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Procedia CIRP 00 (2019) 000–000

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53rd CIRP Conference on Manufacturing Systems

Challenges and proposed solutions for aluminium in laser powder bed fusion

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Abstract

There is a growing interest for additive manufacturing of aluminium in the industry due to its favourable properties. There are, however, many challenges regarding selective laser melting of aluminium alloy powder that must be solved to make additive manufactured aluminium parts more reliable. Among the most highlighted issues are oxidation, high reflectivity and low laser absorption of the powder. In this paper, a brief literature review is conducted to analyse issues related to the named challenges and how these issues can be addressed. As the result, solutions and gaps for porosity, cracks, uneven grain growth and shrinkage effect for laser powder bed fusion of aluminium alloys are identified and presented. Cracking is found to be the most investigated issue among all presented, while shrinkage effect is not addressed in the current state-of-the-art.

Keywords: Additive manufacturing; Aluminium; Powder bed fusion

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1. Introduction

Additive manufacturing (AM) of aluminium (Al) is of great interest in various industries such as automotive and aerospace. AM of Al is an attractive technology due to the lightweight material and mechanical properties, which can be similar or better than for casted Al products [1]. However, the high reflectivity of the powder and low laser absorption make it difficult to melt the Al powder with laser [1-4]. Besides, the Al powder is subject to oxidation, which affects the mechanical properties of as-built parts [5, 6]. These challenges can lead to issues such as porosity, cracks, unsatisfying grain growth, and shrinkage [1, 2, 5, 6].

In many studies [7-10], heat treatment is used to remove process-induced residual strains and address the abovementioned issues. However, post-processing requires more time and additional equipment which negatively affects the cost of the final product. Therefore, this paper presents an analysis of how porosity, cracking, oxidation, unsatisfying grain growth and shrinkage effect can be solved for as-built parts.

Even though in the current state-of-the-art, several studies have already analysed and categorised research according to the focus areas [1, 11], it appears to be a research gap regarding the categorisation of what type of solutions are proposed to the different challenges of AM of Al.

This paper aims at giving an indicator of what type of solutions are already proposed and identifying areas that require more attention. The included types of solutions are adding additives to the Al alloy powder, adjusting the parameters for laser power and scan speed and pre-drying of the Al powder.

A brief theoretical background regarding AM in general, and Al in AM is presented in the next section, followed by the results and a discussion. Conclusion and proposals for future work are presented in section 4.

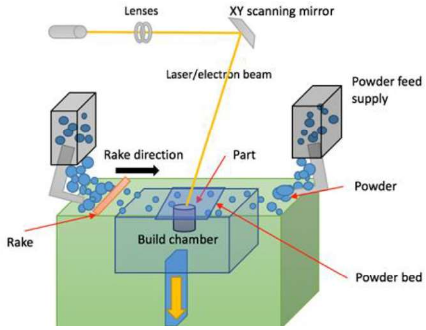

Figure 1 Schematic representation of powder bed fusion process

2. Theoretical background

2.1. Additive manufacturing

According to the ISO/ASTM 52900:2015(E) [12], additive manufacturing is a “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.” AM enables the possibility to produce lightweight parts with complex geometries in one piece [1, 6] instead of producing them as multiple parts with the help of traditional manufacturing technologies [13].

There are seven categories of AM, namely binder jetting, direct energy deposition, material extrusion, material jetting, PBF, sheet lamination, and vat photopolymerization [12]. Each AM process category differs by material, and the type of energy used to fuse the material. Therefore, this paper is limited to the category of PBF and specifically to the technique of laser PBF for metals (LPBF).

The PBF category is associated with polymer laser PBF, metal laser PBF, direct metal laser sintering, selective heat sintering, and electron beam melting (EBM) PBF. The listed processes typically differ by the type of material or energy applied to fuse the powder. For instance, EBM PBF uses a high-energy electron beam to melt the powder particles in a vacuum atmosphere. In contrast, a metal PBF process uses a laser as a source of energy to fuse the metal powder in a controlled atmosphere with an inert gas [14]. As was mentioned above, only LPBF, also known as the selective laser melting (SLM), is considered in this paper.

