Impact of Post-Processing Technologies in Additive Manufacturing for Aerospace Applications – A Review

Gautam, Anurag*+
Department of Chemistry, Geethanjali College of Engineering and Technology, Cheeryal, Hyderabad, Telangana 501301, INDIA

Sharma, Ashutosh*+
Department of Materials Science and Engineering, Ajou University, Suwon-16499, SOUTH KOREA

Singh, Ram Sevak*+
Department of Physics, OP Jindal University, Raigarh, Chhattisgarh-496109, INDIA

Prabhat Gautam
Department of Chemistry, CMR Institute of Technology, Bengaluru, Karnataka 560037, INDIA

ABSTRACT: *Modern aircraft engine components with thin-walled structures and complex shapes pose enough difficulties in the processing of materials which compel the aerospace industry to adopt the use of layered Additive Manufacturing (AM) technology. The aerospace industry is looking toward more durable, smaller, and lightweight components. However, AM technology suffers certain obstacles in the mass production of aircraft components due to critical issues such as part anisotropy, poor mechanical properties, and inadequate surface quality. Therefore, various surface modification and post-processing methods have been proposed to improve the surface characteristics of AM-manufactured parts. In this review, we have overviewed the historical developments, various post-fabrication methods, and applications concerning different metal AM processes. Several kinds of AM and their comparison for aerospace applications, their post-processing technologies, and their integration with AM processes are discussed in this review towards the possibility of future advancement in this field.*

KEYWORDS: *Additive manufacturing; Surface modification; Metal 3D printing; Aerospace; Lightweight.*

INTRODUCTION

Additive Manufacturing (AM) is automated technology that is defined as a process of creating three-dimensional (3D) objects through computer/digital modeling by adding layer by layer via a bottom-up approach therefore, it is also called 3D printing technology. Recently, it has fascinated researchers in different areas such as aerospace technology biotechnology, and biomedical engineering to fabricate objects and devices. The first method of 3D printing was stereolithography which was developed in 1987. It was mostly utilized in biomedical engineering and prototyping

* *To whom correspondence should be addressed.*
+ *E-mail: ganurag13@gmail.com , ashu.materials@gmail.com , singh915@gmail.com*
1021-9986/2023/6/1871-1888 18/$/6.08

applications. The AM technology has many advantages over other existing traditional fabrication technology such as it rapidly produces the complex 3D structure, manufacturing cycles are shorter, and it is an economical process when it comes to production in smaller batches [1-4]. Additionally, for the fabrication of the desired 3D object the AM technology requires mostly raw equipment and materials without requiring complex and sophisticated tools like the traditional manufacturing technology. Moreover, AM technology possesses the additional benefits of on-demand production of the required net shape [3, 5].

AM has revolutionized fabrication technology in particular the aerospace industries. For instance, the first requirement of aerospace technology is lightweight materials that would enable them to have a high strength-to-weight ratio. That will reduce the overall load of the aircraft and will provide better fuel efficiency with reduced emissions of hazardous materials and gases. An estimated 18.2% of the revenue of the AM is generated by manufacturing the aerospace components that constitute both metallic, nonmetallic elements, and polymeric materials by application of energetic laser beams [6]. The energetic laser beam of high density increases the local temperature of the raw materials above their melting point which enables the transformation of the materials into the desired 3D structure. This paper will describe different post-processing technologies in AM for application in aerospace technology.

Traditional and additive manufacturing

Traditional manufacturing can be called a subtractive manufacturing process because it works in a top-down approach where the undesired materials are removed to achieve the desired shape by drilling, sawing, cutting, milling, etc. which requires a longer degree of supply chain [7, 8]. It leads to the production of enormous amounts of waste with limited ability to achieve the desired and complex structure. Therefore, sustainable development (healthy and productive life in harmony with nature) would be difficult to achieve through traditional processes because it is not environmentally friendly as it consumes more energy with the emission of hazardous substances. Additionally, starting from the construction site if that is away from the installation unit then it would further require transportation to the installation point. However, when the construction site is closer to the installation unit there is a huge amount of emission of hazardous gases with the production of significant amounts of other waste products that would further need to be discarded sooner or later point in time. In an estimate around the world, at present, the global traditional manufacturing unit consumes around 40-45 % of the total global energy with about 38-40% of the carbon emission. The carbon emission only from the coal-fired power plant is about 15-16% with the emission of some other hazardous gases that further increase the eutrophication. Typical composition of untreated flue gas after post-combustion from a coal-fired power plant.

However, the AM technology is fabricated in a bottom-up approach in the layer-by-layer arrangement that produces the 3D structure. Therefore, this process consumes only the required amount of the precursor materials and minimizes the generation of the additional waste that is unavoidable in the case of the traditional method of fabrication. Additionally, it requires lower power of the operation together with lower emissions of carbon-related products and other hazardous substances. Generally, an AM process is accomplished by the following three fundamental steps: The first step involves the creation of a digital model of the required design using modeling software which is also called CAD 3D modeling followed by the conversion designed model into a multi-layered structure in the layer-by-layer arrangement by using the slicing software. This process will quantify the number of layers and density of layers in the structure. Subsequently, each layer will be deposited with the profiting machine.

Classification of AM process

AM can be classified mostly in the three categories concerning the starting state of the precursor materials such as (i) Liquid-based system (LBS) (ii) powder-based system (PBS) (iii) solid-based system (SBS) as shown in Fig. 1.

The LBS can be further subdivided into Stereolithography and direct light processing, while PBS is subdivided into Selective Laser Sintering (SLS) and Digital Laser Metal Sintering (DLMS), Electron Beam Melting (EBM), Selective Laser Melting (SLM), Direct Energy Deposition (DED), and Fused Metal Deposition (FMD). The SBS can be divided into three categories which are Fused Deposition Modeling (FDM), Electron Beam Freeform Fabrication (EBFF), and Wire Arc Additive Manufacturing (WAAM) [4-8].

The LBS can be further subdivided into Stereolithography and direct light processing, while PBS is subdivided

Table 1: Typical composition of untreated flue gas after post-combustion from a coal-fired power plant [9, 10].

Molecules	Concentration (volume)
CO_2	15-16%
H_2O	5-7%
O_2	3-4%
SO_2	800 ppm
SO_3	10 ppm
NOx	500 ppm
HCl	100 ppm
CO	20 ppm
Hydrocarbon	10 ppm
Hg	1 ppb
N_2	Balance (air composition)

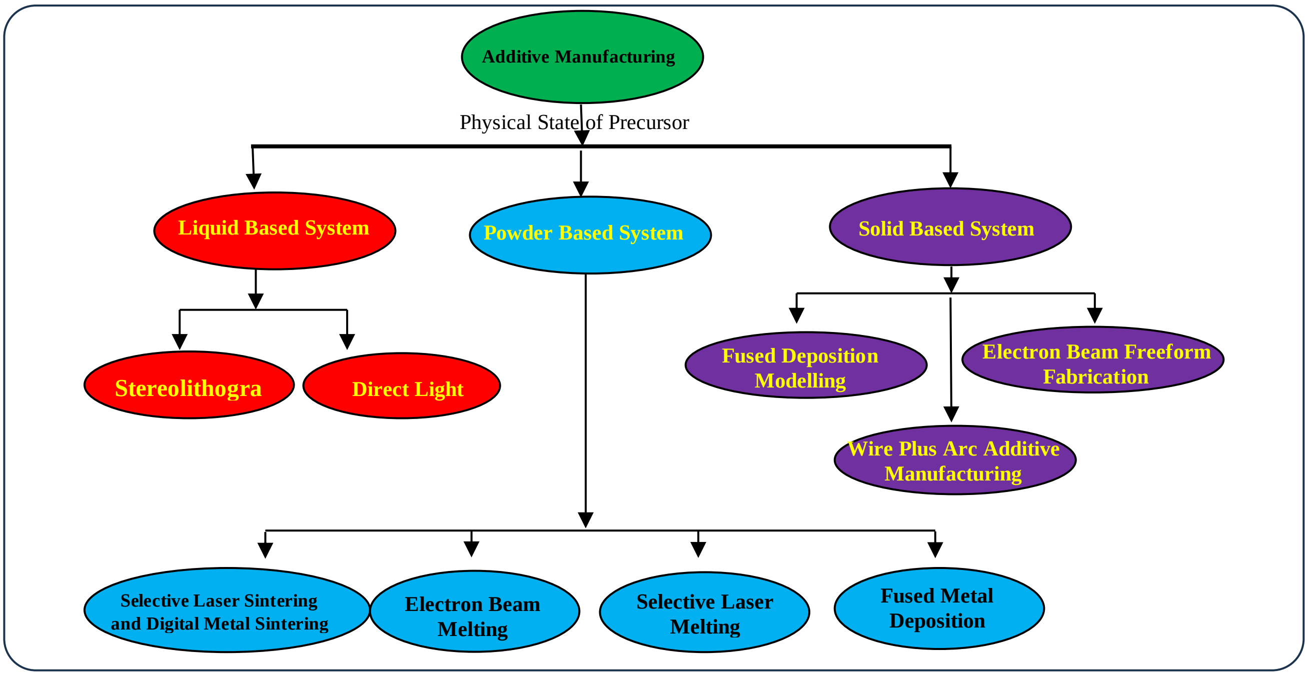

Fig. 1: Schematic classification of the most commonly used 3D process.

into Selective Laser Sintering (SLS) and Digital Laser Metal Sintering (DLMS), Electron Beam Melting (EBM), Selective Laser Melting (SLM), Direct Energy Deposition (DED), and Fused Metal Deposition (FMD). The SBS can be divided into three categories which are Fused Deposition Modeling (FDM), electron beam freeform fabrication (EBFF), and Wire Arc Additive Manufacturing (WAAM) [4-8].

Need for post-processing of AM parts

Although AM technology has overcome the energy and cost requirements of fabricated parts, there are post-fabrication issues in this technology due to its layer-by-layer additive fabrication. Compared to traditional subtractive manufacturing technologies, the surface finishing of the AM parts is inferior to its traditional counterparts. The reason is the layerwise fabrication technology which creates gradient defects at the surface and microstructural heterogeneity. Different AM processes mentioned above (SLS, SLM, EBM, DMLS, FDM, WAAM, EBFF) may give rise to different types of surface finishing, surface roughness, defects, and pores depending upon the source `of energy used for melting the part. The requirements of surface finishing and mechanical properties cannot be met at the same time alone by a single AM technology. Therefore, the post-process finishing of the 3D parts needs to be resolved in AM processes [11, 12].

