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Additive manufacturing of Ti-6Al-4V alloy- A review

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Abstract

The most popular additive manufacturing (AM) technologies to produce titanium alloy parts are electron beam melting (EBM), selective laser melting (SLM) and directed energy deposition (DED). This investigation explores mainly these three techniques and compares these three methods comprehensively in terms of microstructure, tensile properties, porosity, surface roughness and residual stress based on the information available in the literature. It was found that the microstructure is affected by the highest temperature generated and the cooling rate which can be tailored by the input variables of the AM processes. The parts produced from EBM have strength comparable to that of conventionally fabricated counterparts. SLM and DED yield superior strength, which can be up to 25 % higher than traditionally manufactured products. Due to the presense of larger tensile residual stress, surface roughness and porosity, AM fabricated parts have lower fatigue life compared to those of from traditional methods. EBM parts have slightly lower fracture (??) toughness (i.e., lower fatigue life) than conventionally produced parts while SLM and DED have significantly lower fracture toughness. Annealing, hot isostatic pressing, stress relief and additional machining processes improve the characteristics of parts produced from AM. Ti-6Al-4V alloy parts fabricated via AM may have limited applications despite the high demands in aerospace or biomedical engineering. Since rapid product development using 3D printers leads to signigicant cost reductions more recently, it is expected that more opportunities may soon be available for the AM of titanium alloys with newer AM processes such as cold spray additive manufacturing (CSAM) and additive friction stir deposition (AFSD).

Keywords: Additive manufacturing, Ti-6Al-4V alloy, tensile properties, fatigue life, stress analysis

1. Introduction

Titanium (Ti) and its alloys, namely the most popular one Ti-6Al-4V alloy, have rapidly evolved to become one of the most important high-end materials in a variety of industrial applications such as aerospace, biomedical, and power/energy sectors. [1, 2]. This is associated with its excellent corrosion resistance and specific strength, the highest of all metallic elements, as well as low density [3], along with good specific strength at a high-temperature level. Ti-6Al-4V alloy is extremely difficult-to-machine. Titanium and its alloys offered complex and unusual deformation mechanism under extemre working conditions, including the thermal softening property at high temperatures, compared to other commonly available metals such as steel or aluminium [4]. This drawback, coupled with the fact that Ti-alloys have low thermal conductivity and low volume specific heat, results in high cutting temperature [5]. The high temperature causes build-up edge which accelerate tool-wear [4]. Therefore, various attempts have been made in recent decades to develop advanced AM processes for Ti-alloys as alternative manufacturing process.

In traditionally known additive manufacturing (AM), a product is designed, modelled and generated by computer-aided design (CAD) method, then is sliced into multiple thin layers. and built layer by layer from bottom to top using a heat source such as laser, electron beam or ultrasonication to melt and combine materials [6]. As such, from the economical point of view, AM consumes the minimum quantity of materials in net-shape with the significant conservation of resources and consumables. AM techniques have significantly lower manufacturing time when compared with conventional methods due to the fact that many steps in the current conventional methods such as melting, forming, shaping, moulding as well as machining, can be skipped with AM. As AM is capable of fabricating near-net shapes [6], minimal machining is required to achieve good surface finish and shape. AM technologies enable producing a part composed of multi-material such as the reinforcements of pure Ti with

SiC [119], TiB_2 [120], hydroxyapatite [121, 122], Si_3N_4 [123], and Ti-6Al-4V with Cu [124, 125]. Co-Cr-Mo coated on Ti-6Al-4V [126] and TiO_2 coated on pure Ti [127] using AM technologies may feasibly improve wear resistance of metal on metal implants in biomedical applications.

A significant amount research work in this field has been reported in the published literatures [6-17]. Nonetheless, it is difficult to have a good understanding of this field due to somewhat disorganised or less linked scientific results. This current review investigates the latest developments in the AM of titanium alloys available in previous studies and investigations, and links the findings from the prior work more scientifically with the comprehensive overview of material and product developement efforts. This ensures that the associated limimations and drawbacks, as well as precautions can be substantiated to benefit industrialists and researchers in meeting the future challenges in the AM of Ti-6Al-4V alloy.

2. Categories of Additive Manufacturing of Ti-alloys

American Society for Testing and Materials (ASTM) has classified AM into seven process categories [1, 6] including (i) vat photopolymerization (VP), (ii) powder bed fusion (PBF), (iii) directed energy deposition (DED), (iv) material extrusion (ME), (v) material jetting (MJ), (vi) binder jetting (BJ) and (vii) sheet lamination (SL). Among these, only PBF, DED and SL have been applied in additive manufacturing of Ti and its alloys [1]. Powder bed fusion is an AM technique that utilizes a heat source (e.g. laser, plasma, electron beam, etc.) to melt and combine powder material in order to follow the tool path configuration specified in the CAD file in a layer-by-layer manner. Once each layer is produced, a new powder layer is spread over and the process repeats until the end. The entire process is highly capable of producing near net-shape products [18]. Directed energy deposition is an AM technology with the aid of a focused heat source (laser or electron beam) to melt material (in the form of either powders or wires) when deposited through a nozzle. The main difference between DED and PBF is that PBF melt the material before it is being deposited while the melting process in DED takes place while it is being deposited [6, 7]. The part fabricated rests on a baseplate by moving the head according to the CAD/CAM plans developed [19]. Sheet lamination is an AM process where material sheets are bonded together using adhesives, and a guided laser following the tool path data cuts the sheets into a desired shape. A new material sheet is then added, and the process repeats until the product is finished. The two types of sheet lamination are categorized as “bond then form” (sheets are bonded first then cut to shape) and “form then bond” (sheets are cut to shape first then bond). These two types have some differences despite the same major process principles [6].

Commercially available AM technologies utilize either electron beam, laser or ultrasonication as their heat sources to melt and weld powder materials [8-17]. Electron beam-based technologies are operated in a vacuum environment as opposed to laser-based counterparts in an inert atmosphere environment. While inert atmosphere system is cheaper than vacuum system, they have the typical downside in relation to greater residual stress with the requirement of a stress relieving operation [1]. A comparison of PBF, DED and SL technologies involved in the AM of Ti-alloys with their respective work principles are summarized in Table 1.

Table 1: Commercially available AM technologies used for Ti-6Al-4V alloy.

AM type	**Name**	**Manufacturer**	**Work principle**

Electron beam-based	Electron beam melting (EBM)	Arcam AB [9]	Electron beam melt and fuse metallic powders on a bed of powders
Laser-based powder bed fusion	Selective laser melting (SLM)	Selective Laser Melting Solution GmbH [8]	Laser melt and fuse metallic powders on a bed of powders
	Selective laser sintering (SLS)	3D Systems [11]	Laser sinter and fuse metallic powders on a bed of powders
	Direct metal laser sintering (DMLS)	EOS GmbH [12]	Laser melt, sinter and fuse metallic powders on a bed of powders
	Laser melting (LM)	Renishaw plc [10]	Laser melt and fuse metallic powders on a bed of powders
	Laser cusing (CU)	Concept Laser GmbH [13]	Laser melt and fuse metallic powders on a bed of powders
Directed energy deposition	Laser engineered net shaping (LENS)	Optomec Inc. [14]	Laser melt and deposit metallic powders into a molten pool
	Direct metal deposition (DMD)	DM3D Technology, LLC [15]	Laser melt and deposit metallic powders in a closed-loop process

	Electron beam additive manufacturing (EBAM)	Sciaky Inc. [16]	Electron beam melt and deposit metals using wire feedstock in vacuum
Sheet lamination	Ultrasonic consolidation (UC)	Fabrisonic [17]	Ultrasonic energy welds and make the parts out of multiple metal sheets.

PBF technologies are capable of building parts with complex, unusual geometries and features with high accuracy coupled with good surface finish. However, when compared to DED technologies, PBF technologies are limited to build size, single material build, slow build rate, and therefore cannot build additional features on existing parts. In contrast, DED technologies generally build less complicated parts in possession of rougher surface finish as opposed to PBF. On the other hand, DED technologies allow for large and flexible build size. DMD technology is capable of building multi-materials parts in a medium or large size with the provision of considerable advantages over conventional PBF technologies [15]. In addition, DED technologies also yield a higher deposition rate leading to an increase in the build rate.

3. Powder requirements and handling

The AM of Ti-6Al-4V alloy uses pre-alloyed titanium powders as feeding material. Layer thickness as well as minimum buildable size and surface quality of the products depend primarily on the size and shape of powder particles. Additionally, powder size distribution also affects the packing density of PBF processes. The size of powders for PBF processes generally range from 20 - 40 μm in contrast with 45 - 150 μm for DED processes [1]. Depending on the powder preparation process, the particles can vary, typically in irregular, needle-like, flake-like, granular, platelet-like shapes, etc., [1, 20]. However, powder morphology (shape and size) is less important in DED techniques. A consistent flow of powder is essential to warrant successful operation and product quality. Spherical shape powder without any unusual morphology and contamination is highly recommended to achieve a good and consistent flow rate [1, 21]. Generally, 100% pure metal powders are difficult to obtain and additives are required to ensure the fidelity of the powders in most cases. Chemical properties of powders may also vary due to the repeated operations in AM or recycling as the prolonged exposure of thermal effects from multiple build layers can result in the losses of elements [20]. For example, electron beam melting of Ti-6Al-4V powders in a vacuum environment can lead to the loss of Al elements. As such, the additional amount of Al is often added to compensate the loss. The powder density directly affects the porosity where more denser powder is particularly preferred to reduce the porosity which influences properties of the final product accordigly [1] [22].

