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Additive manufacturing processes for metals and effects of defects on mechanical strength: a review

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Abstract

Additive manufacturing (AM) technologies are appreciated all over the world for their great versatility, including the possibility to realize very complex shapes in one step, increasing the design freedom and significantly lowering the production costs. There are different AM processes and the criterion used to classify them is not unique; however, the most common AM technologies for metals can be broadly classified into two categories: Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). Both induce defectiveness in the component, such as concentrated residual stresses, surface roughness, delamination, porosity, and Lack of Fusion (LOF) defects that decrease mechanical resistance and lead to poor fatigue life behavior. The aim of this work is to provide a full overview of AM defects with the associated damage mechanism. The work is completed with a description of the process parameters optimization to minimize the induced defects.

Keywords: additive manufacturing; defects; mechanical strength; balling phenomena; keyhole mode; powder quality; process parameters.

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1. Introduction

There are many terms to identify Additive Manufacturing (AM) technology and these include “3D Printing”, “rapid prototyping”, “rapid tooling” and “freeform fabrication”. It is a new manufacturing technology developed in the last

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1980s and it quickly received worldwide attention thanks to its great strengths. Contrary to previous technologies includes casting, forming, or welding, AM is characterized by adding material instead of removing it. That is the biggest advantage because it is possible to realize parts with complex shapes without the need to use removal or additional post-processes. Complex shapes also include lattice structures characterized by the octet-truss cell (Bellini et al., 2021b). Besides, no molds, removal tools, and metal forming are needed saving a lot of time because the cycle time is much shorter than conventional processes. In addition, additively manufactured parts can be coupled to composite parts to lighten the weight of the final structure (Bellini et al., 2020). On the other hand, there are some limits to AM technology. Firstly, the process is recommended to produce small parts in small series, due to the high cost and time required for building large parts or numberless prototypes. The production time is high due to the limitations of scanning speed, powder feeding rate, and low layer thickness; on the contrary, the production cost is associated with the materials, specifically with the powder production (purity and average powder size), and the energy used for the powder production process (gas atomization). Then, there are different defectiveness that needs to be controlled in a post-process phase. Internal defects (pore, micro-voids, lack of fusion (LOF), residual stresses), and external defects (surface roughness) are harmful to the mechanical performances in AM parts. This amount of defectiveness depends on AM process and the associated process parameters. In fact, due to the non-optimized process parameters, the final component will be characterized by several internal imperfections due to entrapped gases in gas-atomized powders (pores), or due to the incomplete or bad melting regions (LOF defects). Surface roughness also is a critical parameter, and it is never possible to eliminate it during the printing phase without an appropriate post-process treatment. Finally, residual stresses also are dangerous for the mechanical properties, and the main physical factors responsible for their origin are temperature gradient due to localized heating and cooling, and uneven distribution of inelastic strains. For these reasons, AM components have lower mechanical, thermal, and electrical properties than wrought components and their use in industrial fields is quite hindered (Gibson et al., 2010)(Guo & Leu, 2013)(Srinivasulu Reddy & Dufera, 2019)(Wong & Hernandez, 2012). Because additive manufacturing fields are rapidly evolving, a critical review is useful. This work analyzes the emerging research on AM metallic materials and provides a comprehensive overview of the effect of defects and how they can be minimized by optimizing process parameters to reduce the amount of post-processing treatments needed.

2. Additive manufacturing technologies for metals

A first classification of AM processes can be done according to ASTM Standard F2792 (DebRoy et al., 2018) using seven categories: Binder Jetting, Material Jetting, Powder Bed Fusion(PBF), Directed Energy Deposition (DED), Sheet Lamination, Vat Photopolymerization, and Material Extrusion, while AM technologies applied to metals are only two: Powder Bed Fusion and Directed Energy Deposition. Basically, PBF and DED employ the same principle because the component is fabricated using a high energy density heat source, and a layer-by-layer addition of the material with localized melting, following the input of a geometry from a Computer Aided Design (CAD) file. More in detail, the processes have the following main steps in common:

- They start from a 3D-CAD model designing with a CAD software.
- Once the model is created, it is converted to a stereolithography (STL) file in which the component is approximated by a mesh of triangles and sliced in layers of equal thickness (this phase is necessary because STL is the standard file type for AM machines).
- Then the file is transferred to the machine, which needs to be set up (choice of machine configuration and specific parameters).

