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A Review of the Effect of Post-Processing Heat Treatment on 3D Printed Metal Parts

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Abstract

This template guides authors on how to prepare camera-ready manuscripts. The font type to be used throughout is Garamond Metal Additive Manufacturing (AM) is a new technology that has revolutionized the manufacturing of complex, lightweight, and customized metallic parts in various sectors, including aerospace, biomedical, automotive, energy and tooling. The major metallurgical problems, however, are caused by the layer-by-layer fabrication process, which is composed of repeated and fast thermal cycling: high residual stresses, different mechanical properties in different directions, non-uniform microstructures, porosity, and low fatigue strength. This review aims to bring together recent literature about the defects associated with these additive manufacturing processes and how they can be reduced by post-processing heat treatment to improve the performance of additively manufactured metal parts. The stress-relief annealing, solution treatment, precipitation hardening (aging) and Hot Isostatic Pressing (HIP) are discussed with a focus on their influence on the microstructural changes and the mechanical properties. The review also addresses the individual responses of alloys within the major AM metallic systems, including stainless steel (316L), titanium alloys (Ti-6Al-4V), aluminum alloys (AlSi10Mg), nickel-based superalloys, maraging steels, magnesium alloys, and high-entropy alloys, and how various components of the alloy [A1.1], printing parameters, and treatment conditions influence the strength, ductility, fatigue resistance, and dimensional stability of these alloys. The potential of industrial applications in critical sectors is explored, as are ongoing issues, such as the lack of standardized treatment procedures, processing costs and the challenge of achieving a balance between strength and ductility. Lastly, the review pinpoints some research gaps and future directions, such as the use of artificial intelligence and machine learning for predictive process optimization, in-situ heat treatment, and hybrid manufacturing systems, which have potential for improving the reliability and scale-up of metal AM parts.

Keywords: *Initial void ratio, natural moisture content, settlement, compression ratio, one-dimensional consolidation.*

1.0 Introduction

Three-dimensional (3D) printing, also known as additive manufacturing (AM), is one of the most impactful manufacturing technologies of the 21st century. Additive manufacturing differs from traditional subtractive manufacturing techniques, which remove material from a workpiece to achieve the desired shape. AM produces parts layer by layer from a CAD model. This method provides unprecedented design freedom, facilitates the creation of complex geometries, reduces material waste, shortens the production times, and enables the production of customized parts that are not easily or even possibly produced using conventional manufacturing processes [1, 2]. Metal Additive Manufacturing is one of the different types of Additive Manufacturing (AM), which has gained considerable attention due to its ability to manufacture high-performance engineering parts with high dimensional accuracy and mechanical properties. Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), Directed Energy Deposition (DED), and Binder Jetting (BJ) are technologies that have gained greater significance in sectors where lightweight structures, high strength, and complex internal design are demanded. The widespread use of metal AM in sectors such as aviation, auto, bio-medical, energy, tooling and defense makes its applications in other fields more prevalent than ever [3 – 5].

Even with these outstanding benefits, the layer-by-layer construction process creates a number of metallurgical and mechanical challenges, which set the additively manufactured components apart from the conventionally manufactured components. In the process of fabrication, high and steep thermal gradients and frequent heating and cooling cycles are imposed on the material. They can lead to high residual stresses, anisotropy in mechanical properties, non-uniform microstructures, porosity, lack of fusion defects, microcracks, and reduced fatigue strength. These defects can have a substantial impact on the structural strength and durability of printed parts, particularly for complex engineering applications [6, 7].

Overcoming these shortcomings, post-processing is now an indispensable step in metal AM. Post-processing refers to various operations conducted after the printing process, such as support removal, machining, polishing, surface finishing, hot isostatic pressing (HIP) and heat treatment. Heat treatment is one of these techniques that has particular importance because it alters the internal microstructure of the material, and therefore affects its

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mechanical, physical and metallurgical properties. Heat treatment can be used to reduce residual stresses, internal defects, to enhance dimensional stability, improve ductility and toughness, optimize the hardness, and significantly increase the fatigue resistance without changing the overall geometry of the printed component [1, 8].

The effectiveness of post-processing heat treatment is affected by many factors, such as additive manufacturing techniques used, the alloy composition, printing parameters, cooling rate, treatment temperature, holding time and cooling method after treatment. Thus, the thermal post-processing response of various metallic materials varies. For instance, titanium alloys undergo phase changes that help to increase the ductility and fatigue characteristics, and precipitation-hardenable alloys, like maraging steels and Inconel 718, increase in strength and hardness following aging processes. Stainless steels, aluminum alloys, magnesium alloys, and high-entropy alloys also show special microstructural changes and mechanical responses after proper heat treatment processes [9 – 11]. In recent years, many studies have focused on the connection between heat treatment, microstructural changes and mechanical properties of additively manufactured metals. These researchers were able to examine grain morphology, phase changes, pore evolution, crystallographic texture, and mechanical properties at a local scale before and after thermal processing using advanced characterization techniques like Electron Backscatter Diffraction (EBSD), Computed Tomography (CT), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and nanoindentation. These studies have significantly contributed to the understanding of the effect of post-processing on component performance and service life [12, 13].

Moreover, the growing adoption of metal AM for industrial parts production has further grown the need to optimize post-processing strategies. The strength, fracture toughness, corrosion resistance, wear resistance, dimensional accuracy and fatigue life all need to meet stringent requirements for components used in aerospace engines, biomedical implants, automotive systems and industrial tooling. Thus, choosing the appropriate heat treatment schedule is a necessity to ensure that AM parts are compliant with industrial standards and certification requirements [14, 15].

Many studies have focused on specific alloy systems, individual heat treatments, or specific heat treatments for specific alloys including stainless steel (316L), titanium alloys (Ti-6Al-4V), aluminum alloys (AlSi10Mg), nickel-based superalloys, maraging steels, magnesium alloys,and high-entropy alloys; however, the results of these studies are not consolidated in one place. The post-processing of these alloys can be optimised by varying the process parameters, alloy chemistries and thermal treatment schedule, which can lead to varied results in the conclusions of the optimisation. Hence, the need for a continuous effort to synthesise the current knowledge into a review that addresses the impact of post-processing heat treatments on different AM metallic systems. This review paper thus aims to review the effect of post-processing heat treatment on 3D printed metal parts, synthesizing the results of the literature found in recent years. The review highlights the need for heat treatment in MAM, the main thermal post-processing methods used, the changes in microstructures induced by the heat treatment and the effect of such changes on the mechanical properties of printed metallic parts. It also uncovers industrial uses, current challenges, emerging research topics and future trends in optimizing post-processing strategies to enhance the performance and reliability of additively manufactured metal components.

