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Enhancing Properties of 3D Printed Polymers: A Review of Recent Post-Processing Methods

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Abstract – With the introduction of additive manufacturing, traditional manufacturing processes have been reinterpreted, with 3D printing emerging as a transformational technology across multiple industries. Specifically, the utilization of polymers in 3D printing has surged due to their versatility, cost-effectiveness, and ease of processing. However, while 3D printing enables unparalleled design complexity, some properties of printed polymer parts often necessitate further refinement to meet high performance standards. Post-processing techniques have grown in popularity as a result of challenges such as restricted mechanical strength, surface roughness, and material-specific restrictions. This comprehensive review explores recent advancements in post-processing methodologies applied to 3D-printed polymer parts, aiming to enhance their mechanical, thermal, and aesthetic properties. The paper delves into an extensive analysis of various techniques, categorizing them into mechanical enhancements, surface finish improvements, and functional enhancements. Techniques such as annealing or heat treatment have been investigated for their capacity to improve mechanical integrity, while sanding, polishing, and chemical treatments have been employed to refine surface finishes. Coatings, including priming, painting, and specialized nano-coatings, have demonstrated their efficacy in augmenting both functional and aesthetic attributes. Understanding and applying these techniques is critical not just for achieving current performance requirements, but also for realizing the full potential of additive manufacturing across a wide range of industries. This investigation highlights the significance of post-processing techniques in expanding the capabilities and applications of 3D-printed polymer parts.

Keywords – Additive Manufacturing, 3D Printed Polymers, Post-Processing Techniques, Mechanical Enhancement, Surface Finish Improvement

I. Introduction

The emergence of additive manufacturing has significantly transformed conventional manufacturing paradigms. 3D printing, initially developed as a tool for quick prototyping, has experienced significant advancements and now encompasses a diverse range of applications across multiple industries. Unlike subtractive manufacturing methods that involve removing material from a larger block, 3D printing builds objects layer by layer, allowing for unprecedented design complexity and customization [1-5].

Polymers have become increasingly prominent in the field of 3D printing due to their variety, cost, and ease of processing. Polymer-based 3D printing techniques enable the creation of intricate structures with a range of physical and mechanical properties. Consequently, the use of 3D-printed polymer components has been observed in several industries like aerospace, automotive, healthcare, and consumer electronics etc [6-11]. While 3D printing presents an avenue for rapid prototyping and on-demand production, the inherent properties of printed polymer parts often necessitate further refinement to meet stringent performance requirements. Challenges such as limited mechanical strength, surface roughness, and material-specific limitations have prompted a growing interest in post-processing techniques. These techniques aim to enhance the mechanical, thermal, and aesthetic properties of 3D printed polymer parts, thus expanding their scope of application [7, 12-17].

There are a number of available performed valuable research works in literature. The research study [18] introduces a novel laser polishing process for additively manufactured polymer parts, employing a quasi-top-hat scanning strategy with closed-loop temperature control. The study demonstrated a substantial reduction in surface roughness for various materials, such as SLS-printed PA12, PP, TPU, ABS, and PEEK, highlighting the potential of this approach for enhancing the finish of 3D-printed components. Additionally, the paper [19] explored a post-processing method aimed at enhancing the mechanical properties of 3D-printed parts using fused filament fabrication (FFF). The proposed method involved remelting and compacting the printed parts within a granular mold, leading to reduced voids, improved interlayer welding, and increased mechanical properties, particularly in terms of stiffness and strength. The study focused on a green composite material made of poly-(lactic acid) and poly-(hydroxyalkanoate) filled with wood fibers, demonstrating significant improvements in isotropy and mechanical response, albeit with some limitations such as dimensional distortion and sample thickness reduction. The research work [20] focused on post-processing methods aimed at enhancing the surface finish of products manufactured through AM technologies. The study reviewed various techniques and highlights that systematic implementation of post-processing operations, including chemical treatment and laser micromachining, can effectively improve the surface finish of AM-produced parts by addressing challenges such as poor surface quality and material-specific issues.

