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DEFECTS IN ELECTRON BEAM MELTING: A BIBLIOMETRIC ANALYSIS

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RESUMO

Abstract

Metal Powder Bed Fusion technologies have been increasingly applied for end-use part production over the last years, with important contributions to the medical and aerospace sectors. Despite the rapid and constant improvement, additively manufactured parts still can't fully comply with the strict quality standards associated with these industries, being a major barrier for the broader adoption of such technologies. The purpose of this study was to identify the trends and main research topics on defects in Electron Beam Melting (EBM) through a bibliometric analysis. Bibliometrics is a quantitative statistical analysis of scientific publications that provides an overview of the structured knowledge in a given research topic. The results reveal a worldwide growing interest in the topic over the last 10 years, mostly focused on titanium alloys and defects such as internal porosity and elevated surface roughness. The influences of such defects in the mechanical performance of parts are extensively studied by the scientific community, including post-processing treatments such as hot isostatic pressing (HIP) and surface finishing. The findings obtained by this study should enhance the understanding of how this research field is evolving and how it is structured worldwide.

1. Introduction

Until very recently, additive manufacturing (AM) processes were commonly referred to as rapid prototyping, which reflects what is still to date the main application of these technologies. However, the last 10 years have seen exponential growth in expenditure for end-use parts production by AM processes as shown in Figure 1 [1]. Layer-by-layer additive methods allow the creation of complex shapes usually impossible to achieve through traditional manufacturing techniques while eliminating the need for specific tooling and enabling mass-customization at low costs [2]. AM would also have a positive impact on the environment through localized production and higher efficiency in raw material processing [3].

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Figure 1. Annual expenditure on final part production by AM worldwide, in billions of dollars (US$). Adapted from [1].

Electron Beam Melting (EBM) is a powder bed fusion (PBF) process defined by ISO/ASTM 52900 as a “process in which thermal energy selectively fuses regions of a powder bed”. EBM differs from other PBF processes by using a high-energy electron beam rather than a laser to melt metallic powder material. EBM is known for processing titanium alloys more efficiently than other PBF processes due to the higher absorption capacity of electron beams in these materials and for the higher scanning speeds provided by its electromagnetic control [4]. The metallic parts produced are free of residual stresses as the manufacturing chamber is kept at high temperatures (650°C to 1000 °C) and by such eliminating the need for thermal post-processing for stress relieving. EBM technology is often applied by the aerospace industry, most noticeably for manufacturing high-performance jet engine blades for the new Boeing 777X [5]. The medical area also benefits from the flexibility offered by additive manufacturing techniques, so much that by the end of 2018 over 100,000 hip cup implants were successfully produced by EBM [6].

Unfortunately, PBF processes are notoriously known for problems of repeatability and reproducibility, partially due to the high complexity associated with these processes and the difficulties that remain in understanding and controlling them [7]. In addition, parts manufactured specifically by EBM display a level of quality that is insufficient for many industrial applications [8]. In truth, Vo et al. [9] attribute poor part quality and repeatability as the biggest barriers to broader adoption of PBF processes in the industry. Most of the quality issues associated with EBM originate from defects classified by Cooke and Soons [10] into 4 distinct groups: (1) geometric and dimensional defects, (2) surface defects, (3) microstructure, and (4) mechanical properties. The many potential causes of quality-related defects in EBM are constant objects of study by many authors who aim to identify and analyze the phenomena behind its occurrence. Grasso and Colosimo [11] categorize the sources of errors in metallic PBF processes into three distinct groups, with Sames et al. [12] adding a fourth:

1. **Equipment-induced defects**, such as those generated by failures in the electron beam scanning system, in the raw material deposition system, optical aberrations due to lack of calibration, disturbances in the manufacturing chamber environment, among others.

2. **Process-induced defects**, such as the thermal expansion of the material, instabilities in the melt pool, warping, electrostatic repulsion, vaporization of the metallic material, among many others.

3. **Defects originated from the 3D digital model**, including those generated during the

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conversion and approximation of CAD files onto triangular meshes surfaces.

4. **Powder-induced defects**, directly related to the metallic feedstock material quality.