2 Fundamentals of Metal Additive Manufacturing and the Need for Post-Processing Heat Treatment

2.1 Metal Additive Manufacturing Technologies

Metal additive manufacturing (MAM) is a family of advanced manufacturing techniques that produce a metallic part by adding or fusing metallic materials layer by layer according to digital models. Metal Additive Manufacturing offers significant advantages over traditional manufacturing processes like casting, forging and machining, including the ability to create highly complex geometries, lightweight lattice structures and internal cooling channels, and custom-made parts with minimal material waste. Because of these features, it has been widely used in various sectors, such as aerospace, automotive, biomedical, energy, and tooling [2, 6].

Considering the various technologies for metal Additive Manufacture (AM) in existence, Powder Bed Fusion (PBF) is the most popular method due to its high dimensional accuracy and high-density components. Powder Bed Fusion includes Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). These processes involve selectively melting thin layers of metal powder, using either a high energy laser or an electron beam, based on a cross-sectional geometry created from a computer simulation until a complete component is produced. However, because melting and solidification are local and occur at a very high rate, these techniques result in very fine microstructures and cause steep temperature gradients, which may lead to the formation of residual stresses and microstructural heterogeneities [3, 11]. Selective Laser Sintering (SLS) is a powder-bed additive manufacturing process that builds parts layer by layer using a high-powered laser to selectively sinter polymer-based powders. The process begins with a roller spreading a thin layer of material, typically nylon or polyamide, often mixed with additives like chopped fibres, across the build platform, usually at a thickness of around 0.1 mm. The entire build chamber is preheated to just below the material's melting point using external heating elements, which reduces thermal distortion and lowers the laser power required [5]. The laser then scans the build area following the cross-sections of the CAD model, sintering the powder particles together at a surface level without fully melting them. Once a layer is complete, the build platform lowers by one layer height, a fresh layer of powder is spread on top, and the process repeats. Because the surrounding unsintered powder acts as built-in support, complex overhangs and intricate geometries can be produced without additional support structures. Finally, the build platform is allowed to cool gradually in a controlled environment, after which the finished part is removed and cleaned of excess powder [13]. Figure 1 presents the classification of additive manufacturing process while Figure 2 highlights schematic of the selective laser sintering process with fiber-reinforced powder.

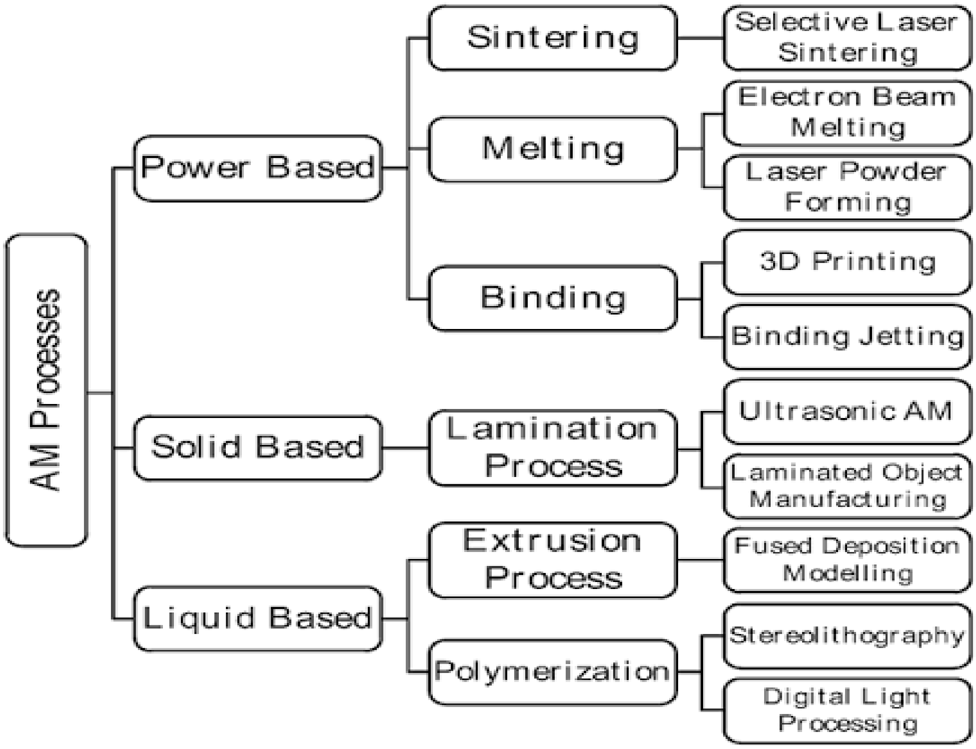

Figure 1: Classification of Additive Manufacturing (AM) Processes [13]

