

Review

Titanium Additive Manufacturing with Powder Bed Fusion: A Bibliometric Perspective

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Abstract: Titanium additive manufacturing using powder bed fusion technologies has seen notable growth since 2015, particularly in high-performance sectors such as aerospace, biomedical, and automotive industries. This study focuses on key areas like metallic powder manipulation, laser optimization, and process control, with selective laser melting emerging as the dominant technique over electron beam melting. Advancements in powder materials and laser systems have been crucial to improving the efficiency and quality of the process, particularly in enhancing microstructure and porosity control. The bibliometric analysis reveals significant global interest, driven mainly by collaborations among institutions in Germany, the United States, and China, where further international cooperation is required to scale titanium additive manufacturing. However, additional research is essential to address challenges in scalability, sustainability, and post-processing, thus expanding the applications of PBF technology across industries. In conclusion, titanium processing via powder bed fusion is poised to make substantial contributions to the future of manufacturing, provided current challenges are addressed through innovation and enhanced global collaboration.

Keywords: titanium; additive manufacturing; 3D printing; powder bed fusion; materials science; bibliometric review



Citation: del Bosque, A.; Fernández-Arias, P.; Vergara, D. Titanium Additive Manufacturing with Powder Bed Fusion: A Bibliometric Perspective. *Appl. Sci.* **2024**, *14*, 10543. <https://doi.org/10.3390/app142210543>

Academic Editor: Zhonghua Sun

Received: 22 October 2024

Revised: 8 November 2024

Accepted: 13 November 2024

Published: 15 November 2024



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1. Introduction

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized various industrial sectors by enabling the efficient and precise creation of complex and customized geometries [1,2]. This technology builds objects layer by layer from digital models, offering significant advantages in terms of design flexibility, material savings, and the ability to produce complex structures that are difficult or impossible to achieve with traditional manufacturing methods [3]. Printing metals is significantly more challenging and costly compared to polymers due to the higher temperatures and controlled atmospheres required for melting metals, as well as the need for more advanced equipment to handle these conditions. Additionally, achieving the desired material properties in metals demands greater precision and control, further increasing the complexity and expense of the process [4].

Among all the metals, titanium possesses exceptional properties, which make it highly valuable in various high-performance applications. Titanium exhibits an outstanding strength-to-weight ratio, making it suitable for aerospace and automotive components where reducing weight without compromising strength is crucial [5–7]. Here, spare parts management is important in these sectors [8,9]. Its excellent corrosion resistance extends its utility in harsh environments, such as marine and chemical processing industries [10]. Moreover, titanium's biocompatibility makes it the material of choice for medical implants and devices [11–15]. The ability to produce complex titanium parts efficiently and with high precision through AM could lead to significant advancements in these critical industries. For this reason, significant efforts have been made to optimize the AM of titanium.

AM is dominated by two primary techniques: powder bed fusion (PBF) and directed energy deposition (DED). On the one hand, PBF involves spreading a thin layer of powder material over a build platform, which is then selectively fused by a heat source, such as a laser or electron beam, to form a solid layer. This process is repeated layer by layer to create the final part [16]. On the other hand, directed energy deposition uses a focused energy source to melt materials as they are being deposited [17]. Both techniques have their unique advantages and are chosen based on the specific requirements of the application.

PBF includes a variety of specialized techniques, each with unique features and uses. The main processes are selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM). SLM uses a high-powered laser to fully melt and fuse metallic powders, resulting in dense and strong parts [18,19]. On the other hand, SLS uses a laser to sinter powdered material without fully melting the particles, operating at lower power levels compared to SLM [20,21]. Both techniques (SLM and SLS) require controlled atmospheres, such as argon or nitrogen, to enhance corrosion resistance or an oxygen-controlled environment, for example, to optimize the microstructure of titanium [22,23]. EBM employs an electron beam as the heat source, offering high efficiency and the ability to work in a vacuum environment, which is particularly beneficial for processing reactive materials like titanium [24,25]. Each of these techniques has its advantages, making them suitable for different applications within the field of additive manufacturing.

Another major technique of additive manufacturing, DED includes advanced techniques such as laser cladding and direct deposition using wires or powders. Laser cladding utilizes a laser to melt and deposit feedstock onto a substrate, creating a strong bond and enhancing surface properties [26]. Direct deposition builds parts layer by layer, either by melting powder with a high-energy source or by using a continuous feed of metal wire [27]. Despite its versatility and benefits, DED is less commonly used in industrial and research settings compared to PBF [28–30]. This is due to its typically lower resolution and higher costs associated with the equipment and materials.