The next work [21] investigated the impact of post-processing on the surface roughness and dimensional accuracy of parts fabricated using extrusion-based 3D printing with PLA material. The research emphasized the significant role of post-processing, specifically vibratory surface finishing, in enhancing the final surface quality of the fabricated parts, reducing surface roughness by 66%. The findings suggest that while larger layer thickness may reduce production time and cost, it leads to poorer surface quality, and post-processing operations like vibratory surface finishing offer a valuable approach for improving the overall quality of 3D-printed components across various polymer materials in industrial applications. The paper [22] focuses on the application of post-processing techniques to enhance the quality of 3D-printed parts using Fused Deposition Modeling (FDM). The study provides a comprehensive classification and analysis of various post-processing methods, evaluating their advantages and limitations based on factors such as material, part geometry, processing time, and treatment specificity. The experimental work, particularly on sanding, demonstrates significant improvements in surface roughness, ranging from 3% to 25%, and underscores the effectiveness of post-processing in optimizing the characteristics of 3D-printed components. The next study [23] focused on optimizing the 3D printing and post-processing of glycol-modified polyethylene terephthalate (PETG) materials. The post-processing investigation emphasizes thermal annealing at specific temperatures and durations while highlighting challenges in determining the ideal solvent annealing procedure due to observed mechanical property losses. In addition, the paper [24] provided a comprehensive review of the application of FDM for 3D printing of continuous fiber-reinforced composites (CFRCs). It extensively covered pre-processing, processing, and post-processing effects on CFRC mechanical properties. In particular, the study highlighted the critical role of impregnation in pre-processing and outlined proven post-processing methods, including hot pressing, vacuuming, and post-heat treatment, for enhancing the mechanical properties of CFRCs. The research work [25] explored the significance of post-processing methods in the context of 3D printing, emphasizing the impact of various techniques on enhancing properties such as mechanical strength, electrical characteristics, surface finish, and aesthetic value. The paper categorized post-processing methods, discussed their advantages and disadvantages, and underscored the importance of considering factors such as printer model, print settings, printing technology, and materials used when determining the appropriate post-processing approach. The next study [26] analyzed different materials, including composite polymers, copper-enhanced and aluminum-enhanced polymers, shape memory alloys, high-entropy alloys, and stainless steels, revealing significant improvements in mechanical characteristics through strategic post-processing methods. The paper underscored the importance of carefully considering and optimizing post-processing treatments, such as annealing, tempering, and precipitation hardening, to enhance the mechanical properties of 3D-printed parts for specific applications, emphasizing the need for further research and experimentation in this area.

This research paper [27] explored chemical post-processing methods to enhance the surface properties of components fabricated through 3D printing. The study concluded that while chemical post-processing shows significant potential in improving surface roughness, flexural strength, abrasion resistance, and water tightness, challenges such as reduced tensile strength and surface deterioration need to be addressed through optimization of process parameters and further research.

The primary objective of this review was to explore and evaluate recent advancements in post-processing methods applied to 3D-printed polymer parts. By delving into the latest research and developments in this field, we seek to provide a comprehensive overview of the diverse strategies employed to improve the performance and characteristics of printed components. Understanding these post-processing techniques is crucial not only for optimizing the mechanical and functional attributes of 3D-printed polymer parts but also for unlocking their full potential across a spectrum of industries. In the subsequent sections, various post-processing methodologies are categorized and analyzed, ranging from mechanical enhancements to surface finish improvements and explore their implications on the broader landscape of additive manufacturing.

II. Post-Process Techniques

A. *Annealing/Heat Treatment*

Annealing, also known as heat treatment, is an important post-processing technique for optimizing the mechanical properties of 3D-printed polymer objects. This method involves subjecting printed components to controlled heating and cooling cycles, typically below the polymer's melting point, to modify their internal structure. The objective of the technique is to improve the mechanical performance of the component and mitigate the residual stresses that are generated during the printing process. By subjecting the polymer to a heat-based treatment, it is possible to modify some properties of the material, including crystallinity and stress distribution. This modification serves to enhance the overall strength, durability, and dimensional stability of the printed components. The process is tailored based on the type of polymer used, requiring careful consideration of the optimal temperature, duration, and cooling rate to achieve the desired material improvements without causing degradation. Different heat treatment methods can be employed to enhance the mechanical strength of the final printed product. These methods include recrystallization annealing, stress relief annealing, and tempering, each serving distinct goals [28-32].