4. Microstructures generated from AM processes

Microstructures directly dictate mechanical properties of metal products. Properties such as tensile strength, ductility and fatigue life are all determined by microstructures which in turn are determined by a thermal history of the alloys [23]. This study focuses on Ti-6Al-4V alloy, which is the most commonly used material in the AM process of Ti-alloys. Ti-6Al-4V is a moderate strength martensitic $\alpha + \beta$ titanium alloy containing 6 wt. % α stabilizing Al and 4 wt. % β stabilizing V [24]. In the cast form, the microstructure contains both α and β phases. The shape and size of these phases are subjected to their heat treatment and thermo-mechanical processing. However, the microstructure evolution of Ti-6Al-4V alloy is very complex and may be affected by corresponding parameters used in AM processes such as cooling and reheating rates, which, however, does not necessarily resemble that of cast alloys [25].

The AM processes have a complex thermal history that depends primarily on many parameters such as energy source input power, scan speed, alloy purity, as well as part geometry and size. This complexity in thermal history makes it difficult to characterize prior β grains [26]. Fig. 1 demonstrates the temperatures of different layers for an AM-produced sample in terms of time or layer number. The temperature of the first layer is above the melting point (i.e. liquidus temperature). It remains above the melting point at the time when the second layer is added. The first layer's temperature drops but still remains above the transus β temperature up to the addition of the fourth layer. The size and thickness of prior β grains do not depend on cooling rate, as explained in the case of α laths, but rather the period between transus β temperature and melting point [27].

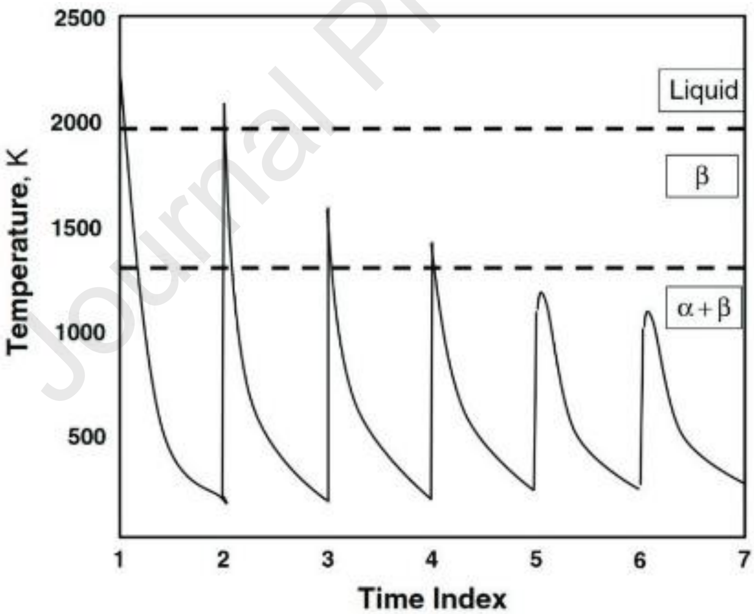


Fig. 1: Thermal history of different layers of AM-fabricated Ti-6Al-4V alloy sample [28].

This results in the formation of characteristics columnar β grains in the microstructures of all AM-processed Ti-6Al-4V alloy [23, 27, 29]. Formanoir et al. [30], Al-Bermani et al. [31] and Liu and Shin [23] stated that β grains nucleate and grow epitaxially on the top surface of previous layers and perpendicular to the molten pool. The size of β grains varies a lot between each AM process. Wu et al. [32] reported a thickness range of 0.2 - 4 mm for β grains. Sandgren et al. [33] found the prior β grain thickness up to 4 mm for the DED process. Both Lancaster et al. [34] and Simonelli et al. [35] reported the thickness values of 246 and 103 μm for prior β grains in EBM and SLM processes, respectively. Generally, DED processes can spot larger prior β grain size than those of PBF (EBM, SLM). According to Liu et al [31], Ti-6Al-4V alloys undergo a complete melting and solidification process during the AM process, which are transformed from α + β (i.e., initial phase of the alloys at ambient temperature) to β due to very high temperature to liquid then back to β and finally to α + β/α′ when the temperature of the molten pool drops below transus β temperature. As such, a sufficient cooling rate, along with build temperature, lower than the martensite start temperature at 780 °C would be required for the formation of α′ martensite [23]. Martensite start temperature varies from 575 to 800 °C [36, 37] which is due to the difference in initial microstructures and uniformity of composition and impurities. It is impossible for these factors to be the same throughout each specimen, thus it leads to different martensite start temperatures as reported in various tests [38-40]. Any cooling rate of 410 °C/s or higher results in complete α′ martensite formation. An incomplete α′ martensite formation is expected in cooling rate range of 410 to 20 °C/s. However, cooling rate below 20 °C/s does not produce any α′ martensite [36].

Though the core working principle is similar for all AM processes such as EBM, SLM and DED, those have different build temperatures and cooling rates. It is reported that the build temperature of EBM is roughly in the range of 600 – 760 °C [41, 42], which is higher than those of SLM and DED. Significantly high build temperature and fast cooling rate take place in these processes as concentrated energy beam is used in these methods for a very short time. Cooling rate is expected to have a wide range even within the same AM process because of many affecting process parameters. The molten pool temperature and corresponding cooling rate in EBM process are around 2700 K [43] and 103 – 105 °C /s [31], respectively. The cooling rate of molten pool of SLM and DED processes is somewhat similar [44]. It can be expected that the α′ martensite becomes dominant microstructures of as-built parts produced by AM processes. However, EBM with the higher build temperature and lower cooling rate may possess different microstructures from SLM and DED. Table 2 summarizes the build temperatures and cooling rate of different AM processes.

Table 2: Build temperatures and cooling rates of different AM processes [43-47].

	Electron beam melting (EBM)	Selective laser melting (SLM)	Direct energy diposition (DED)
Build temperature (°C)	600 – 760	200	–
Molten temperature (°C)	~2700	–	~2973
Cooling rate (K/s)	103 – 105	104 – 106	104 – 106

Typical microstructures of Ti-6Al-4V alloys produced by different AM processes are shown in Fig. 2 and as mentioned earlier, martensitic α + β type microstructures appear to be prevalent. Initially, the molten pool cools down rapidly and the diffusion may occur for less transformation of *β* to martensite α′. Then, the temperature remains somewhat constant at the build temperature range of approximately 600-760 °C until the deposition process is completed. During this stage, the high build temperature of EBM process acts as an in-progress heat treatment resulting in the decomposition of martensite α′ to α + β phase [45-48]. According to Al-Bermani et al. [31], some martensite α′ can still be found within the larger parts produced by EBM. They exist in small parts or very close to the top surfaces where the high cooling rate occurs. The typical microstructure found in α + β dual phase produced by EBM is the

Widmanstättenn microstructure. Due to the high cooling rate of both SLM and DED processes, the microstructures of parts produced by SLM and DED reveal α′ martensite with much finer α phase as opposed to the parts produced by EBM. The α lath thickness of both SLM and DED should also be smaller than that of EBM. In fact, Wysocki et al. [49] reported that the α lath thickness of as-built Ti-6Al-4V in a SLM ranges from 0.2 – 1 μm. Sandgren et al. [33] found that the lath thickness is around 0.7 μm for a DED process. Additionally, Baufeld et al. [50] measured their α lath thickness to be 0.6 μm. As such, withstanding the similar microstructures, the thickness of α laths may vary.

In contrast to complex and different microstructures of produced samples in AM processes, the microstructures of conventional mill-annealed Ti-6Al-4V consist of equiaxial α/β phase, as shown in Fig. 3. in which both of them are subjected to heat treatment. More evidently, the microstructures of these Ti-6Al-4V possess equiaxial α and α′ phases.

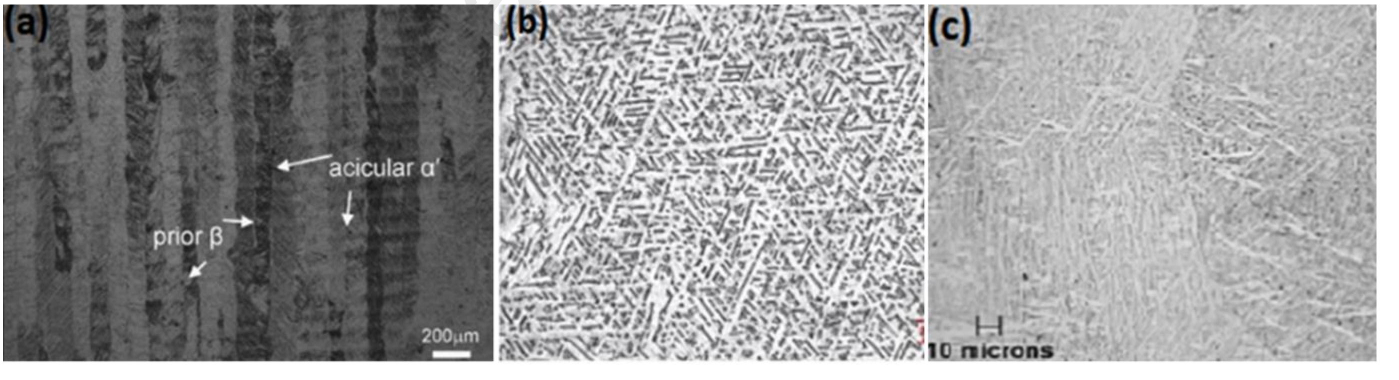


Fig. 2: As-built microstructures of a Ti-6Al-4V parts produced by (a) SLM [51], (b) EBM [52] and (c) DED processes [53].