For the sake of clarity, Figure 1 illustrates the principal processes used in titanium additive manufacturing, as mentioned above.

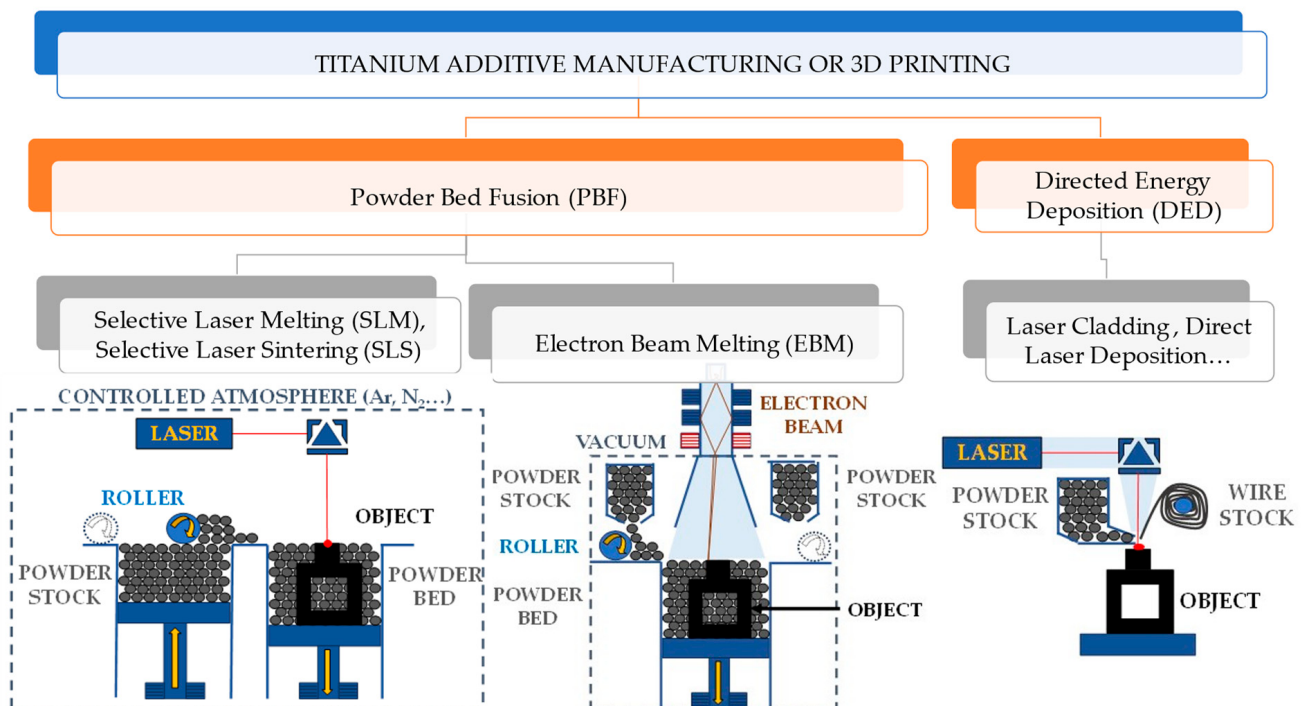


Figure 1. Schematic of the principal processes used in titanium additive manufacturing.

The evolution of research interest in titanium AM is closely aligned with advancements in high-performance industries, particularly aerospace and biomedical sectors. As demand for lightweight, high-strength materials grows, AM has emerged as a viable solution for complex, customized titanium components, indicating that industry needs to significantly drive research activity and innovation. Within this landscape, PBF and DED have established themselves as dominant approaches, each with distinct advantages and adoption patterns. PBF is preferred for high-resolution components in aerospace and medical applications where precision is paramount, while DED excels in producing larger parts and facilitating repairs, finding applications in heavy machinery and aerospace component maintenance. This differentiation highlights the complementary nature of these methods, with each fulfilling specific needs in the titanium industry and contributing to the overall advancement of AM technologies.

