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A Review of Additive Manufacturing Post-Treatment Techniques for Surface Quality Enhancement

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Abstract

Additive manufacturing (AM), also known as 3D printing, produces an object layer by layer with the application of a computer-controlled method. AM creates an object by adding material to a solid block until the finished product is created. AM manufacturing benefits including design flexibility, creativity, rapid prototyping, high productivity, reduced manufacturing cycle, etc. However, AM products have physical quality flaws such as surface roughness, inaccurate dimensioning, porosity, staircase effects, etc. Therefore, there is a need to carry out post-treatment on the AM fabricated components to correct their flaws before they can be used. Seventeen different post-treatment methods (PTM) on AM fabricated components were discussed in this review study. Each of these PTMs, however, has its advantages and disadvantages. The results obtained from the study show that chemical PTM has the ability to improve surface roughness easily, laser polishing can be used to reduce the staircase effects, and thus reduce surface roughness significantly and increase the hardness of AM fabricated component parts. Mechanical PTM helps to join the layers of AM components and improve their toughness, while subtractive machining PTM improves surface quality. Thermal PTMs are used to improve corrosion resistance, reduce surface roughness, eliminate staircase effects, etc. The discussion of various PTMs is clearly highlighted to serve as a guide for AM stakeholders.

Keywords: Additive manufacturing; Post-treatment Method; Physical quality; staircase effects

1. Introduction

The process of layer-by-layer combining materials under computer control, known as additive manufacturing (AM) or 3D printing, produces three-dimensional objects from digital models [1-3]. In comparison to subtractive manufacturing technology (SMT) procedures, additive manufacturing (AM) has seen a significant change in raw material form, manufacturing norms, and component performance [4]

Nomenclature

AD	Acetone Dipping
AM	Additive Manufacturing
CT	Chemical treatments
CHE	Chemical Etch
CP	Cavitation Peening

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FDM	Fused Deposition Modelling
HT	Heat Treatments
HIP	Hot Isostatic Pressing
LAP	Laser Peening
LBT	Laser-based treatments
LP	Laser Polishing
LPBF	Laser Powder Bed Fusion
MPTM	Machining post-treatment method
PTH	Post-treatment hybrids (
RPTM	Rolling post-treatment method
SHT	Solution Heat Treatment
SLM	Selective Laser Melting
SMT	Subtractive Manufacturing Technology
TF	Tumble Finishing
THP	Thermal Post-Processing

3D technology also known as AM can promptly produce three-dimensional intricate basic parts based on the process characteristics of point-by-point melting and layer-by-layer manufacturing [2, 5]. The advantages of AM technology include fast mould production, a low manufacturing cycle, and low production costs [2, 6]. AM technology needs only raw materials and equipment to produce parts, no need for complex tools, machines, moulds, etc. and thus saves money and space for machines assembling. The advantages of AM technology include nanoscale fabrication, small machining tolerance, waste reduction, and high material utilization [7, 8]. The AM products have structural strength and less process-induced stress concentration [9]. The layer-by-layer forming process used to create the component releases the forming stress as each layer condenses into its final form. The benefits of AM technology also include high efficiency of fabricated products, and the capacity to produce a variety of multi-material composites for diverse complicated structures [10]. When AM is compared to traditional manufacturing technologies, the surface quality of AM surface is frequently lesser due to the staircase effect and layer-by-layer processing [11]. The surface roughness of the product is insufficient, and as a result, there is a need to carry out post-treatment [12]. The degree of surface roughness of a manufacturing product and the AM material used will determine the PTM to deploy [13, 14]. At large, the various challenges of AM products could be related to inadequate technical know-how. Because of the complex metallurgical criteria, the interaction mechanisms between the powder bed and the molten pool, as well as the melting processes, are difficult to manage in selective laser melting (SLM) processes [15]. As a result, after the parts are manufactured, post-processing operations are typically needed to improve the mechanical properties and surface quality [16]. This paper introduces different PTMs and their effects on AM-manufactured products.

2.0 Methodology

The goal of this study is to determine how much work has been done on a review of additive manufacturing Post-Treatment Techniques for Surface Quality Enhancement. In the literature, seventeen distinct post-treatment methods (PTM) on AM produced components on various materials were mentioned. The study employs the designed systematic review and makes use of diverse studies to improve data collection.