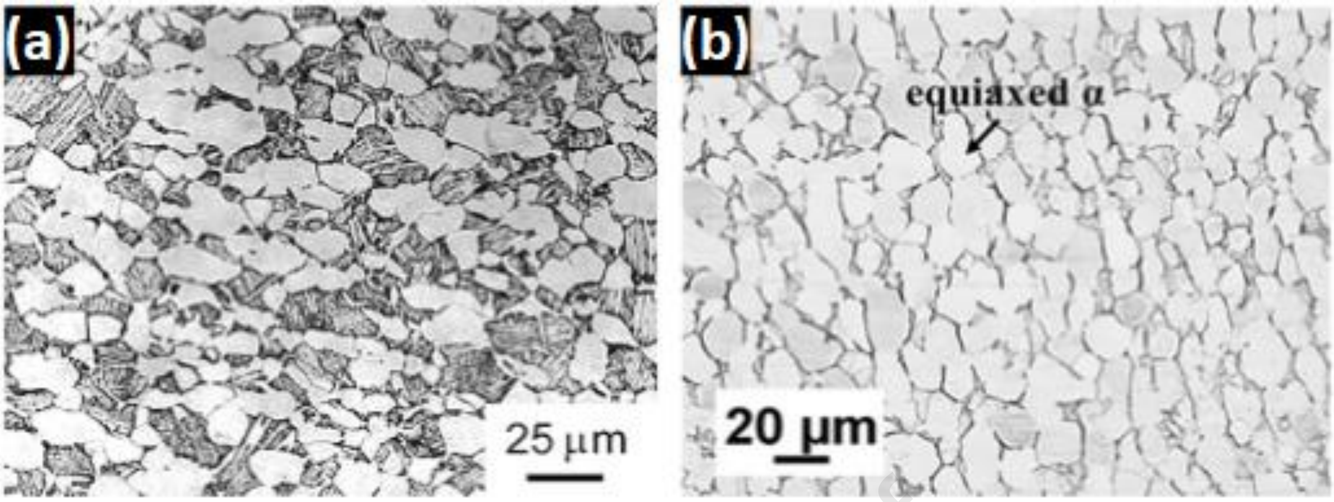


Fig. 3: Microstructure of conventional mill-annealed Ti-6Al-4V: (a) solution treated and overaged alloys showing equiaxial α′ and secondary α + β lamellae [54] as well as (b) mill-annealed Ti-6Al-4V in the presence of equiaxial α [47].

Sometimes parts produced by AM processes are subjected to heat-treatment processes. Such processes coarsen α lath thickness, as shown in Fig. 4 [61]. The average α lath thickness of 1.1 μm to stress relief, 3.5 μm for hot isostatic pressing and 1.0 μm for annealed have been revealed elsewhere [55]. All of these are thicker than as-built SLM and DED α lath thickness. Therefore, these heat-treated Ti-6Al-4V alloys can lower yield strength, despit the improvement of ductility over as-built Ti-6Al-4V alloys via SLM and DED. However, it should be noted that additional heat treatment processes may incur extra production cost. The low scan speed increases the laser interaction time and high energy input which results in higher deposition temperature and lower cooling rate. This might annihilate the stress to some extent. The lower cooling rate of EBM (compare to SLM and DED) and its high build temperature facilitate in-progress heat treatment. Therfore, the average α lath thickness of EBM-produced parts is thicker than those of SLM and DED. The thicker the α lath, the less strength the alloy will sustain. As such, Laser PBF and DED parts are expected to achieve higher strength with lower ductility than those of EBM parts [56]. Since α lath thickness in parts produced from SLM and

DED is smaller than that of EBM, parts produced from SLM and DED should have higher yield strength than EBM despite more poor ductility.

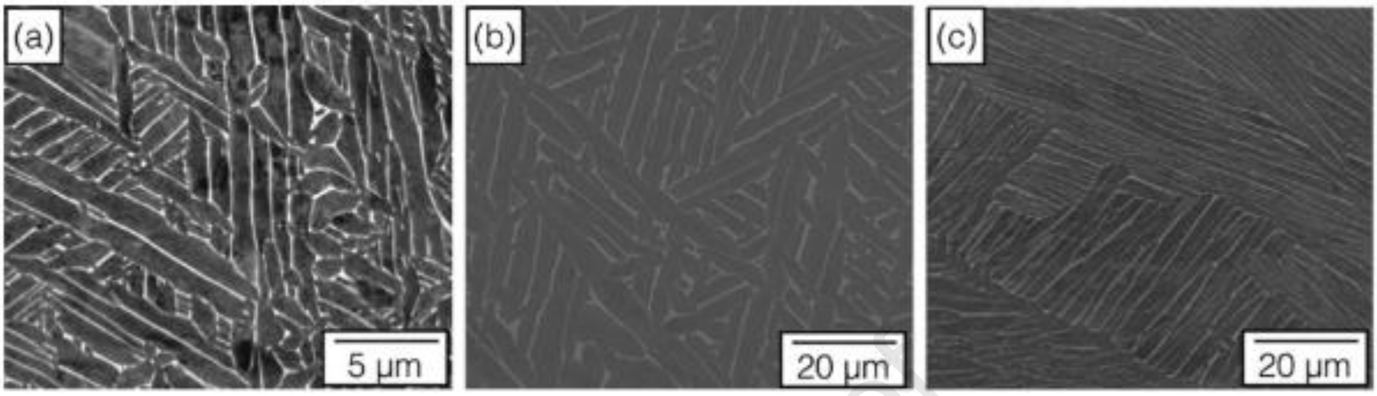


Fig. 4: Microstructures of DED-processed Ti-6Al-4V alloys after different heat treatments: (a) stress relief, (b) HIP and (c) annealing [55].

Since the α lath of conventionally produced Ti-6Al-4V are thicker than those produced by AM processes. It is expected that they have less yield strength and better ductility than EBM while it possess much improved ductility than SLM and DED. This is elaborated in the subsequent sections where tensile strengths and elongations of Ti-alloy produced by AM processed and conventional methods are compared.

5. Tensile properties

One of the key considerations for any AM-fabricated Ti-alloy products lies in whether they have the material properties to compete with those based upon conventionally produced counterparts such as forged, cast or wrought titanium. To be specific, tensile and fatigue properties are the two most used material features to evaluate the performance of AM-produced Ti products. Tensile properties for various AM-processed Ti-6Al-4V alloys samples are compared with conventionally produced Ti-6AL-4V counterparts, as illustrated in Table 3. In contrast, Table 4 demonstrates tensile properties of forged, cast and wrought Ti-6Al-4V alloys as well.

Table 3: Tensile properties of various AM-fabricated Ti-6Al-4V alloy samples.

Electron beam based powder bed fusion (PBF)						
Ref	**Condition**	**Machining**	**Axis**	**Yield strength (MPa)**	**Ultimate tensile strength (MPa)**	**Elongation (%)**
[57]	As-built	No	Z	812 ± 12	851 ± 19	3.6 ± 0.9
[57]	As-built	No	XY	783 ± 15	833 ± 22	2.7 ± 0.4
[58]	As-built	Interior	Z	984.1 ± 8.5	1032.9 ± 12.9	9.0 ± 2.9
[58]	As-built	Exterior	Z	961 ± 7.1	1008.6 ± 15.2	7.1 ± 3.4
[58]	As-built	Interior	XY	982.9 ± 5.7	1029.7 ± 7	12.2 ± 0.8
[58]	As-built	Exterior	XY	966.5 ± 5.3	1017.4 ± 4.9	12.2 ± 2.0
[59]	As-built	Yes	Z	970	1045	10.9
[45]	As-built	No	-	740 ± 10	790 ± 10	2.2 ± 0.3
[47]	As-built	Yes	XY	1006	1066	15
[47]	As-built	Yes	Z	1001	1073	11
[47]	As-built	Yes	XY	973	1032	12
[47]	As-built	Yes	Z	1051	1116	15
[60]	As-built	Yes	Z	869 ± 7.2	928 ± 9.8	9.9 ± 1.7
[60]	As-built	Yes	XY	899 ± 4.7	978 ± 3.2	9.5 ± 1.2
[61]	As-built	Yes	-	830 ± 5	915 ± 10	13.1 ± 0.4
[61]	Hot isostatic press	Yes	-	795 ± 10	870 ± 10	13.7 ± 1.0
[62]	As-built	Yes	XY	905	979	10
[62]	As-built	Yes	Z	910	971	10

[62]	Hot isostatic press	Yes	-	843	932	13
Laser based powder bed fusion (PBF)						
[60]	As-built	Yes	Z	1143 ± 30	1219 ± 20	4.89 ± 0.6
[60]	As-built	Yes	XY	1195 ± 19	1269 ± 9	5 ± 0.5
[49]	As-built	Yes	Z	1150 ± 67	1246 ± 134	1.4 ± 0.5
[49]	As-built	Yes	XY	1273 ± 53	1421 ± 120	3.2 ± 0.5
[59]	Stress-relieved	Yes	XY	961	1032	2.7
[63]	As-built	No	XY	910 ± 9.9	1035 ± 29	3.3 ± 0.76
[64]	As-built	Yes	-	1008	1080	1.6
[64]	Annealed at 800 °C	Yes	-	962	1040	5
[64]	Annealed at 1050 °C	Yes	-	798	945	11.6
[64]	Hot isostatic press	Yes	-	912	1005	8.3
[65]	As-built	No	Z	664 - 802	1040 - 1062	~11.9
[65]	As-built	Yes	Z	984 - 988	1151 - 1157	~10.9
[65]	Annealed at 700 °C	Yes	Z	1045 - 1054	1115 - 1116	~11.3
[65]	Annealed at 900 °C	Yes	Z	905 - 911	987 - 989	~9.5
[65]	Hot isostatic press	Yes	Z	883 - 888	973 - 974	~19.0

[66]	As-built	Yes	-	1234	1286	5.22
[66]	Annealed at 910 °C	Yes	-	1195	1265	9.74
[66]	Annealed at 990 °C	Yes	-	1056	1145	9.32
Directed energy deposition (DED)						
[67]	As-built	Yes	Z	976 ± 24	1099 ± 2	4.9 ± 0.1
[68]	Annealed	Yes	Z	950 ± 2	1025 ± 2	5 ± 1
[68]	Annealed	Yes	XY	950 ± 2	1025 ± 10	12 ± 1
[68]	Hot isostatic press	Yes	/	850 ± 2	920 ± 1	17 ± 2
[69]	As-built	Yes	XY	960 ± 26	1063 ± 20	10.9 ± 1.4
[69]	As-built	Yes	Z (top)	945 ± 13	1041 ± 12	14.5 ± 1.2
[69]	As-built	Yes	Z (bottom)	970 ± 17	1087 ± 8	13.6 ± 0.5
[70]	As-built, low power	Yes	XY	1005	1103	4
[70]	As-built, high power	Yes	XY	990	1042	7
[70]	Annealed	Yes	XY	1000	1073	9
[70]	Annealed	Yes	XY	991	1044	10
[71]	As-built	Yes	XY	961 ± 40	1072 ± 33	17 ± 4

[71]	As-built	Yes	Z	916 ± 26	1032 ± 31	19 ± 4
[72]	As-built	Yes	XY	908	1038	3.8
[72]	Annealed	Yes	XY	959	1049	3.7
[72]	Annealed	Yes	XY	957	1097	3.4
[55]	Stress-relieved	Yes	/	~873	~964	3 - 9
[55]	Annealed	Yes	/	~788	~879	3 - 9
[55]	Hot isostatic press	Yes	/	~773	~881	3 - 9

Table 4: Tensile properties for conventionally produced Ti-6Al-4V alloy sample.