Titanium alloys are extensively utilized in both research and industry because of their exceptional properties. The most common titanium alloys include Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo, and Ti-5Al-2.5Sn. Ti-6Al-4V, also known as Grade 5, is the most prevalent alloy, offering an excellent balance of strength, corrosion resistance, and weldability [31–34]. It is extensively used in aerospace for components such as turbine blades, in the biomedical field for implants and prosthetics, and in automotive and marine industries for high-performance parts. Ti-6Al-2Sn-4Zr-2Mo is used in high-temperature applications, particularly in jet engines and airframe structures, due to its superior creep resistance [31,32]. Ti-5Al-2.5Sn, known for its good weldability and moderate strength, is often used in airframe and cryogenic applications [35,36]. These alloys continue to be a focus of intensive research to further enhance their properties and expand their applications in various high-performance industries.

Computational simulations have become invaluable tools for understanding and predicting complex thermal histories, phase transformations, and resulting microstructures in PBF-manufactured titanium materials. These simulations enable researchers and engineers to optimize process parameters, predict material properties, and improve the quality and performance of components. By integrating multi-scale modeling approaches, from thermal-fluid simulations of melt pool dynamics to microstructure evolution predictions, computational frameworks can provide comprehensive insights into the PBF process for titanium alloys, facilitating the development of tailored microstructures and properties for specific applications [37,38].

Despite significant advancements in titanium additive manufacturing, technical and scientific challenges persist that require a deeper understanding, including aspects such as the quality and consistency of the produced material, mechanical and microstructural properties, and process parameter optimization. In this context, a bibliometric review can provide a comprehensive overview of the current state of research, identifying trends, gaps and future opportunities in this field. Specifically, this review seeks to answer the following research questions: What are the primary thematic trends and key research areas in titanium AM by PBF? How has the geographic distribution of research impacted the development of titanium AM by PBF? Which process parameters and materials dominate the field, and what gaps remain for future exploration? In this regard, the primary objective of this article is to conduct a bibliometric review of research related to titanium AM using PBF technology. Thus, the most relevant scientific publications and notable advancements are analyzed in this paper. This analysis will enable a better understanding of the development of this technology and provide a solid foundation for future research.

2. Materials and Methods

The bibliometric methodology employed in this study comprises five distinct phases (Figure 2). Phase I, Literature Selection: this initial stage involves the careful identification and selection of relevant scholarly works, ensuring a comprehensive and representative sample for analysis; Phase II, Data Collection and Organization: during this phase, bibliometric data are systematically gathered from the selected literature and meticulously

organized into a structured database for further analysis; Phase III, Comprehensive Data Analysis: this crucial stage entails a thorough examination of the collected bibliometric data, employing various statistical and analytical techniques to uncover patterns, trends, and relationships within the literature; Phase IV: Data Visualization: the analyzed data are transformed into visual representations, such as graphs, charts, and network maps, to facilitate a clearer understanding and interpretation of the findings; Phase V, Synthesis and Conclusion: the final phase involves synthesizing the insights gained from the analysis and visualization stages, leading to the formulation of well-supported conclusions and implications for the field of study.



Figure 2. Research methodology phases.

In Phase I (Figure 2), we selected studies from Scopus and Web of Science databases to ensure comprehensive coverage of scientific publications, focusing on peer-reviewed sources of high quality and relevance. These databases provide robust indexing and a wide disciplinary reach, essential for conducting reliable and replicable bibliometric analyses. This choice enabled access to a diverse array of peer-reviewed sources—including journals, conference proceedings, and books—thereby enriching the breadth and depth of our literature review. The data collection process was conducted in September 2024. To guarantee an exhaustive and targeted search, multiple keywords were combined using Boolean operators (Figure 3). This approach ensured the identification of the most relevant articles on the topic.

SEARCH STRING: SCOPUS AND WEB OF SCIENCE
TITLE-ABS-KEY
((metal" OR "metals") AND ("additive manufacturing" OR "3d printing"))
AND
("powder bed fusion")
AND
("titanium" OR "ti*")

Figure 3. Bibliometric database search string.

In order to select and organize the results found on research related to titanium AM using powder bed fusion technology and to enable its subsequent analysis (Phase II, Figure 2), the PRISMA 2020 protocol was used [39]. The PRISMA 2020 protocol is a fundamental tool for bibliometric analysis, as it provides a structured and transparent guide for the elaboration of reviews [40–42]. Here, an initial broad search included journal articles, conference proceedings, and books to ensure comprehensive coverage. However, subsequent filtering focused on peer-reviewed journal articles, as these provide the higher consistency and rigor essential for robust bibliometric analysis.