PBF category is the oldest technology commercially introduced and it can be subdivided into different processes: Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), Direct Metal Laser Sintering (DMLS) (Gibson et al., 2010). These entire processes share the same iterative loop as is shown in Figure 1. An automated process builds the part starting with a powder layer that is firstly applied on a building platform, and a laser or an electron beam is moved in the x-y plane (considering z-axis as the height) to selectively melt the regions of interest. When a layer is completely melted, the build platform is lowered by 20 to 100 μm (an amount equal to the layer thickness) to allow the deposition of another layer and the cycle can be

repeated. After printing phase, platform, support structures, and powder are removed from the powder bed, and a heat treatment or surface finish process can be required to improve the mechanical properties and minimize the defectiveness. The excess powder can be reused and this can result in poor surface finish and mechanical properties (DebRoy et al., 2018).
In the DED category, the material is locally deposited and melted through a source of high energy density (laser beam, electron beam, or electric arc). In other words, DED processes are not used to melt a material that is pre-laid in a powder bed (as is done in PBF) but they are used to melt materials as they are being deposited. Consequently, parts are subjected to a thermal history like multi-pass weld deposits. The energy used during deposition can reheat previously deposited material, changing the microstructure of previously deposited layers and introducing defects (Gibson et al., 2015)

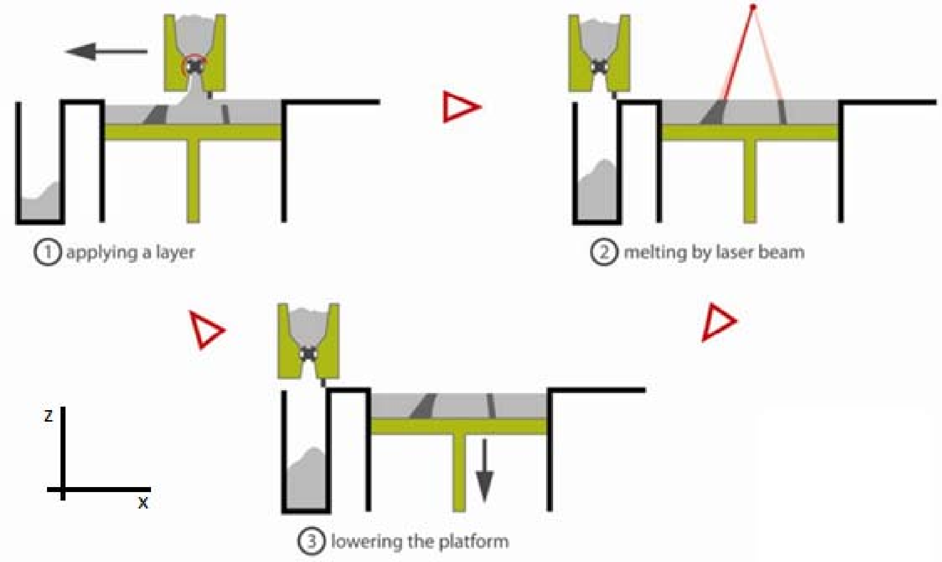

Figure 1 – Three-step iterative process of additive manufacturing technologies (Loeber et al., 2011)

3. Mechanisms and causes of occurrence of defects

Additive Manufactured metals show typical defects that inevitably arise due to the not optimized process parameters. Defects in AM parts can occur for several reasons. For example, there are physical phenomena, such as Keyhole Mode and the Balling Phenomenon that depend on the setting of the process parameters, or there are reasons related to the choice of the feedstock materials quality.

3.1. Conduction mode and keyhole mode

During melting, there is a transition from conduction mode to keyhole mode, depending on the energy density according to equation (1).

$$E_{density} = \frac{P}{v*h*t} \tag{1}$$

Where P is the laser power, v is the scanning speed, h is the hatch spacing, and t is the layer thickness.

While the conduction mode is represented by a melt pool wide and shallow due to the lower heat source intensity, with higher intensity, the melt pool has a different shape, i.e., it is very penetrative and this consent to melt a very large thickness in a single pass. This situation is called keyhole mode. The keyhole is a hole that contains vapor. The reason why the transition from conduction to keyhole mode happens is due to the process explained below. Initially, when the heat source intensity is low, the melt pool is in the conduction mode. Locally, the temperature is going to rise several hundreds of kelvins above the melting temperature of the material, and soon some amount of vapor is formed. The temperature localized is very high and the evaporation has started. The vapor column is amenable for complete absorption of heat, so it is possible to see that the beam is going to penetrate much deeper. The easier absorption in the case of laser beam is because of "Inverse Bremsstrahlung". The laser light is completely absorbed by the vapor in this phenomenon. This happens because the laser absorptivity in solids is very less, a bit higher in liquids, but for vapors, there is the complete absorptivity of laser light. That means the heat delivered to the beam is enhanced. In other words, it starts with some amount of liquid metal that melts and forms vapor. The vapor absorbs more heat and consequently more vapor is formed, until the keyhole is formed.

This process is well explained in Figure 2, where the authors (Cunningham et al., 2019) showed the transition between conduction and keyhole mode that begins after 1030 μs.

In another research, (Dilip et al., 2017) reported a bowl shape geometry of the melt pool at a power level of 100 W, while increasing the laser power to 195 W it was found a keyhole shape. This remarkable change is due to the different modes of melting, as has been said. For lower laser power the heat transfer is due to conduction and convection inside the melt pool, while for higher laser power, melting occurs by keyhole mode, giving rise to deeper penetration. Since keyhole mode is always associated with alloy vaporization, this results in entrapped pores in the melt pool, and after solidification, it is possible to see a large amount of porosity.

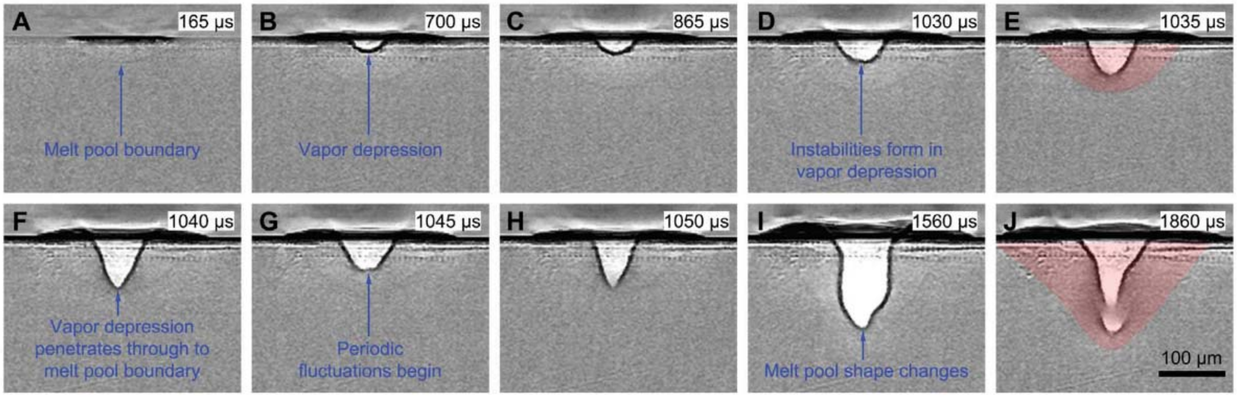

Figure 2 - Evolution of melt pool under static laser [Reproduced from (Cunningham et al., 2019), with permission of The American Association for the Advancement of Science]

3.2. Balling Phenomena

Balling phenomena is a phenomenon due to the variation of two process parameters: laser power (P) and scan speed (v). During the passage of the laser over the powder bed, the metal powder is locally melted on a straight path, but when the process parameters are not optimized, the fused line is affected by a phenomenon called "balling" and it begins to be broken up due to the lesser surface tension. The balling phenomenon happens when the scan speed is high while the laser power is low. In fact, at lower speeds, the powder bed melts more slowly and therefore, the melted track has time to stabilize as a straight and flat path. When the scan speed increases, the track becomes more rounded and sinks into the powder bed. At ever-higher speeds, this phenomenon is clearly observed because real spheres form on the powder bed, instead of having a flat and homogeneous track. For extremely high scan speeds, the track is observed to be a fragile path and only partially melted. In an extreme situation, at the maximum scan speed and the minimum laser power, there is no fusion during the passage of the laser, (Gibson et al., 2010). Some authors (Dilip et al., 2017) observed that for the same low power levels (50 W), the porosity increases as the scan speed was increased. In addition, unmelted powder particles due to inconsistency and fragmentation in the melt track were observed too.

3.3. Quality of powder feedstock

The quality of the material feedstock is responsible for two main defects: surface roughness and spherical micro-pores (also called metallurgical pores). While the surface roughness can be reduced or eliminated with post-processing treatments such as machining, mechanical polishing, chemical milling, and electroplating (Yang et al., 2014), the gas porosity is more difficult to eliminate (Kim & Moylan, 2018).

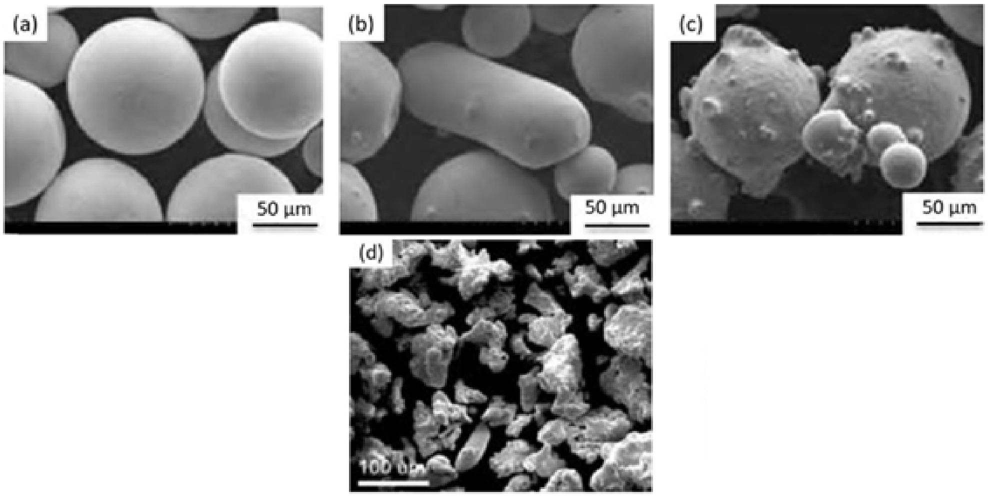

Figure 3 - SEM images of the feedstock powders produced by different processes. (a) plasma rotating electrode process; (b) rotary atomization process; (c) gas atomization process; (d) water atomization process [Reproduced from (DebRoy et al., 2018), with permission of Elsevier]

The main cause of the occurrence of spherical pores is due to gas trapped in the raw metal powder particles. Powder morphology, microstructure, and chemical characteristics could change depending on their manufacturing process (Maamoun et al., 2018). There are different ways to make the alloy powders, for example, it can be used a gas atomization process or a plasma rotating electrode process, and so on. Each process produces different morphologically powders as is shown in Figure 3. The more uniform the powders shape, the higher quality the component will be, because the uniform shape, size, and distribution promote homogenous melting, lower porosity, good interlayer bonding, structure, mechanical properties, and surface quality. However, fabrication processes that produce high quality powders are expensive and often the yield is low. So consequently, the selection of the feedstock materials needs to consider both the quality and the cost of powder particles and it is essential to make the best choice to obtain real savings.

4. Defects type and their effect on mechanical properties

4.1. Porosity and Lack of fusion defects

Porosity is a discontinuity of the material and represents one of the main responsible for the initiation of cracks in the AM parts (Kim & Moylan, 2018). As is shown in Figure 4 there are two different types of porosity visible in PBF fabricated samples: keyhole pores and spherical pores (Maamoun et al., 2018). Spherical pores, also called metallurgical pores, have regular shape and small size (less than 100 μm). They are due to the pores existing inside the gas atomized powder particles, or they may be related to the entrapped gas during solidification when the scan speed is low. Keyhole pores have irregular shapes with a diameter size of over 100 μm. These kinds of pores mainly occur with fast scan speed because the solidification rate is higher, and the molten pool has no time to fill all the substrate. In other words, keyhole pores formation is due to the insufficient energy delivered to the powder particles. They also may be related to the entrapment of gas bubbles between the layers (Maamoun et al., 2018)(Kim & Moylan, 2018).

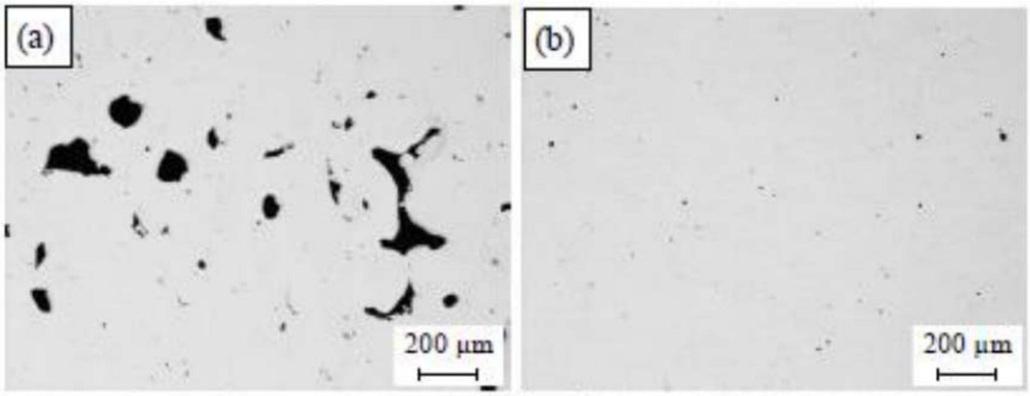

Figure 4 - Pores observed inside the Al alloy sample: a) keyhole pores; b) spherical pores (Maamoun et al., 2018)

Finding the amount of porosity in a component is essential to predict the possible failures because every single pore can represent a zone of stress intensification. In other words, each pore represents a possible point of crack initiation both in the static and cyclic regimes. Some authors (Pirozzi et al., 2019) found that the spherical pores are responsible for a reduction in the true cross section in the tensile specimens, while the keyhole pores are more responsible for the stress concentrations. Both contribute to lower the mechanical strength of the specimen.

LOF defects form when the energy density is not strong enough to melt the entire desired region. As is known (Gibson et al., 2010) laser tracks depend on laser power and scan speed. When the scan speed is low and the laser power is high, the laser tracks appear straight and homogeneous. On the contrary, when the laser power and the scan speed are not accurately optimized, the balling phenomenon occurs and LOF defects arise. This means the laser track does not appear as a homogeneous track, but it becomes a sort of array of balls in a single line. If the balls just touch each other, without overlapping, LOF forms under the connecting point, Figure 5.

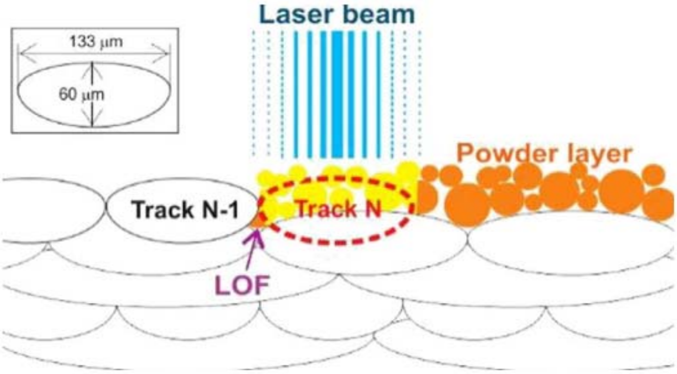

Figure 5 - Schematic illustration of LOF occurring [Reproduced from (Darvish et al., 2016), with permission of Elsevier]

When laser power increases, the melted spot increases and increases the average track size too, thus overlapping coverage is complete, resulting in a small number of LOFs. T. Smith et al. (Smith et al., 2019) found that LOF defects act as starter notches that nucleate microcracks. This nucleation can also coalesce into a growing crack, lowering the fatigue life. Presence of these internal defects at large level was reported to result in reduced elongation at failure under static loading and a significant drop in fatigue strength of the AM material (Razavi et al., 2018) (Razavi et al., 2021).

Other authors (Bellini et al., 2021a) found that due to the incomplete melting of the powder during the printing process, in lattice structures there may be a poor connection between the reticular core and the skin, which leads to lower the mechanical strength.

4.2. Residual stresses and thermal micro-cracks

AM metal components are created layer by layer using a high heat input and, therefore, high thermal gradients cannot be avoided. Residual stresses are generated because of localized heating and cooling, and they are highly dangerous for AM parts because the elastic limit is lowered locally, and failures are achieved earlier. Regarding the process parameter, it was discovered that the scan speed did not affect the residual stresses significantly, while the main process parameter that needs to be considered is the cooling speed. Higher cooling speeds are responsible for larger residual stresses (Kim & Moylan, 2018).

Investigations about residual stresses sensitivity are required to fully understand their effect on mechanical strength. Firstly, to relieve the residual stress it is possible to heat the component higher than 600 °C. While, to reduce the thermal gradient between the deposited layers, to minimize the residual stresses, it is important to apply a preheating technique to the build platform before starting the build (Maamoun et al., 2018). A. Riemer et al. (Riemer et al., 2015) found that Ti6Al4V alloy in its untreated condition shows low and insufficient crack growth data due to the effect of residual stresses on the crack path. For this material heat treatment is necessary to remove residual stress and partly compress micropores.

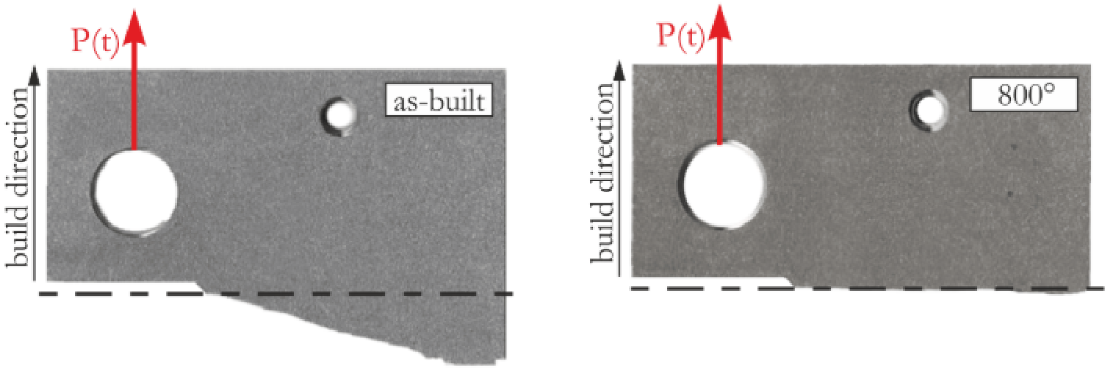

Figure 6 - The effect of residual stresses on the crack path (Riemer et al., 2015)

Figure 6 illustrates the crack path in as-built conditions (that means untreated condition) and at 800° (that means following heat treatment at 800°C) conditions.

The microcracks are a direct consequence of the severe residual thermal stresses induced by the fast cooling rate (Zhou et al., 2020). The size of the micro-cracks depends on the thermal gradient between the deposited layers and this, consequently, depends on the process parameters applied. These microcracks can be very long or they can be quite small with a maximum length equal to the layer thickness (DebRoy et al., 2018), as is shown in Figure 7.

Energy density does not affect that much the crack formation, while the laser scan speed is considered the leading parameter affecting crack formation. The scan speed has a more effect on crack formation than the applied energy density because it controls the rate of solidification (Maamoun et al., 2018). Micro-cracks can be reduced by applying a Hot Isostatic Pressing (HIP) treatment. The crack length decreased with increasing HIP temperature, because the high-temperature diffusion process-induced uniform composition and structure (Zhou et al., 2020).

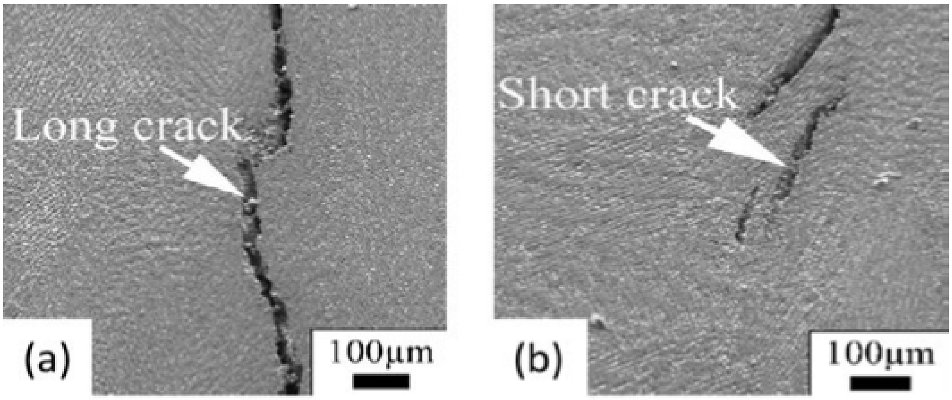

Figure 7 - a) Long cracks; b) short crack [Reproduced from (Zhao et al., 2009), with permission of Elsevier]

4.3. Surface roughness

The surface roughness is one of the most important features in AM components, and it is also one of the most influential defects that could increase the local stress level and affect the crack initiation behavior.

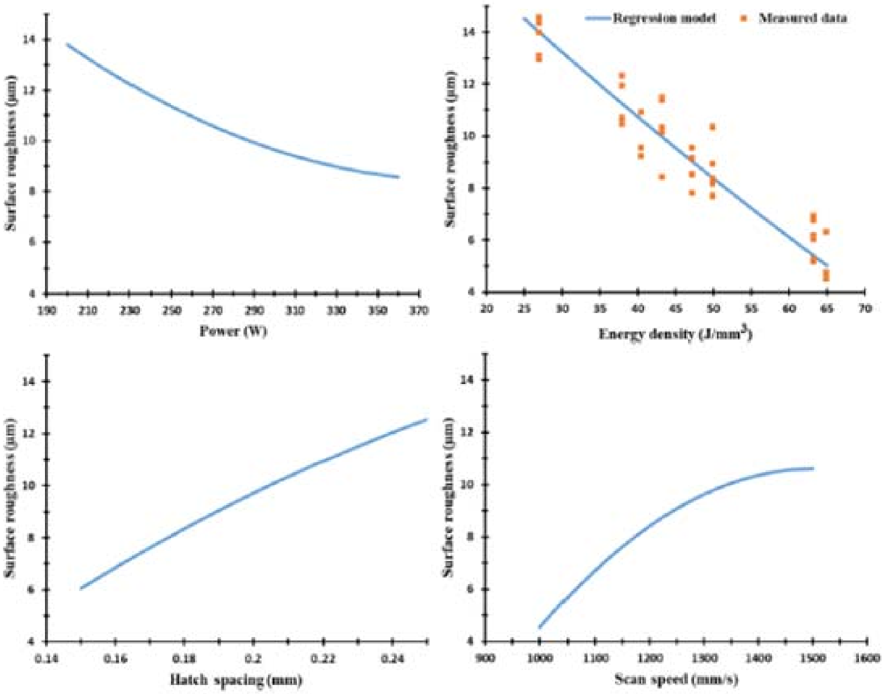

Figure 8 - Effect of the process parameters on surface roughness (Maamoun et al., 2018)

The surface roughness is due to two different mechanisms. The first one is called “stair-step effect” and is due to the stepped approximation by layers of curved and inclined surfaces. The second mechanism is the improper melting of powder particles and balling phenomenon. Therefore, the minimization of the surface roughness depends on the interaction of a large number of process parameters and process conditions (DebRoy et al., 2018).

The effect of process parameters on the surface quality of AM parts is shown in Figure 8. The laser power and the energy density effects reveal similar trends in agreement with the measured values. The hatch spacing and the scan speed show the opposite trend. An increase of hatch spacing resulted in a rougher surface due to decreasing overlap between the melted tracks. While, an increase of scan speed leads to a decrease in the molten layer solidification rate, which increases the surface roughness (Maamoun et al., 2018). It should be noted that based on the geometrical complexity of the input CAD model, a gradient of surface roughness can result in the AM part. In this scenario, the surfaces which have a downfacing area would be mainly supported by the powder bed underneath (in case of powder bed fusion). This would result in lower cooling rate in this area and helps partial fusion of the supporting powders to the surface and possible slight deviation of the geometry from the nominal model (Razavi et al., 2020). Surface roughness can be improved using post-process treatments and this leads to greater mechanical strength. B. Vayssette et al. (Vayssette et al., 2018) investigated both machined and as-built specimens with the aim of investigating the surface roughness effect on the HCF (High cycle fatigue). As-built AM parts show the larger surface roughness therefore the fatigue strength is low. Instead, machined samples show a good fatigue strength. Hot-rolled (HR) samples show the best fatigue strength due to the fine equiaxed microstructure where the nodules are elongated along the rolling direction, Figure 9.

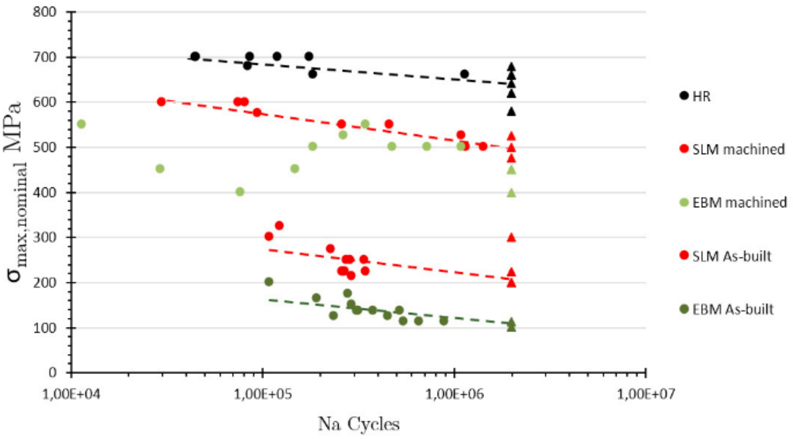

Figure 9 - S-N curves of the five sets of specimens (Vayssette et al., 2018)

5. Conclusions

Material properties of Additive Manufacturing (AM) parts strongly depend on the past thermal and procedural history. All AM parts show typical defects that inevitably arise due to the not optimized process parameters. However, finding the optimal set of process parameters is not easy, because all the parameters mutually influence each other and the degree of effect by each parameter is not well understood. Some authors provide an optimal set of parameters for their individual case, but the single setting cannot be applied to all materials and in all conditions because there are many variables involved that change the printing conditions. However, studying how defectiveness occurs during the printing phase is important to understand which parameters are the most influencing in order to optimize it and lower the number of defects in AM components.

In this review the most interesting aspects found were:

- The occurrence of defects depends on different causes including the quality of the material feedstock, the keyhole mode, and the balling phenomenon, which are in turn dependent on the process parameters.

- The most common types of defects are porosity, lack of fusion, residual stresses, surface roughness, and thermal microcracks that lower the mechanical strength of the component because they represent areas where the stress is amplified.
- In addition to acting on the process parameters, the number of defects can also be minimized by using post-processing treatments.

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