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Laser welding of additively manufactured parts - A review

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Abstract. Additive manufacturing (AM) is a process in which parts are built up layer by layer, introducing novel approaches to how parts can be manufactured with less material waste, shorter lead times and lower costs than traditional manufacturing. One of the key advantages of AM over conventional manufacturing is its design flexibility, which enables for manufacturing of parts with highly detailed geometries in one go, leaving out the need for molding, casting, etc. However, due to the chamber size of the machines, the size of AM parts is limited. To overcome this limitation, joining AM parts together or to wrought or cast material has been proposed. Among the various welding technologies, laser welding is considered a suitable candidate for joining AM parts because of its low heat input, resulting in low deformation, high welding speed, and full automation capability. This study will provide a fundamental understanding of laser welding of AM parts by reviewing current research in the field. The possibility of joining most commonly used AM parts such as AISi10Mg, AISI 316L, Ti6Al4V and Nickel alloy 718 by laser welding are investigated. Furthermore, the effect of laser welding parameters on mechanical and microstructural properties of joined AM parts are discussed.

Keywords: Additive manufacturing, laser welding, AISI 316L, Manufacturing large parts

1. Introduction

Additive manufacturing (AM), known also as 3D printing, has transformed the manufacturing process in such a way that producing parts with highly complicated geometries is now possible due to its freedom in design using a computer-aided design (CAD) model. AM parts can be manufactured layer by layer directly from a CAD model, eliminating the need for costly machining processes compared to traditional manufacturing [1]. Additionally, minimizing waste material is another advantage of additive manufacturing, making it more cost-effective to produce highly complex parts [2].

AM technology can be categorized in seven different methods based on different materials and applications. These methods are laser powder bed fusion (PBF-LB), material jetting (MJT), binder jetting (BJT), material extrusion (MEX), vat photopolymerization (VPP), direct energy deposition (DED) and sheet lamination (SHL) [3]. AM can process a wide range of materials, including ceramics, polymers, and metal alloys [4]. AM has gained particular attention in printing metal alloys due to its near-net-shape capability in manufacturing dense metallic parts with mechanical performances comparing to their conventionally manufactured counterparts. PBF-LB and DED are the most commonly used AM methods for manufacturing metallic parts [5]. Both processes use a laser beam as a heat source to interact with feedstock to build a final part layer-by-layer. The LPBF process is the most widely used and versatile method for producing a wide variety of materials. Consequently, PBF-LB has emerged as a critical manufacturing technology in high-level industries such as aerospace, automotive, medical, and energy [6]. However, the PBF-LB process has some disadvantages, such as dimensional limitation, due to the chamber size of printers, which is why the PBF-LB process cannot be used to produce large-scale parts [7]. To address this limitation, small parts manufactured with PBF-LB can be joined together to form a larger part using different welding technologies [8]. Some of the most popular



welding technologies used in AM are gas tungsten arc welding (GTAW/TIG), plasma arc welding (PAW), friction stir welding (FSW), electron beam welding (EBW) and laser beam welding [9]. Laser welding has been demonstrated to be a suitable joining method for AM parts due to its low heat input and small spot size [10]. This is mostly due to the importance of precision and narrow welds in joining highly complex and thin-walled PBF-LB parts. In other words, laser welding will result in low distortion and a narrow heat affected zone in PBF-LB parts, offering high-quality joints.

The aim of this study is to review the most recent research on laser welding of parts manufactured with PBF-LB. The effect of welding parameters on weld bead geometry of the most commonly used metal materials manufactured with PBF-LB are investigated. In addition, the mechanical and microstructural properties of the laser-welded joint are discussed. This study is particularly important in providing more insights into the fundamental knowledge of the topic because there have been very few studies and research in this area, and thereby paving the way for further research in the future.