In the context of bibliometric analysis, the PRISMA 2020 flow diagram provides a clear and structured visualization of the study selection process, improving the transparency and reproducibility of bibliometric reviews [43–45]. This diagram consists of several key phases (Figure 4): (i) Identification: A total of 2675 records were identified in the two databases, of which 382 were duplicates; (ii) Screening: After the initial review of the identified records, 4 were excluded for being outside the scope of this research; (iii) Eligibility: A total of

2289 results reached this phase, of which 516 were excluded for not being articles, and 451 were excluded for being articles in languages other than English; (iv) Inclusion Phase: A total of 1322 articles was the final number included in this bibliometric research.

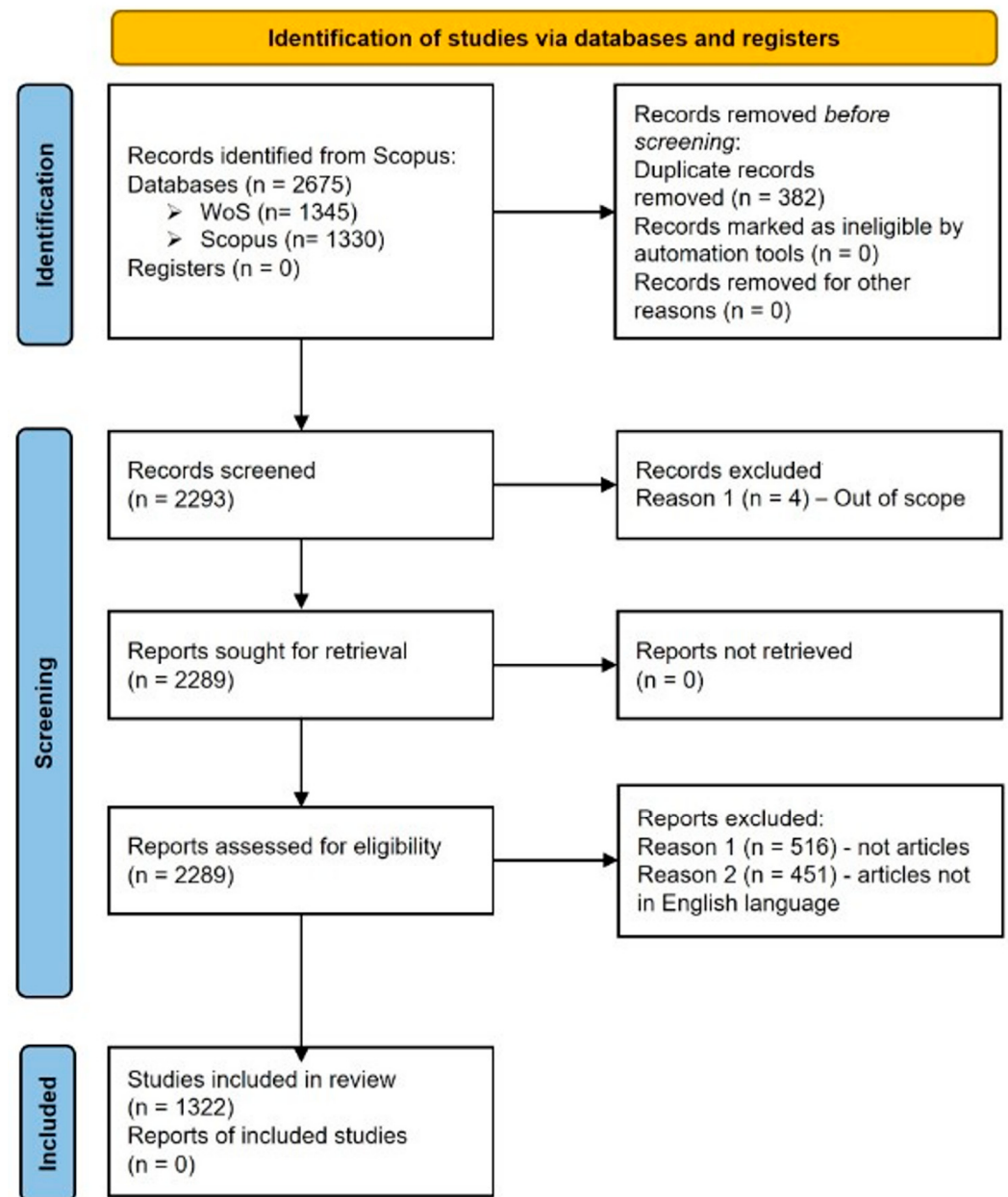


Figure 4. PRISMA 2020 checklist developed in this bibliometric review.