Wrought						
Ref	**Condition**	**Machining**	**Axis**	**Yield strength (MPa)**	**Ultimate tensile strength (MPa)**	**Elongation (%)**
[61]	Annealed	Yes	-	790 ± 20	870 ± 10	18.1 ± 0.8
[49]	-	-	XY	832 ± 10	933 ± 7	13.0 ± 1.5
[49]	-	-	Z	836 ± 9	942 ± 8	12.5 ± 1.2
[73]	-	-	-	930	995	14
[74]	Annealed	-	-	900	970	17
Forged						
[68]	Heat treated	Yes	-	878 ± 4	926 ± 2	20 ± 1
[47]	Annealed	-	-	970	1030	16
-						

[45]	-	-	-	750 ± 2	875 ± 10	4.5 ± 0.2
[73]	-	-	-	865	980	13.5

According to Tables 3 and 4, in can be seen that generally the yield strength and ultimate tensile strength of AM-fabricated Ti samples are comparable or superior to conventionally produced Ti alloy samples. Specifically, electron beam based PBF typically produce the parts with comparable or slightly superior strengths to that of conventionally produced parts. Meanwhile, laser-based PBF and DED technologies appear to produce parts with the superior strength as opposed to traditional methods, while laser-based PBF yields the highest strength. This can be expected based on the microstructural evolution of AM-made samples. The axis orientation of the build does not appear to induce significant effect on the part strength. This is because the strength discrepancies between the two directions XY (horizontal) and Z (longitudinal) are not high enough to influnence in most tests.

The effect of cooling rate, thus the effect of microstructure of AM-processed Ti samples affect the strength and ductility. The columnar α + β yields better strength than equiaxed α + β. EBM, while at its very high build temperature α′ martensite is transformed into columnar α + β, thus resulting in much thicker α laths. SLM and DED give rise to either partial α′ or complete α′ with even narrower α laths. Conventionally produced Ti samples possess equiaxed α + β microstructures with the lowest resulting strength [46].

On the other hand, as-built Ti samples produced in AM processes exhibit lower elongation when compared with conventional Ti couterparts apparently due to the less ductile characteristics for the former samples. The ductility of the parts produced by electron beam based PBF technique with columnar α + β are a few percentages lower than those based on wrought, forged, casted titanium, while the parts produced by laser-based PBF and DED are substantially lower (usually less than half) accordingly. The formation of martensite α′ phase results from faster cooling rate but lower build temperature of laser-based and DED processes leading to either partial α′ or complete α′ transformation depending on different process parameters [1, 23, 24]. As illustrated in Tables 3 and 4, the ductility of wrought and forged Ti-6Al-4V is superior to those from AM-fabricated couterparts. As-built EBM-produced parts with α + β dual phase are slightly worse than wrought and forged equiaxed α + β counterparts. Laser-based and DED produced as-built parts possess the lowest ductility. A majority of specimens do not even reach the half ductility of conventionally produced specimens. However, the ductility of these parts can be improved by additional hot isostatic press and/or heat treatments. Hot isostatic press (HIP) can potentially minimize pores and assist in generating the denser microstructure of the parts, which ultimately becomes favourable in improving the ductility of AM-built Ti parts. Carreon et al. [75] reported that over aging causes the formation of nano-scale α_2-phases (Ti_3Al) in the microstrutute, which improved the mechanical properties (hardness and creep resistsnce) of Ti-6Al-4V alloy. Higher elongation at failure could be achieved for the heat treatment at higher temperature with an additional strength decrease. This must be considered when deciding whether the parts need extra ductility or strength, depending on its specific applications. In light of these, Ti parts produced by AM techniques have the strength required to perform in place of traditionally produced Ti counterparts. Although the ductility is lower, it can be improved with additional heat treatment processes while still maintaining the high strength.

6. Fatigue properties

Fatigue strength is the most considered material property when evaluating the performance of a metallic product [76]. The fatigue perfomnace of any product is depend upon many factors such as microstructure, structural defects, surface quality, porosity, residual stresses, and corrosion resistance. The particular role of some of these factors on microstructures of AM-processed Ti samples and their role on fatigue behaviours are eleborated in the forthcoming sections.

6.1 Porosity

In theory, AM techniques can produce fully dense parts. However, it is practically impossible as non-optimal deposition such as, irregular shape and size of the metal powders inevitiably incorporate porosity. The porosity in a structure can be controlled to alter the mechanical properties, and thus affecting the fatigue properties. According to previous studies [2, 53, 77], pores are used in biomedical field for the stress shielding effect in load-bearing implants. However, not all pores can be manipulated and the uncontrolled pores may deteriorate the properties of parts. Uncontrolled pores can ultimately act as crack initiators. Moreover, the presence of pores also results in an uneven stress distribution across the cross-sectional area, and thus can significantly reduce the effective load bearing area [78, 79]. Vilaro et al. [73] show that the macroscopic ductility could be significantly affected by the shape and orientation of pores. There are two types of pores that are commonly used in most AM produced components, namely, (i) gas pores and (ii) lack of fusion pores, as illustrated in Fig. 5.

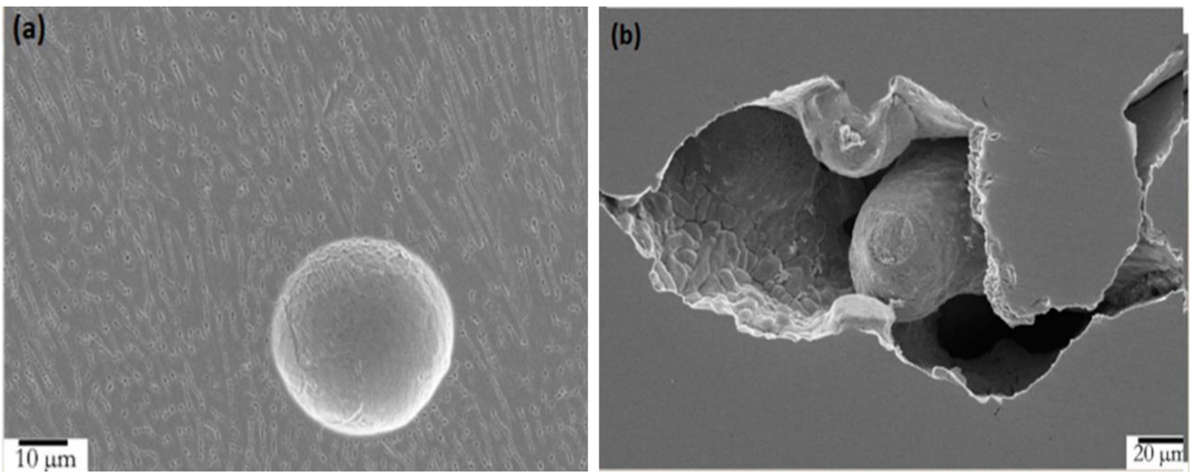


Fig. 5: Different types of pores in AM-processed samples: (a) Gas pore in a low power DED product and (b) lack of fusion pore in a high power DED product [80].

The gas pores are often in either spherical or elliptic and randomly distributed shapes. Gas pores are generated due to trapped gas inside the molten pool during the build process which could not escape in time and thus remain during the solidification process [81, 82]. The formation of unwanted pores negatively influenc the fatigue properties. Dense powder materials are typically recommended over sponge-based powders since the structures of dense powder materials are less likely to generate gas pores compared to the hollow structures of sponge-basedpowders [83]. The settings of AM processes such as laser power and scan speed can also affect the formation of gas pores. Zhong et al. [84] found that higher laser power can reduce the formation of gas pores, which was further confirmed by Erinosho et al [85] as shown in Fig. 6. An average pore size of 171.14 ± 90.75 μm for the material specimens at the laser power of 900 W as well as 125.44 ± 27.4 μm for specimen at 1500 W have been reported accordingly [85].

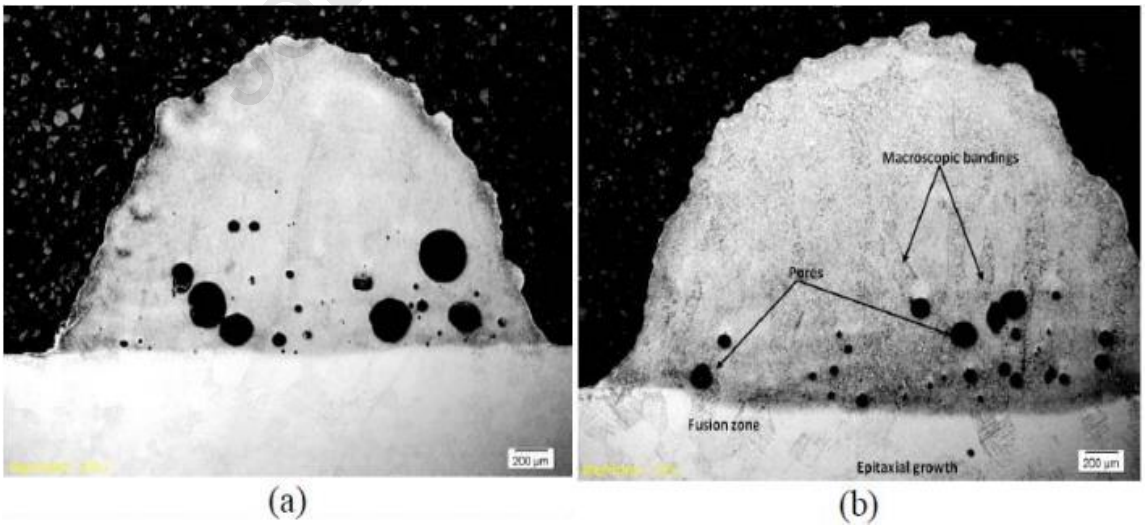


Fig. 6: Pores in AM-processed Ti-6Al-4V alloys at laser powers (a) 900 W and (b) 1500 W [85].