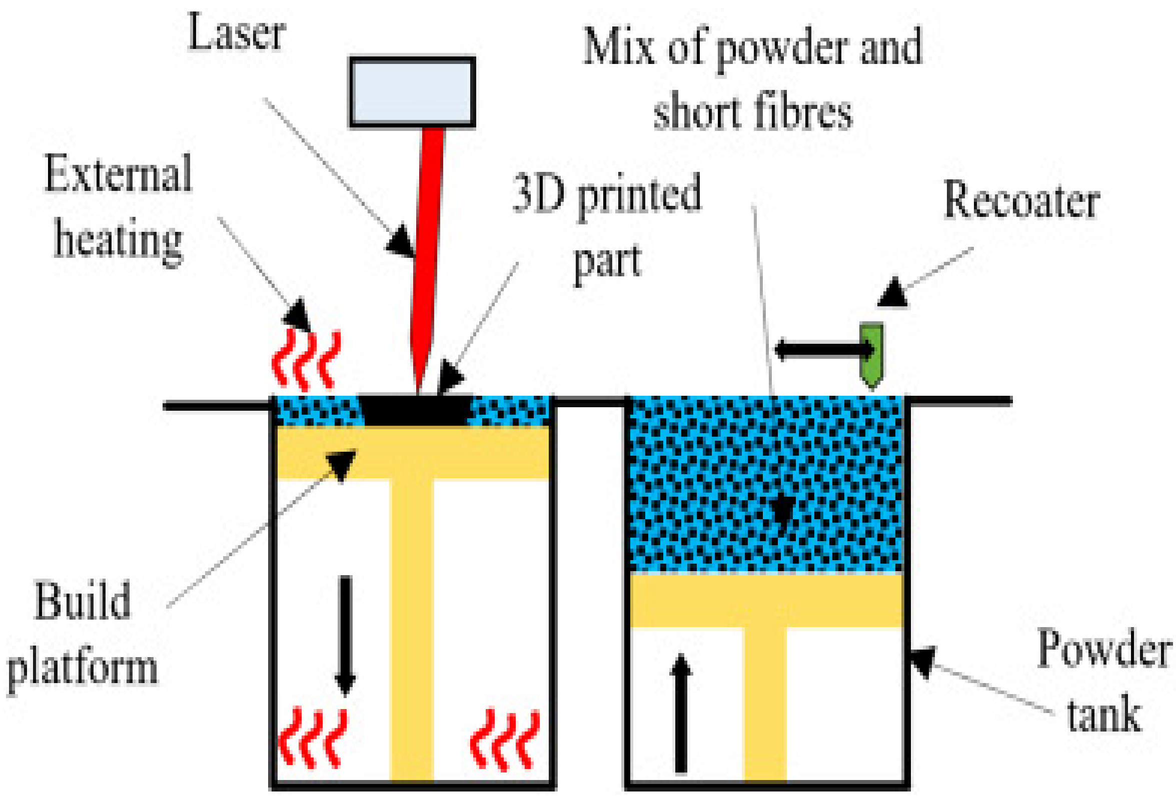

Figure 2: Schematic of the Selective Laser Sintering (SLS) process with fiber-reinforced powder [16]

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Directed Energy Deposition (DED) is another significant metal AM technology. DED is a process that simultaneously delivers the metal powder or wire to a focused energy source, causing the metal to melt and solidify onto the substrate. This is especially suitable for repairs of costly engineering components, manufacturing of large structures and for addition of material to existing parts. In general, however, DED produces lower dimensional precision and surface roughness than Powder Bed Fusion processes, therefore further processing is even more crucial [2, 17].

Other manufacturing techniques such as Binder Jetting and Metal Material Extrusion are also being adopted industry-wide. In Binder Jetting, the metal powder particles are selectively joined with a liquid binder before debinding and sintering. This process is particularly fast and allows for lower thermal distortion in the printing process, but extra thermal treatments are needed to reach full densification and acceptable mechanical properties [18]. Most metal additive manufacturing processes need post-processing to be performed before going into structural applications, irrespective of the manufacturing technology used.

2.2 Metallurgical Challenges Associated with Metal Additive Manufacturing

Additive manufacturing involves several metallurgical challenges, with the ability to affect the structural properties of fabricated parts. While numerous benefits exist in additive manufacturing, several metallurgical issues can negatively impact structural properties of printed components. The rapid heating and cooling that is a key feature of metal additive manufacturing processes affects the material properties. Depending on the process parameters and the material to be printed, cooling rates can be as high as 10^3 °C/s to 10^6 °C/s [18]. A very fast thermal cycle gives rise to non-equilibrium solidification conditions, significantly distinct from those found in the conventional manufacturing [1]. The most important effect of the rapid solidification is the generation of high residual stresses. Newly deposited layers expand when they are heated during the printing process, but are restricted by previously-solidified material. The stresses induced are tensile and compressive as the cooling happens throughout the component. Residual stresses can lead to distortion, warping, delamination, cracking or even catastrophic failure during fabrication or after service [8].

The other great difficulty is anisotropy. The mechanical properties of components may depend on direction of loading due to the stacking and fabrication of the layers. Directional grain growth and preferred crystallographic orientations can lead to very different properties in the build and transverse directions, including strength, ductility, fracture toughness, and fatigue resistance. This anisotropic behaviour is a serious engineering problem as predictable mechanical properties are a must in engineering applications [4]. Another common defect found in additive produced materials of metals is known as porosity. The discontinuities created or a lack of fusion are typically attributed to either melting of powder insufficient, inconsistency of molten pool, entry of gases into the material, or inadequate supply of energy during production of parts through additive manufacturing processes. Figure 3 details the metal additive manufacturing processes including selective laser melting, electron beam melting, Laser Powder Bed Fusion (LPBF), and three-dimensional printing/binder jetting. These discontinuities lead to a reduced effective area subjected to any sort of loading; thus, these are also susceptible to becoming stress risers that may initiate fatigue cracks to lower the fatigue life as well as increase material fracture possibility [2].

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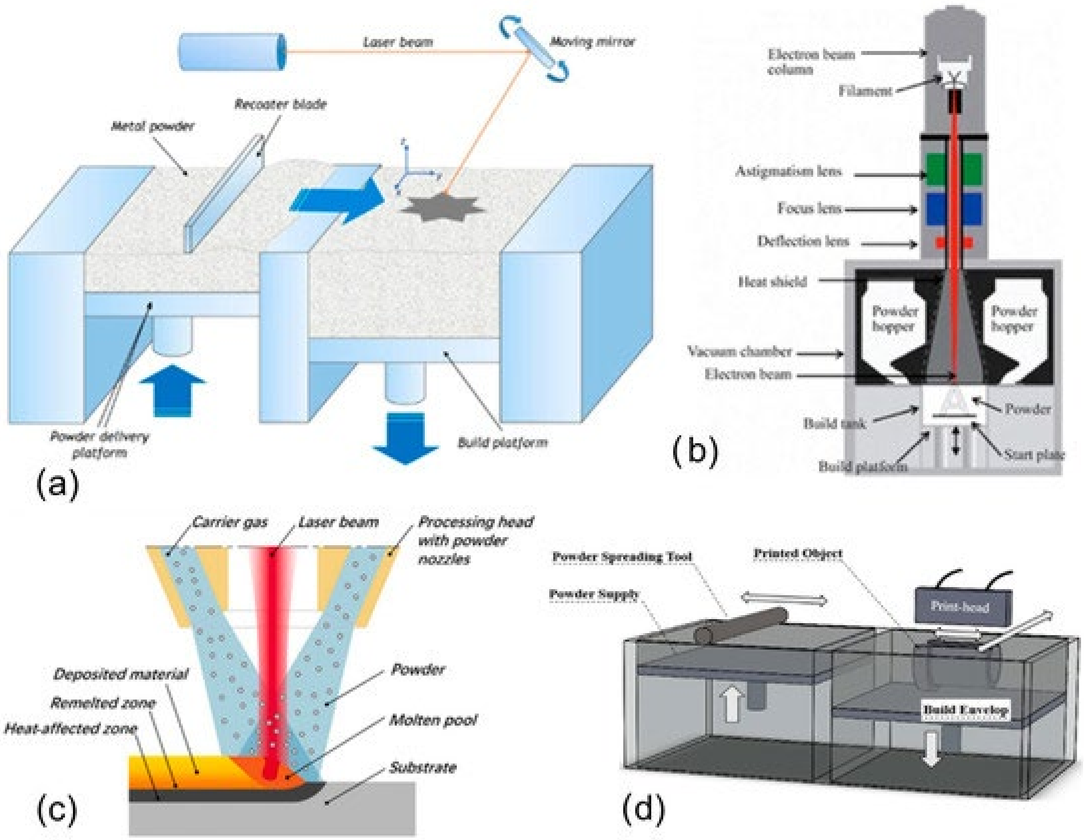

Figure 3: Schematics of metal additive manufacturing processes: (a) selective laser melting, (b) electron beam melting, (c) laser powder bed fusion, and (d) three-dimensional printing/binder jetting [19]

Furthermore, cyclic temperature treatment due to deposition process might lead to heterogeneous microstructures, such as elongated grain, cellular dendritic microstructure, metastable phases and inhomogeneous elemental distribution, These microstructures is generally non-uniform, as a result in non-uniform mechanical properties and degradation of reliability at long term. The challenges are all contributing factors that make post-processing an essential step in the AM [12].