Following the development of the PRISMA 2020 protocol, the subsequent bibliometric analysis (Phase III, Figure 2) was conducted using the specialized software, the Bibliometrix R-4.4.2-package. Bibliometrix offers a wide range of analytical tools, from basic descriptive statistics to advanced techniques such as co-citation networks and factorial analysis. For this reason, the level of development and significance of research is assessed through bibliometric methodology that examines publication trends, citation patterns, co-occurrence networks and thematic mapping. Key metrics, including publication growth, citation frequency, and thematic clustering, provide a comprehensive view of the research landscape.

3. Results

Using the RoB2 tool (version 22 August 2019), the overall bias assessment [46,47] for the 1322 included papers (Figure 5) revealed that 58% (767 studies) were identified as having a low risk of bias across all five domains. Additionally, 24.6% (325 studies) showed ‘some concerns’ in at least one domain, while 1.5% (20 studies) were classified as having a high risk of bias in at least one of the five domains. In terms of overall bias, 67% (886 results) were classified as low risk, while 31% (410 results) were classified with ‘some concerns’, and only 2% (26 results) were considered high risk. This distribution suggests that the literature on titanium AM with PBF is generally robust, with a high proportion of studies demonstrating adherence to rigorous standards. However, the small fraction of high-risk studies points to areas where improvements in methodological transparency and standardization would be beneficial, especially as the field continues to grow and evolve.

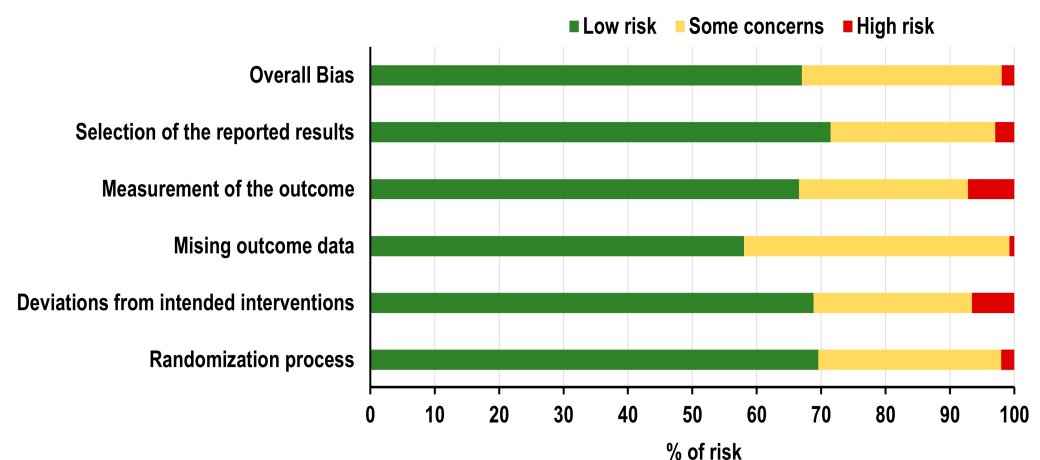


Figure 5. Analysis of risk of bias.

Figure 6 presents a comprehensive overview of bibliometric data, offering insights into the characteristics and trends of a specific body of the research literature. Spanning from 2015 to 2025, the dataset encompasses 1322 documents from 307 distinct sources, including journals and books. The bibliometric review begins in 2015, as previous years show only one or no articles published annually on this topic. However, from 2015 onward, there is a marked increase in research interest and scientific output. The research field demonstrates significant growth, with an impressive annual growth rate of 14.87%. Despite the relatively young average age of documents at 2.15 years, the literature shows a substantial impact, with an average of 25.91 citations per document. This high citation rate suggests that the research in this field is not only current but also highly influential and frequently referenced by other scholars.

The analysis reveals a diverse and collaborative research landscape. With 4456 authors contributing to the body of work, there is a strong tendency towards collaborative research, as evidenced by the average of 5.6 co-authors per document. However, the international collaboration rate of 7.067% indicates that there might be room for increased global cooperation in this field.