2. Additive manufacturing

2.1. Laser powder bed fusion (PBF-LB)

PBF-LB is a powder-based process that melts and fuses powders together layer-by-layer using a laser beam as a heat source. The process is divided into several steps, the first and most important of which is modeling and designing the part with CAD software [11]. This step determines the laser scan path on the powder bed, where the laser selectively exposes only the CAD model-defining powder. The CAD model is divided into layers based on the layer thickness desired, and each layer is built on top of the previous layer until the final part is created. A typical PBF-LB machine is shown in Figure 1. It includes several different components such as a laser source, a build platform, a recoater (used to spread the powders), etc. [12].

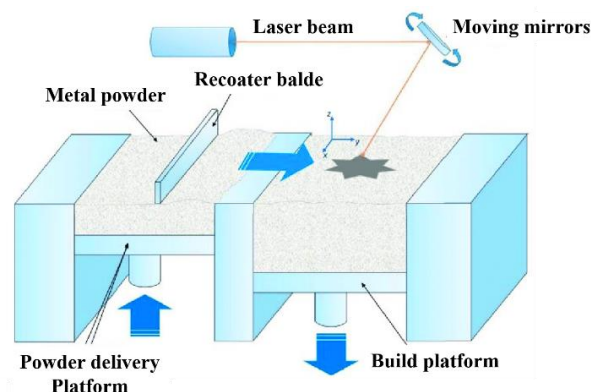


Figure 1. A schematic of PBF-LB machine [12].

The particle size used in PBF-LB is typically between 10 and 70 μm , which allows parts to be printed with a thinner layer thickness, resulting in a dimensionally precise final part [13]. Parts manufactured with PBF-LB have a higher density than parts made with other AM technologies with a superior mechanical property [14]. Hence, PBF-LB is a suitable candidate for manufacturing highly complex parts with excellent surface quality and precise final dimensions for use in medical, aerospace, automotive, etc. Figure 2 displays some of the parts manufactured with PBF-LB [15]. It is important to note that the quality of final parts manufactured with PBF-



Figure 2. Parts manufactured with PBF-LB [15]

LB is primarily determined by process parameters, as some defects, such as pores and lack of fusion, have been reported to degrade part mechanical performance. Developing optimized process parameters is thus a critical step in discovering the full potential of PBF-LB parts [16].

3. Welding technologies in AM

3.1. Laser welding

Laser welding is a method of joining materials in which a high-intensity energy source is focused into a small spot size. The typical spot size of the laser beam is in range between 0.2-0.7 mm for most common welding applications [17]. Because of its heat is concentrated in small spot size compared to other welding technologies, laser welding results in a narrower heat-affected zone and less distortion, which are crucial for high quality joints in most applications, such as the automotive industry, energy sector. Furthermore, recent advancements in fiber lasers have resulted in improved laser source delivery systems for various welding conditions, with higher laser powers reaching several kilowatts [18]. Also, the ability to be fully automated is another advantage of laser welding, which produces high-quality welds at a faster rate than other welding technologies.

Laser welding can be classified into two modes based on the power density, as shown in Figure 3 [19]. In Conduction laser welding, laser power density is lower than 0.5 MW/cm^2 in which a shallow and wide weld seams are the characteristic of this mode. This is because heat is conducted from the centre to the edges of the weld pool during conduction laser welding (Figure 3a). The second laser welding mode is known as keyhole welding in which laser power density is beyond 1.5 MW/cm^2 [20]. Deep narrow welds distinguish the keyhole mode (Figure 3b). Keyhole welding is especially useful for welding of thick metals where high speed welding with fully penetrate welds is required; however, laser welding parameters such as laser power, speed, and focal length need be optimized for each application because keyhole welding can cause defects such as pores due to keyhole instability [21].

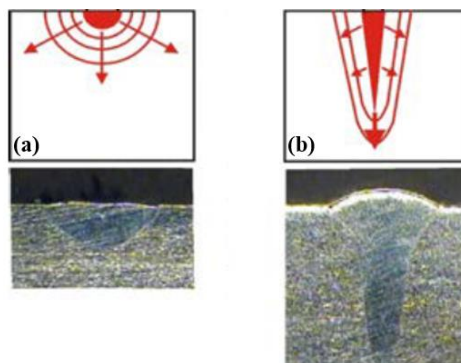


Figure 3. Different laser welding modes a) conduction b) keyhole [19]

4. Laser welding of PBF-LB components

4.1. Stainless steel

Stainless steel is a low-carbon iron alloy used in many different industrial applications due to its high strength and good mechanical performance, as well as good corrosion resistance. The most commonly used stainless steel is AISI 316L, which has superior corrosion resistance to other grades of stainless steel due to the added chromium and molybdenum content. AISI 316L is a good choice for harsh chemical environments such as chemical plants, marine industries, etc. [22]. Welding of 316L has been extensively studied over the last few decades [23-24] whereas data on laser welding of PBF-LB/M/316L is limited.

Matilainen et al. [25] investigated the effect of laser heat input on the weldability of PBF-LB/M/316L and cold-rolled 316L sheet plates. The cross-section of welded samples using bead-on-plate laser welding revealed that full penetration joint in PBF-LB/M/316L sample can be accomplished with lower energy input than in

cold-rolled 316L sample. The better absorptivity of PBF-LB/M/316L is attributed to the easier formation of keyhole. In other words, the higher surface roughness of PBF-LB/M/316L leads to higher absorptivity of laser light into the material, hence keyhole is formed easier in PBF-LB/M/316L even at lower laser energies. Furthermore, despite having different weld geometry, both PBF-LB and cold-rolled 316L joints showed the same melting efficiency. The correlation between microstructure and mechanical properties of laser welded PBF-LB/M/316L was studied by Zhang et al. [26]. The average grain size in the fusion zone was found to be five times that of the base metal, resulting in weaker joint strength in the weld zone due to the coarser grain size. The study found that build orientation had no significant impact on joint strength and concluded that laser welding can be used to successfully join PBF-LB/M/316L components; however, the lower mechanical properties of the joints in comparison to the base metal must be considered in the final application. The effect of heat treatment on the joints of PBF-LB/M/316L to sheet metal 316L was examined by Rautio et al. [27]. The stress-relieving heat treatment (600°C followed by 2 h annealing) performed after and before welding resulted in no significant changes in the hardness of the joint between PBF-LB/M/316L and sheet metal 316L. Despite the fact that the tensile test revealed that the PBF-LB/M/316L joint had the highest yield strength compared to the 316L to 316L and PBF-LB/M/316L to 316L joints, ductility decreased dramatically. The heat treatment also revealed no difference in yield strength and ultimate tensile strength of dissimilar joints of PBF-LB/M/316L to 316L, which is consistent with the hardness result. Yang et al. [28] investigated the effect of laser welding on microstructure and mechanical properties as well as corrosion resistance of the PBF-LB/M/304 and wrought 304. It was reported that the joint of PBF-LB/M/304 despite having an irregular grain orientation along with coarser grain size in the weld zone (Figure 4) which results in a weaker weld joint compared to the base metal, the corrosion resistance of the joint samples was comparable to the wrought counterpart and better than the non-welded PBF-LB/M/304. This was contributed to the fact that the coarser grain size in the weld zone results in lesser grain boundaries and thus superior corrosion resistance compared to the base PBF-LB/M/304 metal.

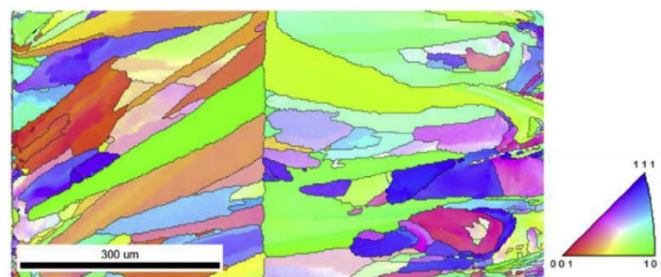


Figure 4. EBSD inverse pole figure mapping of grain size distribution of laser-welded joint of PBF-LB/M/304 [28]

Abroug et al. [29] investigated the effect of laser welding on the fatigue strength of cold-rolled 316L sheet plates and PBF-LB/M/316L. The fatigue strength of cold-rolled 316L sheet samples without welding was the highest, while it was reduced by 40% in non-welded PBF-LB/M/316L. This is because of the high surface roughness and lack of fusion in the PBF-LB process which facilitate the crack initiation. Cold-rolled 316L sheet plates had a 35% reduction in fatigue strength after welding, but PBF-LB/M/316L had the same fatigue strength as non-welded PBF-LB/M/316L samples. The joint of cold-rolled 316L broke at the weld zone while the joint of PBF-LB/M/316L broke at the base metal, demonstrating the possibility of achieving a high strength weld in PBF-LB/M/316L. However, more research is needed to validate this finding due to the scarcity of data on the fatigue life of laser welded PBF-LB/M/316L.

4.2. Aluminium alloy

Aluminium alloys are attractive materials for various industrial applications such as aerospace, automotive, marine, etc. due to their high strength and light weight properties along with excellent corrosion resistance [30]. Due to their low weight, these alloys have been widely used in the body structure of satellites and

automobiles. AlSi10Mg is the most used aluminium alloy in PBF-LB process due to its high mechanical properties and low recycling cost compared to the cast and wrought counterparts. Despite having some appealing properties for many applications, PBF-LB/M/AlSi10Mg suffers from pore formation during the PBF-LB and welding processes, which degrades the mechanical performance of the welded parts [31]. High hydrogen content in PBF-LB/M/AlSi10Mg and small pore formation during the PBF-LB process that could be pushed to the weld zone during welding are two of the main reasons for high pores susceptibility of welded PBF-LB/M/AlSi10Mg [32]. Therefore, a better understanding of microstructural and chemical change in PBF-LB/M/AlSi10Mg during welding is vital to improve the weldability of this important alloy.

Biffi et al. [33] examined the microstructure and mechanical properties of laser welded PBF-LB/M/AlSi10Mg. It was found that the full penetration welding is feasible utilizing laser welding, however, porosities both from gas trapped and high hydrogen content were inevitable in the weld zone. Thus, the ultimate tensile strength (UTS) and ductility were drastically reduced in welded samples compared to as-built PBF-LB/M/AlSi10Mg. In addition, the standard heat treatment (320 °C for 2 h with air cooling) of as-built PBF-LB/M/AlSi10Mg after welding, resulted in further reduction in ductility and UTS due to the stress relieved nature of the heat treatment. Gui et al. [34] introduced a new way of welding PBF-LB/M/AlSi10Mg using layer deposition welding. The cross-section of the joint of PBF-LB/M/AlSi10Mg (Figure 5a), cast AlSi10Mg (Figure 5b) and layer deposition welding of PBF-LB/M/AlSi10Mg (Figure 5c) are shown in figure 5. The layer deposition welding was done on 45° V-groove configuration with root gap where AlSi10Mg powders were deposited in three different layers with different laser parameters. Figure 5 Shows that the layer deposition welding has less porosity compared to the joint of PBF-LB/M/AlSi10Mg, while the joint of cast AlSi10Mg is almost porosity free. This is due to the slower solidification rate of the laser welding compared to the layer deposition welding which means that the weld zone microstructure of layer deposition welding is finer than the weld zone of the PBF-LB/M/AlSi10Mg. Hence, it was reported that the tensile properties of the layer deposition welding were superior to laser welded PBF-LB/M/AlSi10Mg.

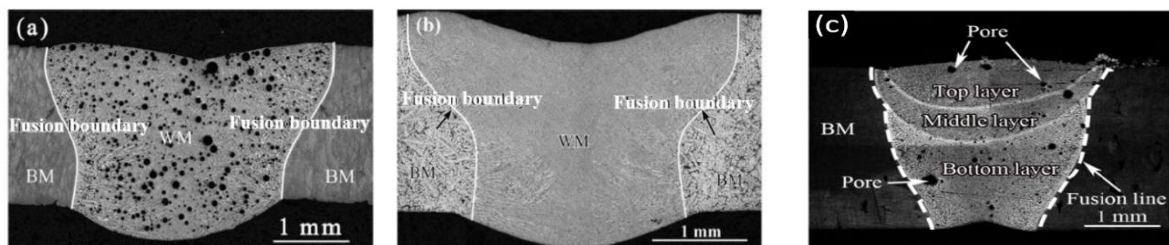


Figure 5. Cross-section of joints (a) laser welded PBF-LB/M/AlSi10Mg (b) laser welded cast AlSi10Mg (c) layer deposition welding of PBF-LB/M/AlSi10Mg [34]

Peng et al. [35] studied the effect of Zr and Er addition in to the filler metal during laser welding of PBF-LB/M/AlSi10Mg. The size of pores and also total porosity of the welded samples were reduced with Zr and Er addition as shown in Figure 6. The pore morphology revealed that the Si-rich phases at inner walls of the pores has transformed from columnar dendrite without Er and Zr addition to the equiaxed dendrite with Er and

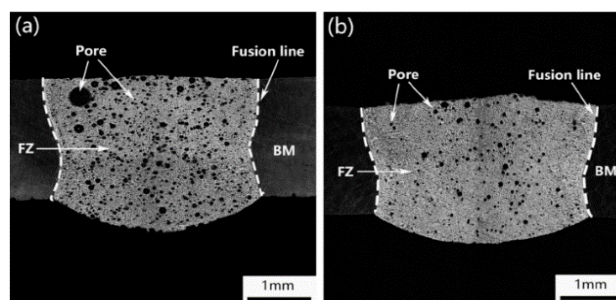


Figure 6. Laser welding of PBF-LB/M/AlSi10Mg (a) without Zr and Er addition (b) with Zr and Er addition [35]

Zr addition as shown in Figure 7. On the other hand, Si-rich eutectic network has significantly enhanced with Er and Zr addition, resulting in strengthening the welded samples as both hardness and UTS was reported to be higher than the weld samples without Er and Zr addition.

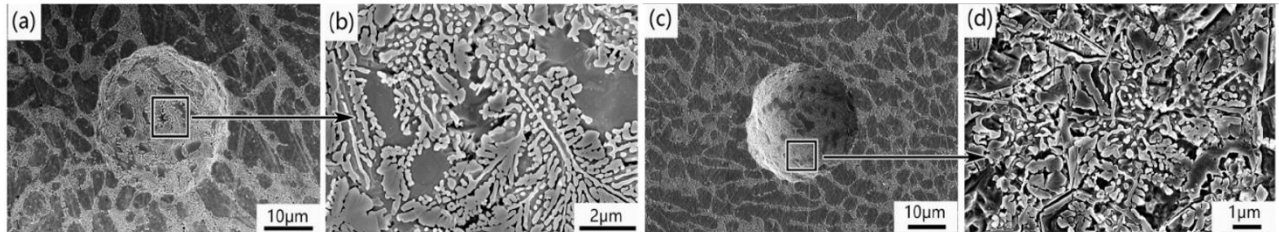


Figure 7. Pore morphology of laser welded PBF-LB/M/AlSi10Mg (a)(b) without Zr and Er addition (c)(d) without Zr and Er addition [35]

The hydrogen pore formation during welding seems to be still the main challenge regarding the laser welding of PBF-LB/M/AlSi10Mg. This is mainly due to the high hydrogen content in the powder itself. The powder has a larger surface area than cast or conventional parts, making it more susceptible to moisture absorption in the environment. Moreover, the powder is exposed to an open air during the powder handling steps which causes more hydrogen absorption from the environment. Therefore, more research is needed to either reduce the hydrogen content of AlSi10Mg powders or keep the powder dry during the various powder processing steps in PBF-LB.

4.3. Titanium alloys

Titanium alloys first introduced to aerospace industries due to their specific strength. However, the application of titanium alloys rapidly extended to some other industries due to other important features such as excellent corrosion resistance, good mechanical strength at high temperature, good creep resistance. In addition, titanium alloys have been vastly exploited in biomedical application due to their unique biocompatibility, elastic modules comparable to human bone and high fatigue strength [36]. Among titanium alloys, Ti6Al4V has been the workhorse alloy used extensively in number of industries such as, aerospace, biomedical, gas turbine engine, etc [37]. Thus, the joining of PBF-LB/M/Ti6Al4V to produce larger parts has always been in high demand. Yu et al. [38] Investigated the weldability of PBF-LB/M/Ti6Al4V using laser welding. Three different welding scenarios were tested in this study as follows, joint of PBF-LB/M/Ti6Al4V followed by stress-relieving (500°C for 2 h followed by furnace cooling), joint of PBF-LB/M/Ti6Al4V to wrought followed by stress-relieving, joint of PBF-LB/M/Ti6Al4V followed by heat treatment (850°C for 2 h followed by furnace cooling) and stress-relieved as-built PBF-LB/M/Ti6Al4V base material (BM) was used to compare the mechanical properties of the joints. In terms of microstructure, it was noticed that the weld zone microstructure of the joint of PBF-LB/M/Ti6Al4V and PBF-LB/M/Ti6Al4V to wrought are similar to as-built PBF-LB/M/Ti6Al4V, however, heat treated joint of PBF-LB/M/Ti6Al4V resulted in coarser acicular structure as shown in Figure 8. The coarser weld zone grains of heat-treated weld samples resulted in inferior microhardness and UTS and YS compared to other welded samples while PBF-LB/M/Ti6Al4V and PBF-

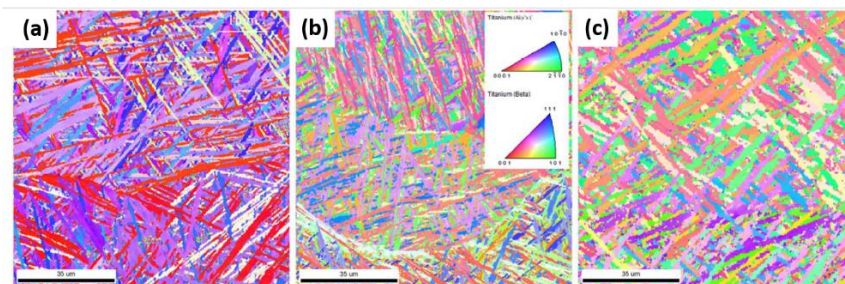


Figure 8. EBSD orientation maps of fusion zone of (a) PBF-LB/M/Ti6Al4V (b) PBF-LB/M/Ti6Al4V to Wrought Ti-6Al-4V (c) heat-treated PBF-LB/M/Ti6Al4V [38]

LB/M/Ti6Al4V to wrought Ti6Al4V and as-built PBF-LB/M/Ti6Al4V all showed similar microhardness and UTS and YS which are much higher than the wrought Ti6Al4V base metal. Furthermore, the fatigue life and fatigue crack growth rate (FCGR) of welded and as-built PBF-LB/M/Ti6Al4V samples revealed that the joint of PBF-LB/M/Ti6Al4V and PBF-LB/M/Ti6Al4V to wrought and heat-treated welds have similar fatigue life despite having different base metals and heat treatment. This means that the microstructure of the weld zone has no effect on fatigue life, and the pore in the weld zone is the most important factor influencing fatigue life. All the welded sample broke at weld zone where cracks initiated from pores and for the as-built PBF-LB/M/Ti6Al4V the crack initiated from pores on the surface. The BM wrought possess the highest fatigue life, owing to its lower porosity, while having the inferior mechanical properties compared with other welded samples. Mechanical properties of laser welded PBF-LB/M/Ti6Al4V in relation to the layer thickness examined by Rautio et al. [39]. The layer thickness of the PBF-LB/M/Ti6Al4V impacted the UTS and YS and elongation, as decreasing the layer thickness from 50 μm to 30 μm led to reduction of UTS and YS by 6 % however elongation increased by 40 %. It is worth noting that the UTS, YS, and elongation of as-built and welded samples were comparable, indicating that laser welding can be used to join PBF-LB/M/Ti6Al4V without losing elongation which in contrast with other studies [40].

4.4. Nickel alloys

Nickel alloys are well-known for their high strength at high temperatures and excellent corrosion resistance in harsh environments. Nickel alloys are widely used in aerospace, turbine engineering, power plants, and chemical applications [41]. Alloy 718 is one the most important nickel-based super alloys that is used in jet engine and gas turbine manufacturing due to its high strength at high temperature. Alloy 718, on the other hand, is a very tough material for machining tools, which raises the cost of the finished product., particularly for jet engine components, which rely heavily on machining due to their complex features [42]. This is where additive manufacturing (AM) can help by eliminating the machining process and thus lowering the cost of final components. It is critical to investigate the possibility of joining PBF-LB/M/IN718 in order to broaden their use and application in other areas. However, Alloy 718 is highly prone to solidification and hot cracking in weld zone and heat affected zone during welding [43].

Schwer et al. [44] examined the effect of low and high energy input on the weld geometry of PBF-LB/M/IN718 and wrought 718 utilizing bead-on-plate laser welding. PBF-LB/M/IN718 samples were produced horizontally, vertically and at 45°. All PBF-LB/M/IN718 joint samples showed high porosity and liquidation cracking in the weld zone. At lower energy input (0.6 kJ/cm PBF-LB/M/IN718 built horizontally showed 31% less molten volume compared to other welded samples. At this energy input only, the partial penetration reached in all samples. At higher energy input (1.8 kJ/cm) full penetration was achieved in all samples however, PBF-LB/M/IN718 in all different built orientation showed excessive weld at the bottom of the weld compare to wrought 718. It was concluded that PBF-LB/M/IN718 joints have up to 18% more molten volume compared to wrought 718. Raitiuo et al. [45] investigated the effect of heat treatment (solution followed by double aging) before and after welding on mechanical and microstructural properties of PBF-LB/M/IN718. The as-built PBF-LB/M/IN718 had a very fine columnar dendrite morphology due to rapid cooling and heating while heat treated PBF-LB/M/IN718 exhibited irregular grains shape where columnar microstructure seemed to be disappeared. The microstructure of as-built PBF-LB/M/IN718 after welding is shown in Figure 9. The weld zone exhibits an elongated large grain morphology toward the fusion zone line with a needle-shape δ phase are precipitated in the interdendrite regions (Figure 9c) and also some microcracks have developed in the weld zone (figure 9d). The as-built PBF-LB/M/IN718 heat treated before welding exhibits MC-type carbide throughout the weld zone while the microstructural of as-built PBF-LB/M/IN718 heat treated after welding shows γ' strengthening phase in the weld zone. The microhardness of the weld zone of heat-treated PBF-LB/M/IN718 after welding was significantly decreased compared with other welded joints. The tensile results were also in agreement with microhardness test, showing that laser welding deteriorated the strength of heat treated PBF-LB/M/IN718. It was concluded that heat treatment can strengthen the weld however it significantly reduces the ductility.

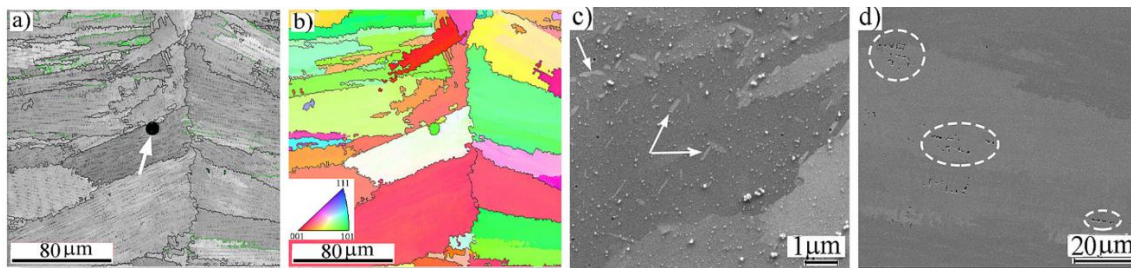


Figure 9. (a)(b) the weld zone microstructure of PBF-LB/M/IN718 (c) δ phase precipitation in the weld zone (d) microcracks [45]

Zhang et al. [46] examined the effect of laser welding on fatigue behaviour of PBF-LB/M/IN625. A low-cycle fatigue at 815 °C were performed on the welded samples and also as-built PBF-LB/M/IN625. The results showed that fatigue behaviour of welded samples was better than the BM as all the cracks initiated at the surface of BMs. It was shown that the hardness of the weld zone increased after the test due to the precipitation of γ'' and δ resulting in better fatigue and durability of the welded samples. It was concluded that laser welding is a feasible way to join PBF-LB/M/IN625.

5. Summary

AM as an emerging technology is changing the concept of manufacturing by introducing a digitalized manufacturing based on CAD models utilizing powder materials in order to minimize waste and maximize the production rate. The concept of design-based manufacturing has enabled the possibilities of producing highly complex components that are almost impossible to be produced by any other conventional technologies. However, the full potential of AM in manufacturing larger size components has been hindered by the size limitation of the AM machines. Laser welding as a robust and versatile joining method particularly for metallic material, is introduced to overcome this limitation. This review is aimed to provide more deep insights into the current studies and research on weldability of PBF-LB components using laser welding. This review is particularly important because of the lack of data in this topic. The outcome of this review can be summarized as follows:

- Laser welding of a wide range of PBF-LB alloys has been demonstrated to be feasible in terms of weld strength, however, ductility may decrease in the weld zone.
- Laser welding parameters play a crucial role in maximizing the joint integrity and strength of PBF-LB components as the optimized parameters have shown to increase the mechanical properties of the PBF-LB joints.
- Post processing (heat treatment) can be utilized depending on the final use and application of welding PBF-LB components, however, it has been concluded that in most cases, heat treatment before welding may lower the joint strength specially in PBF-LB/M/IN718. It needs to be researched more to fully understand the nature of heat treatment on weldability of LPBF parts.
- Laser welding of aluminium PBF-LB seems to be really challenging even using optimized laser parameter due to the high porosity. However, adding some other elements into the raw powder has positively lowered the pores formation.
- A complete understanding of microstructural evolution of welded PBF-LB parts will lead to better understanding of mechanical and fatigue behaviour of the joints.
- Fatigue life of welded PBF-LB and as-built PBF-LB are inferior to their wrought counterpart due to the formation of pores in both as-built and welded PBF-LB while mechanical performance such as UTS and YS might be superior.

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Authors contribution:

Parchegani conducted the literature review and wrote the initial draft of this publication. Piili and Ganvir modified and provided comments to the literature review data base. The final draft was commented, edited and modified by all authors. Salminen reviewed, supervised, provided resources and funding acquisition.

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