Although higher laser power reduces the pore, it cannot completely eliminate them. Kasperovich and Hausmann [65] found that even under optimized SLM settings, the porosity of apprximately 0.08 % still remains and pores with small sizes occupy a considerable volume percentage of the as-built parts. As for EBM produced parts, the pore size can be in a range of 50 - 300 μm [86]. Galarrage et al. [62] found that the porosity was much greater in the centre (0.25 %) of the build platform compared to those at the edge of the build platform (0.09 %). As uncontrolled pores cause undesirable effects, post heat treatment is commonly undertaken to as-built AM-processed Ti parts in order to reduce the porosity as well as pore size. However, as aforementioned, heat treatment processes cannot completely eliminate pores and not all heat treatments are effective for decreasing the porosity. More specifically, only HIP was found to induce an effect on reduced porosity and pore size [62, 64]. Kasperovich and Hausmann [65] observed a reduction in porosity from 0.08 to 0.01 % after using HIP. Similarly, Leuder et al. [64] also report that the pore size was significantly diminished after the use of HIP.

The lack of fusion pores tend to be larger in size (500 μm or even more), possessing irregular shapes with sharp tips at the ends (Fig. 7), which are generally located at the boundary of two adjacent layers [87, 88]. The formation of this type of pore is usually attributed to those metal powders that are not completely melted before being deposited as a new layer on the top of previous layer [89], as shown in Fig. 7, together with poor bonding defects. Such defects are caused by an insufficient melting of metal, thus resulting in poor bonding between layers during the solidification [90, 91]. Unlike gas pores, the lack of fusion pores is generally considered to be more fatal to the performance of AM-processed products [23, 88, 90, 92, 93]. Fortunately, the lack of fusion pore is also easier to avoid as the increased input energy density effectively minimizes the formation of these pores [74].

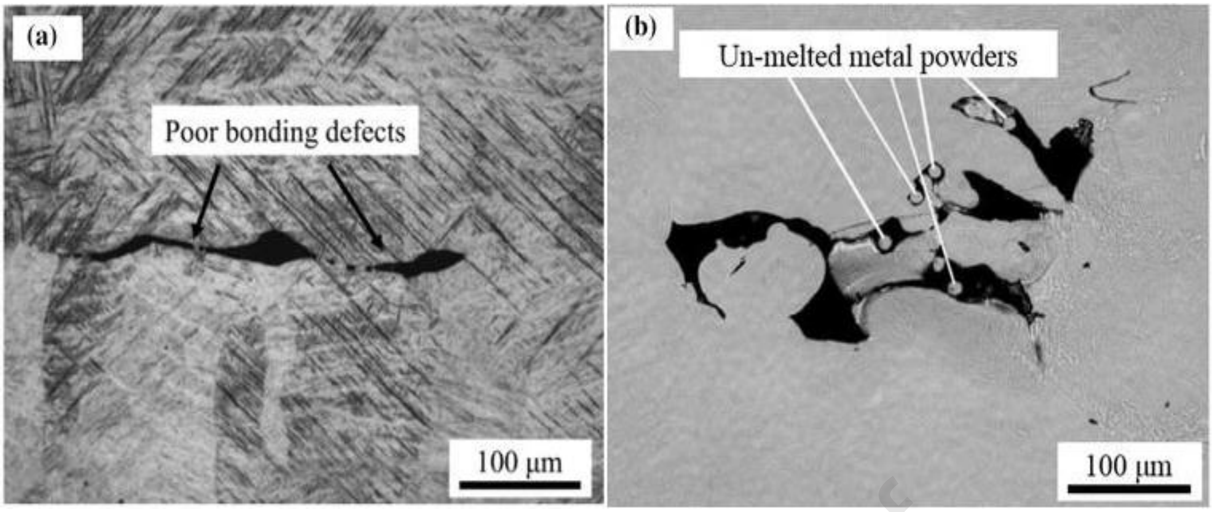


Fig. 7: (a) Poor bonding defects and (b) unmelted metal powder defects in a SLM-produced part [90].

5.2 Surface roughness

Poor surface roughness of as-built parts has always been one of the main limitations in AM processes [94]. The surface roughness of as-built parts greatly depend on specific settings such as, scan speed, powder size and layer height [60]. In general, DED processes produce the components with smoothest surface finish, which is followed by SLM and subsequently EBM. Oxidation and adhesion of partially melted powders at the component surface are significantly influencing factors that dictate the surface roughness of an as-built component [95]. As electron beam-based PBF and laser beam-based PBF keep the unused powders directly in the powder bed while DED blows them away, the adhesion of partially melted powders in turn becomes less for DED compared to EBM and SLM techniques. A visual comparison in relation to surface roughness of fabricated samples via EBM and SLM are shown in Fig. 8 [60]. Evidently, surface finish of SLM-fabricated samples in both build directions are clearly much finer than those produced by EBM. This is due to the fact that the higher thermal radiation associated with high energy electron beam in EBM results in more adhesion of partially melted powders. Toumi et al. [96] reported surface roughness as indicated by R_a values of 7.867 and 29.94 µm, respectively for as-built DMLS and EBM samples. The built direction in AM processes also induce a great impact on the surface roughness of the samples, as illustrated in Fig. 9. Vertically built SLM samples seem to offer comparatively smoother surface finish than that of EBM-processed samples.

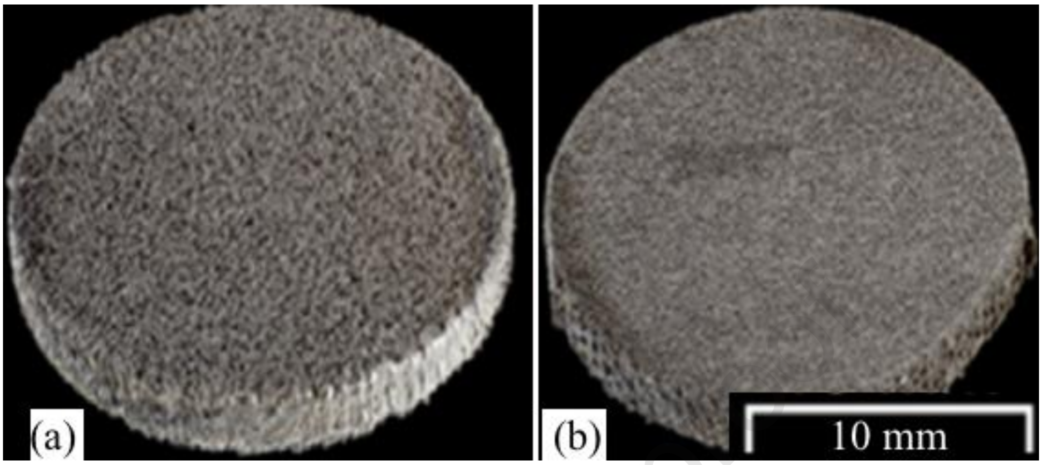


Fig. 8: Surface finish of as-built (a) EBM and (b) DMLS samples [96].