Regarding the evolution of annual scientific production in this field, the presented data show a clear growth trend in the number of publications over the past decade, from 2015 to 2024 (Figure 7). A significant year-on-year increase is observed, starting with a single publication in 2015 and reaching a peak of 275 in 2023. This growth is particularly notable from 2018 onwards, where a considerable jump in the number of publications can be seen. The average annual number of publications during this period is 132.2, but this figure does not fully capture the trend, as the most recent years show much higher numbers than the average.

DESCRIPTION	RESULTS
MAIN INFORMATION ABOUT DATA	
Timespan	2015:2024
Sources (Journals, Books, etc)	307
Documents	1322
Annual Growth Rate %	14.87
Document Average Age	2.15
Average citations per doc	25.91
References	0
DOCUMENT CONTENTS	
Keywords Plus (ID)	6451
Author's Keywords (DE)	2912
AUTHORS	
Authors	4456
Authors of single-authored docs	13
AUTHORS COLLABORATION	
Single-authored docs	14
Co-Authors per Doc	5.6
International co-authorships %	7.067
DOCUMENT TYPES	
article	1172
article; early access	1
article; proceedings paper	3
conference paper	3
data paper	2
note	1
review	131
review; book chapter	2
review; early access	1

Figure 6. Main information about research results.

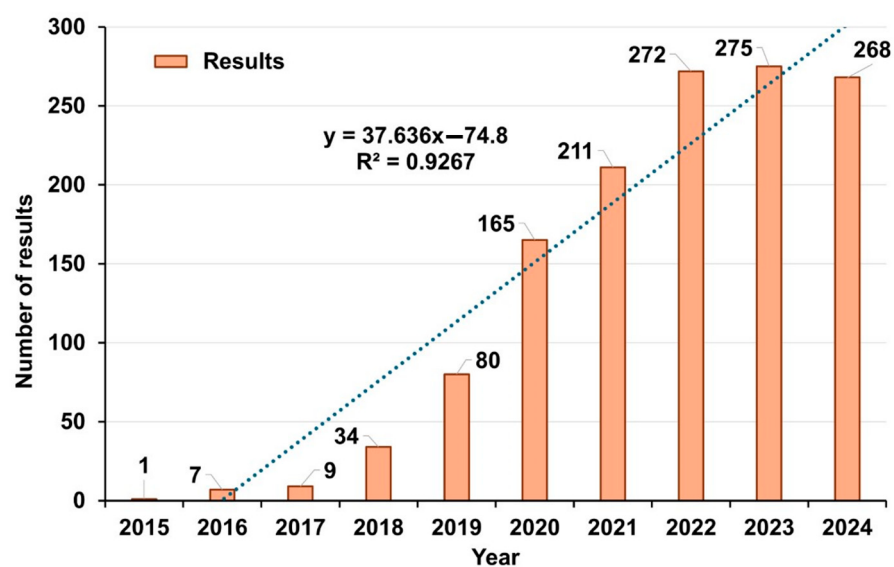


Figure 7. Annual scientific production evolution.

The high standard deviation (121.14) reflects the large spread in the data, which is expected given the rapid increase in publications over time. The compound annual growth rate (CAGR) of 90.67% indicates exponential growth in the field. Using the linear interpolation method $y = mx + b$, the following results are obtained: m (slope) ≈ 37.63 and b (y-intercept) ≈ -74.8 , with regression coefficient $R^2 \approx 0.962$, indicating a strong positive correlation between the data and an average growth of 37 publications per year. The slight drop in results for 2024 is since it is the current year, and it is likely that the final number will exceed 300, consolidating the trend observed since 2015. Overall, these data suggest a rapidly expanding field of research with increasing interest from the scientific community.

The same trend can be observed in the evolution of scientific publications and their impact over time (Table 1). The number of articles (N) shows exponential growth, rising from 1 in 2015 to 272 in 2023, indicating a significant increase in scientific output. The average citations per article (Mean TC per Art) notably increased in 2016 and 2017, with an average exceeding 20. However, since 2020, the individual impact of each article, as measured by citations, has significantly declined.

Table 1. Average citation per year.

