A review on additive manufacturing of AA2024 and AA6061 alloys using powder bed fusion

C Senthamarai Kannan*, S Sai Sree Chandra, G Punith Krishnan and S Pravin Raj

Mechanical Department, Sri Venkateswara College of Engineering, Pennalur Sriperumbudur, Tamil Nadu 602 117, India.

* Corresponding author: senthamarai@svce.ac.in

Abstract. Additive manufacturing (AM) is a production facility for tailoring intricately shaped components. Unlike traditional machinery, ease of manufacturability along with intrinsic material saving nature makes AM gain eminence. This paper solely focuses on the capability of aluminium alloys, especially AA2024 and AA6061, being additively fabricated using the widely preferred AM technique of Powder Bed Fusion (PBF). The mechanism of PBF is elucidated by availing the experimental response mirrored in these alloy systems from erudite literary works. Additionally, a comparative review on yield strength, ultimate strength, elongation and hardness property values between wrought condition and PBF fused samples of these alloys has also been discussed. To the end, challenges involved in PBF built components were also addressed by the subsequent emphasis laid over improvement strategies.

1. Introduction

The additive manufacturing technique is used to fabricate complex design components that are usually not easily accomplished by traditional subtractive manufacturing processes such as milling, drilling, etc. By consolidating layer by layer, this method is highly desirable in producing parts with great accuracy [1]. This unique principle is otherwise called as material incremental manufacturing. It also gets its name as E-manufacturing or digital manufacturing since it converts digital data of a mathematically sliced CAD model into thin powder layers and consolidating all together as one finished product [2].

The metal additive manufacturing was commercialised only during 1995 by EOS which utilised laser sintering technology. However, this was not suitable for the manufacture of aluminium and aluminium alloys. In 2001, Solidica LLC® created a technology called ultrasonic welding and CNC machining to produce aluminium parts [3]. This method was called ultrasonic additive manufacturing (UAM) [4]. The commercial usage of Al parts fabricated using additive manufacturing is limited compared to Co-Cr alloys, tool steels and stainless steel.

However, various research has been conducted for the fabrication of aluminium alloys using additive manufacturing. This is due to superior mechanical properties and the high cost of manufacturing compared to steel. Due to the concept of mass customisation and increasing demands to produce lightweight vehicles, the fabrication of aluminium alloys using additive manufacturing has gained popularity in recent years. Ford motor company has been using AM to create and test prototypes of cylinder heads, brake rotors and rear axles using aluminium alloys [5]. Prosthetic limbs fabricated using titanium alloys and aluminium alloys are gaining popularity due to lightweight. NASA patented additive
manufacturing technique EBF$^3$ (Electron beam Freeform Fabrication) has fabricated parts using AA2219 which can be utilised in aerospace industries [6].

The scope of this paper is to gain insights about the powder bed fusion (PBF) mechanism, one among many other additive manufacturing techniques, and simultaneously qualify its need in processing components made of AA2024 and AA6061, viewed as popular alloys for high-end applications. The mechanical properties of these alloys are compared between traditionally handled components with PBF counterparts. Finally, improvement aspects are discussed to eliminate the current challenges faced by PBF.

2. Aluminium properties and family of aluminium alloys

Aluminium is a silvery-white, non-ferromagnetic element found in the boron group. It is the third most common element next to oxygen and silicon which comprises 8% of the earth’s crust. Aluminium has a density of around 2.7 g/cm$^3$ and shows excellent thermal conductivity (235 - 238 W/mK) and electrical conductivity (3.8x10$^7$ S/m) [7]. Aluminium surfaces are highly reflective which are capable of reflecting visible light, radiant heat and electromagnetic waves. Aluminium alloys are divided into two major categories, wrought alloys (4-digit system) and cast alloys (3 digit system) [8] [9] [10] [11]. Post heat treatment process is required for Al alloys to improve the microstructural and mechanical properties. The types of post heat treatment are natural aging (T1 - T4), artificial aging (T5 – T10), annealing (O) and strain hardening (H). Various heat treatment processes have been discussed briefly in [12].