Through the application of carefully controlled heating cycles and following gradual cooling, the treatment procedure effectively reduces internal stresses and improves the overall mechanical characteristics of the printed components. One of the primary advantages of this method is the noticeable improvement in various mechanical parameters. Through heat treatment, the tensile strength of the parts is improved, significantly reducing the risk of failure under applied loads. Furthermore, this post-processing technique contributes to enhancing ductility and toughness, ensuring better resistance to deformation and impacts [31-36].

This technique is mainly used in the following industries:

– Aerospace: Enhancing the mechanical properties of 3D printed components for aircraft and spacecraft.
– Automotive: Strengthening parts for vehicle applications, improving durability and performance.
– Medical: Creating implants or prosthetics with improved mechanical strength and biocompatibility through controlled heat treatment.

B. Sanding and Polishing

Sanding and polishing are essential post-processing techniques used to refine the surface finish of 3D-printed polymer parts. Manual sanding involves the meticulous use of different grits of sandpaper, starting from coarse to fine, to gradually eliminate visible layer lines and achieve a smoother surface. The successful execution of this procedure necessitates patience and attention to detail, ensuring consistent strokes in either a linear or circular motion. In contrast, automated sanding procedures utilise machines or robotic arms that are programmed to execute exact movements, resulting in consistent and efficient performance. This is particularly advantageous in situations involving large-scale manufacturing or complex geometries [37-39].

After the completion of the initial sanding phase, subsequent polishing operations are performed to further enhance the refinement of the surface. Polishing methods, often utilizing compounds and buffing tools, aim to remove fine imperfections and provide a glossy, smooth finish. Careful application of polishing compounds and gentle circular motions with polishing tools helps in enhancing aesthetics and minimizing surface roughness. Additionally, tumbling and vibratory finishing techniques play a role, especially for small parts. These methods involve placing the parts in containers with abrasive media that tumble or vibrate, effectively smoothing surfaces and deburring multiple components simultaneously. However, it is important to exercise attention since these methods have the potential to modify fine details if not carefully monitored. When selecting sanding and polishing techniques, it is important to take into account the specific polymer utilised in the printing process. Different materials may respond differently to these techniques due to variations in hardness or chemical composition. Moreover, the complexity of the printed parts also influences the effectiveness of these techniques. Intricate designs or internal structures might pose challenges in achieving uniform results. However, regardless of the method chosen, thorough cleaning of parts post-processing is crucial to remove any debris or residue. This step ensures the final surface quality meets the desired standards [25, 38, 40, 41].

C. Chemical Treatments

Chemical treatments encompass various methods aimed at enhancing 3D-printed polymer parts, including vapor smoothing, chemical baths, surface activation, and solvent dyeing. Vapor smoothing is used to improve the surface finish of 3D printed parts by melting the surface layer slightly, reducing visible layer lines and creating a smoother appearance. In this process, parts are exposed to a vapor containing a solvent (like acetone for ABS) or a specific polymer-compatible solvent. The solvent vapor interacts with the outer surface, melting and fusing the polymer layers together. As a result, it enhances part aesthetics, reduces roughness, and minimizes visible layer lines, resulting in a uniform surface finish. Conversely, chemical baths immerse parts in specific solutions containing solvents or chemicals to dissolve or smooth the surface layer, enhancing aesthetics by reducing roughness and layer visibility. Additionally, chemical surface activation modifies the surface properties of 3D printed parts to enhance adhesion or facilitate subsequent coating applications. Treatment involves exposing the part to chemical agents or plasma to alter the surface chemistry, creating reactive sites that improve bonding with coatings, adhesives, or other materials. On the other hand, solvent dyeing allows the customization of part colours by immersing them in solvent-based dye solutions, enabling colour alteration without significantly impacting mechanical properties. Each method requires careful consideration of material compatibility, safety, and precise control of treatment conditions to achieve desired outcomes without compromising the part's structural integrity or dimensional accuracy. These techniques collectively offer diverse options for post-processing enhancements in terms of aesthetics, adhesion, and colour customization for 3D-printed polymer parts [42-46].