2.2. Laser powder bed fusion

PBF is an “additive manufacturing process in which thermal energy selectively fuses regions of a powder bed” [12], and its schematic representation is shown in Figure 1. In LPBF, high-power laser beams are used to melt metal powder particles into parts with a near-net-shape where the part requires minimal post-processing to finalize the part [15, 16]. The process of LPBF can be described as a deposition of a thin layer of powder, which is scanned with a laser beam. The process is repeated, layer by layer, until the part is formed [17]. When a new layer of powder is added, it has to be melted into the previous layer to be able to create a solid part [14]. The process is done in a closed chamber with an inert controlled atmosphere to prevent oxidation [1].

One of the biggest drawbacks of LPBF, together with some other AM technologies, is the production time. At this point, the low build-speed makes it unsuitable for commercial production and is mainly used by designers and product developers [3]. One solution to shorten the production time is to increase the scan speed, but this can result in poorer quality of the produced part. Increasing laser power, layer thickness, and beam diameter can also reduce the build time [18].

2.3. Aluminium in laser powder bed fusion

Al has some favourable properties such as high strength combined with light weight [1], which makes it more attractive in e.g., automotive and aerospace industries [5]. These industries are also interested in AM due to the possibilities for complex geometries and low weight trough e.g., topology optimization [4]. However, there are today only a few Al alloys that can be reliably printed [19]. Al-Si-Mg alloys are used in AM because they are relatively easy to melt with laser and therefore are suitable for LPBF. This is due to properties like near-eutectic composition that results in small solidification range compared with some high strength Al alloys, like the 7000 series [20, 21]. Up to this point, mainly conventional casting alloys such as AlSi10Mg and AlSi12 has been used for LPBF [2] because they are relatively easy to process compared to high strength Al alloys [17].

There are many challenges regarding Al in AM due to the properties of Al [4]. Al powder has high reflectivity and low laser absorption due to the wavelength commonly used in LPBF, which can result in defects [1]. Due to the high reflectivity of the Al alloy powder, to achieve a density close to 100%, the laser power has to be at least 150W with a scan speed of 50 $^{mm}/_{s}$ and with a layer thickness of 50 μm, but with a laser power of 250W, the scan speed can also be increased. This, in turn, can result in reduced quality [3].

2.4. Types of defects

There are many challenges regarding Al in AM due to the properties of Al that can result in defects like porosity, cracks, poor surface finish, shrinkage oxidation and residual stress [1, 2, 4-6].

The challenge of oxidation is that an oxide film is created on the Al powder. The fact that the powder particles are small (between 10-60 μm) [5], and the powder is lightweight makes it even more prone to oxidation [1, 6]. The oxidation film on the Al powder has a higher melting point than the powder itself, and this can result in an unevenly melted melt pool, where the Al powder is fully melted while parts of the oxidation layer are still solid [6]. The unmelted oxide is trapped inside the melt pool and result in pores and other defects in the final part. Porosity of the parts produced with LPBF is a challenge, and different types of pores can occur.

The conditions of the solidification of the Al part affects the microstructure of the part, such as the size and shape of the grains [18]. *Sc*- and *Zr*-modified Al-Mg alloys exhibit a bimodal grain size distribution, with distinct coarse-(CG), and fine-grained (FG) regions [22].

Often, Al parts produced by LPBF is prone to cracking, and the different types of cracks can occur for different reasons [23].

It is also important to note that the parameters differ from LPBF machine to machine, which means that some issues can be related to the machine and that an issue that occurs in one machine does not necessarily occur in another [1].

There are varying reasons for different defects to occur, and there can also be various reasons for the same type of defect. A combination of high laser power and low scan speed can create a large melt pool, which, in turn, can lead to a balling effect. This can influence the powder and result in defects [19].

The challenges are categorised into the following groups: *cracking, porosity, grain growth, oxidation* and *shrinkage*. Different approaches to solve these challenges are presented in the next section.

2.4.1. Proposed solutions

There are four categories of proposed solutions that are considered in this paper. These are *additives, laser power, scanning* and *powder drying*. The category *additives* contain solutions, where it is proposed to add additives to the Al alloy powder or new alloys, or alloy blends, are created to enhance the desired properties. *Laser power* contains solutions where it is proposed to either increase or decrease the laser power. This is often combined with other solutions such as changing the scanning speed. The category *scanning* includes solutions, where the scan parameters are changed, such as changing the scan speed or performing a double scan. *Powder drying* contains solutions where it is proposed to pre-dry the Al alloy powder before melting the powder.