2.1. Data Collection Methods

The research study considered peer-reviewed articles from Scopus, Web of Science, Google Scholar, EBSCO, ProQuest, IEEE, and ERIC. The search involved the use of title, abstract, and keyword parameters. However, in the beginning, many articles were identified. Due to the validity of the study, only the peer-reviewed sources mentioned above were selected.

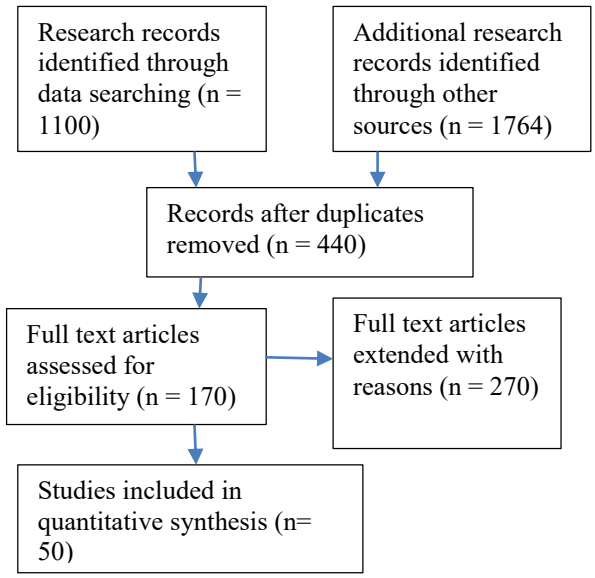

Fig. 1. Design flow chat of articles selection process.

The search peer-reviewed ranged from Additive manufacturing, Post-treatment Method, Physical quality, and staircase effects. All English peer-reviewed journal papers were considered for this study. In order to adequately trace the transition of AM post treatment techniques for quality enhancement, reviewed publications from 2019 to 2023 were reviewed. From Google scholar, using AM post treatment techniques, about 2764 articles were found. Furthermore, Moher's framework was used to streamline the steps followed by narrowing down the methodology of data collection of the literature consulted as shown in Figure 1. Hence, 440 documents were selected. The main inclusion criteria were the combination of AM post treatment methods for different materials. 270 documents were excluded, and 170 full articles were assessed for eligibility, out of which articles were further excluded because they did not meet the research criteria. Going forward, 50 articles were fully reviewed for reliable data.

3. Post-Treatment Methods (PTM) on AM Manufacture Parts

This paper examined different PTMs used on AM products in an attempt to address issues with poor aesthetic value and mechanical properties of the AM-manufactured components. Sections 2.1 to 2.17 summarised the seventeen PTMs that can be used on AM manufacture parts:

3.1. Machining post-treatment method (MPTM) is a PTM that uses cutting tools to smooth a manufactured component to a desired surface finish [16]. Mechanical machining is a common manufacturing product post-treatment employed to

reduce the surface roughness of AM metal material parts. Previous studies on the effect of machining on the surface characteristics of LPBF parts made on various products are indicated by Vukkum *et al.* [17]**.** The PTM is indicated to have significantly reduced the surface roughness of metallic AM-manufactured parts. The surface roughness of as-built LPBF Ti-6Al-4V samples with an arithmetic mean (Ra) of 34 µm was reduced to 0.9 µm after machining [18].

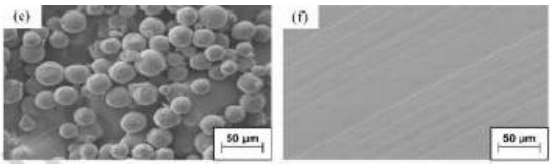

Fig. 2. The effects of machining post-treatment techniques in reducing the surface roughness of AM metallic materials.

3.2. Rolling post-treatment method (RPTM) is a post-treatment method that deploys rollers of different sizes and shapes on the AM-manufactured components' surface. It is used to reduce the thickness or to control the surface level of the fabricated components to meet operational use [19, 20]. RPTM has been used on manufactured products by using wire in the field of metallic AM [21]. PRTM can cause compressive residual stresses in the treated layer and invariably help to promote mechanical properties and reduce surface roughness.

3.3. Cavitation peening (CP) uses cavitation impact rather than solid objects. CP process promotes the aesthetic of AM-manufactured products value and induces compressive residual stresses in the surface layer. This help to eliminate the fatigue on metallic materials. The flow pattern in the region where the bubbles collapse can control CP, which is a hydrodynamic phenomenon [22]. The CP effect on AM-manufactured components indicated increased surface hardness [23].