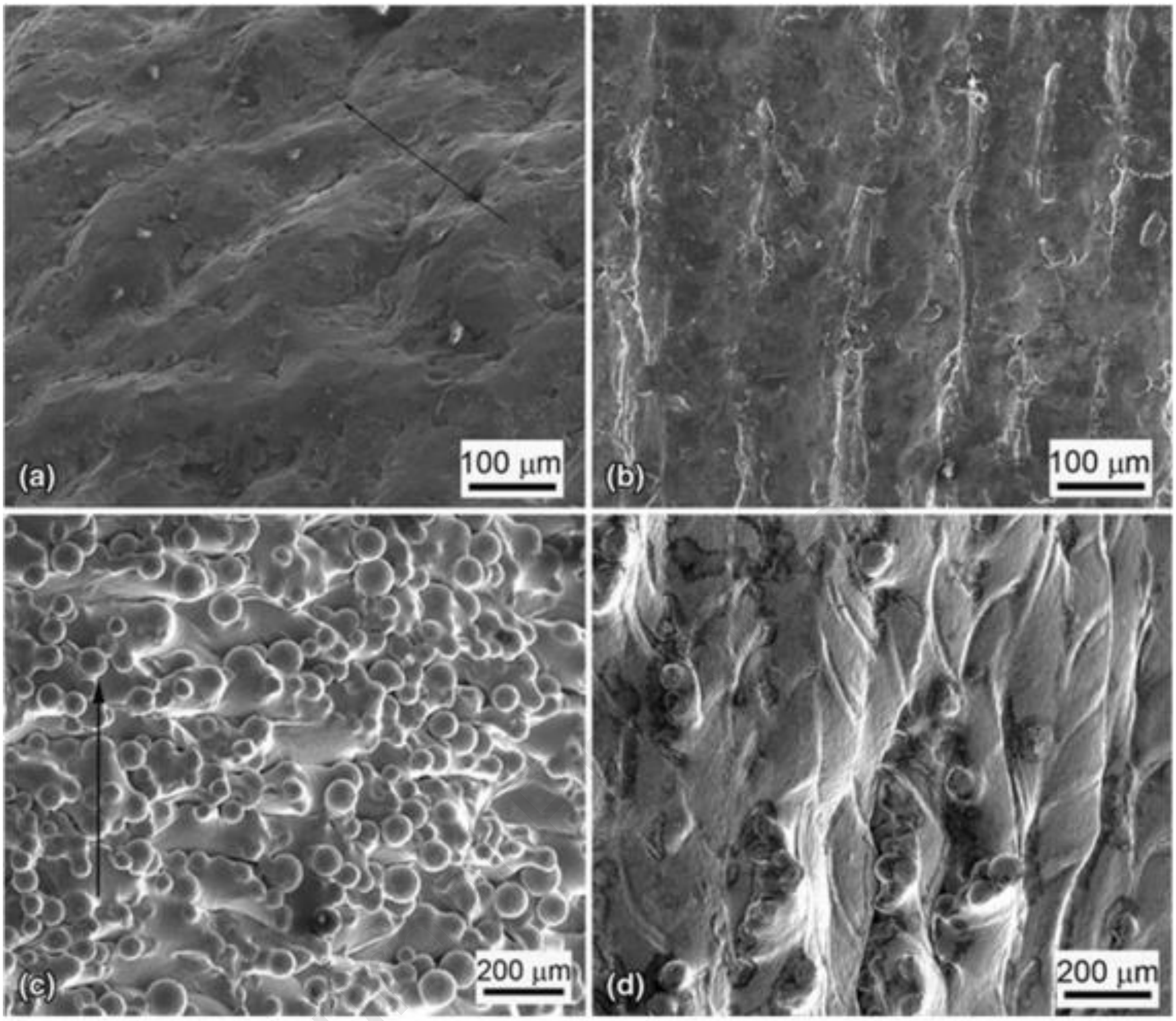


Fig. 9: Surface morphology of (a) vertically built SLM, (b) horizontally built SLM, (c) vertically built EBM and (d) horizontally built EBM parts [60].

The surface roughness of components produced by EBM is very similar to that of feedstock powders. Consequently, very fine powders are highly preferred for EBM processes as they would improve their surface finish. The optimization of AM settings can only improve surface finish of parts to a certain extent. Additional post processing such as machining or chemical etching is still required for nearly all AM parts. The effect of surface roughness on the mean fatigue life of various AM -processed samples are shown in Fig. 10. As expected, the fatigue life of the samples increases with decreasing surface roughness. The surface roughness of rolled products are one order of magnitude lower than that of AM-processed samples, thus marginally reducing their fatigue life.

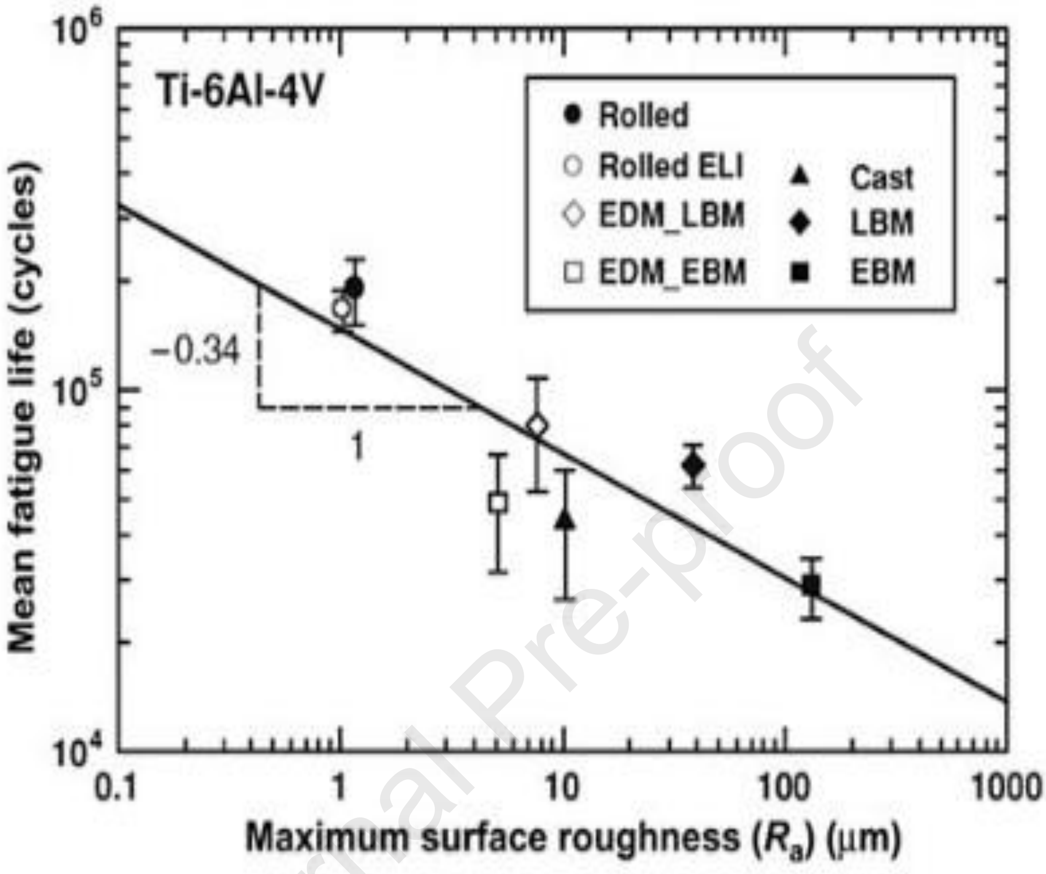


Fig. 10: Impact of surface roughness on fatigue life cycles [97].

5.3 Residual stresses

AM processes, particularly laser-based AM processes, are prone to a significant amount of induced residual stresses because of their inherently large temperature gradients [16,112–114], which is normally in the order of ~5 × 10^4 K/cm [115]. The residual stresses in AM-processed components will tend to increase with increasing layer numbers [116], and the peak value always occurs at or near the free surface of the final deposited layer [108,115,117]. The residual stress profile is made up of a large amount of tensile stresses at the top region of the parts, particularly relating to the yield strength of parts [118]. With the addition of new layers on the previously built layers, the tensile stresses can be converted into compressive stresses due to subsequent thermal cycling [117].

The deposition strategy and track length also induce prevalent impact on residual stress levels. It has been detected that residual stresses are higher along the scan direction than those in the perpendicular direction due to the larger thermal gradient along the scan direction [16]. As such, an anisotropic stress distribution can be generated in the final parts [16,117]. Moreover, residual stresses also increase with the scan length [117,118]. It is well known that residual stresses contribute to the crack formation and warping in the part, leading to the disconnection of builds from the substrate and cracks in the finished parts [117,128]. These failures will always cause immediate and fatal consequences of impairing the geometrical accuracy and damaging the structures. Therefore, SLM and EBM built parts may require supporting structures to restrict bending or distortion during manufacturing processes. The residual strees was removed or reduced by suitable heat treatment process [115]. Systematically calculated residual stresses formed in single-track EBM Ti-6Al-4V by varying the pre-heating temperature of the fusion bed suggests that the bed pre-heating temperature has the most significant impact on the residual stress. Quantitatively, each increment by 50 °C in pre-heating temperature shows a stress reduction by 20 % approximately. The EBM process maintains a build temperature of 600–750 °C throughout the deposition [70–72]. Generally, it takes about 5 hours to achieve a complete stress relief at this temperature while EBM deposition cycles mostly run longer than 5 hours. Therefore, contrary to the DED and SLM processes, it is widely accepted that residual stresses can be negligible in the EBM process. For example, Honnige et al [45] utilized neutron scattering to measure residual stresses in EBM Ti6Al4V parts and did not find a significant level of residual stresses. Zhang et al [71] performed stress relief annealing at 640 °C for 4 h for the SLM-built Ti-6Al-4V specimens before a fatigue test.

Based on the microstructures and tensile strength of AM made parts, as mentioned earlier, it can be expected that SLM and DED products would have higher threshold stress ($\Delta\sigma_w$) than

EBM countparts. This mean that the fatigue strengths of the parts produced by SLM and DED are better than those by EBM owing to their higher yield strength. On the other hand, the crack propagation threshold ΔK_{th} for EBM is expected to be higher than those of SLM and DED. This should be the case as the parts produced by EBM appear to be more ductile and thus increased the fatigue toughness. Post heat treatment processes such as, stress relief and hot isostatic press are also expected to further improve the fatigue properties of as-built AM-processed Ti-6Al-4V as they can effectively reduce defects, pores and other fatigue factors. Tables 5 and 6 show the fatigue properties of various as-built AM-processed Ti-6Al-4V samples as well as Ti-6Al-4V parts manufactured by conventional methods. All samples are machined as surface defects have an impact on the fatigue properties of parts.

Table 5: Fatigue properties of Ti-6Al-4V parts produced different AM methods.