2.3 Importance of Post-Processing Heat Treatment

Post-processing includes any manufacturing process carried out after printing to enhance the properties, performance, appearance or quality of an additively manufactured product. The following operations are carried out: Support Removal, Machining, Polishing, Shot Peening, Surface Coating, Hot Isostatic Pressing, Heat Treatment. Within these processes, heat treatment is considered to be one of the most effective, as it alters the internal structure of the material instead of only affecting its external appearance [19]. The main purpose of heat treatment is to adjust the micro structure of metals by a controlled heating and cooling process. Proper heat treatment can redistribute the alloying elements, encourage recrystallization, relieve residual stresses, encourage desirable phase transformations and reduce crystallographic defects. Therefore, the mechanical properties of the printed object can be significantly enhanced without altering its total size, or shape [20].

The first advantage of post-processing heat treatment is the ability to remove stress that may exist from the manufacturing process. Stress-relief treatments enable atomic rearrangement in the crystal lattice to lower the internal stress concentration that can lead to distortion or premature failure. Typically, a component that has been treated for stress relief has greater dimensional stability and is less prone to cracking when it undergoes machining or service [6]. They are also made more ductile and tough by heat treatment. Although many of these AM metals have high strength when produced, the fine microstructure and high dislocation density in AM materials typically results in low ductility. Under controlled thermal conditions, grain refinement and/or recrystallization can be performed, thereby reducing the brittleness and increasing the plastic deformation at failure [1]. One of the other key benefits is improvement in fatigue performance. Common causes of fatigue failure are internal defects, residual stresses, or stress concentration locations. Heat treatment is known to relieve residual stresses and reduce internal defects that would be present in the components, especially in combination with Hot Isostatic Pressing (HIP) and thus delay crack initiation and slow down the crack propagation thereby extending the fatigue life of engineering components [4].

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2.4 Major Post-Processing Heat Treatment Methods

Various thermal post-processing methods have been developed for various metallic alloys and production processes. The choice of the treatment will be greatly influenced by the composition of the alloy, the application for which it is to be used, and the required mechanical properties. Stress-relief heat treatment is typically the first post-processing step after printing. Components are heated to medium temperatures below the transformation range and maintained for a certain amount of time before the controlled cooling. The main aim is to relieve stresses and limit alterations of the existing microstructure. Stress-relief treatments are commonly performed on stainless steels, titanium alloys, aluminum alloys, and nickel-based superalloys right after they are fabricated [11].

Another common heat-treatment process is annealing. In the annealing process, the material is heated above the recrystallization temperature and then slowly cooled down in the furnace. The resulting treatment softens the material and makes it easier to machine, increases the ductility, and creates a more uniform grain structure. But high annealing temperatures may cause grain coarsening which decreases hardness and yield strength [2]. Solution heat treatment is routinely used on alloys that can be precipitation hardened, including aluminum alloys and nickel-based superalloys. Before rapid cooling, the alloy is heated to a temperature high enough to ensure that all of the secondary phases are in a single solid solution. Later, aging treatments can be used to control the precipitation of strengthening particles, which significantly enhance the hardness and tensile strength [8].

Precipitation hardening (aging) is carried out by heating the solution treated material at intermediate temperatures to form finely dispersed precipitates in the matrix. Such precipitates interfere with dislocation movement and greatly contribute to the strength and hardness with acceptable ductility. In maraging steels, Inconel 718 and some aluminum alloys, the aging process is particularly effective [20]. Hot Isostatic Pressing (HIP) is one of the most effective of all the post-processing techniques used to enhance the integrity of the structure. In HIP, various components are subjected to both high gas pressure and high temperature at the same time, which causes pores and lack of fusion defects to close. This process can significantly improve the density, fracture toughness and fatigue resistance of the parts, making it essential for critical applications such as aerospace and biomedical components where reliability is a critical requirement [4].

2.5 Factors Influencing the Effectiveness of Heat Treatment

Many variables interact and play a role in the effectiveness of post-processing heat treatment. The first is the alloy composition, as different metallic systems have different phase changes when heated and cooled. For instance, titanium alloys undergo α–β phase transitions while precipitation-hardenable alloys are strengthened mainly by precipitation reactions [9, 21]. The printing parameters also have a significant influence. Initial microstructure and residual stress distribution are determined by laser power, scanning speed, hatch spacing, layer thickness and build orientation. Thus, components that are produced using different process conditions can exhibit different responses to the same heat-treatment process [12, 22].

Other parameters like heat-treatment temperature, holding time, heating rate, cooling rate, furnace atmosphere etc., also affect the final mechanical properties. The high temperature and the extended holding time can cause grain coarsening and decrease hardness, while the low temperature may not completely eliminate residual stresses, and the mechanical performance may suffer. So, it is still an important research field to optimize the parameters for heat treatment [2, 23]. The post processing heat treatment is generally a necessary last stage in metal additive manufacturing due to its ability to overcome many of the metallurgical issues associated with metal fabrication. The use of suitable thermal treatment processes can convert printed components with residual stresses and microstructural variations into engineering materials that have better strength, ductility, fatigue performance, dimensional stability, and service reliability. Table 1 highlights the factors influencing post-process heat treatment effectiveness.