Sames et al. [12] also emphasize the importance of understanding quality-related issues and the mechanisms associated with them as they contribute to a better understanding of the physical phenomena and consequently help to improve the quality and reliability of the process as a whole. This consists of a crucial milestone for a breakthrough of EBM in the industry as an end-use part manufacturing method. With this in mind, the present study focuses on exploring the research trends on defects associated with EBM using bibliometric tools and indicators. The most cited publications were closely analyzed to identify the main research topics and the lines of studies in development. While there have been review articles on process-related defects in EBM, none has used such an exploratory approach and methodology of this work.

2. Materials and Methods

Bibliometric analysis is a quantitative research method that evaluates measurable data from academic publications through mathematical and statistical techniques. It relies on large publication databases and provides an overview of a scientific field from which a deeper analysis can then be performed. This study was based on data acquired from books, journals and proceedings indexed on the Web of Science (WoS) database. The data collection was performed at the WoS online search platform and was done iteratively to obtain the most relevant dataset within the target subject area. The search terms that revealed to be most suitable are displayed in Table 1. These terms were searched in titles, abstracts, and keywords of indexed papers published between 2011 and 2020, with the data collection performed in October 2020.

Table 1. Search terms used for dataset collection at the Web of Science database.

Topic	**Operator**	**Term**
1	-	"*Additive Manufacturing*", "AM"
2	*AND*	"*Electron Beam*", "*Electron Beam Melting*", "*Selective Electron Beam Melting*", "*EBM*", "*SEBM*"
3	*AND*	"*Defect*"

The initial dataset of publications was exported and each publication was analyzed, one by one, to verify its compatibility and relevance to the study. Around 35% of all publications were discarded for being related to other manufacturing processes, such as laser PBF and other electron beam processes (wire feed, welding), as well as EBM publications unrelated to defects altogether. By such, the final dataset was guaranteed to have only relevant data for the subsequential processing

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and analysis.

The data were mostly processed using Microsoft Excel, except for the keyword analysis which was performed by the VOSviewer software. This analysis examines the occurrence of keywords in a database and evaluates their relationships according to their correlation. A keyword co-occurrence network (KCN) is a graphical representation of the most outstanding keywords in a database and how they relate with each other, thus providing meaningful insights on knowledge patterns of a research area [13]. Both the author’s keywords and those generated by the WoS database (Keywords Plus®) were considered for this analysis. Some keywords had to be standardized so that they were counted correctly. For example, “Ti-6Al-4V” and “Ti6Al4V”, although spelled differently, have the same meaning and should be considered equivalent. The KCN was created with keywords with a minimum occurrence of 7 times.

Finally, the 20 most cited publications from the dataset were further studied as they are considered the most useful and important publications in the area [14].

3. Results

The final dataset was composed of 156 research papers published between January 2011 and October 2020. There has been a gradual increase in the number of articles published in the period as shown in Figure 2. This considerable growth reveals the importance and current relevance this subject has gained over the last years, confirming the premise of this study and its initial motivation. The dataset is mostly composed of articles published in journals (82%), with the remaining being proceedings papers (13%) and reviews (5%). Table 2 shows the 10 journals with the most publications on the topic, which combined account for more than half (55%) of all articles and reviews from the dataset. By far the most studied material in the dataset is Ti-6Al-4V (72%), followed by Inconel 718 (17%) and Ti-48Al-2Cr-2Nb (4%). Other materials include Stainless Steel (316L), Co-Cr-Mo, and other Titanium alloys.

Figure 2. Total number of publications per year (from January 2011 through October 2020).

Table 2. Top 10 journals in number of publications on the topic.

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Source	**Number of Publications**
Additive Manufacturing	13
International Journal of Fatigue	11
Materials Science and Engineering	10
Materials	9
Materials Characterization	7
Acta Materialia	5
Journal of the Minerals, Metals & Materials Society (JOM)	5
Journal of Alloys and Compounds	5
Journal of Materials Engineering and Performance	5
Journal of Materials Processing Technology	5

The analysis performed by the VOSviewer software showed a total of 26 different keywords with a minimum frequency of 7 occurrences each. The correspondent KCN of this analysis is seen in Figure 3 as a density map, which highlights the most important regions within the bibliometric study [13]. The map follows a thermal color palette, in which the color intensity assigned to each item refers to the total number of occurrences of that keyword while their positions on the map reveal the strength of the correlations among their neighbors. The central cluster, with warmer colors, is composed of the following keywords: “Microstructure”, “Mechanical Properties”, “Fatigue”, “Surface roughness” and “Ti-6Al-4V”, together with the ones directly related to the search terms such as “Additive manufacturing” and “EBM”. Other keywords with high occurrence include “Porosity”, “Heat treatment”, “Titanium Alloy” and “Laser”.