2.1. AA2024 and AA6061 alloys

AA2024 alloy is classified under the alloy system characterized by high strength. This 2xxx series alloy of Al incorporates high strength when subjected under the criteria of heat treatment [13]. Made available in 1931 by Alcoa, the 2024 system is used in automobiles and extensively in aviation (aircraft fuselage skin) for concomitant qualities such as fatigue resistance and stress corrosion cracking [14]. The composition of the 2xxx series consists of a base Al with Cu as the major alloying element and Mg (& Mn) as a minor additive element which aids for quenching properties [15]. By carefully altering the composition, damage tolerance can be improved as stated by [16], in which, transversely oriented test samples in the form of 2mm sheets exhibit increased fracture toughness with lowering of Cu, lowering of Mn and increase in Mg, when these variations are exhibited separately.

The microstructure of the 2xxx series reveals that, next to the major α-phase (Al), precipitates such as φ-phase (Al$_2$Cu) and S-phase (Al$_2$CuMg) are formed and distributed all over as secondary major phases [17]. Investigation of aluminium alloy sheet with 2024-T3 composition shows that the presence of comparatively lower sized grains to that of other sophisticated metals in the microstructure aids for better tensile strength [18]. Also, the strengthening of the alloy is through the locking behaviour of the movement of the dislocations offered by the above-mentioned phase particles, which is attributed as precipitation hardening.

Like 2024, Al alloy 6061 is heat treatable with superior strength to weight ratio. In addition to strength inducing metastable precipitates formation, the alloy gets its hardness through the process of ageing [19]. With attributes like weldability, ductility and machinability, AA6061 is susceptible to different manufacturing techniques and can be produced into sheets, tubes, bars, foils and other standardized forms with ease [20]. Unlike the previous alloy, AA6061 has a very convoluted precipitation sequence. More detailed studies are available in [21] [22] [23]. A simple illustration of the precipitates is made here along with their compositions (table 1).

| SSSS → Mg, Si (atomic clusters) → GP-zones → β″ → β′, U1, U2, B′ → β, Si |

Where, SSSS- super-saturated solid solution, GP- Guinier Preston zones.

The process of welding is similar to PBF since in both of these methods, melting and fusing of the material takes place. Useful insights could be drawn from the welding studies of the concerned alloys. In 6061, with temperature increase, transformation of phases through dissociation was seen. This statement is backed by the literature from [24]. In the joints of AA6061-T6 welded using tungsten inert gas – cold metal transfer (TIG-CMT) welding process, different temperature affected zones comprise variations in precipitation. β″-phase acts as the rudimentary hardening precipitate that occupies the majority of the base metal at a farther distance from the welded zone. As these particles are
thermodynamically unstable, β”-phase is dissociated into β’ and further into β particles due to surging temperature while moving towards the source affected region. This transformation towards low hardness contributing β-phase results in lowering of mechanical properties. In the welded zone, where the temperature exceeds 500 °C, complete dissolution of the hardening phase and loss of Mg by evaporation prevail. As a result, tensile strength and hardness are lowered. Thus, it can be implied that hardness value is influenced by temperature in the alloy of 6061.

Table 1. Composition of precipitates present in AA6061

| Precipitate phase | GP-zones       | β” | β’ | U1 | U2 | B’ | β   |
|-------------------|----------------|----|----|----|----|----|-----|
| Composition       | AlMg5Si6 (needle), Mg5Si6, Mg5Si5, MgAl2Si2, MgAlSi, Mg9Al3Si7, Mg2Si |

From different welding literature sources [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36], the composition of AA6061 and AA2024 alloys have been identified through their elemental % wt. ranges in table 2.

Table 2. Composition of AA6061 and AA2024 alloys by elemental % wt.

| Element | Mg   | Si   | Fe   | Cu   | Cr   | Mn   | Zn   | Ti   | Al   |
|---------|------|------|------|------|------|------|------|------|------|
| AA6061  | 1.8  | 0.5  | 1.2  | 0.7  | 0.7  | 0.4  | 0.07 | 0.19 | 0.015|
|         | 0.49 | 0.49 | 0.7  | 0.17 | 0.17 | 0.19 | 0.015| 0.015| 0.015|
| AA2024  | 1.2  | 0.5  | 1.8  | 0.5  | 0.5  | 0.5  | 0.7  | 0.7  | 0.7  |
|         | 0.49 | 0.49 | 0.7  | 0.17 | 0.17 | 0.19 | 0.015| 0.015| 0.015|

Despite having similar alloying elements, the percent variation in elemental addition can differentiate the behaviour of each alloy system. For example, the corrosion rate in 2024-T3 is higher than that of 6061-T6 because of increased Cu content [37]. Nevertheless, the aircraft body is fabricated by 2024 alloy, given corrosion-resistant cladding enforcement, for its better yield strength due to relatively high concentration of Mg and Cu than that of available in 6061, with the former having a yield strength of 325MPa (T4 treated) and latter with 275MPa (T6 treated) [38]. Furthermore, 6061 shows lesser stiffness than 2024, thus making 6061 propitious towards machining rather than forming.

For all the above minute trade-off between the alloy systems, their notable attributes make them palatable in high strength applications. These sophisticated Al alloys surely demand prudent processing methods over traditional technologies. Though subtractive manufacturing played a big role for generations, it suffered from the disdain effect of wastage. For instance, a highly tediously extracted metal, such as titanium, 80% of the material which gets wasted in the form of chips during the machining process does not do any good [39]. Benefits derived are ephemeral by the concept of chips recycling since it is not economically feasible in the long run. Another detrimental effect is through the usage of metalworking fluids which pose a threat to the environment by contamination and causing irritation or allergies to operators. Few water-based cutting fluids could become toxic if there is interaction with microbes such as bacteria [40].

To counter the above consequences, additive manufacturing is emphasized. After fusing the particles into a single part, the left out unused powders can be recycled aiding toward minimal material wastage of AM technology. Even though chips are re-melted and reused, migrating away from traditional methods to AM is preferred since no chips are produced. Therefore, functionally or material-wise, this process of material addition is holistically viewed as a key to unlock wider perspectives and manufacturability with ease.

3. Powder bed fusion

Powder bed fusion additive manufacturing is a layer-wise powder consolidation technique used for making parts with greater accuracy (±0.05 mm [41]). This process is integrated with two systems namely powder delivery and energy delivery modules. A thin layer of powder from a powder stock is distributed
evenly over a build plate using a coater. The powder stock is contained within a piston assembly that has an upward incremental movement. The build plate is also attached to another piston which does the housing purpose of the finished part. These two pistons and the coater fall under the powder delivery system.

Once a layer is applied over the plate, it is irradiated by a laser or electron beam (energy delivery system) through an employed scan strategy and thereby fusing the powder particles. After a single cross-sectional scan, the second layer of powder is evenly applied over the existing bed of powder with the help of the coater in such a way that precise downward increment of the build plate piston and same upward increment of the powder stock piston takes place. These repetitive layering-fusing cycles take place until the final desired geometry is achieved as generated in the CAD file. For shielding the part from metal fumes and laser splatter, the working chamber is made O₂ free and supplied with an inert atmosphere of nitrogen and argon [42]. Machine setup is illustrated in figure 1.

The powder bed fusion process can be classified, based on [43] [44], as SLS- selective laser sintering, SLM- selective laser melting, DMLS- direct metal laser sintering, Laser cusing and EBM- electron beam melting. In a short note, PBF can be broadly classified based on the energy source used; laser or electron beam, and based on powder processing; melting or sintering. Indeed, the actual classification can be narrowed down to SLS and SLM, other names of PBF exist since various companies came up with PBF printers with their naming style.

3.1. Selective Laser Sintering

SLS binds the metallic powder using a relatively low melting binder, polymer or metal. The SLS process can be divided into indirect SLS- polymeric binding, direct SLS- structural material in solid and binder material in liquid and partial melting SLS- either single or multi phases. All the indirect SLS parts are to be given with post-processing which adds to the overall cost [45].

In indirect SLS, metal powder particles are given with polymeric coating and sintered into the desired model by laser beam where the interaction time between the energy source and the particles ranges from 0.5 to 25ms [2]. The final part has to be de-bounded from the polymer material through a post furnace treatment to get a plain complete metal part [46]. The infiltration of metallic elements is highly useful in lowering the porosity level. Nevertheless, heat-treated sintered parts are still not as strong as forged components.

Oxide films are a threat to the sintering process. Since the formation of oxides is unavoidable, they have to be disrupted for achieving high-density parts. Shear created during compaction is utilized for these layers to disintegrate in press and sintering processing, whereas benign additives serve the purpose in the case of un-pressed or un-compacted sintering. Generally, powder manufactured alloy parts resemble that of wrought alloy material [47]. Therefore, additives play a pivotal role in safeguarding the integrity of powder AM processes. In [48], the author has performed 6061 alloy sintering with polyethyl methacrylate (PEMA) powder binder, by maintaining a 15 vol% liquid phase that essentially wetted the pre-alloyed powder particles. With an increase in temperature, thermal de-binding of the resin took place to yield a low-density green part. The elemental addition of Mg (1%) progressively disrupted the oxide layer and further wetting enhancement took place by infiltration with 0.5% of Sn or Pb as they are partially soluble in the Al phase, thereby lowering the surface tension of the sintering liquids and promoting density.

In the results elucidated by [49], it was found that sintered elemental 6061 aluminium powder specimens under vacuum conditions gave rise to internal pore formation due to the trapped gases during processing and high compacted builds were also vulnerable to this defection. On the other hand, a positive response through densification was seen in the samples that were worked under a pure N₂ atmosphere. Typically, porosity relieved test pieces were also fabricated with the addition of sintering aids (Pb, Sn, Ag), yet, they were susceptible to failure as a result of low strength solidified brittle intermetallic grain boundaries. The binding mechanism using metal as a binder happens through solid state sintering, chemically induced binding and liquid phase sintering [50]. Solid state sintering is a slow process and requires a powder bed preheating to increase the physical particle diffusion rate. Conversely, chemically induced binding avoids the concept of diffusion rather undergo partial disintegration into sub-components that
react and act as binding phase (E.g. ceramics) [51]. Moreover, limited literature is available for these two mechanisms since most of the SLS processes are realized by the LPS technique. Liquid phase sintering works by wetting liquid phase binder with the retained solid phase metal particles [52]. The laser parameters are adjusted in such a way that sufficient energy is produced to melt the binder material while maintaining temperature far below the melting point of the core metal particles that act as a structural material. The partial melting term can be used in the case of single-component powders where the outer surface of the metal powder particles alone melt and provide the necessary binding of the particle’s inner cores. Binder material takes various forms in two-component powder systems which are solely defined by the grain types such as separate grains- structural powder grains are larger than the binder ones, promoting high surface-to-volume ratio; composite grains- through alloying of powders that result into encapsulated composite powder grains of binder and structural materials; and coated grains- binder is coated on the surface of the metal powders.

In each of the cases, the principle remains the same; lower melting point binder gets transformed into a liquid phase by laser energy absorption and bonding the structural metal particles that remain in the solid phase because of a relatively higher melting point. Binary alloy can also act as a binding medium such as Al-Cu in the process of selective sintering of 6061, attested in [53]. Each of the involved stages in liquid phase sintering is depicted in figure 2.

Despite facing downside in the form of shape distortion (compact slumping) [55] due to excess liquid phase, the benefits are spoken when at-most priority is given to rapid sintering which is achieved because of hindrance offered by liquid to particle diffusion friction. By conducting a rapid solidification experiment on 6061 powder and by studying its sintering behaviour under various operating temperatures (610-650 °C) and compaction pressures (110-550 MPa), [56] concluded that surge in specimen elongation and ultimate tensile stress was attributed with increasing sintering temperature and compaction pressure. Longer holding time at peak temperature along with minimal heating rate also accounted for progression in the above properties.

3.2. Selective Laser Melting

SLM is like any other welding process that works in layer-wise consolidation fashion. Selective laser melting is lauded for its acceptance of various metals, alloys, composites and even ceramics. This method is highly reliable in tailoring nonferrous pure metals like Al, Ti, and Cu. Cohesive solid mass with a density of up to 99.9% with no visible voids can be achieved even without incorporating post-treatments [2]. Predominant laser melting can be replaced with an electron beam and thus calling the
process as electron beam melting (EBM). Unlike EBM, which has a very slow cooling rate by maintaining the bed at an elevated temperature of 870K and more [57], SLM has a rapid solidification rate and is unfit for brittle materials, unless provided with preheating of the powder bed. Another difference between SLM and EBM is that the former works in an inert atmosphere (N₂ & Ar) while the latter in a complete vacuum condition.