Table 1: Factors influencing post-process heat treatment effectiveness

Influencing Factor	Description	Key Effects	References
Soaking Temperature (^{0}C)	Target heating temperature (e.g., relative to the β-transus in Ti alloys)	Relieves residual stress; controls α' → α+β phase change; promotes recrystallization or grain growth	[16, 18]
Holding Time (hr)	Duration at the target temperature	Controls extent of phase change and grain evolution; longer times risk over-coarsening and lower strength	[13, 16]
Cooling Rate	Quench, air cool, or furnace cool	Fast cooling can reform martensite; slow cooling yields coarser, more ductile structures	[16, 18]
Atmosphere	Vacuum, inert gas (e.g. Ar), or air	Prevents oxidation and brittle α-case on reactive metals such as Ti-6Al-4V	[13]

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Influencing Factor	Description	Key Effects	References
As-Built Anisotropy	Starting microstructure from the AM process (LPBF/EBM, orientation, layer boundaries)	Directional grains from printing must be broken down by tailored heat treatment	[13, 18]
HIP Pressure	High-pressure inert gas applied with heat	Closes internal pores and lack-of-fusion defects while refining microstructure; greatly improves fatigue life	[16]

3 Effects of Post-Processing Heat Treatment on the Microstructure and Mechanical Properties of 3D-Printed Metal Parts

3.1 Microstructural Evolution During Post-Processing Heat Treatment

The microstructure of metallic components has a significant influence on the performance. The microstructures of additively manufactured metals exhibit significant differences when compared with those manufactured by traditional casting or forging methods, due to the special thermal history they undergo during the layer-by-layer process. Rapid cooling and crystallization during laser or electron beam processing led to the formation of fine cellular dendritic structures, elongated columns, high dislocation densities, formation of metastable phases and large residual stresses. These properties can also be beneficial for high strength, but they can decrease the ductility, fracture toughness and fatigue resistance [1, 2].

These microstructures can be modified by controlled atomic diffusion and phase transformations by post-processing heat treatments. In the heating process, stored strain energy in the crystal lattice will facilitate recovery and recrystallization and reduce the density of dislocations and internal stresses. Grains can become more equiaxed, precipitates can dissolve and re-precipitate, and undesirable phases can change to more stable microstructures depending on the treatment temperature and alloy composition. These changes in turn affect the mechanical properties of the material [20, 24]. One of the most important microstructural changes is recrystallization. Recrystallization produces new grains with no strain, replacing the grains that may be highly strained as a result of rapid solidification. This process helps to increase the uniformity of the grain, minimize the crystallographic defects and increase the ductility. The effects of high temperatures for long periods may lead to grain growth, which can decrease the strength of the product based on the Hall–Petch relationship [8].

Another very important phenomenon is phase transformation. The mechanical properties of many engineering alloys are dependent on the presence of certain phases which can be modified by thermal treatment. The α (alpha) is the strong but less ductile low-temperature phase, while β (beta) is the softer, more ductile high-temperature phase; in additively manufactured Ti-6Al-4V, rapid cooling traps an unstable brittle version (α' martensite), and heat treatment transforms it into a balanced α+β mixture that provides both strength and toughness. Some alloys, for instance, titanium alloys, undergo α to β phase changes, and precipitation-hardenable alloys like Inconel 718 and maraging steels produce strengthening precipitates during aging treatments. These transformations can be controlled to meet the material properties required for specific applications such as providing a balance between strength, hardness and toughness [25]. Microstructural heterogeneity is also decreased during heat treatment. Additive manufacturing processes typically involve repeated heating and cooling cycles that can lead to areas of different crystal grain size, crystallographic orientation, and elemental segregation. Diffusion is encouraged by controlled thermal exposure, which creates more uniform mechanical properties across the component and a more uniform microstructure [25].

3.2 Effect of Heat Treatment on Mechanical Properties

The microstructural changes occurring during post-processing heat treatment have direct correlations with mechanical properties of the additively manufactured metal. Several engineering properties are continually improving after adequate thermal treatment, with the degree of improvement varying with the type of alloy, the printing process, and the heat-treatment process parameters [2]. One of the main improvements is the minimization of residual stress. Residual stresses are commonly found in additively manufactured parts, which often cause part distortion, cracking and premature failure. These stresses can be greatly reduced by stress-relief heat treatment, providing better dimensional stability and reducing the likelihood of crack initiation. This benefit is especially critical in precision engineering components which require high dimensional accuracy [27].

The effects of heat treatment also on tensile strength and yield strength. In some alloys, especially precipitation-hardening alloys, an aging treatment can be used to increase the strength by generating precipitates in the material that block the movement of dislocations. However, if too much annealing is used, it may cause grain coarsening and therefore a decrease in strength. Thus, it is necessary to optimize the heat treatment schedules to provide an optimum combination of strength and ductility [20]. Stress relief and annealing treatments usually increase ductility due to a decrease in dislocation density and the grain structure. The higher ductility allows the material to absorb more plastic deformation before breaking, making it more suited for application where loading is dynamic and/or impact [28].

Fatigue resistance is another important property that is affected by heat treatment. Typically, fatigue failure starts from small defects, pores and residual stresses at the initiation of the cracks. Thermal post-processing can markedly improve fatigue life by decreasing these defects and by homogenizing the microstructure. Fatigue behaviour can be similar to, or even better than, conventionally manufactured material, especially when used in conjunction with HIP to reach performance level of traditionally processed materials [29]. Toughness, wear resistance and other properties can similarly be augmented with subsequent appropriate heat treatments. As one example, the research conducted by Deirmina et al. [21] showed a small post-process annealing gave better fracture toughness of 3D printed H13 tool steel, whilst maintaining effective temper resisting.

3.3 Effect of Heat Treatment on Stainless Steel (316L) and Titanium Alloys

Metal additive-manufactured 316L stainless steel is widely researched due to its superior corrosion resistance, weldability, and biocompatibility. The material is used extensively in biomedical implants, the marine industry, food production machinery, and chemical processing [3]. Owing to the high cooling rate during selective laser melting, 316L parts exhibit a very fine cellular microstructure with numerous dislocations, which imparts relatively high strength and significant residual stresses, as well as microstructural anisotropy that can lead to fatigue effects [11].

The parts are generally stress-relief heat-treated immediately after manufacturing. This relieves the stresses without significantly altering the overall grain structure, thereby improving dimensional stability and stability during further machining. At a higher level, solution annealing refines the grains, leading to more homogeneous equiaxed grain formation [3]. Designed solution annealing provides higher ductility and corrosion resistance by reducing elemental segregation [11]. However, solution annealing may slightly reduce yield strength and hardening [11]. Hot isostatic pressing can be added to eliminate lack-of-fusion and internal porosity defects, thereby greatly enhancing fatigue life and toughness, making it suitable for critical structural applications such as biomedical implants [30]. Titanium alloy Ti-6Al-4V is one of the most important materials in metal additive manufacturing due to its high strength-to-weight ratio, excellent corrosion resistance, and biocompatibility. Ti-6Al-4V is widely used in aircraft structures, turbines, orthopedics, and medical and dental prostheses [15].