3. Results and discussion

A total of 18 studies was considered in this paper. The approached challenges with corresponding proposals for solutions are presented in Table 1.

Research has been performed on different alloys in the collected literature, where four studies focused on Al6061 [3, 19, 21, 24], two studies analysed Al7075 [2, 19], five studies investigated AlSi10Mg [18, 25-28], one study investigated Al-12Mg, one study focused on Al5083 and five studies investigated new alloy blends or new custom developed Al alloys for LPBF [29-32]. This shows that the most researched alloy in the collected literature is AlSi10Mg. This might be due to the good weldability of this alloy, and thus is suitable for LPBF [17]. The new alloy blends and new custom alloys are presented in section 3.1.

3.1. Proposed solutions

Adding additives to existing alloys or creating new alloys or alloy blends was proposed in nine different studies, where one added *Si* to Al7075 [2] two added *Si* or *Zr* to Al6061 [19, 24], one added *Si* to AlSi10Mg [28], one added *Zr* to Al5083 [34] and four was creating new Al alloys or alloy blends with added or increased levels of *Zr* [32, 33], *Si* [30] or manganese (*Mn*) +

Table 1 Challenges and proposed solutions. The different alloys are shown by numbers; Al 6061: (1), Al 7075: (2), AlSi10Mg: (3), AlSi7Mg (4), Al-12Mg (5), Al 5083 (6) others (x). Increased laser power is marked with ↑ and decreased laser power is marked with ↓. Increased scanning rate is marked with ↑ and decreased scanning rate is marked with ↓. Double scan is marked with =. Pre-drying of powder is marked with time of drying (t) and temperature (°C). Where parameters have been adjusted both up and down with promising results it is marked with ↑↓

	Additives	Laser power	Scanning	Powder drying
Cracking	Si (2) [2] Zr (1)(2) [19] Si (1) [24] Mn, Sc (x) [29] Si (x) [30] Zr (x) [33] Si (3) [28] Zr (6) [34] Zr (x) [32]	↑↓ (1)[24] ↑ (3) [28] ↑↓ (6) [34] ↑↓ (3) [18] ↑ (2) [2]	↑↓ (1)[24] ↓ (x) [33] ↓ (3) [28] ↑↓ (6) [34] ↓ (x) [31] ↓ (x) [32] ↓ (3)(4) [27] ↑↓ (3) [18] ↓ (2) [2]	
Porosity	Zr (6) [34] Zr (x) [32]	↑ (1) [3] ↑↓ (6) [34] ↑↓ (3) [18] ↑↓ (1)[24]	↑ (1) [3] = (3) [15] ↑↓ (6) [34] ↓ (x) [32] ↑↓ (3) [18] ↑↓ (1)[24]	(3)(4) 16h, 200°C [27] (5) 1h, 100°C [35] (3) N/A h, 90°C/200°C [26]
Grain growth	Si (2) [2] Zr (1)(2) [19] Mn, Sc (x)[29] Zr (x) [33] Zr (6) [34] Zr (x) [32]	↑↓ (6) [34] ↑↓ (3) [18]	↑↓ (3) [25] ↓ (x) [33] ↑↓ (6) [34] ↓ (x) [32] ↑↓ (3) [18]	
Oxidation		↓ (1) [21]	↑ (1)[21]	
Shrinkage				

scandium (*Sc*) [29]. *Zr* and *Si* were added in four studies each, where *Mn* and *Sc* were only added in one study.

In the study by Jia, et al. [29] it was found that adding Mn + Sc improved the processability of the Al alloy and therefore created an Al-Mn-Sc alloy with high thermal stability. Casati, et al. [30] investigated the effect of Si addition and created two new alloy blends based on the Al7068 alloy. They added different amounts of Si to the alloy (3 wt% and 4.5 wt%) to create a new Al-Zn-Si-Mg-Cu alloy. The experiment showed that the mix with 3 wt% Si show fewer cracks than without any Si addition, while the mix with the 4.5 wt% Si resulted in no cracks with full density. As a result, a new Al-Zn-Si-Mg-Cu alloy was developed, which had close to full density with no cracks.