Need for this study

Post-processing is an essential requirement of the fabrication but some techniques such as SLS, SLM, WAAM, DED, and EBM produce highly dense components with the same mechanical strength and may not require post-processing therefore are more relevant for the aerospace industry from the above-mentioned AM process. Moreover, the SLS is utilized to fabricate metal, ceramics, and plastics while the SLM can be used to fabricate many materials. DMLS is also similar to SLS but can be more specifically applied to fabricate metal alloys. EBM is another technique used to fabricate void-free with high mechanical strength components but is only applicable to fabrication from metals. Other important techniques such as WAAM which is also known as direct energy deposition arc with wire as feedstock widely used in repairing the product with very high quality.

Despite such developments in AM, there is not sufficient information for understanding influential parameters due to the complex metallurgical and thermos-physical phenomena occurring inside the adjacent layers at high-temperature gradients. Defects such as balling, pores, cracked zones, agglomerates, and residual stresses would appear between the adjacent layers which degrade the final properties of the 3D part [11, 12]. Various post-processing options are available in the literature, however, not all processes are applied to all the AM technologies same time. Therefore, this article reviews the widely used post-processing technologies, e.g., thermal annealing, laser polishing, laser peening, micromachining, and abrasive finishing. The introductory background of this review is introduced in section 1. Section 2 reviews the current status of AM in aerospace. Section 3 presents the various challenges of AM in aerospace. Section 4 and 5 overview the post-processing techniques used in AM and real-world status in aerospace. Section 6 covers the 4D printing followed by conclusions and future prospects in section 7.

PRESENT STATUS OF AM IN AEROSPACE

The aerospace industry is one of the most powerful and largest industries in the world that produces in-space and space launch systems, military and commercial aircraft, satellites, general aviation, and missiles. This industry had $ 342.2 billion in revenue in 2019, which was reduced to $ 298 billion in 2020 due to the recent COVID-19 pandemic. Nevertheless, the high demand for new commercial aircraft, high market activity in the space sector, increased global military expenditure, and ongoing research and development during the pandemic would further grow the aerospace industry, leading to the expected $430.87 billion revenue by 2025 [13]. The AM market receives 18.2% of revenue from the aerospace industry [14]. Over the last decade, there has been an exponential growth of research on AM in aerospace. It is expected that AM digital transformation, commonly referred to as industry 4.0, will grow the AM market size in the aerospace zone to $3.187 billion by the year 2025, and will produce an average Compound Annual Growth (CAGR) of 20.24% [15]. Table 2 shows the comparison of various metal AM processes used in aerospace.

As shown in Table 2, we can choose the process according to the parameters and their effects on the final part. The desired attributes include maximum build rate, build volume, efficiency, and minimum energy to reduce build time and cost. We can see that the build rate increases with layer height due to an increase in the melt pool geometry.

Materials used in AM for aerospace applications.

Materials used in AM are metals for critical aircraft parts and non-metals (mostly polymers) for non-critical aircraft parts. Commonly used metals are aluminum alloys, titanium alloys, nickel- and iron-based superalloys, copper alloys, refractory alloys, cobalt alloys, stainless steel, and steels [31].

Metallic materials

Metal alloys having fascinating characteristics, such as high corrosion resistance, high strength-weight ratio, composite compatibility, and a wide range of temperature compatibility are highly demanded in AM for aerospace applications. Depending on the process, most of these metal alloys are used either in powder form or in wire form. Aluminum alloys are the most popular materials used in the aerospace sector, owing to their low cost, lightweight, high strength-to-weight ratio, and ease of manufacturing characteristics. However, poor corrosion resistance and poor elevated temperature capabilities are the limitations of some high-strength aluminum alloys [32]. Titanium alloys have received much attention in AM for aerospace applications due to their superior corrosion resistance, high-temperature stability, and large specific

Table 2: Comparison between all processes based on literature.

S.No.	Process variable/Parameter	Values	AM method	Ref.
1	Energy	100-1000 W	Laser beam-PBF	16
2	Process efficiency	2-5%	Laser beam-PBF	17
3	Dimension accuracy	±0.04	Laser beam-PBF	18
4	Build volume (max)	500 × 350 × 300 mm3	Laser beam-PBF	16
5	Layer thickness	20-100 μm	Laser beam-PBF	18, 19
6	Surface roughness	4-11 μm	Laser beam-PBF	18, 20
7	Features size (min.)	40-200 μm	Laser beam-PBF	16
8	Build rate (Ti64)	0.1-0.18 kg/h	Laser beam-PBF	16
9	Energy	3500 W	Electron beam - PBF	21
10	Process efficiency	15-20%	Electron beam - PBF	17
11	Dimension accuracy	±0.05	Electron beam - PBF	22
12	Build volume (max)	200 × 200 × 180 mm3	Electron beam - PBF	16
13	Layer thickness	100 μm	Electron beam - PBF	23
14	Surface roughness	25-35 μm	Electron beam - PBF	20
15	Features size (min.)	100 μm	Electron beam - PBF	16
16	Build rate (Ti64)	0.26-0.36 kg/h	Electron beam - PBF	24
17	Energy	500-3000 W	Laser metal deposition as DED	25
18	Process efficiency	2-5%	Laser metal deposition as DED	17
19	Dimension accuracy	±0.13	Laser metal deposition as DED	17
20	Build volume (max)	900 × 1500 × 900 mm3	Laser metal deposition as DED	26
21	Layer thickness	500-1000 μm	Laser metal deposition as DED	24
22	Surface roughness	20-50 μm	Laser metal deposition as DED	18, 24
23	Features size (min.)	150-200 μm	Laser metal deposition as DED	27
24	Build rate (Ti64)	0.1-0.141 kg/h	Laser metal deposition as DED	24
25	Energy	2000-4000 W	WAAM	17
26	Process efficiency	70%	WAAM	28
27	Dimension accuracy	±0.2	WAAM	17
28	Build volume (max)	No limit	WAAM	29
29	Layer thickness	1000-2000 μm	WAAM	30
30	Surface roughness	500 μm	WAAM	30
31	Features size (min.)	2000 μm	WAAM	30
31	Build rate (Ti64)	0.5-4 kg/h	WAAM	29

resistance [33]. They are also electrochemically compatible with polymer matrix-carbon fiber composites (PMCs) which are widely used in modern aircraft [34]. Titanium alloys, showing no transition from ductile to brittle at cryogenic low temperatures, have potential applications in rocket propellant tanks [34]. GE Avio Aero has developed low-pressure turbine blades utilizing titanium aluminide (TiAl) alloy in AM [35]. However, relatively high cost and poor machinability are disadvantages of titanium alloys. Stainless steel of various classes including precipitation hardened (PH), maraging, and austenitic, are also used in AM due to their excellent mechanical properties at elevated temperatures, high strength-to-weight ratio, outstanding durability, and hardness, high corrosion, oxidation, and wear resistance [36]. They are mostly used for components of engine and exhaust systems, heat exchangers, structural joints, hydraulic components, and landing gear systems of aircraft [37]. Most of the metal alloys exist as feedstock for AM, and optimization of process parameters and post-processing operations is needed to minimize residual stress, porosity, and crack propensity to improve the properties of the materials.

Non-metallic materials

Non-metal materials (polymers or polymer composites) most relevant to the aerospace industry include glass-filled nylon, nylon 12, standard resin, castable resin or wax, clear resin, digital ABS (acrylonitrile butadiene styrene), PC (polycarbonate), PC-ABS (*Polycarbonate*/acrylonitrile butadiene styrene), ULTEM (Polyetherimide) [38, 39], etc. For example, glass-filled nylon is used in the fabrication of heat-resistant engine compartments [40] while nylon 12 is used to produce flexible parts like ducts and bellow directors for airflow [41]. NASA has developed a Rover named Desert RATS consisting of around 70 parts that have been additively manufactured. These parts are made of PC, PC-ABS, and ABS [42]. Recently, polymer nanocomposites have received enormous interest in aerospace applications [43]. They have nanofillers of different shapes like fibers, and platelets in a polymer matrix [44]. Compared to conventional composites, polymer nanocomposites offer atomic oxygen resistance, enhanced modulus, molecular penetration resistance, increased ablative performance, and thermal performance. Clay, graphene and graphene oxide, carbon nanotubes are some of the nanocomposites commonly used in aerospace applications [45-47]. However, these nanocomposites suffer from poor strength and do not fulfill the strength requirements for aerospace components. Thus, multiscale composites are developed by making a hybrid of conventional composites and nanocomposites for applications in aerospace [48].

CHALLENGES AND ISSUES IN AM PARTS

Although AM is being rapidly adopted in the aerospace, medical, and automotive fields, it is still considered a growing technology due to many challenges and issues in AM parts.

Lack of universal standards and certifications

AM components lack established associated standards and certification due to which the use of most current AM is prohibited for non-mission-critical applications in the aerospace industry [49]. To solve these issues, researchers along with regulatory aviation bodies are progressively working on the development of a new standard to meet the current requirements of AM [50]. Furthermore, due to a lack of unified standards, commercial companies and academic institutions have developed their classifications of AM technologies, which usually contradict the nomenclatures and categorization of AM processes [51]. To date, varieties of standards generally for metal AM have been developed, including the ASTM F3122-14 for the evaluation of mechanical properties, the ISO/ASTM52900-15 for standard AM technology, and the ASTM F3049-14 for the evaluation of metal powders utilized in AM [52]. However, many of these standards do not fulfill the requirements of AM in the aerospace industry. Efforts in this direction are therefore still needed.

Material printing issues

There are also several challenges and issues with materials used in AM. Many common metal alloys synthesized by traditional methods have challenges in AM due to the formation of cracks or pores, oxidation, or other undesired properties. As such, the development of new and custom metal alloys is required which can allow more optimized processing to mitigate these challenges. Custom aluminum alloys including 6061-RAM2, 7A77, Scalmolloy, and AlSi10Mg offer high strength and are more compatible with AM processes [53, 54]. NASA has also initiated the development of advanced alloys such as GRCop-42 and GRCop-84 copper alloys for high heat flux applications [55].

Process time and cost

Another key challenge in AM parts is a reduction in processing time and hence cost reduction. Components of aerospace are generally complex to fabricate and mostly require unique alloys that need a long time for procurement and sufficient processing time to form, machine, and assemble to obtain a final part. The time required in these processes is called lead time. The lead time is further added to the time spent in inspections and traceability of materials and parts during the process. A rigid process to ensure the parts are fabricated safely and meet the certifications and standards and the design intent are strictly followed for aerospace applications. As such, there is no opportunity to reduce the time spent in these processes. However, the lead time can be reduced substantially with a simplified supply chain by using new parts designs for replacements or spares that are out of production [56, 57].

