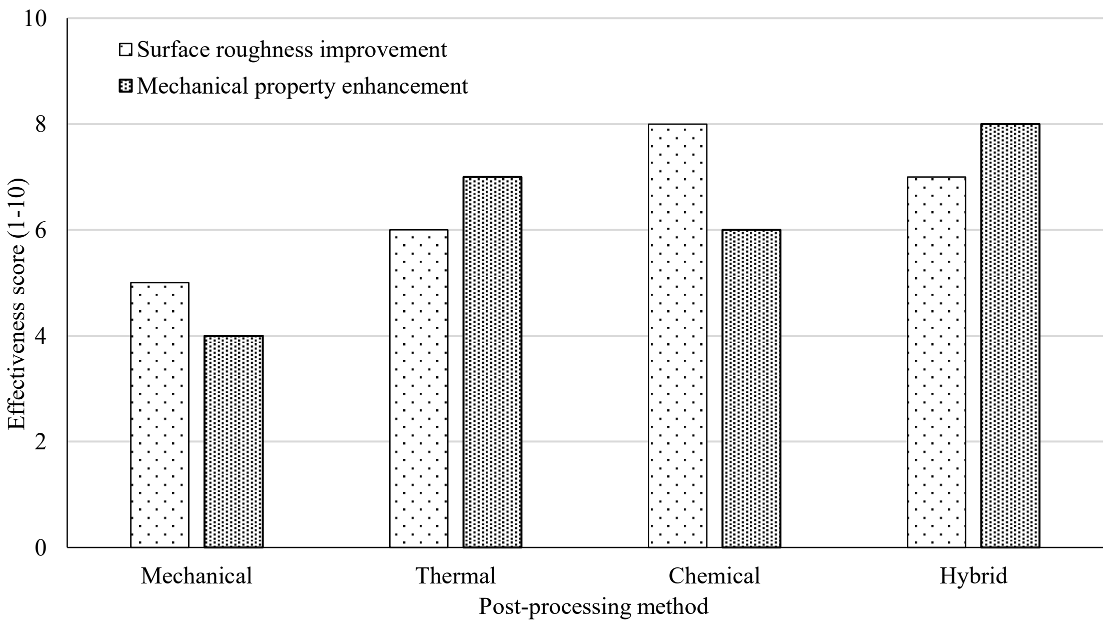

Figure 1. Effectiveness of post-processing methods in additive manufacturing.

CONCLUSION

Post-treatment processes play a critical role in determining the final performance, reliability, and applicability of additively manufactured components. While additive manufacturing enables complex geometries and design flexibility, as-built parts often suffer from surface roughness, residual stresses, porosity, and anisotropic mechanical properties that necessitate further refinement. Mechanical post-processing techniques—such as machining, shot peening, and abrasive finishing—offer effective means of improving dimensional accuracy and surface finish. Thermal treatments, including annealing, hot isostatic pressing (HIP), and laser remelting, primarily target internal defects and residual stresses, thereby enhancing mechanical integrity and fatigue life. Chemical approaches, such as electrochemical polishing and solvent vapor smoothing, provide uniform surface modification for intricate geometries, particularly in polymer- and metal-based systems.

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