During the rapid solidification stages at low temperatures, metastable α'-martensite transformation occurs, resulting in high strength and hardness but poor fracture toughness. Therefore, thermal treatments are often necessarily introduced to avoid this combination of high hardness and low fracture toughness [4]. Solution annealing in titanium alloy promotes the conversion of brittle α'-martensite into a stable α+β microstructure, improving ductility and impact behavior without sacrificing strength [2]. To achieve favorable structural and physical properties in AM Ti-6Al-4V, it is essential to tailor the grain size distribution and phase distribution through heat treatments. This allows engineers to find a balance between tensile strength, fatigue, and fracture toughness. It has been shown that well-designed heat treatments can improve the fatigue performance of additively manufactured Ti-6Al-4V parts, particularly for structural components in the aerospace and biomedical industries, where fatigue life is a critical parameter for success [20]. Hot Isostatic Pressing is also widely used for titanium alloys: it seals internal pores that can act as fatigue-crack initiation sites, yields near-full-density parts with enhanced mechanical reliability, and contributes to improved structural integrity and long-term clinical performance of titanium implants [27]. Overall, post-processing heat treatment converts the initially brittle and highly stressed microstructure of AM Ti-6Al-4V into a more stable and balanced structure that meets the high-performance requirements of modern aerospace and biomedical engineering.

3.4 Effect of Heat Treatment on Aluminum Alloys (AlSi10Mg), Nickel-Based Superalloys (Inconel 718) and Maraging Steel

Aluminum alloys, especially AlSi10Mg, are among the most commonly used materials in metal AM because of their low density, high specific strength, strong corrosion resistance and thermal conductivity. They are desirable for lightweight structural components in the aerospace, automotive and electronics industries. Rapid solidification during the AM process produces a fine cellular silicon network and a supersaturated aluminum matrix that differs markedly from conventionally fabricated AlSi10Mg [2]. Residual stresses and non-equilibrium microstructures result in relatively high strength but low ductility in the as-built condition; post-processing heat treatment is used to optimize silicon-particle distribution, relieve residual stresses and achieve a better strength–ductility balance [8]. Stress relieving of the components is generally performed as soon as the part is fabricated. Typical post-processing solutions for the T5/T6 material designation include a combination of solution heat treatment, high quench rate, and artificial aging treatment (T6 method). While solution heat treatment is used to dissolve alloying elements into the aluminum base metal, aging develops fine strengthening phases, which account for much of the mechanical property gain [17].

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Heat treatment has also shown promising ability to enhance hardness, ductility, wear resistance, and tensile strength compared to as-built parts. However, excessive temperatures can cause aggregation of silicon particles and grain growth during solution treatment, leading to a decrease in hardness and yield strength [20]. Nickel-based superalloys (such as the widely studied Inconel 718) are frequently utilized for high-temperature applications due to their enhanced temperature, wear, and creep resistance, and are used in gas turbine jet engines and nuclear power systems. Additive manufacturing provides greater feasibility for producing complex-shaped parts with cooling channels or reduced weight compared to conventional manufacturing (CM) processes [4]. However, the rapid cooling rate in AM causes elemental segregation, stress concentration, and unstable phases, so AM-processed components require heat treatment to precipitate the strengthening phases needed for high-temperature applications [2]. Generally, Inconel 718 is treated at high temperatures of approximately 1050 °C (solution treatment) and is then followed by a double-aged treatment. Solution treatments are performed to remove unwanted segregated phases, resulting in a homogeneous elemental composition of the alloy. Aging, in combination with fine precipitate formation, produces phases that can trap dislocations and enhance strength, hardness, creep resistance, and tensile strength [29], and may significantly increase the fatigue resistance of INCONEL parts at higher temperatures when compared to untreated ones [29].

Furthermore, the addition of hot isostatic pressing (HIP) can further strengthen fatigue performance and improve fracture toughness while reducing overall internal porosity. These capabilities are crucial for any aerospace part operating under high-temperature and high-loading conditions [20]. Maraging steel belongs to this class of superalloys and derives its ultra-high strength from precipitation hardening rather than carbon as the primary strengthening phase (hence its name, derived from "martensitic aging"). Due to its combined characteristics of high strength, toughness, and dimensional stability, it is often applied in dies, molds, punches, aircraft frames, high-performance cutting tools, gears, and other special-purpose components [2]. After AM, maraging steel has a very soft martensitic structure as a result of rapid cooling and needs to be strengthened using an aging heat treatment, which develops fine precipitates throughout the martensitic matrix that enhance hardness, yield strength, and tensile strength while maintaining acceptable levels of ductility [2]. It has been noted that heat treatment can result in doubling the hardness value while maintaining a high value of fracture toughness [6]. The intensive presence of grains also ensures very high rigidity, which is why maraging steels are among the main candidate materials for wear-resistant and high-stability precision tooling [6].

3.5 Effect of Heat Treatment on Magnesium Alloys, High-Entropy Alloys and Comparative Analysis

Mg alloys have been a focus of study due to their low densities and high strength-to-weight ratios, which make them ideal candidates for weight-critical applications in aerospace, transportation, and biomedical engineering. However, they are challenging to fabricate using AM due to their high chemical reactivity, tendency toward non-uniform microstructures, and susceptibility to oxidation [9]. Post-process heat treatments are critical in increasing the integrity of these structures. Solution treatment and aging lead to decreased elemental segregation and dissolution of undesirable secondary phases, forming a less segregation-rich, more homogeneous microstructure, which enhances ductility while having no negative impact on strength [9]. Heat treatment can also enhance corrosion resistance—an especially valuable attribute for biodegradable biomedical implants. However, magnesium alloys are highly sensitive to thermal exposure; temperatures must be carefully controlled to avoid excessive grain growth and oxidation. Optimization of post-processing for additively manufactured magnesium alloys therefore remains an active research area [14, 15].

High-entropy alloys (HEAs) are advanced multi-principal-element alloys that offer attractive combinations of strength, ductility, corrosion resistance, wear resistance and thermal stability, making them candidates for next-generation additive-manufacturing applications [10]. As-built HEAs frequently contain residual stresses, chemical segregation and microstructural heterogeneity caused by rapid cooling. Appropriate post-processing heat treatment promotes atomic diffusion, elemental homogenization and stabilization of desired phases, thereby improving structural uniformity and mechanical properties [10]. Optimized heat-treatment schedules have been shown to enhance tensile strength, ductility, fracture toughness and corrosion resistance while reducing microstructural heterogeneity. Because HEAs are relatively new materials, standardized heat-treatment procedures have not yet been established—an important direction for future research [10]. Table 2 shows the effect of heat treatment on various alloys.