METHODOLOGIES - POST-PROCESSING TECHNIQUES FOR AM

Heat treatment

Thermal heat treatment and annealing procedures can significantly release thermal stresses, decrease cracking and distortion, and homogenize the acicular α'-martensite [58–61]. Various thermal heat treatment procedures have been reported in past years including solution heat treatment, hot isostatic pressing, and T6 heat treatment for AM AlSi10Mg parts for aerospace. Post-annealing methods have been frequently used to control the microstructure and mechanical properties of the AM parts [62–67]. The thermal annealing process was recently used by *Ahn et al*. to homogenize the duplex ($\alpha + \beta$) microstructure of SLM Ti-6Al-4V alloy. The authors varied the annealing temperature from 650-1000ºC to study the morphology of α'-martensite. Their results indicated an enhancement of the anisotropy due to the transformation of acicular α'-martensite to globular α'-martensite structures [68].

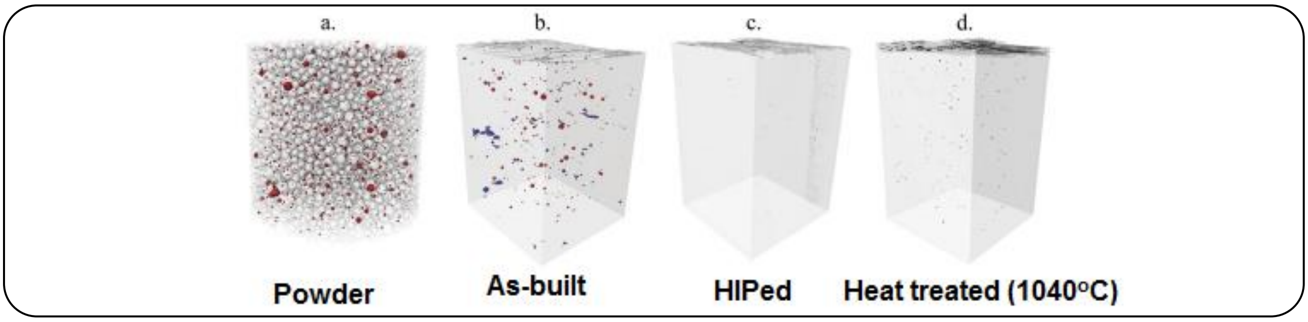

***Fig. 2:** X-ray microtomography showing porosity in powder and as-built sample (a-d) [75]. (Copyright 2017, open access)*

Similar results were seen by *Vrancken et al*. when they heat-treated SLM-Ti-6Al-4V alloy at 850 °C. The results showed the transformation of α′- martensite phase to a lamellar α + β microstructure [69]. *Kim et al*. also found a decline in the hardness and strength of SLM Ti-6Al-4V as well as mechanical anisotropy after heat treatment [70]. In general, heat treatment alleviates the thermal stresses and controls mechanical anisotropy. Despite various annealing heat treatment procedures, optimal conditions for meeting the surface finish and mechanical properties are not consistent in the literature due to the complex thermal history and microstructure of 3D parts.

Hot isostatic pressing of powders combines high-temperature (1000-2000ºC) and pressure (200MPa) applied to the part evenly in all directions to increase the density and uniformity. The use of HIP minimizes energy consumption and production cycle and maximizes the yield. HIPing results in the elimination of printing defects and pores during the powder bed fusion (PBF) process [71, 72]. Additionally, HIPing can reduce the crack initiation points in the part and improve the fatigue strength of Ti-6Al-4V produced by EBM [71-73]]. HIPing is used often to improve the mechanical properties of the EBM parts. The HIPing process reduces the pore formation and un-melted powder particles and also reduces the microstructural coarsening during the high-temperature HIPing.

In [74], the authors compared the effects of HIPing and HIPing + heat treatment on the EBM-fabricated Inconel 718 alloy. HIPing was used to post-process the surface defects. Combined HIPing + heat treatment caused a significant reduction in shrinkage porosity, lack of fusion, and liquefaction cracks during the welding of layers. The combined heat treatments enhanced the part density almost completely. The closing of the defects can be related to the various creep and diffusion of the powder particles during HIPing except for the surface defects and pores that are difficult to close by HIPing. *Ross et al*. further showed that porosity in EBM fabricated Ti-6Al-4V reduced after HIPing treatment but it may increase after further heat treatment as shown in Figure 2 [75]. The porosity decreases and becomes negligible in HIPed samples but again rises slightly with heat treatment at 1040ºC.

Such an increase in the growth of pores after heat treatment of HIPed specimen is a concern for post-HPAing procedures in AM industries. Slow strain rate testing and corrosion assessment of HIPed EBM Ti-6Al-4V alloy were studied by *Leon et al*. [76]. The as-built and HIPed specimens showed columnar microstructure due to the epitaxial growth of parent β-grains [77]. After HIPing, the microstructure of Ti-6Al-4V was relatively more homogeneous than that of the as-built sample. The columnar grain structure was not changed and showed the formation of discontinuous α-grain boundary, fine Widmanstätten α, and primary α nucleated over the primary β-grains boundary due to the rapid solidification process [78]. The Widmanstätten structure α-lath was wider in HIPed samples due to diffusion-controlled coarsening of α-lath [79]. Other researchers have shown that physical, mechanical, and microstructural properties can be significantly improved by post-heat treatment. *Bagherifard et al*. [80] reported that an optimum heat treatment condition can improve the fatigue strength of AM AlSi10Mg parts. Along the same lines, *Butler et al*. [81] demonstrated that the thermal conductivity of AM AlSi10Mg alloy can be remarkably increased after suitable post-processing.

Compared to laser-based PBF methods, DED-fabricated 3D parts are associated with tiny amounts of pores due to their highly concentrated source of energy [82]. Additionally, there is a huge difference in DED parts before and after post-processing [83]. *Bassini et al*. [84] studied the effects of different heat treatments on the microstructure of laser beam-PBF Inconel 718. As shown

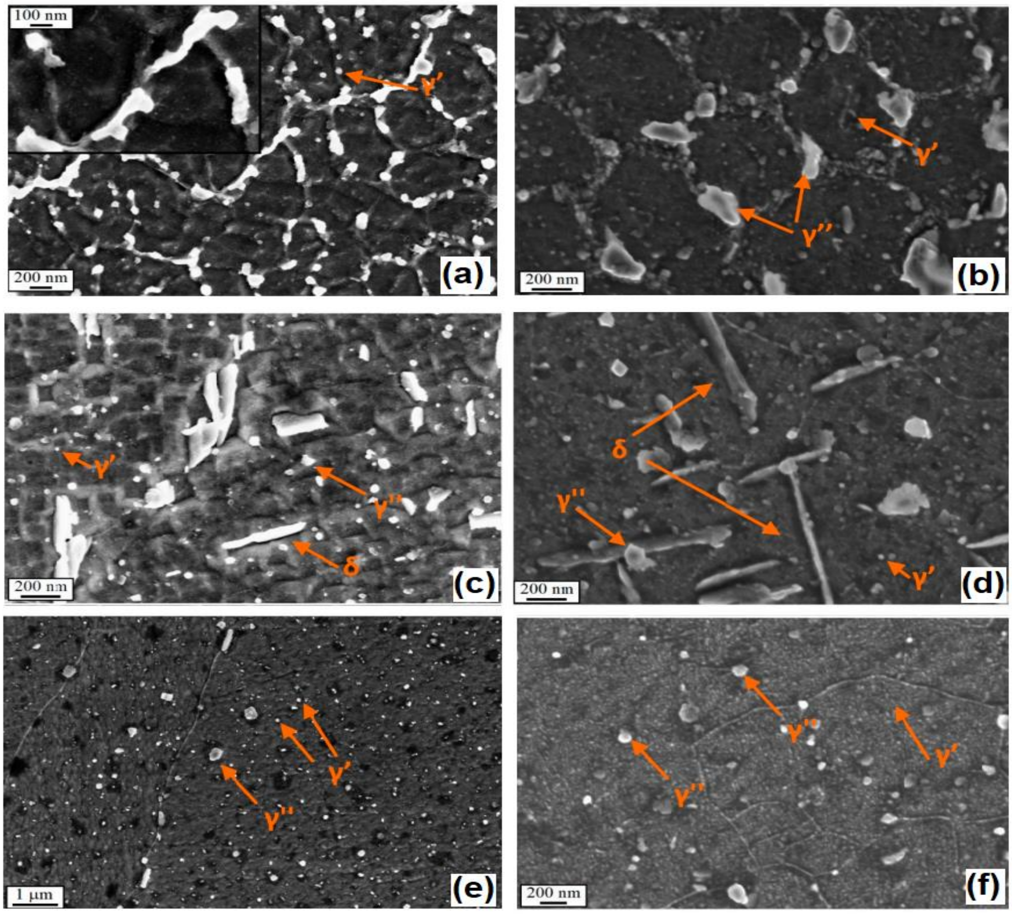

Fig. 3: Surface morphology of laser beam-PBF Inconel 718. (a, b) Direct aging at 650°C and 720°C for 8h, (c) Solution annealing at 980◦C for 2 h and subsequent aging at 650 ◦C for 8 h (d). Solution annealing at 980 ◦C for 2 h and subsequent aging at 720 ◦C, (e) Solution annealing at 1065 ◦C for 2 h and subsequent aging at 650 ◦C for 8 h, and (f) Solution annealing at 1065 ◦C for 2 h and subsequent aging at 720 ◦C for 8 h [84]. (Copyright 2021, open access)

in Fig. 3, the as-built specimens are composed of columnar γ-dendrites with a smaller fraction of γ + Laves in the interdendritic region.

Direct aged specimens showed heterogeneous γ''/γ' precipitates around Laves as shown in (Fig. 3 a, b). The size of the precipitates increased with an increasing aging temperature from 650-720°C. The solution annealing treatment and aging resulted in a decrease in the micro-segregation of leaves (Fig. 3c,d). The distribution of γ''/γ' becomes uniform (Fig. 3e,f). As shown in Fig. 3g,h, further homogenization combined with solutionizing and aging treatment resulted in the disappearance of micro-segregation and Laves phases while γ''/γ' precipitates were re-distributed in bimodal grain structures [84]. Similarly, *Careri et al*. demonstrated that a combination of heat treatment with post-machining of DED fabricated parts can significantly improve machinability, reduce surface roughness, and improve the hardness of the part [85]. Further, machining and double aging treatment were also proposed as better alternatives to improve the machinability of the material.