Electron beam powder bed fusion (PBF)						
Ref	**Condition**	**Machining**	**Axis**	**R**	$\Delta\sigma_w$ **(MPa)**	ΔK_{th} **(MPa $\sqrt{m}$)**
[98]	As-built	Yes	Vertical	0.3	-	4.0 - 4.8
[98]	As-built	Yes	Horizontal	0.3	-	3.4 - 5.0
[98]	As-built	Yes	Horizontal	0.1	-	3.8
[98]	Hot isostatic press	Yes	Vertical	0.3	-	4.7 - 5.1
[98]	Hot isostatic press	Yes	Horizontal	0.3	-	4.8 - 5.0
[92]	As-built	Yes	-	0.1	200 - 250	-
[92]	Hot isostatic press	Yes	-	0.1	550 - 600	-
[92]	Stress-relieved	Yes	-	0.1	200 - 250	-
[60]	As- built	Yes	-	0.1	340	-
Laser beam powder bed fusion (PBF)						
[60]	As-built	Yes	-	0.1	550	-

[94]	Stress-relieved	Yes	Vertical	0.1	500	3.48
[94]	Stress-relieved	No	Vertical	0.1	210	-
[64]	As-built	Yes	Vertical	0.1	-	1.7
[64]	As-built	Yes	Horizontal	0.1	-	1.4
[64]	Annealed at 800 °C	Yes	Vertical	0.1	-	3.7
[64]	Annealed at 1050 °C	Yes	Vertical	0.1	-	6.1
[64]	Annealed at 1050 °C	Yes	Horizontal	0.1	-	3.9 ± 0.4
[64]	Hot isostatic press	Yes	Horizontal	0.1	620 ± 5.4	4
Direct energy deposition (DED)						
[99]	As-built	Yes	Vertical	0.1	~590	-
[47]	As-built, high power	Yes	Vertical	0.1	-	3.5
[47]	As-built, high power	Yes	Horizontal	0.1	-	3.4
[47]	As-built, low power	Yes	Vertical	0.1	-	2.8
[47]	As-built, low power	Yes	Horizontal	0.1	-	2.8
[47]	Aged, high power	Yes	Vertical	0.1	-	3.8
[47]	Aged, high power	Yes	Horizontal	0.1	-	3.2
[47]	Aged, low power	Yes	Vertical	0.1	-	3.0

[47]	Aged, low power	Yes	Horizontal	0.1	-	2.9

Table 6: Fatigue properties Ti-6Al-4V parts produced by conventional methods.

Wrought						
Ref	**Condition**	**Machining**	**Axis**	**R**	$\Delta\sigma_w$ **(MPa)**	ΔK_{th} **(MPa** $\sqrt{m}$**)**
[100]	-	-	-	-1	600 - 670	-
[101]	-	-	-	-1	630 - 680	-
[65]	-	-	-	-1	600	-
Forged						
[47]	Mill-annealed	-	-	0.1	-	4.4
[102]	Mill-annealed	-	-	-1	590 - 605	9
[102]	Mill-annealed	-	-	0	-	4.4 – 4.7
[102]	Mill-annealed	-	-	0.7	-	2.4
[102]	Solution -treated	-	-	-1	590	10
[102]	Solution -treated	-	-	0	-	4.9 – 5.2
[102]	Solution -treated	-	-	0.7	-	2.4
Cast						
[60]	Annealed	-	-	0.1	430	-
[103]	As-built	Yes	-	0.1	230 - 380	-
[103]	As-built	No	-	0.1	150 - 270	

Based on the data shown in Table 5, the components fabricated using SLM and DED exhibit higher fatigue strength ($\Delta\sigma_w$) but lower fatigue toughness (ΔK_{th}) as opposed to those fabricated by EBM. The superior fatigue strength of SLM and DED components are ascribed to the presence of fine α′ martensite. The fatigue toughness of as-built EBM parts ranges from 3.4 - 5.0 while the fatigue toughness of as-built SLM parts only between 1.4 and 1.7. The fatigue toughness of as-built DED-fabricated parts vary from 2.8 - 3.5 depending on different power settings. SLM parts also display the highest fatigue strength, which is followed by DED at slightly lower values. EBM parts display the lowest fatigue strength, which is much lower than those of SLM and DED. This finding is in line with what have been discussed in tensile properties of SLM parts in possession of highest yield strength, which is followed by DED. EBM parts have the lowest tensile strength, and further the lowest fatigue strength. When compared to conventionally produced Ti-6Al-4V parts, SLM produced components have somewhat similar fatigue strength to wrought and forged Ti with DED parts, which is followed by slightly lower strength of EBM parts comparable to that of cast Ti-6Al-4V. However, despite the comparable fatigue strength, AM produced Ti-6Al-4V parts do not seem to be able to achieve high fatigue toughness similar to those conventionally produced. This is due to the fact that the surface roughness of as-built AM-processed parts is generally worse compared to those produced traditionally. As the components produced by AM are plagued with pores in the as-built condition, heat treatment processes such as hot isostatic press can help improve the fatigue properties of AM-processed parts. Additionally, annealing can also be used to increase the fatigue toughness to achieve the high strength, low toughness in AM processes such as, SLM and DMLS. This is attributed to the decomposition of α′ martensite to increasing ductility [47]. As can be seen in Fig. 11, in the case of EBM-processed specimens, hot isostatic press significantly improved the fatigue properties of specimens, namely fatigue strength and to some extent, fatigue toughness. The effectiveness of hot isostatic press process is also confirmed by Seifi et al. [98]. As hot isostatic press process is known to induce positive effect on reducing the porosity as well as pore size, it is as expected that the fatigue properties of the specimen would be improved after the HIP process. On the other hand, Hrabe et al. [92] did not notice any difference between the as-built and stress-relieved specimens.

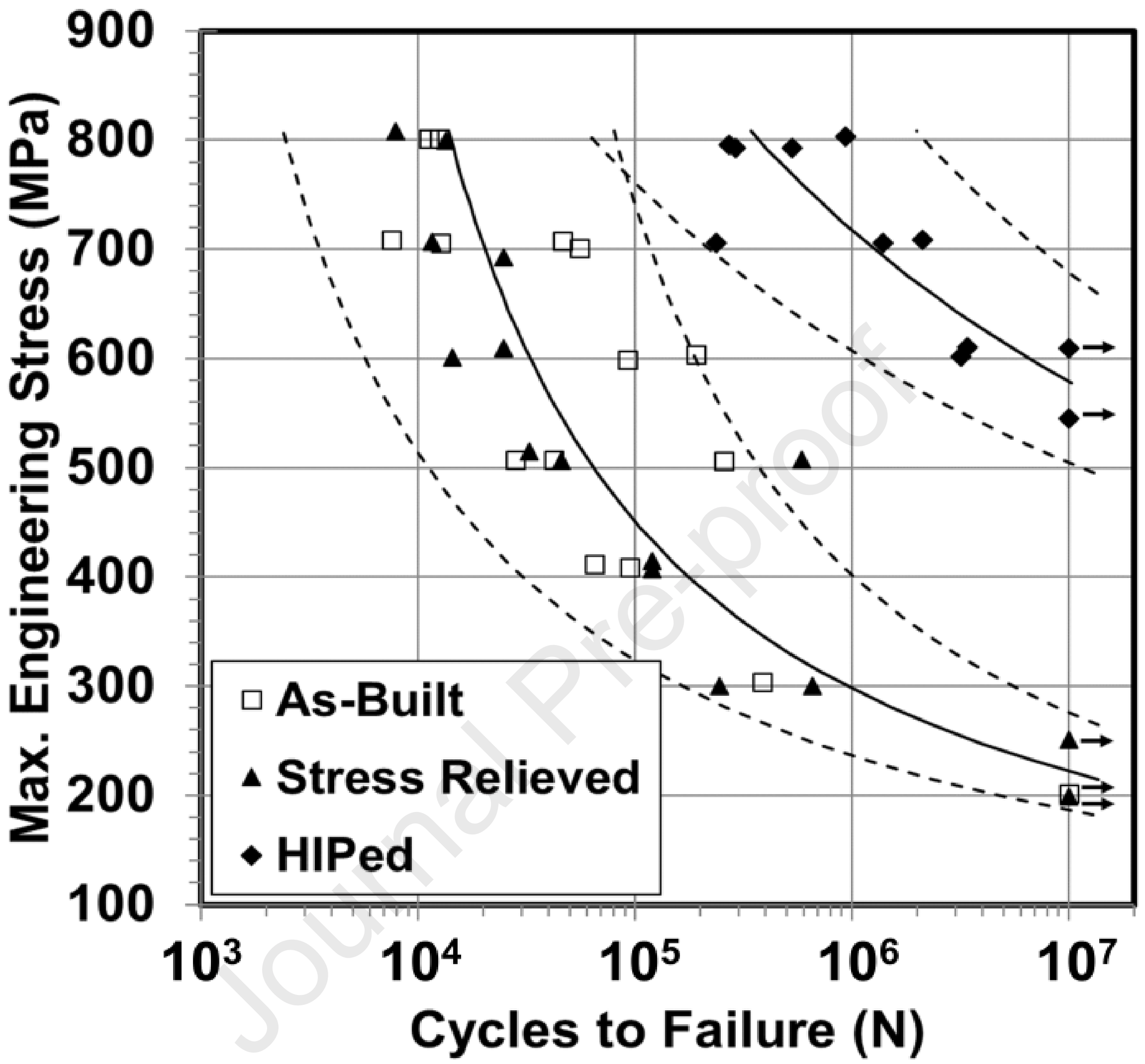
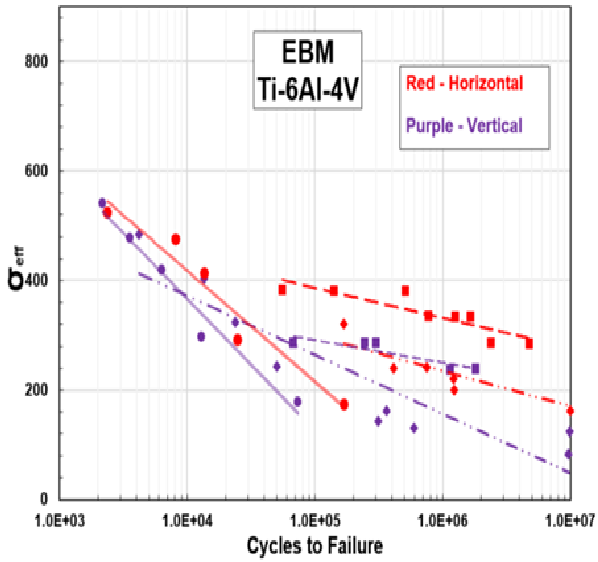


Fig. 11: Effect of post-processing stress relief on the fatigue behaviour of EBM made specimens. Arrows indicate the specimen that did not fail [92].

According to Chern et al. [104], as shown in Fig. 12, the horizontal builds appear to always yield better fatigue properties as opposed to vertical builds without any post processing. However, for machined samples, the fatigue strengths based on vertical builds are slightly higher than those from horizontal builds.