SLM is focused on pre-alloyed powders, spread as layers with a thickness ranging from 20 to 50 μm [58]. The bulk material is broken down to powder form through plasma or gas atomization, with spherical morphology for effective processing. These powders can be reused once the part has been built by the same system. Type 1 powder is one that is characterized by undesirable laser spatter and metal processed condensate. On the other hand, type 2 powder, with similar morphology to that of pristine fresh powder, can be successfully recycled for other builds by the process of sieving [59]. Fabrication of Al parts using SLM is highly challenging. Though SLM is versatile enough in controlling the desired properties by playing with process parameters, care must be taken while dealing with Al alloys. Due to high reflectivity, poor flowability and high thermal conductivity, slow scanning speeds with high laser power, desirable conditions for balling effect (splash induced balling to be more precise [2]), are necessarily maintained in SLM processing of aluminium powder. Small traces of O₂ in the processing chamber can lead to oxides formation which hinders the overall density of the part. In response to the above-mentioned hindrance, [60] has evaluated results based on the laser melting of aluminium 6061 powder. Identifying an optimal speed range of 100–200 mm/s with a hatch distance of 0.15mm, the part was tailored by a 50W ytterbium fibre laser beam which yielded a density of 83.7% and further improved by increasing the source to 100W. The author further added that oxide layer formation is inevitable and is relatively more concentrated at the sidewalls of the molten tracks with upper oxide layers being vaporized by the laser intensities and the bottom layer to get stirred into the molten pool due to Marangoni forces. As a result, wetting and fusing of the adjacent hatched tracks is hampered by these adherent oxide walls and thus become weakening sites in the part. High energy densities and low scanning speeds will cause a lowering of viscosity and surface tension of the molten phase, and therefore higher relative density of the part is achieved by the effective spreading of the liquid metal through wetting action. 6061 alloy has a better layer consolidating quality (due to the presence of Si and Mg) over pure Al which has an inclination towards globules formation and micro porosity. The major problem of oxidation during melting has been reduced by adding 30%wt. Cu to the 6061 powder along with an improved hardness was discussed in [61].

Samples of Al-Cu-Mg powder having a composition that could be treated similarly with commercially available 2024 alloy were made with different hatching spaces by a 200W IPG YLR-200 fibre laser source (λ=1.07 μm) and proved to be having the highest densities was discussed in [62] when tailored using 5m/min of scanning speed. In contrast, higher density parts were also obtained by increasing the scan speed to 15 m/min when the Al-Cu-Mg powder is incorporated with Zr particles [63]. Through Zr addition, cracking due to solidification was reduced and grain refinement took place as a result of Al3Zr precipitated particles in the base Al matrix. This also improved the yield strength (YS) from 253 ± 9.8 MPa to 446 ± 4.3 MPa by sacrificing elongation. Also, the yield strength to ultimate tensile strength (UTS) ratio became almost equivalent to 1, which could be implied that plastic deformation is neglected and the specimen showed brittle nature. It is expected that 2024 alloy might also respond similarly with the addition of Zr as shown in the above Al-Cu-Mg system which has a very minute increase in Mg content to that of 2024 alloy composition.

Literature is available about the corrosion behaviour of 2024 aluminium alloy specimens [64]. SLMed 2024 revealed microstructure with θ-phase (Al₃Cu) as a secondary major phase over S-phase (Al₆Cu₂Mg), one that is associated with wrought AA2024-T3. θ'-phase, discussed previously, has the same chemical composition as Al₃Cu and distributed over the entire microstructure in contrast with the confined grouping of θ-phase precipitate [18]. Though precipitated as a strengthening agent, S-phase is vulnerable to localized corrosion in AA2024-T3. This implies, due to the high content of Si in the processing powder along with the inherent rapid solidification rate of the SLM process, the absence of S-phase is benign in terms of de-alloying and pitting. Thus lowering the corrosion rate of Al in SLM 2024 parts by 5 times to that of wrought counterparts.
The properties of 2024 and 6061 alloys are illustrated in a tabular form. In table 3, properties such as yield strength, ultimate strength, % elongation and hardness for SLM (as-fabricated & T6) and wrought (T4 & T6) samples of AA2024 alloy system have been depicted. Since explicit literature was not available, values of 2024 SLM as-fabricated samples are clubbed with that of SLM samples made of Al-4.24Cu-1.97Mg-0.56Mn, composition tantamount to 2024. Likewise, SLM-T6 properties are written using another similar composition samples of Al-3.5Cu-1.5Mg-1Si. Alloy 6061 properties are as well mentioned and compared in the form of SLM (as-fabricated & T6), SLS (T6) and wrought (T4 & T6) samples in table 4. In SLS-T6, ranging was done by sorting the samples fabricated from both elemental and pre-alloyed powders in a nitrogen environment, under compaction pressure (250-510 MPa).