Laser surface modification

Laser-based surface modification processes have been considered promising post-processing alternatives for AM parts. Laser-based processes induce ablation or melting of the part which leads to material relocation and induce planarization. The surface macro-roughness can be controlled by using a continuous wave laser while a pulsed laser can bring the surface roughness down to micrometer levels (Fig. 4a).

As shown by *Zhou et al*. [86], after laser polishing of AlSi10Mg alloy, the valleys and projections were more

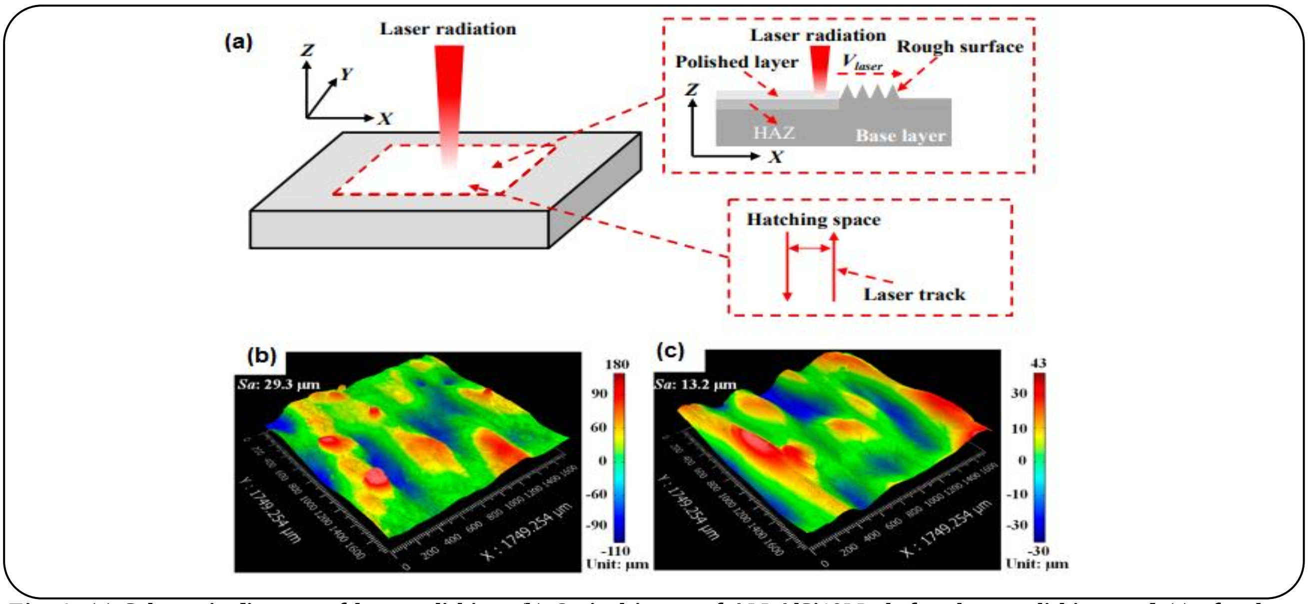

***Fig. 4:** (a) Schematic diagram of laser polishing, (b) Optical image of AM AlSi10Mg before laser polishing, and (c) after laser polishing [86].*

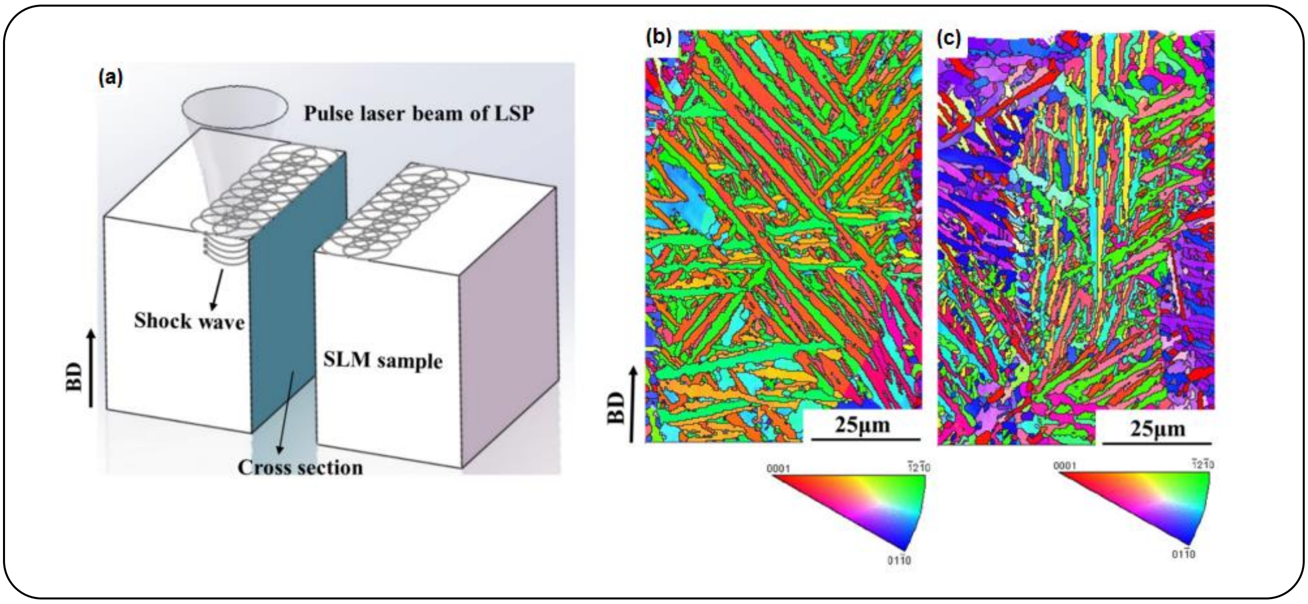

***Fig. 5:** (a) Laser shock peening principle for an SLM sample and (b-c) Electron backscatter diffraction (EBSD) cross-section maps of SLM-Ti-6Al-4V samples before (a) and after (b) laser shot peening [94]. (Copyright 2021, open access)*

regular and ordered. The height of the projected particles and depth regions were significantly reduced. The surface roughness of the samples reduced from 29.3 to 8.4 µm after laser polishing. The last 20 years have seen a rise in laser polishing of different materials including AM parts. In [87], the authors reduced the roughness of AISI 304 from 195 to 75 nm. *Guo et al*. [88] reported a decrease in surface roughness of AM part from 0.4 to 0.12 µm. *Ma et al*. [89] observed a decrease in surface roughness from 90 to 4 µm after laser polishing of Ti-6Al-4V processed by laser AM. Their results showed that as a result of surface melting, various peaks, and surface projections melted away and valleys were filled down with the molten metal under the forces of surface tension and gravity.

Lee et al. [90] laser-polished the surface of the Ti-6Al-4V specimen prepared by laser beam-PBF. The laser beam caused the re-melting of the powder particles and surface morphology was modulated. It is seen that an extremely

Table 3: Laser power and different laser shot peening numbers.

S.N.	No. of shots	Laser power (W)
1	3	0.14
2	5	0.14
3	7	0.14
4	3	0.17
5	5	0.17
6	7	0.17
7	3	0.2
8	5	0.2
9	7	0.2

rough surface can be significantly smoothened down without a tiny amount of wastage of material. The cross-sectional area was significantly decreased from 5.4 - 1.7% after laser polishing.

Avilés et al. [91] investigated the effect of laser polishing on the high cycle fatigue behavior of AISI 1045 steel. They demonstrated that in the absence of inert gas, laser polishing can enhance the fatigue properties of AISI 1045 steel. *Chen et al*. [92] demonstrated that laser polishing improved the surface roughness of AM AISI 316 steel from 4.84 to 0.65 µm. The proportion of low-angle grain boundaries (2º–5º) was decreased and grains were refined. Similarly, *Rosa et al*. [93] studied multiple laser polishing parameters and controlled the surface roughness of AISI 316 L down to 0.79 µm.

Laser shot peening

Laser shot peening involves plastic deformation (compression) of the material perpendicular to the surface causing expansions in lateral directions. The schematic of laser shot peening for SLM fabrication of the sample is shown in Fig. 5a. A high-power laser shock pulse is applied on the part surface to produce the compression as shown in Fig. 5a.

The concept of lateral expansion and compression is common to all deformation-based post-processing treatments. *Lan et al*. investigated the laser shot peening of SLM Ti-6Al-4V as shown in Fig. 5b-c. The SLM Ti-6Al-4V exhibited thicker laths (α' and no β-phase) due to the characteristics of SLM. The morphology, as well as their orientation of α'-laths, changed laser peening. The grains turned finer while the orientation (0110) was increased and a decrease in (0001) orientation occurred after laser peening [94].

In [95], authors reported laser shot peening of PBF processed Inconel 718. The effect of laser power was studied with different laser shot peening numbers as shown in Table 3.

The results showed that laser shot peening improved the morphology of the AM part at the optimum power of 170 mW for 7 laser shots. The effect of the number of laser shots was more prominent than the laser power. In a previous study, the effect of laser shot peening was studied on the morphology and porosity of SLM AlSi10Mg alloy [96]. The results indicated a reduction of porosity by 15–30% after laser shot peening. Similar results were obtained by *Sagbas* [97] for DMLS AlSi10Mg parts where the authors observed an increased hardness and reduced surface roughness after laser shot peening. *Maamoun et al*. [98] reported different laser shot intensities to modify the surface morphology of AlSi10Mg parts. *Uzan et al*. [99] demonstrated that the fatigue resistance of AlSi10Mg parts improved after laser shot peening even after the surface was polished (25–30 µm) after shot peening.

Post-curing and chemical methods

Often a post-curing method is applied in resin-based AM to cross-link the unreacted polymer chains before actual applications. The curing process is mainly employed for stereolithography, FDM, and sheet lamination. Due to the difference in part size and shape, resin formulation, and stabilizers used, there is no universal post-curing method that fits all the resin-based AM. Different polymers require different time and temperature conditions to fully cure the 3D part. Most of the former literature is concentrated on the effect of various processing parameters [100-104], and there is limited information on the post-curing process on the performance of AM parts in aerospace.