Year	Mean TC per Art	N	Mean TC per Year	Citable Years
2015	30	1.00	3.00	10
2016	269.14	7.00	29.90	9
2017	183	9.00	22.88	8
2018	65.91	34.00	9.42	7
2019	68.17	80.00	11.36	6
2020	49.93	165.00	9.99	5
2021	33.9	211.00	8.47	4
2022	18.05	270.00	6.02	3
2023	8.26	272.00	4.13	2
2024	1.25	263.00	1.25	1

An interesting aspect is the relationship between citable years (Citable Years) and the average citations per year (Mean TC per Year). As shown in Table 2, the fewer citable years, the fewer citations per year. This is expected since more recent articles have had less time to accumulate citations. However, the decline in Mean TC per Year is more pronounced than would be expected from this factor alone, dropping from 29.90 in 2016 to 4.13 in 2023. This may suggest a saturation in the field, where the growing number of publications is diluting the individual impact of each article, or it could indicate a shift in the quality or relevance of research published in recent years.

Table 2. Most relevant sources.

Journal	Articles
<i>Additive Manufacturing</i>	167
<i>Materials</i>	77
<i>International Journal of Advanced Manufacturing Technology</i>	63
<i>Metals</i>	50
<i>Materials and Design</i>	36
<i>Journal of Manufacturing Processes</i>	29
<i>Progress in Additive Manufacturing</i>	28
<i>Materials Science and Engineering: A</i>	25
<i>International Journal of Fatigue</i>	22
<i>Journal of Materials Processing Technology</i>	22

Regarding the most relevant journals (Table 2), the top journals in the field are *Additive Manufacturing* (19.8 citescore, 10.3 impact factor), *Materials* (5.8 citescore, 3.1 impact factor), and the *International Journal of Advanced Manufacturing Technology* (6.4 citescore, 2.9 impact

factor). The average number of articles published across the 10 most relevant journals is approximately 51.9. The range of published articles is 145 (from 167 to 22), with a standard deviation of approximately 45.7, indicating high variability in the data. The top three journals contribute 59.5% of the total number of published articles. Notably, *Additive Manufacturing* publishes more than double the number of articles than *Materials*, the second most frequent journal in this field. On the other hand, the five less influential journals collectively account for 126 occurrences, which is fewer than *Additive Manufacturing* alone. These findings suggest a highly skewed distribution, with a significant concentration of articles in *Additive Manufacturing*, while most other journals are less frequent contributors.

A similar situation is observed when analyzing the local impact of the most relevant journals (Table 3). In addition to being the most influential journal in terms of the number of published articles (NP), *Additive Manufacturing* also has the highest total number of citations (TC), surpassing most of the other top journals in the field. The total citations range widely, from 349 to 6937, with an average of 1503.3 citations. However, this average is heavily influenced by the high citation count of *Additive Manufacturing*.

Table 3. Sources' local impact.

Journal	h_index	g_index	m_index	TC	NP	PY_start
<i>Additive Manufacturing</i>	48	75	5.333	6937	167	2016
<i>Materials</i>	17	32	2.429	1178	77	2018
<i>Materials and Design</i>	17	36	3.4	1850	36	2020
<i>International Journal of Advanced Manufacturing Technology</i>	16	29	2.286	999	63	2018
<i>Metals</i>	16	31	2.286	1014	50	2018
<i>Materials Science and Engineering: A</i>	13	23	2.167	549	25	2019
<i>Journal of Manufacturing Processes</i>	12	26	2	691	29	2019
<i>International Journal of Fatigue</i>	11	22	1.375	680	22	2017
<i>Journal of Materials Processing Technology</i>	11	18	2.2	349	22	2020
<i>Acta Biomaterialia</i>	10	10	1.667	786	10	2019

The publication start year (PY_start) indicates the year when each journal began publishing research specifically related to titanium additive manufacturing. For the journals in this analysis, PY_start ranges from 2016 to 2020, with most journals introducing related articles between 2018 and 2020. In terms of bibliometric indices, the average h-index is 17.1, with a range from 10 to 48. The average g-index (the largest number such that the top g articles have together received at least g^2 citations) is 30.2, with a range from 10 to 75. The average m-index (obtained by dividing the h-index by the number of years a researcher has been active) is 2.514, with a range from 1.375 to 5.333. *Additive Manufacturing* significantly outperforms in all indices and metrics. While *Materials* and *Materials and Design* share second place in terms of the h-index, they differ in other metrics, highlighting variations in their bibliometric impact.