Table 2: Effect of Heat Treatment on Various Alloys

Alloy	As-Built Issues	Treatments	HT Cycle	Main Benefits	Limitations	References
316L	Residual stress, anisotropy	Stress relief, anneal, HIP	Anneal ~900°C or HIP ~1100°C	Better ductility, corrosion resistance;	Slight drop in strength	[2, 3, 11]

Alloy	As-Built Issues	Treatments	HT Cycle	Main Benefits	Limitations	References
				HIP improves fatigue		
Ti-6Al-4V	Brittle α' martensite	Stress relief, HIP	Stress relief ~700°C / 2h; or HIP ~920°C / 4h	α' → α+β; higher ductility & fatigue life	Needs careful process control	[2, 4, 15, 20]
AlSi10Mg	Low ductility, residual stress	Stress relief, T6 aging	Stress relief 300°C; T6: 530°C solution + age 170°C	Higher strength, hardness & fatigue	Overheating lowers strength	[2, 8, 20]
Inconel 718	Segregation, residual stress	Solution + aging (± HIP)	Solution 980°C + aging 720→620°C	Higher strength, creep & fatigue resistance	HIP often needed for full density	[2, 4, 8, 20]
Maraging Steel	Soft martensite	Aging	Age 480–520°C / 3–6h	Hardness more than doubles	Best suited for tooling	[2, 6, 20]
Mg Alloys	Oxidation, non-uniform structure	Solution + aging	Solution 400–450°C + age 150–250°C	Better ductility & corrosion resistance	Highly heat-sensitive	[9]
HEAs	Segregation, residual stress	Homogenization	Homogenize 1000–1200°C / 1–24h	Better strength, ductility & corrosion resistance	No standard HT yet	[10, 31]

Generally, post-processing heat treatment has a beneficial effect on the performance of AM metals, although the magnitude and nature of the benefit differ across alloy systems. Stainless steels primarily benefit from stress relief, recrystallization and improved corrosion resistance. Titanium alloys undergo phase transformations that greatly improve ductility, fracture toughness and fatigue life. Precipitation hardening is highly effective for aluminum alloys, while solution treatment plus aging confers high-temperature strength and creep resistance on nickel-based superalloys [12, 20]. Maraging steels achieve substantial gains in hardness and tensile strength through precipitation hardening; magnesium alloys show improved microstructural homogeneity and corrosion resistance; and homogenization treatments stabilize desirable phases and reduce chemical segregation in high-entropy alloys [9, 10].

Common improvements observed across nearly all metallic systems include lower residual stresses, higher dimensional stability, enhanced fatigue resistance, reduced porosity (especially when combined with hot isostatic pressing), higher fracture toughness, and more uniform microstructures. Excessive treatment temperatures or prolonged holding times, however, can produce undesirable grain growth, hardness reduction, or loss of strength. Optimization of post-processing parameters therefore remains essential for achieving the desired combination of mechanical properties for specific engineering applications [4, 8]. Overall, the reviewed literature demonstrates that post-processing heat treatment is not merely an optional finishing step but an essential process in the production of high-performance 3D-printed metal parts. Judicious selection of thermal treatment regimes according to alloy composition and service conditions can greatly enhance the structural integrity, reliability, and service life of additively manufactured metallic components.

4 Industrial Applications, Challenges and Future Perspectives

4.1 Industrial Applications of Heat-Treated 3D-Printed Metal Parts

The ever-evolving growth of AM technologies has brought 3D-printed metal parts back into the industrial arena. In many cases within the engineering industry, it is impractical to use components immediately after fabrication. There is too great a risk of them being produced with residual stresses, insufficient mechanical properties from an anisotropic perspective, or even internal porosity and microstructural variations. This is why heat treatment is a very common post-build manufacturing procedure, employed to bring the finished product up to the required specifications [2, 32].

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4.1.1 Aerospace Industry

Aerospace applications represent one of the most demanding sectors for metal AM technology due to the requirements for lightweight parts with high strength and intricate designs. Techniques such as SLM, DMLS, and EBM have become increasingly applicable to the production of turbine blades, fuel nozzles, combustion chambers, brackets, heat exchangers, and engine casings [4]. Since fatigue, high-temperature exposure, and operational stresses are cyclic in nature, fatigue strength and structural integrity are exceptionally important attributes of aerospace components. The application of post-process treatments such as stress relieving, solution treatment, aging, and HIP can significantly enhance fatigue properties by removing residual stresses, eliminating internal pores, and developing a more uniform microstructure, thereby improving service life and minimizing the risk of in-service failure [20, 33].

4.1.2 Biomedical Industry

The biomedical industry has also seen stunning growth in the usage of metal AM. The excellent dimensional accuracy of AM enables the production of customized orthopedic implants, dental implants, cranial plates, spinal cages, and prosthetic devices, which are now routinely manufactured from titanium alloys and stainless steels [15].

With regard to these implants, heat treatment has an unreplaceable position in the guarantee of their long-term performance. Thermal processing can relieve the residual stresses and improve the microstructural homogeneity, which can decrease the possibility of implant failure in long-term service, and improve the fatigue resistance and fracture toughness. In addition, solution treatment and annealing processes increase the corrosion resistance and biocompatibility of the implants that are used in human bodies [14].

4.1.3 Automotive Industry

Additive manufacturing is increasingly being used by automotive manufacturers to manufacture lightweight engine components, transmission parts, brake assemblies, prototype components and customized performance parts. For both conventional and electric vehicles, weight reduction is a direct benefit to better fuel economy and emissions reduction, and this is where additive manufacturing becomes interesting [2]. Automotive service conditions demand mechanical strength, wear resistance and dimensional stability, which are provided by the heat-treated aluminum alloys, stainless steels and maraging steels. Post-processing is also beneficial for machinability, allowing it to be processed to the desired tolerances in final processes, such as the final finish [6].

4.1.4 Energy, Oil and Gas Industries

This application involves the use of AM metallic parts in the energy industry, such as gas turbines, heat exchangers, drilling equipment, valves and pressure-resistant parts working under extreme mechanical and heat conditions. The Ni-based superalloys are especially significant with regard to their high-temperature and corrosion resistance [4], among which Inconel 718 stands out. The heat treatment which follows the process is called post-processing heat treatment, and it is used to develop a precipitation-hardened microstructure required to achieve mechanical strength at prolonged high-temperature exposures. Along with HIP, thermal processing also reduces the growth of internal defects, which may lead to fatigue cracks under cyclic loading and enhance the operational safety of components along with their lifespan [20].