Chemical-based methods are simple and economical to use for improving the surface quality of the AM parts [105]. Chemical processing methods such as peeling/etching, electrolytic polishing, and electroplating have been generally applied for AM parts. Chemical post-processing methods are mostly used for surface cleaning and polishing of the AM components [106]. However, there are a limited number of research works in the chemical polishing of AM components for aerospace and future research directions. In previous studies, chemical polishing has been used for ABS (acrylonitrile butadiene styrene) parts produced with FDM as the chemicals can penetrate the polymers better [107].

Chemical baths containing HF and HNO_3 are preferred for Ti-6Al-4V alloys [108]. *Łyczkowska et al.* [109]

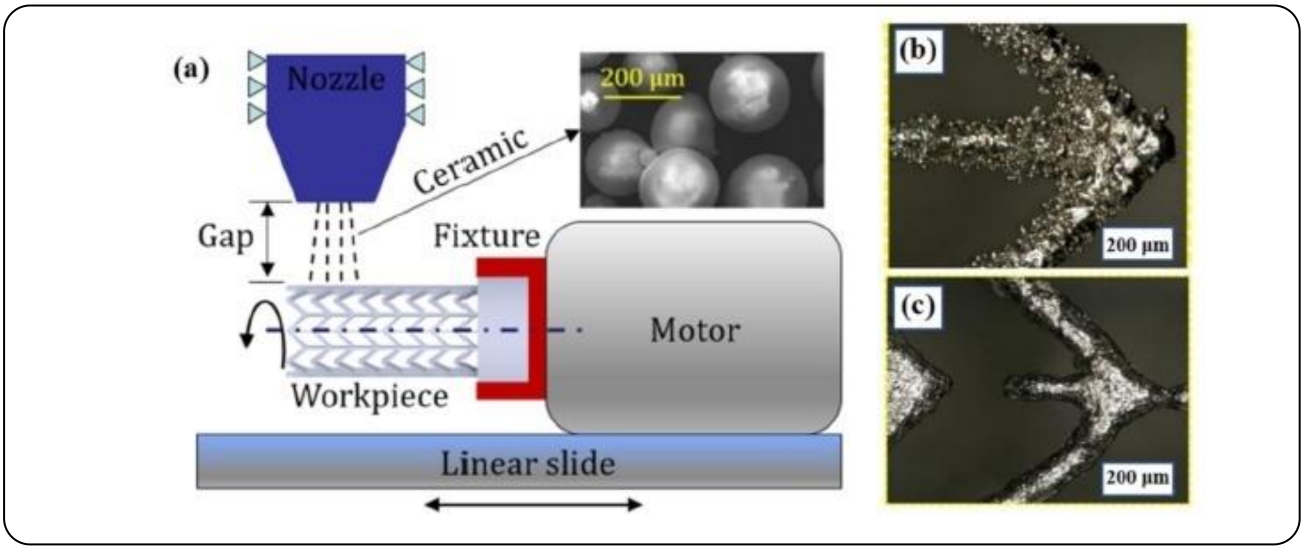

Fig.6: (a) Micro-blasting of SLM Ti-6Al-4V lattice struts and (b-c) lattice structure (b) before and after (c) blasting [118] (Copyright 2021, open access)

used chemical polishing of SLM Ti - 6Al - 7Nb alloys and reported that mass loss is related to the non-adherent, un-melted powder particles from the surface. *Wysocki et al*. also reported similar results with a chemical bath of 2.2 % HF and 20 % HNO3 for titanium samples. Some research also reported a decrease in Young's modulus and compressive strength by 70 and 30 % [110]. Researchers have also shown enough decrease in surface roughness of DMLS 316 steel from 5 to 0.4 µm [111]. Some researchers have used electrolytic polishing to improve the surface quality of AM parts. *Jain et al*. [112] used SLM Inconel 718 parts for electrolytic polishing. The various process parameters, such as current density, duty cycles, and polishing times were varied. The authors obtained an optimum surface finish at a current density of 0.7 A mm^{-2},aduty cycle of 75 % for the polishing duration of 90 s. *Baicheng et al*. [113] demonstrated that the surface roughness of SLM Inconel 718 parts was reduced by 40% and nano hardness was decreased by 35 % and Young's modulus by 45 % after electrolytic polishing. However, due to the multivariable process, electrolytic polishing often produces considerable results and can be considered a major drawback of this method.

Machining and abrasive finishing

Post-machining methods are used to improve the dimensional accuracy and finish of AM parts. Various studies have been done in the past with advanced Computer Numerically Controlled (CNC) milling machines. Previous authors have used CNC milling to process A131 steel fabricated by DED. CNC milling can reduce the surface roughness of the specimen from 22.78 to 0.6 µm. High-speed cutting promotes a more sharp surface finish without any change in the material hardness of the DED specimens. *Ni et al.* employed ultra-precision machining to post-process SLM Ti-6Al-4V alloy and demonstrated a gradient in surface roughness of the SLM parts [114, 115]. The surface roughness from the top to the front surface of the part increased but there was no difference in cutting force observed. Such anisotropy in surface finishing is related to the microstructural anisotropy of the AM products. Other authors also used non-conventional machining like ultrasonic elliptical vibration-assisted machining to achieve 5.1 nm surface roughness [116], or diamond turning which can achieve a surface roughness of 10.2 nm.

Abrasive methods have been used to polish the AM parts using abrasives. Magnetic abrasive finishing has been used to polish the SLM AISI 316L. The results showed a 75.7% enhancement in the surface finish and almost all the balling and fusion defects disappeared [117]. Automatic micro-blasting was used to polish SLM AISI 316 L steel with a tubular lattice cage. A schematic of micro-blasting is given in Fig. 6

The authors investigated the effect of air pressure and standing distance on the surface finish of the part. Their results indicated that micro-blasting removed the partially adhered particles on the fragile lattice struts. The effect of ultrasonic abrasive finishing has been shown to enhance the quality of AM parts [119]. *Teng et al*. [120] demonstrated that a combination of grinding and MAF of SLM AlSi10Mg can reduce the surface roughness (7 µm to 0.155 µm) and improve the surface quality. Abrasive flow machining has been used by *Guo et al*. [121] to improve the surface quality of Inconel 718.

RESULTS AND DISCUSSION

- POST-PROCESSING REALITIES FOR AEROSPACE

Although there are various post-processing methods widely used for improving the final quality and finish of AM parts, the aerospace industry lacks a universal qualification standard for AM components [120]. There are a large number ofstudies needed to regulate the AM parts in the aerospace industry. The use of AM components for aerospace applications is not unique, the process of research and development of reliable standards are in the beginning and gradual. [106]. The present standards often specify the details of raw materials, defects classification, and inspection details of AM parts. However, post-processing surface finish, surface modification, and damage tolerance are promising areas for future research [1120-122].

Concerning aerospace applications, most of the PBF processes including DED will need a specific type of post-processing to improve the final surface quality [123]. Powder processing methods generally lead to inherent porosity and defects inside the part. As discussed, all these defects and finishing quality can be improved with several steps such as thermal treatment, hot isostatic pressing, and post-machining. Post-surface treatment also increases the part strength and mechanical reliability [119, 123, 124]. Heat treatment steps are often used to compact grains and control the morphology of the product [123].

Traditional surface finishing methods are used to machine the AM components in aerospace applications. For complex parts, non-conventional machining tools are often used such as ultrasonic vibrations and sandblasting [123]. Such methods can limit the geometry complexity and need to be applied cautiously [125], as these methods can consume time and energy and reduce the buy-to-fly ratio. However, these methods can still be beneficial and need to be improved with a further hybrid manufacturing strategy.

4D PRINTING

4D printing is a relatively newer technology than 3D printing and it is obtained by the addition of the 4th dimensions of the time on the 3 D structural materials. Consequently, the 4D printed materials will show any change occurring in the structure/ properties concerning the time upon interaction with external stimuli applied such as heat, and light, under the influence of an electric/magnetic field [126, 127]. The advantage of adding the 4th dimension of time, the changes in the printed object occurs dynamically according to the requirement and demands of the market. The materials used in 4D printing are usually termed smart materials (more flexible and deformable such as biomaterials) which do not require humans or any additional accessories for that transformation to occur. It occurs in an automated way only with the time of interaction with the external stimuli by proper programming of the 4D materials that need to be printed [128]. The future of the 4D printing materials will be in the same direction as for the 3D printed materials such as aerospace industries, military defense, health sector, and construction industries. 4D printing will add more value to the health sector for in-vivo application because human organs to be implanted can be of biocompatible materials that can be modified with time by action of light or heat [129]. This will be advantageous because the inherent body is a moving system. Each part is exposed to a different unique environment such as different pH, therefore the materials must have dynamic change over time for the in vivo application [130, 131].

CONCLUSIONS AND FUTURE PROSPECTS

In this article, we have reviewed several methods to enhance the surface finish of additive-manufactured products. The various conclusions drawn from this study are as follows.

1. The various post-processing technologies highlighted in this study are thermal annealing heat treatments (solution heat treatment, T6 heat treatment, hot–isostatic pressing), laser surface modification (laser polishing and laser shot peening), abrasive machining and finishing methods including their applications.

2. AM technology in aerospace requires several processing stages before the actual application, such as powder wiping, stress alleviation, hot isostatic pressing, wire cutting, and final finishing. Most of these post-processing steps require highly skilled operations such as laser-based surface modifications and thermal heat treatment to release the thermal stresses from the part.

Some traditional methods including machining approaches require ordinary skill levels.

3. Each method hasits own merits and drawbacks for each type of AM fabricated part. Thus, if several hundred or thousands of parts are produced in a single batch, demand for automated post-processing becomes urgent. Automated processing systems are lacking in metal AM manufacturing as compared to polymers in aerospace.

4. Most of the traditional machining is still being used at a higher scale for aerospace parts. Therefore, advanced 4D printing concepts, as well as robotic manufacturing technologies that can install printing parts, remove powder particles after printing, and clean and unload parts for post-processing together, can be a good solution for aerospace industries to increase the buy to fly ratio.

5. Although the development in this area is still slow yet increased number of post-processing solutions and industry standards would certainly rise in the future, to meet the demands of the growing AM solutions for aerospace industries.

Received : Jul. 02, 2022 ; Accepted : Nov. 27, 2022

REFERENCES

[1] Sharma A., Ahn B., Vacuum Brazing of Al_2O_3 and 3D Printed Ti6Al4V Lap-Joints Using High Entropy Driven AlZnCuFeSi Filler, *Sci. Rep.*, **11(1)**: 1-15 (2021).