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Figure 3. Density keyword co-occurrence network (KCN) based on the dataset collected.

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The 20 most cited publications are responsible for 64% of all the 5021 citations from the 156 publications in the dataset. More than half of these articles are experimental works focused on either (1) characterizing and understanding defect generation in EBM, (2) verifying the influence of defects on the mechanical performance, or (3) analyzing the effectiveness of post-processing treatments and mitigation strategies for avoiding defects. The remaining are composed of bibliographic reviews and articles presenting mathematical simulation models of the EBM process with respect to defect generation. Out of the 20 most cited publications, the defects analyzed were mostly porosity and elevated surface roughness, sometimes simultaneously and often presenting solutions for mitigation or further post-processing.

4. Discussion

The growing interest in EBM process defects by the academic community is illustrated by the increasing number of publications covering the topic over the last years (Figure 2). This growth pattern is similar to the annual expenditure on end-part production by AM shown in Figure 1, a relation that is very coherent since current fabrication standards are very strict concerning the overall part’s quality.

Moreover, both the KCN (Figure 3) and the analysis of the most cited publications showed great concern with the mechanical performance of as-built parts produced by EBM, specifically those related to fatigue. In fact, the International Journal of Fatigue is the second journal in number of publications within the dataset, with 11 articles. Although mechanical properties are determined mainly by their microstructure, they are also strongly influenced by micro and macroscopic physical defects. Internal porosity and surface roughness are both notoriously known for their negative influences on static and on dynamic performance [15, 16].

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The concern with mechanical properties and fatigue life could be explained partially due to the great interest of both aerospace and medical industries in EBM, where components are frequently subjected to cyclical efforts. This hypothesis is also supported by the materials studied by the publications, in which Ti-6Al-4V is predominant. This alloy is best known for its low density and superb mechanical properties, being originally developed for aircraft structural applications. Ti-6Al-4V is also widely used for producing medical implants as it presents high biocompatibility and corrosion resistance.

The most prominent post-processes used in EBM parts are hot isostatic pressing (HIP) and surface finishing processes such as machining and shot peening. These are often applied for addressing internal porosity and surface roughness, respectively, and both their effectiveness and influences on overall mechanical properties are the main subject of many publications within the dataset. Mitigation strategies such as process parameter optimization are also often proposed, being verified usually through experimental (DoE) studies or computer simulation. Finally, different non-destructive inspection methods like X-ray computed tomography (XCT) are extensively applied and studied in order to access the internal integrity of EBM manufactured parts, mostly in regards to porosity and crack initiation. *In-situ* monitoring and control systems have also been proposed by many publications, where both hardware and software systems are being developed.

5. Conclusions

This study has provided an overview of research activities and trends in process defects in EBM via a bibliometric analysis of scientific publications from the last 10 years. A total of 156 publications composed the final dataset used for the analysis that leads to the following conclusions:

· Most studied materials in regards to EBM process defects are Ti-6Al-4V (72%), Inconel 718 (17%) and Ti-48Al-2Cr-2Nb (4%).

· Internal porosity and surface roughness are the most common defects addressed by the publications.

· Process defects greatly influence mechanical properties, especially fatigue performance associated with porosity and surface roughness.

· Post-processing techniques such as HIP and surface finishing processes are largely applied for addressing the afore-mentioned defects, and their effects on mechanical properties and microstructure are the focus of numerous publications within the dataset.

· Defect mitigation strategies such as process parameters optimization are widely studied, either through experimental studies or simulation.

· X-ray computed tomography is the main non-destructive inspection method for checking and measuring internal defects such as porosity. *In-situ* monitoring is also a popular solution proposed to access the internal integrity of parts during the manufacturing process.

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PALAVRAS-CHAVE: Additive Manufacturing, Electron Beam Melting, EBM, Bibliometric Analysis, Defects

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