3.4. Ultrasonic Nano-crystal surface modification (UNSM) technique reduce surface roughness on AM fabricated components by using repetitive ultrasonic impacts of a tungsten carbide (WC) tip under a controlled static condition as depicted in Figure 3. UNSM treatments, can induce high compressive residual stresses on the surface deposit and generate surface grain refinement [24]. It was also reported that corrosion resistance improved significantly, as evidenced by a significantly lower corrosion current, promoting surface and mechanical properties [24]

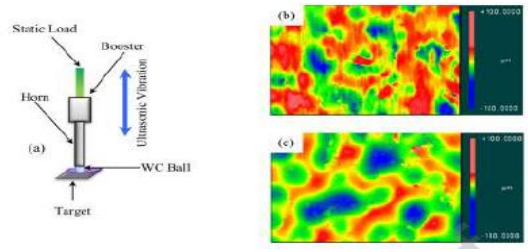

Fig. 3. depicts the UNSM technique on metallic manufacture parts [25].

3.5. Abrasive polishing (LP) method helps to polish the surface of a workpiece to a desired smooth finish surface quality. Many studies have reported using mechanical polishing to improve the surface quality of AM metallic materials with the goal of improving fatigue behaviour [26]. The comparison of the line profiles of machined, polished, and as-built LPBF 316L surfaces confirmed that polishing could be more effective for roughness elimination, and fatigue life improvement than the machining process [27]. Other polishing-based methods with applications on roughness reduction of AM materials have been considered to result in improved surface roughness. Figures 3a and 3b show magnetically driven abrasive polishing.

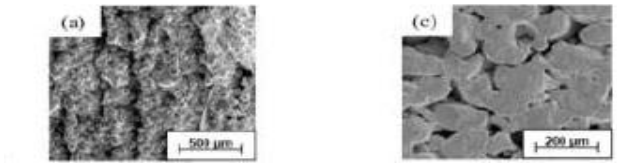

Fig 4. Initial and final magnetically driven abrasive polishing with Ra 4 m on PBF pure Cu samples using SEM and confocal imaging; source [28].

3.6. Laser peening (LP) is a method of compressing manufactured products perpendicular to the surface, leading to lateral expansions. The capacity to resist transverse strain causes a build-up of local stresses when laser peening is done on thick or restricted materials [29]. Laser peening alters the strain and shape of thinner pieces. The basic idea behind laser shot peening is depicted in Figure 5. It is important to note that all deformation-based post-processing techniques share the ideas of lateral expansion and plastic compression. This technique is used to increase the fatigue life of a jet engine fans and compressor blades.

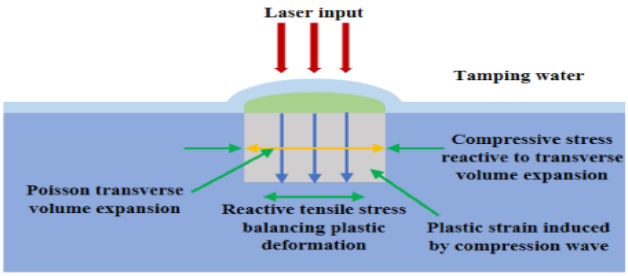

Fig. 5. Process flow diagram for the laser peening techniques; source [25].

3.7. Tumble finishing (TF) is a surface improving process that involves placing a mixture of parts, and chemicals in a container that rotate at a pre-determined speed to reduce surface roughness [30]. The process generates friction by tumbling parts against one another, hence reducing the surface roughness of the components. The use of TF on LPBF Ti-6Al-4V samples resulted in a slight reduction in surface roughness from 21.5µm to 18.9 µm, which resulted in a significant improvement in fatigue life [28]. The TF was applied to the LPBF Ti-6Al-4V ELI part, as shown in Figures 5a and 5b.

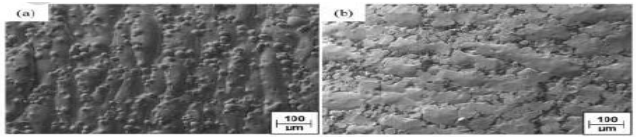

Fig. 6. SEM micrographs illustrating the surface morphology of LPBF Ti-6Al-4V ELI samples: (a) as-built, (b) after tribo-finishing adopted.

3.8. Laser-based treatment (LBT) is a type of post-treatment that uses a variety of wavelengths, waveforms, and pulse

durations. The laser beam is focused on the material's surface by the use of femtosecond [31]. The use of femtosecond laser micro-machining on LPBF Ti-6Al-4V parts, as shown in Figures 6a and 6b, significantly reduced surface roughness in terms of Ra from 4.21µm to 0.83µ m for the as-built and treated materials, respectively.

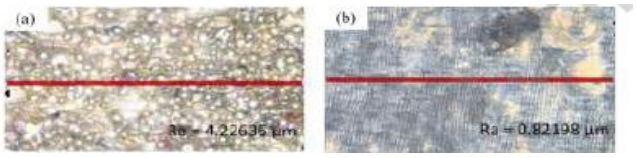

Fig. 7. Ti-6Al-4V surface morphology following femtosecond laser micromachining (a) and as-built (b) [28].

3.9. Chemical treatment (CT) is another method that reduces the unattractive surface roughness of as-built AM manufactured parts. Chemical surface treatments, unlike other post-treatments, allow access to internal complex surfaces; thus, they are mostly used for parts and components with intricate geometries such as lattice and cellular structures. Chemical treatments are also commonly used to improve the surface finish of metallic AM parts after the support structure has been removed [32, 33]. It helps to promote corrosion resistance and surface roughness.

2.10. Chemical etching (CHE) is a process of applying chemical solution on the product surface to reduce surface roughness [34]. Chemical etching employs diluted and concentrated aqueous hydrochloric (HCl), sulphuric (H2SO4), nitric (HNO3), and hydrofluoric (HF) acid, as well as concentrated aqueous solutions such as oxalic acid ((COOH) 2) and aqua regia (HCl + HNO3). This post-processing method was observed to be used to remove the roughness of intricate tools and equipment used in the biomedical engineering [35].

3.11. Surface treatment is a method of no material removal improve. The surface and mechanical properties of AM parts is achieve by inducing surface plastic deformation without removing any material [36]. Plastic deformation is typically caused by the application of loads, as well as the transmission of kinetic/thermal energy in the case of bulk material [37]

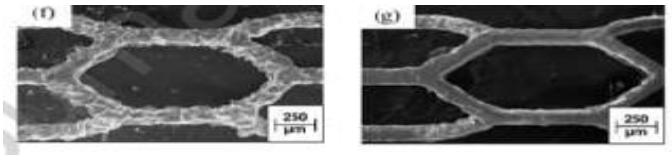

Fig. 8. LPBF CoCr stent surface morphology (f) before to and (g) following ECP adapted from [28].

3.12. Sandblasting is the process of propelling abrasive material such as sand or ceramic beads against a target surface under high pressure. This treatment is commonly used in a variety of industrial sectors to smoothen surface roughness, shape thin structures, or remove surface oxides or contaminants [28]. Figure 9 depicts a schematic representation of the SB process. The use of a highly controlled SB on LPBF AlSi10Mg samples successfully reduced the roughness, resulting in a surface roughness even lower than that of shot-peened (SP) samples [38].

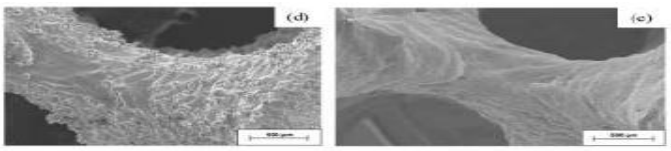

Fig. 9. LPBF Ti-6Al-4V cellular architectures before and after ceramic blasting: effects adapted from [28].

3.13. Electroplating is the electrochemical formation of a metallic film on a metallic or non-metallic material surface. Electroplating methods are used on AM-fabricated parts to achieve the desired surface smoothness and mechanical properties that cannot be obtained by using other post-processing methods [39]. Electroplating increases the parts' Young's modulus, making them more durable, and preventing corrosion, and can be used for aesthetic purposes [40]. This method is frequently used in AM products.

3.14. **The coating** is regarded as a practical method for controlling surface characteristics or imparting new surface functionalities to AM materials. Coatings have been used to reduce roughness, cover defects, and improve surface quality. Coatings are also obtained to improve tribological or corrosion resistance. Coatings are also used in some cases to create controlled surface morphologies to improve the biological performance of AM metallic materials [41, 42].

3.15. Post-treatment hybrids (PTH) is the application of two or more post-treatment methods to achieve the desired surface or bulk properties for the AM metallic material. Combining heat treatments (HT) with various other surface treatments is the most common post-treatment combination used on AM metallic materials. HPT is a standard method for homogenizing microstructures, eliminating anisotropy, and releasing undesirable tensile residual stresses in AM metallic materials [43, 44]. Figure 10 show the macro-morphology of the lattice structure, demonstrating that the HCl etching eliminated the tiny cracks caused by SB, resulting in a more uniform and smooth surface

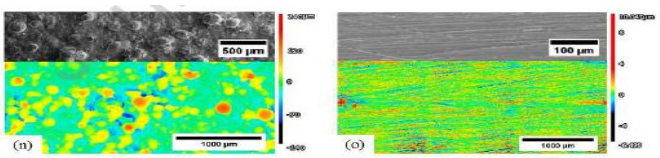

Fig. 10. Surface morphology of LPBF AlSi10Mg samples as seen in SEM, adapted from [44].

3.16. Thermal post-processing (THP) on AM fabricated parts can significantly reduce residual stresses, cracking, and homogenization [45]. Thermal post-processing techniques for AlSi10Mg parts, such as solution heat treatment (SHT), hot isostatic pressing (HIP), and T6 heat treatment (T6 HT), can significantly improve part quality. Recent research has focused on the thermal post-processing method, including its effects on the microstructure and mechanical properties of AM parts [46]. The HIP is a common thermomechanical treatment method that combines high-temperature and high-pressure manufacturing technology. Its heating temperature typically ranges from 1000 ºC to 2000 ºC.

3.17. Acetone Dipping (AD) is a cleaning agent that penetrates deep into the surface of the material to polish the parts. This process, which is applied to ABS parts produced with the most FDM in studies, improves the surface quality of parts by immersing them in an acetone solution (90% dimethyl ketone and 10% water) for a set period of time [47]. Furthermore, the acetone dipping technique can improve flexural strength, wear resistance, and water tightness; however, 1% shrinkage can affect the part's accuracy but is often overlooked [48].

4. AM Post-Treatment Future Needs

This paper has reviewed various methods to improve the surface finish of the AM parts by summarizing different post-processing technologies and their applications in AM processes. However, most of the post-treatment methods discussed in this paper follow the conventional method and the results depend on the experts of the operators. The inconsistent outcome of AM post treatments as a result of conventional methods has been a daunting challenge in the AM post-treatment industries. Going forward, there is a need to introduce Industry 4.0 in AM post-treatment industries to properly manage the challenges associated with conventional methods of AM post-treatment techniques. Adoption of Industry 4.0 and smart technology in AM treatment will help to effectively manage the proper selection of AM methods to be deployed for each category of product defects and thereby, promote energy utilization, productivity and operation cycle time in AM post-treatment.

5. Conclusion

The goal of this study was to review existing works on additive manufacturing Post-Treatment Techniques for Surface Quality Enhancement. This was achieved via a systematic literature review. Since the existing additive manufacturing processes produce parts with poor surface quality, significant effort has lately been made to develop surface post-treatments that control the surface topography. Here, a thorough assessment of post-treatments on AM-manufactured products were carried out [28].

In order to achieve the desired performance and favourable surface qualities on AM finish products, it is essential to apply post-treatments to a variety of materials and structures that have been made using AM technology, according to the results that have been presented in the literature. The AM manufactured products surface morphology, surface roughness, staircase, residual stress, corrosion, fatigue behaviour, biocompatibility, and biological performance, can all be customized with the right finish treatments. Although the usage of surface post-treatment on AM metallic materials is already prevalent in many industries, there are still many questions regarding the function of key factors in each post-treatment. The needed surface post-treatment methods should be chosen depending on the type of surface treatment, its effectiveness, and any relevant constraints in order to improve other specific target attributes [49]. In addition to considering the impact of process variables, material qualities, geometrical factors and constraints, scalability, and cost of the treatment, choosing the right surface post-treatment can be fairly difficult. Future research is anticipated to clarify the connection between certain process parameters and the desired qualities [50].

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