[2] Sharma A., Oh M.C., Kim J.T., Srivastava A.K., Ahn B., Investigation of Electrochemical Corrosion Behavior of Additive Manufactured Ti–6Al–4V Alloy For Medical Implants In Different Electrolytes, *J. Alloy. Compd*., **830**: 154620 (2020).

[3] Gopinath S., Devan P.K., Sabarish V., Sabharish Babu B.V., Sakthivel S., Vignesh P., Effect of Spray Characteristics Influences Combustion in DI Diesel Engine – A Review, *Mater. Today: Proc.*, **33**: 52-65 (2020).

[4] Kumar S., Goel S., Sharma A., Pandey C., Direct Energy Deposition, “Advances in Additive Manufacturing Processes”, 184-200 (2021).

[5] Han D., Yang H., Kong M.S., Lee C., Sharma A., Ahn B., High Precision Electrolytic Polishing of Ni–Ti Shape Memory Alloy for Biomedical Vascular Stents, *Mater. Express*, **10(8)**: 1249-1259 (2020).

[6] Bibin C., Senthil Kumar S., Aravindhan N., Gopinath S., Sheeja R., Ramachandran M., Flow Analysis of Secondary air Injection in Conical Rocket Nozzle, *AIP Conf. Proc*., **2393**: 020048 (2022).

[7] Gautam A., Komal P., Gautam P., Sharma A., Verma N.K., Jung J.P., Recent Trends in Noble Metal Nanoparticles for Colorimetric Chemical Sensing and Micro-Electronic Packaging Applications, *Metals*, **11(2)**: 329 (2021).

[8] Devan P.K., Gopinath S., Rajesh K., Madhu S., Improving the Characteristics of Engine Oil Using Nanofluid as Coolant in Combat Vehicles, *Mater Today: Proc*., **22**: 1130-1134 (2020).

[9] Sumida K., Rogow D.L., Mason J.A., McDonald T.M., Bloch E.D., Herm Z.R., Bae T.H., Long J.R., Carbon Dioxide Capture in Metal–Organic Frameworks, *Chem. Rev*., **112**: 724-781 (2012).

[10] Granite E.J., Pennline H.W., Photochemical Removal of Mercury from Flue Gas, *Ind. Eng. Chem. Res.*, **41**: 5470-5476 (2002).

[11] Zhang J., Chaudhari A., Wang H., Surface Quality and Material Removal in Magnetic Abrasive Finishing of Selective Laser Melted 316L Stainless Steel, *J. Manuf. Process*. **45**: 710–719 (2019).

[12] Sharma A., High Entropy Alloy Coatings and Technology, *Coatings* **11(4)**: 372 (2021).

[13] The Business Research Company, “Aerospace Global Market Report 2021: COVID 19 Impact and Recovery to 2030”, (2021).

[14] Wohlers, Wohlers Report, "3D Printing and Additive Manufacturing State of the Industry", *Annual Worldwide Progress Report*, Wohlers Associates: Fort Collins, Co., (2017).

[15] Market Research Future, “Global Aerospace Additive Manufacturing Market Research Report”, Forecast 2016-2021 (2019).

[16] Bhavar V., Kattire P., Patil V., Khot S., Gujar K., Singh R., “A Review on Powder Bed Fusion Technology of Metal Additive Manufacturing”, *International Conference and Exhibition on Additive Manufacturing Technologies*-AM (2014), September 1 &2 (2014), Banglore, India.

[17] Ding D., Pan Z., Cuiuri D., Li H., Wire-Feed Additive Manufacturing of Metal Components: Technologies, Developments and Future Interests. *Int. J. Adv. Manuf. Technol*., **81(1–4)**: 465–481 (2015).

[18] Gu D., "Laser Additive Manufacturing (AM): Classification, Processing Philosophy, and Metallurgical Mechanisms", Berlin: Springer (2015).

[19] Ruban W., Vijayakumar V., Dhanabal P., Tridhar T., Effective Process Parameters In Selective Laser Sintering Effective Process Parameters in Selective Laser Sintering, *Int. J. Rapid Manuf*., **4(2–4)**:148–164 (2014).

[20] Vayre B., Vignat F., Villeneuve F., Metallic Additive Manufacturing: State-Of-The Art Review and Prospects. *Mechanics & Industry*, **13(2)**: 89–96 (2012).

[21] Baumers M., Dickens P., Tuck C., Hague R., The Cost of Additive Manufacturing: Machine Productivity, Economies of Scale and Technology-Push, *Technological Forecasting and Social Change*, **102**: 193–201 (2016).

[22] Ding D., Z., Cuiuri D., Li H., A Multi-Bead Overlapping Model for Robotic Wire and Arc Additive Manufacturing (WAAM), *Robotics and Computer-Integrated Manufacturing*, **31:**101–110 (2015).

[23] Murr L.E., Martinez E., Amato K.N., Gaytan S.M., Hernandez J., Ramirez D.A., Shindo P.W., Medina F., Wicker R.B., Fabrication of Metal and Alloy Components by Additive Manufacturing: Examples of 3D Materials Science. *Journal of Materials Research and Technology*, **1(1)**: 42–54 (2012).

[24] Dutta B., Froes F.H., The Additive Manufacturing (AM) of Titanium Alloys. *Metal Powder Report*, **72(2)**: 96–106 (2017).

[25] Cao S., Gu D., Laser Metal Deposition Additive Manufacturing of Tic/Inconel 625 Nanocomposites: Relation of Densification, Microstructures and Performance. *Journal of Materials Research*, **30(23)**: 3616–3628 (2015).

[26] Frazier W.E., Metal Additive Manufacturing: A Review. *J. Mater. Eng. Perform*., **3(6)**:1917–1928 (2013).

[27] Mahamood R.M., Akinlabi E.T., Shukla M., Pityana S., "Laser Metal Deposition of Ti6Al4V: A Study on the Effect Oflaser Power on Microstructure and Microhardness". *International Multi Conference of Engineers and Computer Scientists*, II, 23(6), 1917–1928 (2013).

[28] Ríos S., Colegrove P.A., Martina F., Williams S.W., Analytical Process Model for Wire + Arc Additive Manufacturing. *Additive Manuf*., **21:** 651–657 (2018).

[29] Williams S., "Large Scale Metal Wire + Arc Additive Manufacturing of Structural Engineering Parts", *69th IIW Annual Assembly and International Conference*, Melbourne, 10-15 July (2016).

[30] Williams, S.W., Martina F., Addison A.C., Ding J., Pardal G., Colegrove P., Wire + Arc Additive Manufacturing. *Mater. Sci. Technol*., **32(7)**: 641–647 (2016).

[31] Herzog D., Seyda V., Wycisk E., Emmelmann C., Additive Manufacturing of Metals, *Acta Mater*., **117**: 371–392 (2016).

[32] Rambabu P., Eswara Prasad N., Kutumbarao V.V., Wanhill R.J.H., Aluminium Alloys for Aerospace Applications, "Aerospace Materials and Materials Technologies", Prasad N., Wanhill R., Ed., Springer, Singapore, (2017).

[33] Peters M., Kumpfert J., Ward C.H., Leyens C., Titanium Alloys for Aerospace Applications, *Adv. Eng. Mater*., **5 (6)**: 419–427 (2003).

[34] Williams J.C., Boyer R.R., Opportunities and Issues in the Application of Titanium Alloys for Aerospace Components, *Metals*, **10 (6)**:705 (2020).

[35] Kellner T., "This Electron Gun Builds Jet Engines", GE Aviation., General Electric (2014).

[36] Adeyemi A., Akinlabi E.T., Mahamood R.M., Powder Bed Based Laser Additive Manufacturing Process of Stainless Steel: A Review, *Mater., Today: Proc*. **5(9)**:18510–18517 (2018).

[37] Sharma A., Kumar S., Duriagina Z., "*Engineering Steels and High Entropy-Alloys*", InTechOpen (2020).

[38] Angrish A., Nagar S., "A Critical Analysis of Additive Manufacturing Technologies for Aerospace Applications", In *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, USA, 1–8 March 2014.

[39] Alghamdi S.S., John S., Choudhary N.R., Dutta N.K., Additive Manufacturing of Polymer Materials: Progress, Promise and Challenges, *Polymers*,**13**: 753 (2021).

[40] Langnau L., "Better Materials for High Temperature SLS" (2011).

[41] "3D-Printed Functional Lightweight Components with Maximum Flexibility in Product Design", EOS GmbH, March 4, (2013).

[42] Ortiz-Acosta D., Moore T., Functional 3D Printed Polymeric Materials, in "Functional Materials"; Sahu, D.R., Ed.; IntechOpen: London, UK (2018).

[43] Joshi M., Chatterjee U., Polymer Nanocomposite: An advanced Material for Aerospace Applications. In "Advanced Composite Materials for Aerospace Engineering", Elsevier Ltd: Cambridge, UK, (2016).

[44] Njuguna B.J., Pielichowski K., Polymer

Nanocomposites for Aerospace Applications: Properties. *Adv. Eng. Mater.*, **5:** 769–778 (2003).

[45] Kausar A., Rafique I., Muhammad B., Aerospace Application of Polymer Nanocomposite with Carbon Nanotube, Graphite, Graphene Oxide, and Nanoclay. *Polym. Plast. Technol. Eng*. **56**: 1438–1456 (2017).

[46] Singh R.S., Li D., Xiong Q., Santoso I., Yu X., Chen W., Rusydi A., Wee A.T.S., Anomalous Photoresponse in the Deep-Ultraviolet due to Resonant Excitonic Effects in Oxygen Plasma Treated Few-Layer Graphene, *Carbon*, **106:** 330-335 (2016).

[47] Muthukumar C., Krishnasamy S., Thiagamani S.M.K., Jeyaguru S., Siengchin S., Nagarajan R., Polymers in Aerospace Applications, in "Reference Module in Materials Science and Materials Engineering", Elsevier UK (2021).

[48] Soundararajana G., Aravindhan, N., Pranith Kumar J., Pragadeeswaran M., Santhosh Kumar K., Sarath Kumar M., Comparative Analysis and Testing of Impact Attenuator, *AIP Conf. Proc.***2393**: 020185 (2022).

[49] Brien M.O., Alues A.L.V., "Existing Standards as the Framework to Qualify Additive Manufacturing of Metals". In *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, USA, 3–10 March (2018).

[50] Mies D., Marsden W., Warde S., Overview of Additive Manufacturing Informatics: A Digital Thread, *Integr. Mater. Manuf. Innov*. **5**:114–142 (2016).