Zr was added to an Al-Cu-Mg alloy by [33], which together with decreasing the scan speed resulted in ultrafine grain growth and the elimination of cracks. The pores, however, was not eliminated, but they become more regular in shape and achieved up to 99.8% density. Zhou, et al. [34] added *Zr* to Al5083 and found that this resulted in near full density and a negligible number of cracks and pores. By adjusting the laser power and scan speed, the authors found that increasing both laser power and scan speed resulted in just as good results as decreasing both the laser power and scan speed. Nie, et al. [32] also used *Zr* as an additive, but in an Al-Cu-Mg-Mn alloy together with changing the scan speed. The results showed that the addition of *Zr* together with decreased scan speed resulted in smaller grains and fewer cracks and pores.

Si is a popular additive in the considered literature, which also was researched by Hanemann, et al. [28] that made two different blends of AlSi10Mg powder and Si powder, 25wt% and 50wt% of *Si,* respectively. The authors investigated different laser powers and scan speeds and found that with increased laser power and decreased scan speed, fewer cracks occurred. However, this also resulted in reduced density and increased number of pores due to unmelted powder.

Some of the studies proposed to adjust the process parameters, and in this paper, the laser power and the scan speed have been considered. These two parameters were sometimes adjusted together, where one was increased while the other one was decreased [18, 24, 28, 34]. This solution was proposed for addressing cracking, porosity and grain growth challenges. Adjustment of either the scan speed, while the laser power was kept the same, or the laser power was proposed in [15, 25, 27, 31-33]. Adjusting the laser power while keeping the scan speed stable was not proposed in any of the studies. Aboulkhair, et al. [15] proposed in their study to do a double scan, which means that first a scan with half laser power needs to be performed, and then a scan with full laser power should be used. As a result, reduction of pores has been achieved.

In some of the studies, multiple combinations of laser power and scan speed was investigated, and it was concluded that different laser power and scan speed combinations could give satisfying results [18, 25, 34]. In [3], the goal was to reduce the build time, while also achieve parts with high density and little imperfections such as pores. They concluded that if both the laser power and scan speed was increased, it was possible to produce dense parts with little pores in a shorter time.

It should also be noted that some of the studies used energy density as their measure of adjustment, which is a function of laser power, scan speed, hatch spacing and layer thickness [36]. This, however, was not considered in this study. Adjusting the laser power and scan speed was proposed as a solution for the cracking, porosity, grain growth and oxidation challenges.

The study by Yang, et al. [27] showed that when the scan speed was decreased, fewer cracks occurred. They also investigated different ways to pre-dry the powder and found that pre-drying resulted in fewer pores. Pre-drying of the powder was also investigated by Weingarten, et al. [26] and Li, et al. [35], but only as a solution for less porosity.

3.2. Categorised challenges

The collected studies indicate that cracking is the most researched challenge with 12 studies approaching this issue [2, 18, 19, 24, 27, 28, 30-34]. Adding additives was proposed by nine studies, adjusting laser power and scan speed is proposed by five studies and adjusting the scan speed without adjusting the laser power is considered by four studies. Except for the several studies [19, 29, 30], cracking issue has been addressed by using additives or creating new alloy blends in a combination with adjusting laser power and/or scan speed.

The porosity issue was covered by nine studies [3, 15, 18, 24, 26, 27, 32, 34, 35]. This was the only issue that had pre-drying of the powder as a proposed solution [26, 27, 35]. In this work, only those studies, who have explicitly reported that their solutions resulted in decreased amount or size of pores, are included in the category *porosity*.

Grain growth was mentioned by multiple studies, but only those, who talked about a change in the grain growth as a result, was mentioned in the category *grain growth* [18, 19, 25, 29, 32-34]. Only Thijs, et al. [25] looked solely on the grain growth without considering any of the other challenges that are mentioned in this paper.

Oxidation was only covered by Louvis, et al. [21]. However, oxidation can be a source of defects such as pores and can, therefore, be indirectly covered by other studies that cover e.g., porosity issue.