Table 3. AA2024 properties as in SLM (as-fabricated); SLM (T6 treated); wrought (T4 treated) and wrought (T6 treated).

| Sample          | Yield Strength (MPa) | Ultimate Strength (MPa) | % Elongation | Hardness Value (HV) | Reference |
|-----------------|----------------------|-------------------------|--------------|---------------------|-----------|
| SLM As-fabricated     | 212-317.2            | 316-413                 | 1.3-18.8     | 111-129             | [62] [63] [65] [66] |
| SLM-T6(Al 3.5Cu-1.5Mg-1Si) | 362-374             | 445-465                 | 4.4-8        | -                   | [67]      |
| 2024-T4          | 295-351              | 450-492                 | 19-21.9      | 114-137             | [31] [68] [69] |
| 2024-T6          | 393-403              | 476-496                 | 8.6-10       | 126-145             | [31] [62] |

Table 4. AA6061 properties as in SLM (as-fabricated); SLM (T6 treated); SLS (T6 treated); wrought (T4 treated) and wrought (T6 treated).

| Sample     | Yield Strength (MPa) | Ultimate Strength (MPa) | % Elongation | Hardness Value (HV) | Reference |
|------------|----------------------|-------------------------|--------------|---------------------|-----------|
| SLM As-fabricated     | 66-246.7             | 133-396.5               | 11-15        | 51.5-96             | [70] [71] |
| SLM-T6      | 282-290              | 308-318                 | 3.5-5.4      | 113-125             | [70]      |
| SLS-T6      | 92-236               | 140-275                 | 4-12         | 92-128              | [49] [72] [73] |
| 6061-T4     | 145-165              | 205-268                 | 16-23.4      | 65                  | [71] [74] [75] [76] |
| 6061-T6     | 273-279              | 310-330                 | 12-20        | 95-107              | [72] [77] [78] [79] |

Figure 3. Graphical comparative study of yield strength for AA2024 and AA6061 alloys

From the above tables, it could be inferred that the heat treatment of as-fabricated SLM samples improved yield strength for both the alloys. Wrought 2024 is of higher strength and hardness when compared with SLM counterparts. Conversely, 6061 as-fabricated can take more stress before failure than wrought 6061 in the T6 condition. SLS 6061 samples yielded higher hardness to that of SLM and wrought. A general trend of decrease in elongation was seen in as-fabricated SLM test pieces of both
the alloys when heat treated to T6 state. In 6061 alloy, the decrease in yield strength from as-fabricated to heat-treated version (T6) can be attributed to the extant literature of decrease in strength during welding of 6061. Phase transformations and absence of Mg in the weld zone suggest the lowering of strength as a result of temperature rise. Also, as the precipitates are altered by heating, precipitates locking behaviour of dislocations might have reduced and could have concluded for the lesser % elongation of heat-treated PBF samples to that as-fabricated ones. From the chart, it is clear that the tensile properties of AA2024 are relatively higher when compared to AA6061. The least variation in strength is observed in the SLM T6 condition whereas almost close to a 110 percent increase was observed in the wrought T4 condition.

4. PBF challenges and improvements
Qualification of PBF as a better AM technique requires understanding the current challenges faced by PBF and subsequent identification of improvement methods. Density is a vital aspect in PBFed parts that could be altered by most commonly occurring physical imperfections (defects) such as incomplete fusion holes, porosities and cracks [80]. Apart from scanning speed, laser wavelength used, particle absorptivity and other parameters, the defects mainly arise due to the balling phenomenon. Laser energy fuses the power particles into continuous molten tracks along the scan line. To achieve a final stable equilibrium, these cylindrical tracks break up into numerous spherical shaped balls (surface energy diminishes). This results in discontinuities in the scanned paths and also hinder the uniform spread of the fresh powder layer. The balling phenomenon thus creates porosity and nuclease for crack propagation. Detailed control methodologies are illustrated in [2]. Another undesirable effect is in the form of induced residual stress, which could be explained by the thermal gradient mechanism. During the process of layer consolidation, a steep temperature gradient between a melting top layer and an already solidified bottom layer induces large amounts of stresses. Elastic compressive strains are induced due to the restriction offered by the underlying solidified material to the heated top layer’s expansion. This can further transform into plastic deformation of the top layer if the yield strength of the material is crossed by the induced stress. Paper [81] discusses the reason how a zone of tensile stress is seen in the top and bottom regions, and conversely, a zone of compressive stress in the middle layers of a finished part that has been removed from its base plate (substrate).

Having said about the drawbacks, enhancement of PBF is mainly concentrated in density improvements. Elimination of porous morphology will account for increased density. In SLSed parts, at the end of the particles rearrangement stage, the difference between the liquid phase binder volume ($V_L$) and volumetric space within the solid metal particles ($V_O$) should be maintained as minimal as possible to target zero porosity (in practice $V_O > V_L$) [52]. Heat conduction during part formation also affects density. This correlation is spoken in [82]. SLM cubes fabricated of 2024 material with support structures evolved with higher density to that of without support. These structures were of lesser cross-section and therefore reduced the overall heat transfer. The inference is that managing rapid solidification in SLM has to be considered for denser fabrications and one of the controlling means is through supports. Finally, PBF can be enhanced by part qualification through the modelling approach [83]. Since there is a lot of physics involved in understanding the powder bed mechanism, simulation and computational models can enhance the mechanism’s performance. This could be done by effective medium model- treating the part as a multi-physics entity and predicting the residual stresses which are quantified through a heat transfer and solid mechanics concepts, and powder model- modelling the powder-laser interplay by taking into account the melting process, molten metal flow parameters and inclusive trap gases.

5. Conclusion
The processing response of AA2024 and AA6061 under laser sintering and melting topics attests renowned usage of PBF under additive manufacturing. The following points based on the alloy systems can be inferred which heightens the PBF scope.
Additives play a crucial role in PBF. In the 6061 alloy system, Mg addition in SLS and Cu addition in SLM disrupt the oxide formation and aid towards density. Since it is convenient for such additions in the form of powder, oxide control is better in PBF than in conventional methods.

Though producing 6061 components is slow in PBF that adopts the SLM process, the elemental addition of Sn and Pb will enhance the wetting characteristics of SLS and leads to rapid sintering of 6061 components.

Apart from additives, wetting can also be improved in PBF by varying the process parameters to slow scanning speeds with high laser power. By doing so, more particle-energy source interaction prevails and wetting is enhanced by lowering the viscosity and surface tension of the molten phase.

A single traditional machine employed to work with tensile material will fail if programmed to deal with brittle material. This situation can be easily countered by PBF, especially SLM, where the powder bed can be preheated and the solidification rate can be adjusted in favor of brittle powder particles.

N₂ environment machines are preferred over vacuum condition when density is given with the most priority. Nevertheless, a vacuum is necessary when dealing with high temperature melting metals/alloys used in the EBM technique.

Since S-phase precipitate is not identified in SLM fabricated 2024 alloy, the rate of corrosion is very low in a 2024 PBF component than that of traditionally tailored.

From the above-tabulated properties, improved qualities are identified in SLM 6061 when compared with the wrought state. To reflect the same in 2024 PBF parts, more research has to be carried out.

The ease of using additives and process parametric control propels the scope of PBF for numerous applications. Literature availability of material addition manufacturing of 2024 and 6061 alloys through SLM/SLS is limited but the positive results concluded in those studies open a wide window of opportunities for these alloys to be employed in high-end applications with least wastage.

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Authors’ background

| Name                  | Prefix     | Research Field                  | Email                      | Personal website                  |
|-----------------------|------------|---------------------------------|----------------------------|-----------------------------------|
| C Senthamarai Kannan | Assistant  | Vibration Analysis              | senthamarai@svce.ac.in     | https://orcid.org/0000-0001-6365-6427 |
|                       | Professor  | Bio Composites                  |                            | Scopus Author ID: 56313342800     |
|                       |            | Behaviour of materials          |                            | linkedin.com/in/senthamaraikannan-chinnasamy-a6a4b579/ |
|                       |            | Polymer materials               |                            |                                   |
| S Sai Sree Chandra    | Undergraduate | -                             | saisreechandra171999@gmail.com | https://www.linkedin.com/in/sai-sreechandra-s-6431441b4 |
| Name               | Undergraduate | -          | Email                          | LinkedIn URL                                      |
|--------------------|---------------|------------|--------------------------------|--------------------------------------------------|
| G Punith Krishnan  | Undergraduate | -          | gpunithkrishnan@gmail.com      | https://www.linkedin.com/in/punith-krishnan-0579471a9/|
| S Pravin Raj       | Undergraduate | -          | pravinraj535@gmail.com         | https://www.linkedin.com/in/pravin-raj-3289051a3   |