[51] Uriondo A., Esperon-Miguez M., Perinpanayagam S., The Present and Future of Additive Manufacturing in the Aerospace Sector: A Review of Important Aspects. *Part G, J. Aerosp. Eng*. **229**: 2132–2147 (2015).

[52] George C., Marshall Space Flight Center, "Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals", NASA Marshall Space Flight Center: Huntsville, AL, USA (2017).

[53] Essop, "NASA Becomes First Customer of HRL High Strength Aluminum 3d Printing Powder", NASA (2019).

[54] Waller D., Polizzi A., Iten J., "Feasibility Study of Additively Manufactured Al-6061 RAM2 Parts for Aerospace Applications", *AIAA Scitech 2019 Forum* 7-11 January 2019 San Diego, California(2019).

[55] Katsarelis C., Gradl P., Protz C., Jones Z., "Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications", *JANNAF*, (2019).

[56] Najmon J.C., Raeisi S., Tovar A., Review of Additive Manufacturing Technologies and Applications in the Aerospace Industry, In "Additive Manufacturing for the Aerospace Industry", Elsevier, (2019).

[57] Westerweel B., Basten R.J.I., van Houtum G.J., Traditional or Additive Manufacturing? Assessing Component Design Options Through Lifecycle Cost Analysis, *Eur. J. Oper. Res*., **270(2)**: 570–585 (2018).

[58] Maamoun A.H., Elbestawi M., Dosbaeva G.K., Veldhuis S.C., Thermal Post-Processing of AlSi10Mg Parts Produced by Selective Laser Melting Using Recycled Powder, *Addit. Manuf*., **21**: 234–247 (2018).

[59] Ma P., Prashanth K.G., Scudino S., Jia S., Wang H., Zou C., Wei Z., Eckert J., Influence of Annealing on Mechanical Properties of Al-20Si Processed by Selective Laser Melting, *Metals*, **4**: 28–36 (2014).

[60] Bermingham M., Nicastro L., Kent D., Chen Y., Dargusch M., Optimising the Mechanical Properties of Ti-6Al-4V Components Produced by Wire + Arc Additive Manufacturing with Post-Process Heat Treatments, *J. Alloys Compd*., **753**: 247–255 (2018).

[61] Bai Y., Wang D., Yang Y., Wang H., Effect of Heat Treatment on the Microstructure and Mechanical Properties of Maraging Steel by Selective Laser Melting, *Mater. Sci. Eng. A*, **760**: 105–117 (2019).

[62] Aversa A., Lorusso M., Trevisan F., Ambrosio E.P., Calignano F., Manfredi D.G., Biamino S., Fino P., Lombardi M., Pavese M., Effect of Process and Post-Process Conditions on the Mechanical Properties of an A357 Alloy Produced *via* Laser Powder Bed Fusion, *Metals*, **7**: 68 (2017).

[63]. Li W., Li S., Liu J., Zhang A., Zhou Y., Wei Q., Yan C., Shi Y., Effect of Heat Treatment on AlSi10Mg Alloy Fabricated by Selective Laser Melting: Microstructure Evolution, Mechanical Properties and Fracture Mechanism, *Mater. Sci. Eng. A*, **663**: 116–125 (2016).

[64] Fiocchi J., Tuissi A., Bassani P., Biffi C., Low Temperature Annealing Dedicated to AlSi10Mg Selective Laser Melting Products. *J. Alloys Compd*., **695**: 3402–3409 (2017).

[65] Aboulkhair N.T., Maskery I., Tuck C., Ashcroft I., Everitt N.M., The Microstructure and Mechanical Properties of Selectively Laser Melted AlSi10Mg: The Effect of a Conventional T6-Like Heat Treatment, *Mater. Sci. Eng. A*, **667**: 139–146 (2016).

[66] Tradowsky U., White J., Ward R., Read N., Reimers W., Attallah A., Selective Laser Melting of AlSi10Mg: Influence of Post-processing on the Microstructural

and Tensile Properties Development, *Mater. Des*., **105**: 212–222 (2016).

[67] Aboulkhair N.T., Tuck C., Ashcroft I., Maskery I., Everitt N.M., On the Precipitation Hardening of Selective Laser Melted AlSi10Mg, *Met. Mater. Trans. A*, **46**: 3337–3341 (2015).

[68] Ahn B., Microstructural Tailoring and Enhancement in Compressive Properties of Additive Manufactured Ti-6Al-4V Alloy through Heat Treatment, *Materials*, **14(19)**: 5524 (2021).

[69] Bey V., Lore T., Kruth J.P., Jan V.H., Heat Treatment of Ti_6Al_4V Produced by Selective Laser Melting Microstructure and Mechanical Properties, *J. Alloy. Compd*., **541**:177–185 (2012).

[70] Kim Y.K., Park S.H., Yu J.H., Mangour B.A., Lee K.A., Improvement in the High-Temperature Creep Properties *via* Heat Treatment of Ti-6Al-4V Alloy Manufactured by Selective Laser Melting. *Mater. Sci. Eng. A*, **715**: 33–40 (2018).

[71] Tillmann W., Schaak C., Nellesen J., Schaper M., Aydinöz M., Hoyer K.P., Hot Isostatic Pressing of IN718 Components Manufactured by Selective Laser Melting. *Addit. Manuf*. **13**: 93–102 (2017).

[72] Rosenthal I., Tiferet E., Ganor M., Stern A., Post-processing of AM-SLM AlSi10Mg Specimens: Mechanical Properties and Fracture Behavior, *Weld. Equip. Technol*., **26**:33–38 (2015).

[73] AboulkhairN T., Maskery I., Tuck C., Ashcroft I., Everitt N.M., The Microstructure and Mechanical Properties of Selectively Laser Melted AlSi10Mg: The Effect of a Conventional T6-like Heat Treatment, *Mater. Sci. Eng. A*, **667**: 139–146 (2016).

[74] Goel S., Sittiho A., Charit I., Klement U., Joshi S., Effect of Post-Treatments Under Hot Isostatic Pressure on Microstructural Characteristicsof EBM-Built Alloy 718, *Addit. Manuf*., **28**: 727–737 (2019).

[75] Cunningham R., Nicolas A., Madsen J., Fodran E., Anagnostou E., Sangid M.D., Rollett A.D., Analyzing the Effects of Powder and Postprocessing on Porosity and Properties of Electron Beam Melted Ti-6Al-4V, *Mater. Res. Lett*., **5 (7)**:516–525 (2017).

[76] Leon A., Levy K.G., Ron T., Shirizly A., Aghion E., The Effect of Hot Isostatic Pressure on the Corrosion Performance of Ti-6Al-4 V Produced by an Electron-Beam Melting Additive Manufacturing Process, *Addit. Manuf*., **33**: 101039 (2020).

[77] Xu W., Lui E., Pateras E., Qian M., Brandt M., In Situ Tailoring Microstructure In Additively Manufactured Ti-6Al-4V for Superior Mechanical Performance, *Acta Mater*., **125**: 390 – 400 (2017).

[78] Al-Bermani S.S., Blackmore M.L., Zhang W., Todd I., The Origin of Microstructural Diversity, Texture, and Mechanical Properties in Electron Beam Melted Ti-6Al-4V, *Met. Mater. Trans. A*, **41**: 3422–3434 (2010).

[79] Galarraga H., Lados D.A., Dehoff R.R., Kirka M.M., Nandwana P., Effects of the Microstructure and Porosity on Properties of Ti-6Al-4V ELI Alloy Fabricated by Electron Beam Melting (EBM), *Addit. Manuf*., **10**: 47–57 (2016).

[80]. Bagherifard S., Beretta N., Monti S., Riccio M., Bandini M., Guagliano M., On the Fatigue Strength Enhancement of Additive Manufactured AlSi10Mg Parts by Mechanical and Thermal Post-Processing, *Mater. Des*., **145**: 28–41 (2018).

[81]. Butler C., Babu S., Lundy R., Reilly Meehan R.O., Punch J., Jeffers N., Effects of Pro Cessing Parameters and Heat Treatment on Thermal Conductivity of Additively Manufactured AlSi10Mg by Selective Laser Melting, *Mater. Charact*., **173**: 110945 (2021).

[82].Debroy T., Wei H.L., Zuback J.S., Mukherjee T., Elmer J.W., Milewski J.O., Beese A.M., Wilson-Heid A., De A., Zhang W., Additive Manufacturing of Metallic Components-Process, Structure and Properties, *Prog. Mater. Sci*., **92**: 112–224 (2018).

[83]. Wang X.Q., Gong X.B., Chou K., Review on Powder-Bed Laser Additive Manufacturing of Inconel 718 Parts, *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf*., **231**: 1890–1903 (2016).

[84]. Bassini E., Marchese G., Aversa A., Tailoring of the Microstructure of Laser Powder Bed Fused Inconel 718 Using Solution Annealing and Aging Treatments, *Metals*,**11**: 921 (2021).

[85] Careri, F., Imbrogno S., Umbrello D., Attallah M.M., Outeiro J., Batista A.C., Machining and Heat Treatment as Post-processing Strategies for Ni-Superalloys Structures Fabricated Using Direct Energy Deposition, *J. Manuf. Process*., **61**: 236–244 (2021).

[86] Zhou J., Han X., Li H., Liu S., Shen S., Zhou X., Zhang D., In-Situ Laser Polishing Additive Manufactured AlSi10Mg: Effect of Laser Polishing Strategy on Surface Morphology, Roughness and Microhardness, *Materials*, **14**: 393 (2021).

[87] Mai T.A., Lim G.C., Micromelting and Its Effects on Surface Topography and Properties in Laser

Polishing of Stainless Steel, *J. Laser Appl*., **16**: 221–228 (2004).

[88] Guo W., Hua M., Tse P.W.T., Mok A.C.K., Process Parameters Selection for Laser Polishing DF2 (AISI O1) by Nd:YAG Pulsed Laser Using Orthogonal Design, *Int. J. Adv. Manuf. Technol*., **59**: 1009–1023 (2012).

[89] Ma C., Guan Y., Zhou W., Laser Polishing of Additive Manufactured Ti Alloys, *Opt. Lasers Eng*., **93**: 171–177 (2017).

[90] Seungjong L., Zabihollah A., Jonathan W.P., Masoud M.S., Nima S., Laser Polishing for Improving Fatigue Performance of Additive Manufactured Ti-6Al-4V Parts, *Opt. Laser Technol*., **134**: 106639 (2021).

[91] Avilés R., Albizuri J., Lamikiz A., Ukar E., Avilés A., Influence of Laser Polishing on the High Cycle Fatigue Strength of Medium Carbon AISI 1045 Steel, *Int. J. Fatigue*, **33**: 1477–1489 (2011).

[92]. Chen L., Richter B., Zhang X., Bertsch K.B., Thoma D.J., Pfefferkorn F.E., Effect of Laser Polishing on the Microstructure and Mechanical Properties of Stainless Steel 316L Fabricated by Laser Powder Bed Fusion, *Mater. Sci. Eng. A*, **802:**140579 (2021).

[93]. Rosa B., Mognol P., Hascoët J.Y., Laser Polishing of Additive Laser Manufacturing Surfaces, *J. Laser Appl*., **27**: S29102 (2015).

[94] Lan L., Xin R., Jin X., Gao S., He B., Rong Y., Min N., Effects of Laser Shock Peening on Micro-Structure and Properties of Ti–6Al–4V Titanium Alloy Fabricated via Selective Laser Melting, *Materials*, **13**: 3261 (2020).

[95] Jinoop A.N., Subbu S.K., Paul C.P., Palani I.A., Post-Processing of Laser Additive Manufactured Inconel 718 Using Laser Shock Peening, *Int. J. Precis. Eng. Manuf*., **20**: 1621–1628 (2019).

[96] Damon J., Dietrich S., Vollert F., Gibmeier J., Schulze V., Process Dependent Porosity and the Influence of Shot Peening on Porosity Morphology Regarding Selective Laser Melted $AlSi_{10}Mg$ Parts, *Addit. Manuf*., **20**:77–89 (2018).

[97] Sagbas B., Post-Processing Effects on Surface Properties of Direct Metal Laser Sintered $AlSi_{10}Mg$ Parts, *Met. Mater. Int*., **26**: 143–153 (2019).

[98] Maamoun A.H., Elbestawi M.A., Veldhuis S.C., Influence of Shot Peening on AlSi10Mg Parts Fabricated by Additive Manufacturing, *J. Manuf. Mater. Process*, **2**: 40 (2018).

[99] Uzan N.E., Ramati S., Shneck R., Frage N., Yeheskel O., On the Effect of Shot-peening on Fatigue Resistance of AlSi10Mg Specimens Fabricated by Additive Manufacturing using Selective Laser Melting (AM-SLM), *Addit. Manuf*., **21**: 458-464 (2018).

[100] Aznarte E., Ayranci C., Qureshi A., "Digital Light Processing (DLP): Anisotropic Tensile Considerations". In Solid Freeform Fabrication 2017: *Proceedings of the 28th Annual International* (2017)

[101] Ibrahim A., Sa'ude N., Ibrahim M., "Optimization of Process Parameter for Digital Light Processing (DLP) 3D" In *Proceedings of Academics World 62nd International Conference*, Seoul, South Korea, (2017).

[102] Chockalingam K., Jawahar N., Chandrasekhar U., Influence of Layer Thickness on Mechanical Properties in Stereolithography, *Rapid Prototype*. J., **12**: 106-123 (2006).

[103] Bonada J., Muguruza A., Fernández-Francos X., Ramis X., Influence of Exposure Time on Mechanical Properties and Photocuring Conversion Ratios for Photosensitive Materials Used in Additive Manufacturing. *Procedia Manuf*., **13**: 762–769 (2017).

[104] Lee Y., Lee S., Zhao X.G., Lee D., Kim T., Jung H., Kim N., Impact of UV Curing Process on Mechanical Properties and Dimensional Accuracies of Digital Light Processing 3D Printed Objects, *Smart Struct. Syst*., **22 (2)**: 161–166 (2018).

[105] Sharma A., Das S., Das K., Pulse Electroplating of Ultrafine Grained Tin Coating, *Electroplating of Nanostructures* **2**, (2015). DOI: 10.5772/61255

[106] Sharma A., Das S., Das K., Pulse Electrodeposition of Lead-Free Tin-Based Composites for Microelectronic Packaging, *Electrodeposition of Composite Materials* **3**, 253-274, (2016). DOI: 10.5772/62036

[107] Havenga S., Beer D.D., Tonder P.V., Campbell R., Effectiveness of Acetone Postproduction Finishing on Entry Level FDM Printed ABS Artefacts, *RAPDASA Conference Proceedings* 2015, 4 – 6 November 2015, Roodevallei, Pretoria

[108] ASM Handbook, Metallography and Microstructures, Vol 9, ASM International, *Chemical and Electrolytic Polishing*, Table 3 Applicability of Electrolytes in Table 2 to Electropolishing of Various Metals and Alloys, (2004).

[109] Łyczkowska P., Szymczyk P., Dybała B., Chlebus E., Chemical Polishing of Scaffolds Made of Ti–6Al–7Nb Alloy by Additive Manufacturing, *Arch. Civil Mech. Eng*., **14(4)**: 586-594 (2014).

[110] Wysocki B., Idaszek J., Buhagiar J., Szlązak K., Brynk T., Kurzydłowski K.J., Święszkowski W., The Influence of Chemical Polishing of Titanium Scaffolds on Their

Mechanical Strength and in-vitro Cell Response, *Mater. Sci. Eng. C*, **95**: 428-439 (2019).

[111] Tyagi P., Goulet T., Riso C., Garcia-Moreno F., Reducing Surface Roughness by Chemical Polishing of Additively Manufactured 3D Printed 316 Stainless Steel Components, *Int. J. Adv. Manuf. Technol.*, **100(9-12)**: 2895-2900 (2019).

[112] Jain S., Corliss M., Tai B., Hung W.N., Electrochemical Polishing of Selective Laser Melted Inconel 718, *Procedia Manuf.*, **34**: 239-246 (2019).

[113] Z. Baicheng, L. Xiaohua, B. Jiaming, G. Junfeng, W. Pan, S. Chen-nan, N. Muiling, Q. Guojun, W. Jun, Study of Selective Laser Melting (SLM) Inconel 718 Part Surface Improvement by Electrochemical Polishing, *Mater. Des.*, (2017).

[114] Ni C., Zhu L., Zheng Z., Zhang J., Yang Y., Bai, Y., Weng, C., Lu W.F., Wang H., Effect of Material Anisotropy on Ultra-Precision Machining of Ti-6Al-4V Alloy Fabricated by Selective Laser Melting, *J. Alloys Compd*. **848**: 156457 (2020).

[115] Ni C., Zhu L., Zheng Z., Zhang J., Yang Y., Hong R., Bai Y., Lu W.F., Wang H., Effects of Machining Surface and Laser Beam Scanning Strategy on Machinability of Selective Laser Melted Ti6Al4V Alloy in Milling, *Mater. Des.*, **194**: 108880 (2020).

[116] Bai Y., Shi Z., Lee Y.J., Wang H., Optical Surface Generation on Additively Manufactured AlSiMg0.75 Alloys with Ultrasonic Vibration-assisted Machining, *J. Mater. Process. Technol.*, **280**: 116597 (2020).

[117] Zhang J., Chaudhari A., Wang H., Surface Quality and Material Removal in Magnetic Abrasive Finishing of Selective Laser Melted 316L Stainless Steel. *J. Manuf. Process*, **45**: 710–719 (2019).

[118] Peng X., Kong L., YingJ., Fuh H., Wang H., A Review of Post-Processing Technologies in Additive Manufacturing, *J. Manuf. Mater. Process*, 5:38 (2021).

[119] Wang J., Zhu J., Liew P.J., Material Removal in Ultrasonic Abrasive Polishing of Additive Manufactured Components, *Appl. Sci*.,**9**: 535 (2019).

[120]. Teng X., Zhang G., Zhao Y., Cui Y., Li L., Jiang L., Study on Magnetic Abrasive Finishing of AlSi10Mg Alloy Prepared by Selective Laser Melting, *Int. J. Adv. Manuf. Technol.*, **105**: 2513–2521 (2019).

[121] Guo J., Song C., Fu Y., Au K.H., Kum C.W., Goh M.H., Ren T., Huang R., Sun C.N., Internal Surface Quality Enhancement of Selective Laser Melted Inconel 718 by Abrasive Flow Machining, *J. Manuf. Sci. Eng.*, **142**: 1–42 (2020).

[122] Han S., Salvatore F., Rech J., Bajolet J., Courbon J., Effect of Abrasive Flow Machining (AFM) Finish of Selective Laser Melting (SLM) Internal Channels on Fatigue Performance, *J. Manuf. Process*, **59**: 248–257 (2020).

[123] Lu L.X., Sridhar N., Zhang Y.W., Phase Field Simulation of Powder Bed-Based Additive Manufacturing, *Acta Mater*., **144**: 801–809 (2018).

[124] Zhang J., "Micro-Blasting of 316L Tubular Lattice Manufactured by Laser Powder Bed Fusion", 19th *International Conference of the European Society for Precision Engineering and Nanotechnology*, Bilbao, Spain, 3–7 June (2019).

[125] Ni C., Zhu L., Zheng Z., Zhang J., Yang Y., Hong R., Bai Y., Lu W.F., Wang H, Effects of Machining Surface and Laser Beam Scanning Strategy on Machinability of Selective Laser Melted Ti6Al4V Alloy in Milling, *Mater. Des.*, **194**: 108880 (2020).

[126] Qi G., Conner K.D., Qi H.J., Dunn M., Active Origami by 4D Printing, *Smart Mater. Struct.*, **23**: 094007 (2014).

[127] Khoo Z.X., Teoh J.E.M., Liu Y., Chua C.K., Yang S., An J., Leong K.F., Yeong W.Y., 3D Printing of Smart Materials: A Review on Recent Progresses in 4D Printing, *Virtual Phys. Prototyp*., **10**: 103–122 (2015).

[128] Pei E., 4D Printing: Dawn of an Emerging Technology,*Cycle Assembly Autom*, **34**: 310–314 (2014).

[129] Lipson H., Kurman M., "*Fabricated: The New World of 3D Printing*", John Wiley & Sons Inc., New York, NY (2013).

[130] Gautam, A., Komal P., Synthesis of Montmorillonite Clay/Poly (Vinyl Alcohol) Nanocomposites and Their Mechanical Properties, *J. Nanosci. Nanotechnol*. **19**: 8071-8077 (2019).

[131] Gautam A., Ram S., Shape-Controlled Silver Metal of Nanospheroids from a Polymer-Assisted Autocombustion Reaction in Open Air, *J. Alloy. Compd*. **463:** 428-434 (2008).