4.1.5 Tooling and Manufacturing Industry

The production of conformal cooling channels for molds, dies, injection molding inserts and cutting tools has been revolutionized by the development of metal additive manufacturing processes that optimize manufacturing efficiency. The most popular materials used for such applications include maraging steel and H13 tool steel [21]. However, H13 do not respond to heat treatment in the same way when produced via AM because their microstructures differ from those formed by conventional methods. This has driven research toward new materials specifically designed for AM, such as lean hot work tool steels like HWTS 50, which offer properties similar to H13 but with better processability and tempering resistance. Other examples include martensitic stainless steel 420 used in WAAM for die repair and high-carbon tool steels processed with powder-based techniques. Regardless of the material, post-processing heat treatments are essential, but they must be tailored to the unique AM microstructure to achieve meaningful gains in hardness, toughness, and wear resistance—thereby extending tool life and reducing maintenance costs. Additional surface engineering methods like plasma nitriding further enhance performance, ultimately boosting productivity across all manufacturing sectors [21].

4.2 Challenges Associated with Post-Processing Heat Treatment

While it has many benefits, post-processing heat treatment is still a technical and economic challenge that researchers are still interested in. A key problem is the lack of common heat-treatment schedules. Variations in chemical composition, precipitation mechanisms and phase transformation behavior among different alloys mean that they do not always react in the same manner to the same thermal cycles. Therefore, the process of optimizing the heat-treatment parameters for each alloy must often be optimized individually for each manufacturing process [2].

Another major challenge is to achieve a balance of strength and ductility. While higher treatment temperatures could be effective in relieving any residual stresses and enhancing ductility, excessive heat exposure could also stimulate grain growth that in turn will decrease hardness and tensile strength. Thus, when optimizing the process, manufacturers have to consider different requirements on the mechanical property of the product [8]. Production cost is also a major constraint. Special furnaces, controlled atmosphere, special personnel and lots of energy is needed for heat treatment. There are other processes that further contribute to the manufacturing price, like Hot Isostatic Pressing, which would increase even more the manufacturing cost, as it is one of the most expensive stages of Additive Manufacturing (AM) [1]. Also, the geometry of complex components can cause non-uniform heating and cooling, causing distortion or incomplete stress relaxation at certain points. The challenge becomes more critical for large structural parts or assemblies that have different thicknesses of walls [12]. Lastly, the absence of common international standards for heat treatment of numerous AM alloys makes the process of industrial certification challenging, especially in industries such as aerospace and biomedical, where quality standards are stringent and must be met [4].

4.3 Future Perspectives

Despite substantial progress made in the body of knowledge on post-thermal processing (PT) of additively manufactured metals, a few critical research gaps remain to be filled. Limited process windows and the narrow variety of alloys used in most published work hinder direct comparisons of outcomes across studies. Experimental data often exhibit wide variations due to differences in printer types, laser power, scan patterns, layer thicknesses, and heat treatment regimes [2]. More critically, knowledge of long-term performance under operational service conditions after heat treatment is scant. While many experimental reports focus on investigating the effects of PT on mechanical properties, only a few have examined its influence on other service behaviours such as creep, corrosion-fatigue interaction, wear under realistic operating conditions, and long-term microstructural evolution [20]. In this regard, new alloy families—namely high-entropy alloys and multi-material construction designs—for which established PT standards are very limited, should be prioritized for investigation [10]. Another exciting issue worthy of consideration is the interrelationship between process parameters in AM technologies and the conditions applied during subsequent heat treatment. A thorough understanding of these relationships could facilitate the achievement of optimal end-product characteristics without resorting to cumbersome trial-and-error-based experimental approaches [8]. The outlook for development in post-processing heat treatment of additively manufactured metals is likely to focus on smart process optimization, integration with digital fabrication, and sustainable production.

For intelligent process optimization, the application of Artificial Intelligence (AI) and Machine Learning (ML) to predict ideal post-processing heat treatment parameters will enable the prediction of optimal mechanical properties for given metal compositions, manufacturing parameters, and target property requirements, thereby reducing experimental costs and improving consistency. Another area of development lies in in-situ heat treatment (in-situ HT) of additively manufactured parts during the fabrication process, with the aim of minimizing residual stresses, reducing the need for additional PT, and consequently saving time. A third avenue could be the development of hybrid manufacturing systems that can perform additive manufacturing, machining, and thermal treatment in a single process station, aiming to improve efficiency and reduce costs, errors, and handling difficulties [8]. Sustainability will be a greater factor in the considerations. Future research could include energy efficient heat treatment technology, reducing greenhouse gas emissions, optimizing furnace operation and minimizing overall manufacturing cost with high component quality. In general, further improvements in materials science, modelling, artificial intelligence and manufacturing technologies are likely to further drive the effectiveness of post-processing heat treatment, enabling metal additive manufacturing to be more widely adopted in more demanding engineering applications.

5 Conclusions

The post-processing heat treatment is an essential step in the manufacturing of high-quality metal 3D-printed components. Though additive manufacturing has the potential of designing with unprecedented freedom and manufacturing flexibility, the very high operating temperature range of metal printing inevitably causes residual stresses, non-uniform microstructures, anisotropic mechanical properties and defects in the printed components, which can negatively influence component properties. These challenges can be overcome by heat treatment, which induces controlled thermal exposure to the material to alter its microstructure, which in turn can improve the material properties of strength, ductility, fatigue resistance, fracture toughness, corrosion resistance, and dimensional stability. It has been found from the literature review that there is no single heat-treatment procedure that is suitable for all metallic alloys. Rather, the effectiveness of thermal post-processing is influenced by a number of factors, such as the composition of the alloys, the process of additive manufacturing, the printing parameters, the temperature of the treatment, the holding time, the cooling conditions, and finally the service environment. Therefore, it is crucial to choose suitable heat-treatment schedules in order to optimise the performance and reliability of additively manufactured components.

The review also demonstrates that the use of advanced post-processing techniques, such as Hot Isostatic Pressing, combined with the conventional heat treatment, can significantly reduce the porosity and improve structural integrity of 3D-printed parts for demanding applications in aerospace, biomedical, automotive and energy sectors. With the ongoing development of additive manufacturing, post-processing optimisation will continue to be extremely important in order to enable the widespread application of metal 3D printing in safety-critical engineering applications. Finally, future research should focus on establishing standardized heat-treatment protocols for new alloy systems, gaining a greater understanding of how print parameters and heat-treatment affect performance, evaluating the alloys' performance over time under realistic service conditions, and the use of artificial intelligence to optimize heat-treatment. Solving the aforementioned issues will lead to more efficient manufacturing processes, lower production costs and the potential to achieve the maximum utilization of metal additive manufacturing in today's engineering.

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