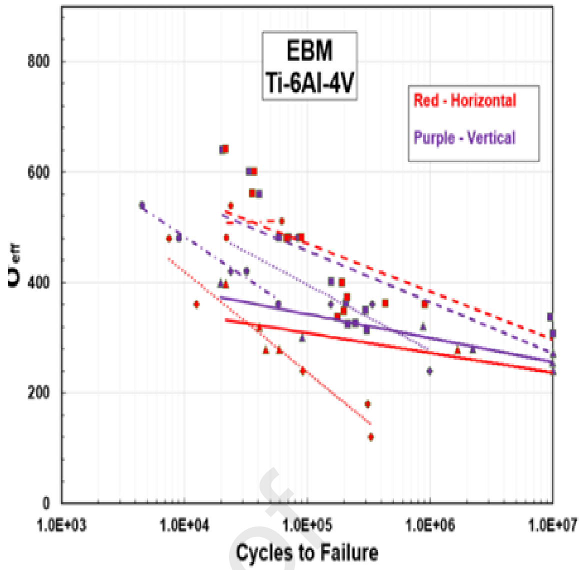


Fig. 12: Fatigue properties of different build orientations (left) non-machined, non-HIP and (right) machined, non-HIP [104].

6. Advantages and challenges of AM processes of Ti-alloys

PBF technologies are better for complex geometries with support for hollow, void structures owing to the smaller beam/layer size. On the other hand, DED with large beam size and thicker layer has lower accuracy, but much higher deposition and production rate relative to PBF. DED is also cheaper to produce per part according to a study conducted by Optomec [17]. Another advantage of DED over PBF and conventional methods is that reparation and reconfigureration is possible for DED processes [128]. This may be one of the most unique advantages for DED technique. According to DM3D Technology [34], their closed-loop technology offers low heat-affected zone. This minimal heat-affected zone is beneficial in repairing parts as this assists in retaining the properties of the parts. Repairing a part is not possible with PBF or via conventional methods such as wrought, cast or forge, and thus eliminate for the cost associated with remanufacturing. Moreover, DED technologies such as LENS, DMD or EBAM have the ability to add metals on to the surfaces of existing parts [128]. There is a considerable advantage of DED as such this capability is not available with PBF or conventional manufacturing methods which provides great flexibility in the operation of DED. Adding extra features on existing parts can offer the most cost-effective option while remanufacturing parts with new builds using PBF or conventional methods would be required to start again from the beginning. Such a case would be a huge waste because the cost for recalibrating, redesign and/or moulding is significant as well as time-consuming. It is also applicable in situations where the main large parts can be mass produced by traditional methods while the additional features can be customized and added using DED per requirement.

With small beam size and layer thickness, PBF technologies such as SLM and EBM are capable of producing complex parts with high accuracy, as well as good as-built surface quality. PBF can also produce a complete part within a single build operation. This eliminates the necessity for multiple part building operations, as well as the cost for part assembly, thus resulting in significant cost reduction [2]. High accuracy means the parts are produced with good as-built geometry and surface quality, eliminating the need for additional machining as opposed to DED or conventional methods such as casting or forging. However, the production time of PBF is much slower while also having higher manufacturing cost. Additionally, for very high-precision applications such as threads, screws or seals, additional surface machining process is still required.

Additionally, 3D printers usually have the capability to perform specific tasks autonomously with little human supervision. For example, Attaran et al [17] stated that many consumer-level 3D printers have an inbuilt feature called auto levelling. As the printer is able to calibrate itself with this ability, the process of levelling the printing platform requires no human supervision. Currently, industrial sized 3D printers only have partial autonomous capability. Having a fully autonomous printer would significantly cut down cost and manpower. In conclusion, PBF is better for smaller parts with complex geometries that require high precision and that production time is less of a concern. DED is more suitable for larger parts with simpler geometries with the specific requirement of high manufacturing rate. Table 7 below summarizes the characteristics, capabilities and limitations of the three main titanium AM techniques.

Table 7: Characteristics, capabilities and limitations of AM technologies [27-35, 129].

	Electron PBF	**Laser PBF**	**DED**
Beam size	Thin	Thin	Thick
Layer thickness	Thin	Thin	Thick
Build size	Small to medium	Small to medium	Large
Geometry	Complex geometry, good resolution, hollow structures supported	Complex geometry, very good resolution, hollow structures supported	Simpler geometry, lower resolution, limited support for hollow structures
Output rate	Slow	Slow	Fast (up to 10 times faster than PBF)
Surface quality	Good	Good	Vary (mostly coarse)
Residual stress	Low to none	High	High
Additional treatment	HIP may be applied	Requires additional stress relief. HIP may be applied	Requires additional stress relief. HIP may be applied
Machining	May be required for high precision applications.	May be required for high precision applications.	Required
Reparation	No	Limited, only for horizontal builds	Yes
Reconfigurati on	No	No	Yes
Multi-material	Yes	Yes	Yes
System price (Euro)	450000 – 600000	450000 – 600000	500000 – 800000
Powder price ($/Kg)	600	600	160

Despite some favorable advantages, AM processes are still at the infancy, and not without some major disadvantages. The three main disadvantages of AM techniques are built size, production rate and economics. Even though DED allows for greater build size, it is still very limited compared with conventional methods that usually have almost unlimited build size. EBM and SLM are restricted to even smaller build sizes, as shown in Table 7. Due to size restriction, larger parts are required to be fabricated in smaller components, and then joined together, which defeats the single piece build advantage in AM processes. In addition, the slow production rate of AM processes is also a major demerit when compared with traditional methods where at the industrial level, large quantities are usually demanded in short time. It is indeed true that conventional methods also require sufficient time for preparation, moulding and tooling. However, once they start, traditional methods are capable of achieving mass production more easily with much higher output rate than the currently available AM processes.

Another major disadvantage of AM processes lies in manufacturing cost, as shown in Table 7. The cost for one machine is quite high while it is also similar to the cost of material powders. The savings from lead time reduction, moulding and machining can only reduce the production cost of AM-fabricated products to some extent. With the current technologeies and the costs of AM system and materials, AM processes may be only cheaper than conventional manufacturing for small quantity orders, as reported by Azteni and Salmi [130] on the manufacturing cost of a landing gear using AM processes and conventional methods.

Ultimately, due to the above-mentioned disadvantages, AM processes of Ti alloys are still quite limited in normal industries as the traditional methods remain the preferred mechanism thanks to their already developed applications, high production rate and cheaper manufacturing cost at large quantities. The applications of AM-fabricated Ti is also limited to most aerospace and biomedicine applications due to the disadvantages earlier mentioned as these two industries favour customized parts with high -precision demands. With the current development pace and greater availability of AM machines, additive manufacturing of Ti alloys is expected to expand greatly into other fields such as automobiles as well as home appliances.

7. Conclusions

AM processes for Ti-6Al-4V alloys have improved significantly during the last ten years. The technological advances have met many expectations in diffrenet areas of applications. AM has the ability to quickly fabricate a part without the stringent requirement for moulding, tooling while also producing less wastes and with less time. Ti-6Al-4V parts can be produced with the superior strength, but lower ductility and fatigue life compared to conventional methods. Fortunately, the ductility and fatigue life of AM-produced parts can be improved via additional heat treatment and machining such as polishing or turning to be comparable to those conventionally manufactured products. On the other hand, with the current technologies, AM-fabricated Ti is still only viable for a small quantity or very high demanding applications such as aerospace, biomedical and some other advanced industries due to high mass production cost, high system cost as well as low production rate. As AM processes of Ti alloys are being made available with cost reduction, more opportunities for a wider range of applications are expected in the near future though admittedly some manufacturing challenges may be encountered as well.

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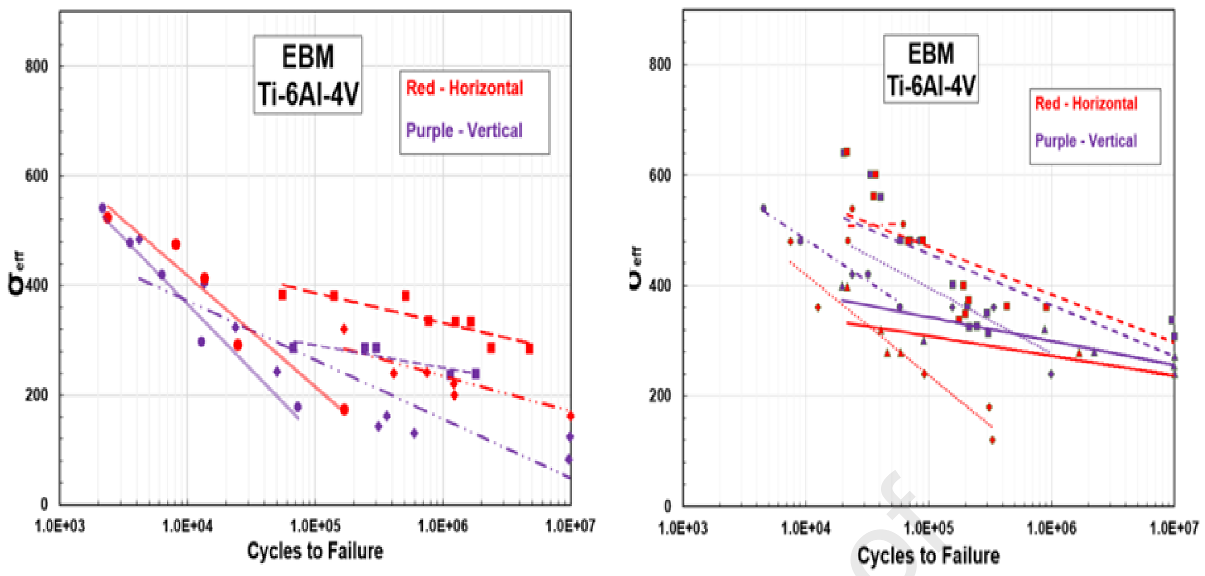

Fig. 12: Fatigue properties of different build orientations (left) non-machined, non-HIP and (right) machined, non-HIP [104].

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: