A Review on Laser-Based Powder Bed Fusion Additive manufacturing of Ceramics and Ceramics-based Composite Materials

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Ceramics and ceramic composite materials have attracted increasing attention due to their ability to withstand extreme thermal and chemical environments where conventional metallic materials often fail. They are promising candidates in aviation and aerospace industries due to superior high-temperature stability, chemical resistance, functional properties, etc. In particular, ceramic components with complex structures (e.g., thermal protection lattice cores and heat exchangers) are increasingly required to meet the stringent performance and weight constraints of next-generation aerospace systems. In recent years, additive manufacturing (AM) has emerged as a transformative approach for ceramic fabrication by offering unprecedented geometric freedom. Among various AM techniques, laser-based processes are especially attractive for ceramic manufacturing due to their high energy density and localized thermal input, which are essential for processing high-melting-point ceramic materials. This literature review focuses on the fabrication of ceramic components using Laser Powder Bed Fusion (L-PBF) AM technique and provides an assessment of its applicability for ceramic fabrication. In this review, the process-structure-property relationships governing ceramic fabrication via both L-PBF are systematically discussed across a range of ceramic material systems. The influences of key parameters (e.g., laser wavelength and absorptance, feedstock characteristics, and process parameters) in laser-based AM process on defects, mechanical, thermal, and electrical properties are examined. Finally, this review identifies key research gaps, particularly the limited material diversity, challenges in achieving high-purity ceramics without additives, the lack of unified process optimization frameworks, etc. Future research directions are outlined to advance L-PBF toward reliable fabrication of crack-free and high-performance ceramic components.

I. Introduction

ASTM F42 Technical Committee defines additive manufacturing as "*process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing technologies"* [1]. Additive manufacturing (AM) of ceramic materials provides great flexibility to manufacture complex parts for aerospace industry, automotive sector, healthcare, electronics etc. Recent evolutions in additive manufacturing technologies have made it possible to use high energy laser sources to create more complex and precise parts, by melting or sintering the build material. Laser-based AM technology can further be branched into different categories based on the working principle of each method. This paper focuses on using Laser Powder Bed Fusion (L-PBF) technique for ceramic and ceramic composite materials. The biggest challenge in using laser-based AM technology for ceramics is avoiding crack formation and propagating in the part during the print process. Experiment conducted by Deckers et.al. focused on overcoming this challenge by synthesizing crack free and pore-free ceramics [2]. Many research works have also focused on fabrication of bulk ceramic structures whose mechanical properties resemble the structures produced using conventional methods. While there

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have been some studies conducted for using ceramics with this technology, there are not many reviews on the current state-of-the art. This paper thoroughly discusses L-PBF technology, gives a brief overview of various ceramic materials compatible with this technique along with process-parameter optimization, and discusses the properties of L-PBF manufactured ceramic parts.

Figure 1 presents a schematic representation of the L-PBF process and highlights the distinction between Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) methods. As seen, L-PBF is a laser-based additive manufacturing technique that uses high energy laser beam to interact directly with powder feedstock spread on the powder bed [3]. It is generally conducted in a protective gas environment like N_2, Ar etc. to help reduce porosity and prevent oxidation of material [4]. L-PBF can be further divided into two categories: Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). Selective laser Sintering process assembly involves using a build platform also known as a powder bed, a platform connected to piston, and a roller that together function as a powder delivery system, a laser point source and a scanner that directs the laser beam to a particular area. The piston moves up, and the roller pushes some powder to the bed. Then the laser and scanner work together to shoot the laser beam to the layer of the spread powder. This sinters the powder according to the geometry of the CAD model, and the process keeps repeating to build subsequent layers.

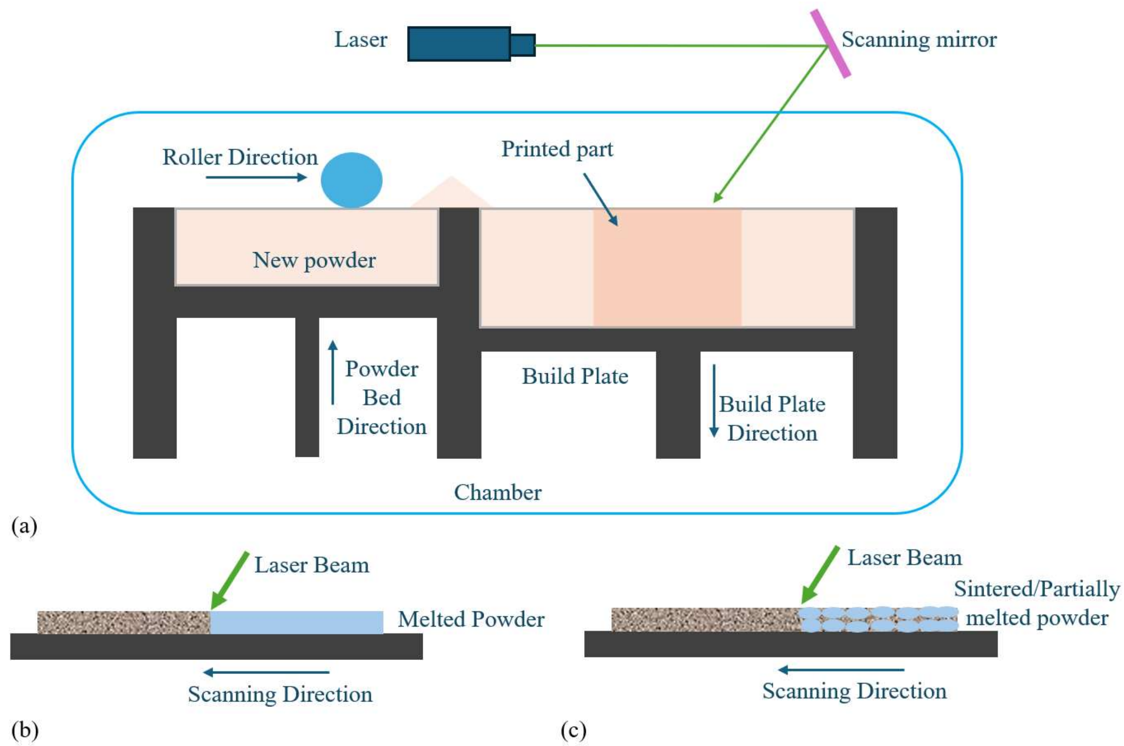

Fig. 1 (a) Schematic diagram for L-PBF process (modified based on [5]), (b) and (c) D-SLS and D-SLM processes (modified based on [6])

When working with ceramics, mechanical and thermal properties play a very important role in distinguishing parts based on their applications. Some of these important mechanical and thermal properties to take into consideration are hardness, fracture toughness, strength, thermal conductivity, thermal expansion, specific heat capacity, thermal shock resistance etc. Some of these properties influence the selection of printing parameters, while others are altered during processing and ultimately determine the characteristics of the final part. Both of these aspects are discussed in this review. Additionally, Ullah, Abid, et al. [7] provides a comprehensive summary of commonly used ceramic materials compatible with various additive manufacturing (AM) techniques, offering valuable context for material selection. This literature review particularly focuses on the materials compatible with L-PBF and provides a brief discussion regarding the applications of parts manufactured using this technology.

II. Applications

Manufacturing process of ceramic components using D-SLS or D-SLM is still in the initial stages, driving limitations in their applications. Although there is ongoing research on fabricating ceramic components using laser-based additive manufacturing, these parts have yet to fully demonstrate their functionality. However, future research works on this technology can reveal the capability of these components due to their exceptional properties. Ceramics possess high compressive strength and phenomenal mechanical properties, making them suitable for industrial applications. Additively manufactured ceramic parts have been used in areas such as dental prostheses and crowns, root analogue implants, and dental implants. Ceramic materials such as zirconia are biocompatible with oral tissues and do not produce allergic reactions, making them well suited for prosthodontic applications. As noted by Galante R. et al., a composition of 41.5 wt% zirconia and 58.5 wt% alumina manufactured using L-PBF has been applied in dental restorations and prototypes [8]. Nevertheless, despite these promising developments, the application of L-PBF in this domain has not yet fully demonstrated its long-term functional reliability and clinical viability.

In aerospace industry, turbine technologies require components capable of sustaining elevated temperatures and corrosive environments. Traditional manufacturing processes are often time-consuming and costly, in which case D-SLS can prove to be an efficient method. It offers an alternative to produce moldless cores and complex structures, making it ideal for producing components of turbine blades. Porous Si_3N_4 ceramics are also widely used in aerospace due to their lightweight, high strength, and high wave transmission characteristics [9]. Chen et al. employed L-PBF to manufacture ceramic molds with alumina-based cores which were used in turbine blade manufacturing [10].

Despite these developments, the limitations associated with using SLS and SLM methods for ceramic feedstock materials necessitate further research and hence applications for ceramics manufactured through these techniques remain limited.

III. L-PBF of Ceramics

Laser Powder bed fusion is commonly used additive manufacturing technique for metals because of the ability to manufacture complex geometries and internal features. However, with ceramics it becomes very challenging to use this method due to some technical limitations. Firstly, ceramic powders, as compared to metals, often flow poorly, resulting in imperfect spreading on the powder bed surface. Second, and more importantly, for ceramics, low thermal conductivity often leads to large temperature gradients that result in residual stress [11]. According to Grossin, David, et al. the quality and homogeneity of a spread powder bed is significantly affected by powder flow [12]. Hence, it also affects the density of the final printed parts. Over the years, there has been some research on overcoming these issues by optimizing material characteristics, addition of certain types of materials, optimizing printer parameters etc. Some main factors that affect the properties of the printed parts listed by Zhang H et al. are mentioned in Fig. 2 [11]. Additionally, not all materials are suitable for L-PBF. Some of the common ceramics that can be used in this process include SiC, Al_2O_3, ZrO_2, MgO, and TiB_2 [7]. These materials, including some others, can further be categorized as suitable for SLS or SLM processes. SLM as mentioned before, involves melting the powder to its fullest to fuse the particles together. However, not all ceramics can be fully melted due to lack of existence of liquid phase. For materials that cannot be melted, the term selective laser sintering is often used. One of the examples of such materials is Silicon Carbide with a decomposition temperature of approximately 2700ºC.

Ceramic materials suitable for SLS and SLM can be of different types: Oxides, Carbides, Nitrides, and Borides. These are typically combinations of metal and non-metallic elements like oxygen, carbon, nitrogen and boron. Oxides and Nitrides are usually known for their high temperature strength and wear resistance compared to borides and carbides which typically exhibit very high hardness values and superior thermal stability.

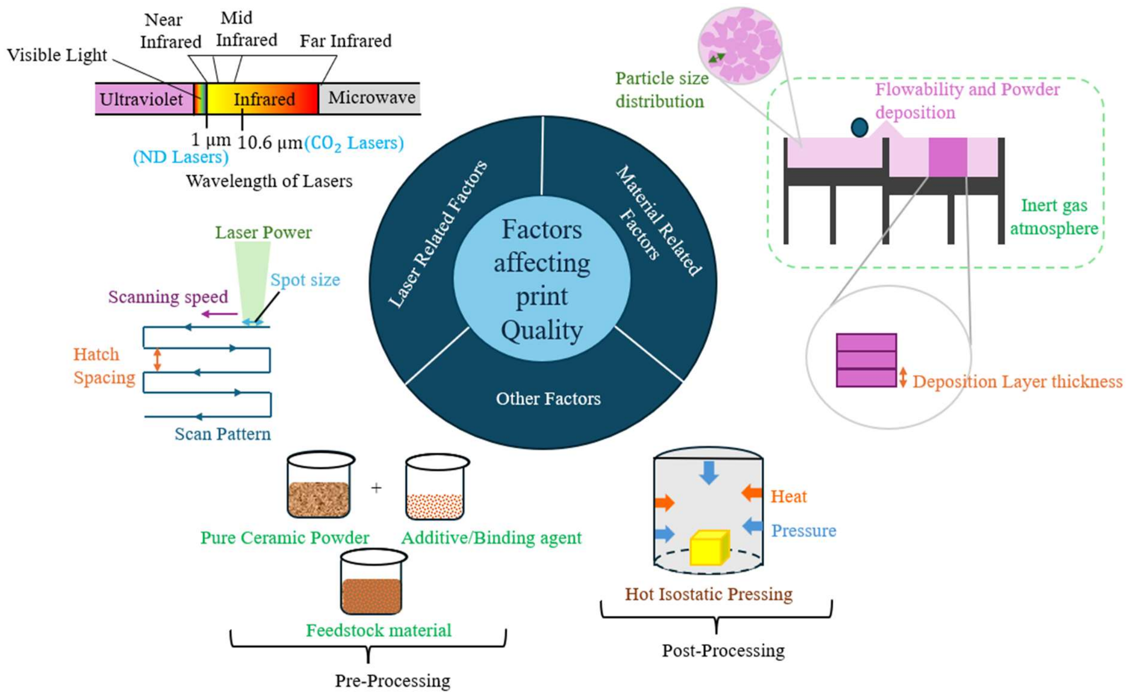

Fig. 2 Factors controlling quality of the manufacture component in L-PBF

L-PBF technology uses two different types of lasers: ND: YAG and CO_2 lasers. ND: YAG lasers comprise of a solid-state laser that uses yttrium aluminum garnet doped with Neodymium. CO_2 lasers on the other hand use a gaseous mixture of carbon dioxide, helium and nitrogen. ND: YAG and CO_2 lasers operate around 1.06 and 10.06 μm wavelengths respectively. The former is suitable for carbide ceramics like SiC due to their efficient energy absorption at this wavelength, enabling precise and rapid melting. Other examples in this category include ND: YAG, YB: YAG, and ND: YVO_4. CO_2 lasers with longer wavelength (10.06 μm) are more suitable for oxides of ceramics like Al_2O_3, TiO_2, and ZrO_2, which absorb better in the far-infrared region [7, 11]. Absorptance of these materials towards the laser drives porosity and crack initiation during the manufacturing process. Low absorption rate can lead to insufficient energy absorbed by the powder, thereby resulting in incomplete melting and pore formation. This accompanied by the rapid temperature changes because of constant heating and cooling accumulates residual stress leading to crack formation. Further details regarding these defects are discussed towards the end of this paper.

A) Oxide Ceramics

When metals/non-metals react with oxygen, the resulting compound is known as an oxide ceramic. One of the most common oxide ceramics used in Laser Powder Bed Fusion process is Al_2O_3. However, in the absence of an apparatus comprising of CO_2 laser, using pure metal oxide as a feedstock material in L-PBF gets challenging due to low absorptance of these materials towards ND: YAG laser. There have been multiple attempts made by researchers to improve their absorptance by adding dopants or absorbance enhancer materials. Florio K, et al. attempted to increase the absorptivity of Al_2O_3, by adding metal oxide dopant. For a full layer, using Fe_2O_3, as dopant resulted in increased absorptance for Al_2O_3, which was important to generate stable melt pool [13]. Melt-pool stability controls formation of cracks, pores and density of the final part by ensuring proper melting and good bonding between the subsequent tracks and layers, leading to a uniform microstructure. Best results were obtained with these two groups of scanning conditions – 10W with (25.6 mm s^{-1}, 12.8 mm s^{-1}, and 8.6 mm s^{-1}) scanning speeds, and 18.5 W with (47.4 mm s^{-1}, 23.7 mm s^{-1}, and 15.8 mm s^{-1}) scanning speeds, with 130 μm hatch distance for each group. The absorptance of Fe_2O_3 doped powder was 84%.

Similarly, zirconia (ZrO_2) presents comparable challenges in L-PBF when processed in its pure form. Due to its intrinsic material properties and processing limitations, ZrO_2 is commonly stabilized with yttria, resulting in yttria-stabilized zirconia (YSZ), which exhibits improved structural stability and processability during L-PBF. Urruth, Giovanni, et al. exhibited to increase the absorbance of Yttria Stabilized Zirconia (YSZ) at a wavelength of approximately 1.065 μm, using the minimum amount of additive possible [14]. Out of the two absorbance enhancers (SiC and TiC) used in the experiment, TiC was found to be the more effective yielding the final absorbance value of 0.57 and 0.67 for 0.25 wt % and 0.75 wt% of additive respectively. In addition to the absorbance of the material, optimal process conditions were also tested during the experiment. It was found that for a constant laser scanning strategy (N90) and a hatch distance of 50 μm, the best processing conditions that gave a broader range consolidated and structurally stable parts were having medium laser power (50 W) and relatively slow scanning speeds (32 $mm\ s^{-1}$). These parts were also produced at higher power (~90 W) and high scanning speed (~66 $mm\ s^{-1}$) however, slightest change from these values resulted in compromised part quality.

Compared to Al_2O_3, YSZ has higher melting point and lower thermal conductivity (2-3 W/m*K) resulting in a need for higher laser power to melt the powder particles. However, excessive power leads to melt-pool instabilities affecting the final quality of the print. When high power is paired with adequately high speeds that are enough to sinter the powder particles, this issue can be avoided. However, for materials like YSZ, this strategy may not give a broad range of laser power and scanning speeds to work with.

B) Carbide Ceramics

A chemical reaction of metal or semi-metal with carbon forms carbide ceramics that generally show higher absorptance rate for ND lasers. Despite the high absorbance of these materials, lower material stability remains one of the biggest concerns with carbide ceramics. They are more prone to decomposition or undergo phase transformations at higher temperatures which affects grain growth. Producing densified, crack free and pure parts remains a common challenge between oxides and carbides of ceramics.

Scanning speed, laser power and hatch distance are crucial factors that show the highest effect on porosity and density of the print [15, 16]. Pairing these parameters appropriately is the key to overcome low density and high porosity issues in carbide ceramics. High laser power sinters and fuses the powder more effectively resulting in densified parts. However, elevated values of power paired with slow scanning speed chemically decomposes the powder rather than melting. This leads to larger volume of Si and C particles in the final part thereby decreasing relative density of SiC part. Low density and low purity are also a result of slow scanning speeds due to the creation of uneven microstructure resulting in pore formation. Abdelmoula, Mohamed, et al. depicted that among all process parameters, scanning speed had the most effect on both purity and relative density in D-SLS of SiC [15]. As reported in the experiment, the optimal printing conditions for SiC are 45 W laser power, 100 $mm\ s^{-1}$ scanning speed, and 40 μm hatch distance resulting in an average density of 86.4%, and 76.23% SiC in the final part. With the same hatch distance, a laser power of 40 W and scanning speed of 300 $mm\ s^{-1}$ resulted in a print that was 81.4 % dense and contained 88.97% SiC particles. Montón, Alejandro, et al. found two sets of optimal conditions to produce SiC parts: 76W, 300 $mm\ s^{-1}$, and 40 μm, and 52 W, 900 $mm\ s^{-1}$, and 40 μm [16]. While the first set of parameters resulted in partial decomposition of SiC into elemental Si, the second group offered partial sintering with no melting. Alongside these laser parameters, hatch spacing also affects the densification of the final part to some extent due to the overlap between the scanning paths. According to Sai, Manchu Mohan Krishna, and Amitava Mandal, reduced hatch spacing increases overlap between consequent paths and hence densifies the part, however, it also increases the risk of thermal stress accumulation [17].

Another common material used in L-PBF of carbides is zirconium carbide. Wilson-Heid, Alexander E., et al. used the method of normalized enthalpy to find the laser parameters that produces densified parts using 99.5% pure ZrC with powder particle size of 96 μm [18]. As the laser parameters are very interdependent on each other, varying one of them changed the effect of other, creating multiple test possibilities. To overcome this issue, researchers came up with a way to combine all these parameters into one quantity known as normalized enthalpy ratio [17]. This reduces the chances of missing optimal test conditions due to a large number of possible options. Post simulation and experimental results suggested that the optimal laser parameters were a laser power of 150 W, scanning speed of 200 $mm\ s^{-1}$, and hatch distance of 60 μm, leading to 85% average density [18].

C) Other Ceramics

Some of the other types of ceramics include Nitrides, Bromides and composites of ceramic materials. Laser powder bed fusion of pure nitride and bromide ceramics are not studied as extensively as compared to oxides and carbides of ceramics. Hence, there is a big gap in the material diversity for L-PBF of ceramics. There could be multiple reasons for this like lack of functionality of these materials, challenging material properties, involvement of more cost and time in the process, etc. According to Chen, An-Nan, et al. various types of ceramic powders and binders are needed to fabricate ceramic products like Al_2O_3, ZrO_2, Si_3N_4 and SiC [19]. As seen in previous sections, there are some studies to overcome this challenge however possible solutions to solve this issue for nitrides is still lacking. In addition to this, SLS/SLM of Si_3N_4 is extremely challenging due to poor sinterability caused by low absorption of laser beam energy as mentioned in the studies by Dong, Xingjie, et al. [20]. Some other studies suggest alternate methods to fabricate dense Si_3N_4 using the process of nitrification or cold pressing methods to improve the density of final parts [21, 22]. Moreover, Li, Zhi, et al. attempted to manufacture dense parts made from $TiB_2 - B_4C$ composites using D-SLS [23]. In this experiment, a mix of Ti and B_4C powders as feedstock material, and a Yb+3-doped fibre laser of 1.064 μm wavelength were used to fabricate complex composite parts. Despite these material-related challenges, research efforts continue to expand into other advanced ceramic systems. Zhang, Zhizhou, et al. studied laser-based AM of ultra-high temperature Ta_4HfC_5 components [24]. A ytterbium fiber laser of 1.07 μm wavelength was used to sinter Ta_4HfC_5 powder with particle diameter less than 44 μm. Experimental results suggested that laser power of 190 W, scanning speed of 400 mm s^{-1}, hatch distance of 50 μm and layer thickness of 50 μm were the optimal parameters yielding with minimal cracks and relative density of 98.3%.

D) Defects

In the L-PBF process for ceramic and ceramic composite materials, the most significant challenges are the occurrence of cracks and porosity. This section outlines these defects and the corresponding properties that are altered by them.

1. Crack Formation

Brittle nature of ceramics combined with thermal gradients during printing process make the components more prone to surface cracks. The rapid heating and cooling cycle generate large temperature gradients causing tensile residual stress to accumulate throughout the part. Unlike metals, ceramics cannot undergo plastic deformation, making it harder to release these stresses. When these accumulated stresses exceed the strength of the material, cracks start appearing on the surface of the part. They can reduce the density of the part, adversely affect mechanical properties like toughness and strength, and decrease the dimensional accuracy of the part. For example, pure ZrO_2 ceramics exhibit numerous microcracks, impacting their mechanical performance. This phenomenon is attributed to their martensitic phase transformation (t-ZrO_2↔m-ZrO_2) during heating or cooling, which results in an increase or decrease of volume (~4%) [25]. Contrarily, phase transformation of TiC to TiO_2 (rutile) achieved crack healing in production of Titanium Carbide parts [8]. Figure 3 shows the crack formation and propagation in the different materials at respective process conditions.

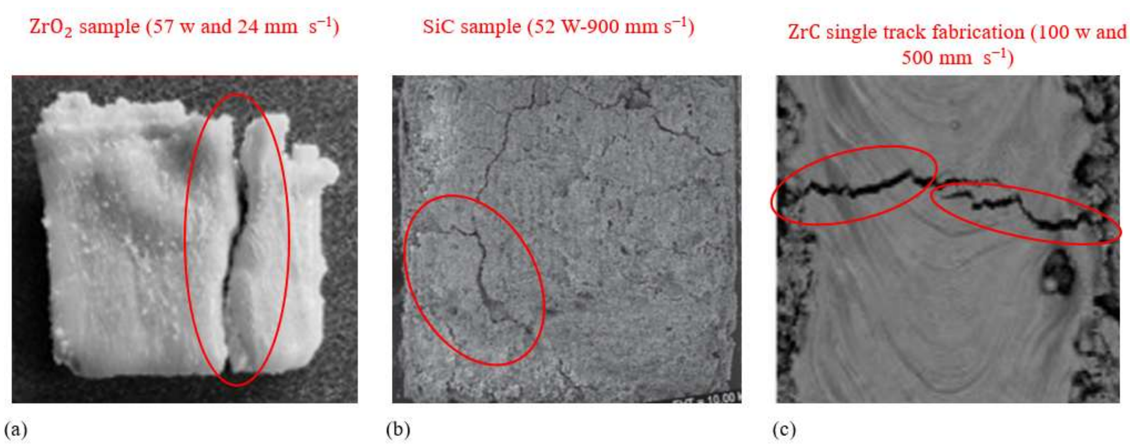

Fig. 3 Crack formation and propagation corresponding to the process conditions in (a) in ZrO_2 sample (modified based on [14]), (b) SiC sample (modified based on [16]), (c) ZrC (modified based on [18])

2. Porosity

Porosity is one of the most common defects in L-PBF of ceramic. In general, pores formed using ceramic L-PBF process are classified as spherical pores/gas pores and Lack of Fusion (LOF) pores/irregular pores. Gas pores occur because of entrapped gases in powder particles that get released during the printing process or between the layers due to rapid melting and cooling [7]. Feedstock preparation highly affects the former cause. During the production process, a rapid stream of gases, used to solidify the material, is passed through the droplets of the material. Sometimes, these gases get trapped within individual powder particles, which during the printing process, if not given enough time to escape, get trapped in the final parts and appear as pores.

Due to insufficient energy input, high scanning speed and rapid cooling rates, powder particles at that site do not melt sufficiently, resulting in LOF pores [7]. Additionally, lack of overlap between subsequent layers because of low melt-pool depth, creates voids between layers, contributing to this type of porosity. LOF pores are typically large and irregular in shape which makes it easier to distinguish them from the gas pores. Conversely, large energy inputs paired with slow scanning speeds result in keyhole porosity. Extremely high energy input causes the powder in the melt pool to vaporize, creating a cavity where gases, generally from the environment (argon, helium, nitrogen etc.) get trapped as bubbles. The final printed part exhibits keyhole porosity in this case. Surface morphology of some highly porous samples is shown in Fig. 4.

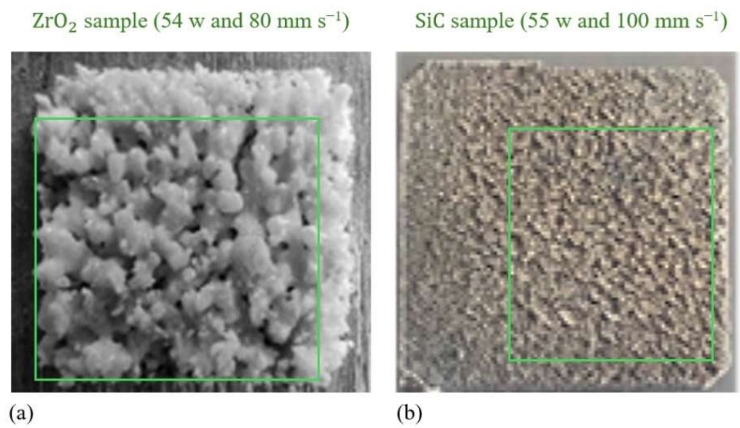

Fig. 4 Porosity induced from processing conditions in fabrication of (a) ZrO_2 sample (modified based on [14]) and (b) SiC sample (modified based on [15])

Porosity significantly affects the density of the final part-almost showing an inverse relation with it. Increase in porosity, increases number and volume of voids in a part and consequently, decreases mass and volume of the solid, resulting in decreased density of the print. It can cause significant effects on mechanical properties due to generations of areas of stress concentrations, crack propagation, and surface irregularities. These can lead to decreased fracture toughness and fatigue in the solid over time. Porosity can also change the path of crack propagation which can lead to decrease in wear resistance of the material. The size of the part has a major impact on its porosity and, consequently, its relative density. Large parts require longer scan path and build times which extends thermal cycles and accumulates more residual stresses, resulting in significant amount of LOF pores and cracks.

E) Properties

Ceramics are known for their special properties such as high strength, corrosion resistance, and temperature stability [7]. However, ceramic parts printed using L-PBF technique exhibit defects like porosity, cracking, spattering and surface roughness which affects their mechanical and thermal properties. This section covers the influence of previously discussed defects on mechanical, thermal, and electrical properties of the manufactured parts.

1. Compressive Strength

Compressive strength is the ability of the specimen to withstand compression loads. High compressive strength of ceramics makes them an attractive choice for certain applications. For example, 96% pure Al_2O_3, can have compressive strength as high as 2000 MPa, and 99% pure SiO_2 has a compressive strength of 600 MPa in amorphous form and around 2070 MPa in crystalline form. However, presence of the defects like cracks and porosity significantly affects the strength of L-PBF manufactured components. Pores in final printed parts serve as internal stress concentrators. Under loads, these stresses get amplified resulting in cracks nucleation and thereby depicting poor compressive strength. For example, SiO_2 and Al_2O_3 parts produced using L-PBF exhibit a compressive strength of only 0.8 MPa and 140.8 MPa respectively [11, 26].

2. Hardness and Wear Resistance

The ability of a material to withstand permanent deformations like indentation and scratching is termed as hardness. Wear resistance is a material's ability to resist surface degradation from erosion, abrasion etc. Generally, wear resistance of a material increases with increase in hardness. Porosity and cracks induced in the part during the manufacturing process reduce the effective load bearing cross-sectional area and decrease the hardness of the specimen. The stress-concentration points induced during the process promote micro-fractures and grain pull-out making it easier for the material to get removed during abrasion. A very common way to measure hardness of the parts is Vicker's hardness test. ZrC samples fabricated by Abdelmoula, Mohamed, et al. had Vicker's microhardness value of 20.9 ± 1.9 GPa [15].

3. Thermal and Electrical Conductivity

Thermal conductivity allows a material to pass heat energy through itself due to the temperature differences. While thermal conductivity is an important property that makes ceramics suitable for high-temperature applications, it is also very crucial parameter for deciding the compatibility of these materials in L-PBF process. Ceramic materials in general have low thermal conductivity compared to metals making them challenging to use for this process. This results in hinderance in efficient heat dissipation and creates steep thermal gradients within the melt pool, thereby significantly influencing the shape and dynamics of the melt-pool [27].

Thermal and electrical conductivities of ceramic materials also get affected during the manufacturing process. As per the model developed by Alkunte, Suhas, et al., thermal and electrical conductivities decrease with increase in porosity [28]. Consequently, heat transfer in ceramics primarily occurs through lattice vibrations rather than electron movement. These lattice vibrations, known as phonons, govern thermal transport within the material. However, phonon scattering limits the rate at which heat can be conducted. L-PBF-fabricated ceramic parts generally contain a considerable amount of porosity. This increases phonon scattering and further reduces thermal conductivity in the final component. While this reduction may be detrimental in applications requiring heat dissipation, it can be advantageous for thermal barrier applications such as furnace linings, turbine blades, and heat shields.

4. Corrosion Resistance

Ceramics are formed through strong ionic and covalent bonds making them less reactive and hence, less prone to corrosion. Some ceramics like ZrO_2 and SiC form stable oxide layers that prevent further attacks of corrosion. Some literatures depict a direct relation between porosity and corrosion. For porous structures, increase in pores increases room for acids and liquids to penetrate through the surface, thereby increasing the contact area and decreasing the corrosion resistance [29]. To evaluate the corrosion behaviour of ceramic samples, common methods include immersing parts in acids and molten salts, as well as high-temperature oxidation tests. Treated parts are then analyzed using SEM/EDX microscopy or X-ray Diffraction.

IV. Future Works

Laser based additive manufacturing of ceramics remains relatively new concept and further studies are required to prove its compatibility with ceramic materials. In this context, the following areas are suggested for future research.

A) Material Range

Current research on laser-based additive manufacturing of ceramics is limited to a small group of materials such as ZrO_2, Al_2O_3 and SiC. This narrow focus is mainly due to their inherent brittleness, high melting points and low absorptivity to certain laser wavelengths. As a result, using materials like MgO, TiB_2, Si_3N_4, ZrC as feedstocks remain unexplored. Addressing these material-specific challenges could significantly expand the range and functionality of additively manufactured ceramic components.

B) Purity of parts

Most of the current studies on D-SLS or D-SLM of ceramics involve using binders or additives for various reasons thereby compromising the purity of the parts. Highly pure ceramic parts are necessary in certain applications like dentistry driving the need for future research.

C) Densification of Parts

Although most research covered in this review focuses on improving the density of the ceramic parts manufactured using L-PBF, there has not been a significant success in this area. Densification is one of the biggest challenges due to the response of ceramic materials towards laser wavelength, heat input, melt-pool characteristics, scanning patterns, and thermal cycles. Due to these challenges, many post-processing methods are used to achieve the desired density of the manufactured parts. This costs additional time and monetary value thereby depreciating value of rapid manufacturing offered by the L-PBF technology. This necessitates further detailed work finding advanced methods to mitigate the need of post-processing and producing as-built densified parts.

D) Diversified research

L-PBF of ceramics is an emerging field, and substantial research efforts are still needed to further advance this area. Some areas that of exploration are- effect of particle size on the print quality, effect of laser parameters, more works to strengthen the current state-of-the art, process-parameter optimization, crack mitigation, simulation and modelling techniques, multi-material printing etc.

V. Conclusion

In summary, this paper examines laser powder bed fusion for manufacturing ceramic components, highlighting suitable ceramic materials and composites as well as the critical processing conditions required for successful fabrication. It also delves into the effects of laser and printer parameters on the mechanical, thermal, and electrical properties of the printed parts. The discussion of structural defects like porosity and cracks highlights their influence on the overall part quality, which deteriorates with increasing porosity, creating opportunities for future research in this area. Although L-PBF of ceramics remains an emerging field with limited material diversity and processing optimization, it demonstrates considerable potential. Future research on diversifying material compatibility, mitigating the need for post-processing, and producing crack-free and highly dense parts can amplify the application of L-PBF produced ceramic parts.

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