As can be seen from Table 1, despite the importance of the dimensional accuracy for the automotive industry, the shrinkage effect has not been addressed in current state-of-the-art.

3.3. Interconnected problems

In Table 1, the defects, namely porosity, cracking and unsatisfying grain growth, are related to the microstructure, while oxidation is a chemical reaction and shrinkage effect can be considered as a geometrical change. Both shrinkage and oxidation can lead to defects such as porosity and cracks [4, 21], and therefore this might be covered implicitly in the other categories.

Solutions for one issue do not necessarily solve all issues, or in some cases, it could lead to new challenges. For instance, in the study [19], large cracks were eliminated by the addition of *Zr*, but residual pores still occurred. In the study [28], the number of cracks was reduced with the addition of *Si* and adjustment of laser power and scan speed, but it also resulted in an increased amount of pores.

Some of the studies have presented the test parts with heat-treatment, which has an effect on the strength of the test parts. This can have influenced the mechanical properties of the test part, but it requires more time and is a less cost-effective solution. As a result, any post-processing of Al parts produced by AM technology has not been included in this work.

3.3.1. Identified gaps

Shrinkage was not the subject of direct investigation in any of the considered literature, and this indicates a big gap in the research of Al in AM. Shrinkage effect has been considered indirectly in the literature since it could be a root cause for other defects, which are analysed in this work.

No studies were performed to investigate possible solutions of pre-drying the powder to deal with the challenges regarding cracking, grain growth, oxidation or shrinkage. Pre-drying of the powder might influence the oxidation of the powder, which, especially with regards that oxidation can lead to pores. Pores were the only challenge approached with pre-drying of the powder. If powder drying can influence grain growth, it could also influence the appearance of certain types of cracks.

Oxidation was only investigated in one study [21] where the laser power and scan speed was adjusted. The lack of understanding of how oxidation can be reduced by adding additives to the Al alloys or pre-drying powder before using it is another research gap present in the current state-of-the-art. Thus, more focus needs to be directed towards the investigation of other solutions for oxidation effects. Besides, a dependence between different types of defects needs also to be investigated in more detail. By establishing an interdependence between different issues, a better understanding of possible solutions could be achieved.

Development of the new alloys, on the one hand, is considered as one of the solutions for the presented issue in additive manufacturing of aluminium. A number of studies has proposed using different Al alloys, which result in different types of defects. As a result, there is a lack of understanding of how laser powder bed fusion process parameters need to be adjusted to benefit from the new alloys. On the other hand, there is a significant number of studies, which focused on the AlSi10Mg alloy due to its weldability properties. Even though this alloy has gained more attention from the researchers, yet oxidation and shrinkage effect is not investigated for this alloy.

4. Conclusion and future work

In this paper, a brief review of proposed solutions for challenges of Al in LPBF was presented. The considered challenges were cracking, porosity, grain growth, oxidation and shrinkage effect. The considered solutions were adding additives to the Al alloy powder, adjusting laser power and scan speed, and pre-drying of the Al alloy powder. From this, some conclusions can be drawn:

1. The cracking in Al parts produced with LPBF is the most approached issue. The usage of additives in the Al alloy powder and adjustment of the scan speed is the most frequently proposed solutions for this issue.
2. Optimization of the scan speed was the most investigated solution and was proposed for the majority of the issues such as cracking, porosity, grain growth and oxidation.
3. Only three studies have proposed to use pre-drying as a solution for porosity.
4. The least covered challenges were oxidation and shrinkage, where oxidation was covered in only one study and shrinkage was not covered in any of the considered studies.

Since solutions for shrinkage effect and oxidation have not been presented in the current state-of-the-art, it would be of interest to address these gaps in future works. Besides, evaluation of interdependence between various issues could result in a better understanding of cause-effect relationships between material behaviour and other parameters. Additionally, more attention should be paid to variations in the quality of Al parts that could be a result of using different laser powder bed fusion machines. In other words, in order to be able to use AM for production of the aluminium products, from machine to machine variations should be investigated in future work.

Acknowledgements

This research is funded by the Department of Manufacturing and Civil Engineering at the Norwegian University of Science and Technology.

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