D. *Coatings*

Coatings applied to 3D-printed polymer parts serve various purposes, from improving aesthetics to enhancing functionality and protection. Priming and painting are common processes in which primers are utilised in order to improve adhesion and establish a base for subsequent layers of paint. The procedure begins with thorough surface preparation, such as cleaning and sanding, and ends with primer application to provide enhanced bonding between the substrate and the paint layers. Various techniques, including spraying, brushing, and dipping, are utilised to apply specialised paints that are compatible with polymer surfaces. These coatings have a dual purpose of improving aesthetics by effectively masking layer lines, while also providing protection against various environmental factors such as UV radiation, moisture, and chemical exposure. Proper surface preparation is crucial for good adhesion and durability of the coating [25, 47-49].

Furthermore, the utilisation of surface modification coatings is employed in order to modify surface properties with the aim of achieving certain functional enhancements. These coatings have the ability to alter surface roughness, incorporate hydrophobic or particular chemical properties, and improve biocompatibility or adhesion. They allow customization of surface properties based on application requirements. In addition, there are also Nano-coatings which are a type of highly technologically advanced coatings that are applied at the nanoscale level in order to provide specialised functionalities. The process of applying coatings on 3D-printed polymer parts involves the deposition of thin layers of nanoparticles, such as silica or graphene, onto their surfaces. Various purposes are served by these materials, which encompass the improvement of mechanical features such as strength or toughness, as well as the incorporation of particular attributes like antibacterial capabilities. Despite their ultra-thin nature, nano-coatings offer superior performance, enabling lightweight yet high-performing applications. These coatings demonstrate promising potential in various industries, including healthcare, electronics, aerospace, and automotive due to their ability to impart exceptional properties at a reduced coating thickness [49-52].

III. CONCLUSION

Notably, polymer-based 3D printing has gained popularity due to its versatility, cost-effectiveness, and ease of processing. The extensive use of 3D-printed polymer components in aerospace, automotive, healthcare, and consumer electronics demonstrates the technology's enormous potential. While 3D printing allows for remarkable design freedom, the inherent properties of printed polymer parts frequently require modification in order to meet demanding performance criteria. Challenges such as limited mechanical strength, surface roughness, and material-specific limitations have prompted an increased focus on post-processing techniques. These techniques are crucial in improving the mechanical, thermal, and aesthetic qualities of 3D-printed polymer parts, thereby expanding their application scope.

In this comprehensive review, we explored and evaluated an array of post-processing methodologies applied to 3D-printed polymer parts. Techniques such as annealing, or heat treatment have developed as crucial methods for enhancing the mechanical integrity of components across various industries. Surface finishing techniques such as sanding, polishing, and chemical treatments have been widely used to improve aesthetics and reduce visible layer lines. Coatings, such as priming, painting, surface modification coatings, and nano-coatings, have demonstrated their effectiveness in improving both the functional and aesthetic properties of 3D-printed polymer parts. Each of these post-processing techniques offers distinct advantages and considerations.

Understanding and implementing these post-processing processes is critical for improving the performance and potential of 3D-printed polymer parts. Beyond addressing current performance requirements, advances in post-processing techniques are positioned to promote innovation and expand the limits of additive manufacturing. Further research and development in this area will continue to unlock new opportunities, driving the widespread use of 3D printed polymer components across industries. As additive manufacturing continues to evolve, the integration of robust post-processing techniques will remain fundamental in the utilization of the full capabilities of 3D printing, ultimately shaping the future landscape of manufacturing.

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