When analyzing the scientific output of the five most relevant journals over time (Figure 8), it is evident that the dominant position of *Additive Manufacturing* began in 2019 and continues strongly through 2025 (though the data for 2025 have not yet been fully consolidated). The other journals show a similar trend, with their output also increasing significantly from 2019 onwards. In recent years, these journals have published between 40 and 90 scientific articles annually, reflecting a general rise in production across the field.

Regarding the most relevant authors (Table 4), the data highlight a group of prolific researchers with total citations ranging from 16 to 21 and impact factors between 1.89 and 3.05. While L. Chen leads in total citation count, X. Zhang has the highest average citations per article, suggesting that their work may be more frequently cited or published in higher-impact journals. L. Chen, despite having the most citations overall, ranks third in terms of average citations per article. Conversely, X. Zhang holds the third highest total citation count but leads in average article citations. T. Sun has the lowest average

article citations, even though they share the same total citation count as H. Wang, who holds the second highest average article citations. In conclusion, there appears to be no strong correlation between the number of publications and their corresponding impact, as measured by citation averages.

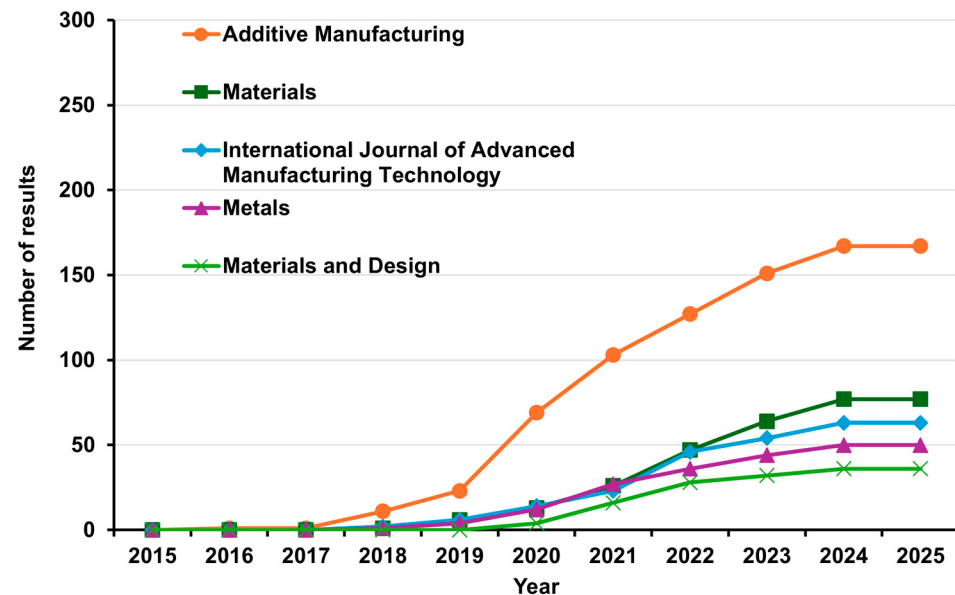


Figure 8. Sources' production over time.

Table 4. Most relevant authors.

Author	TC	Average Article Citations
Chen, L.	21	2.81
Matthews, M.	20	2.31
Zhang X.	19	3.05
Fezzaa, K.	18	2.14
Li, y.	17	2.51
Liu, Y.	17	2.56
Sun, T.	16	1.89
Wang, H.	16	2.86
Wang, J.	16	2.34
Zhang, Y.	16	2.47

Lotka's law explains the distribution of author publication frequency, stating that the number of authors who produce n publications is approximately $1/n^2$ of those who produce just one. Essentially, this means the number of authors contributing a specific number of papers decreases in inverse proportion to the square of that number. Analyzing the results (Table 5), a sharp decline in the number of authors as the number of publications increases can be identified, aligning with Lotka's general pattern. This suggests that, in this specific field or dataset, there is an even greater concentration of publications among a smaller group of highly productive authors. A large proportion of authors (3206 authors, 71.9% of the total) have published only one article, and the majority (over 4000, around 95% of the total) have published no more than four articles. Less than 5% of authors have published more than five articles on this subject. These results indicate that publishing multiple papers in this field may be more challenging or that productivity is particularly concentrated among a small group of prolific authors.

Table 5. Author productivity through Lotka’s law.

Documents Written	N. of Authors	Proportion of Authors
1	3206	71.9%
2	698	15.7%
3	212	4.8%
4	125	2.8%
5	70	1.6%
6	40	0.9%
7	29	0.7%
8	20	0.4%
9	12	0.3%
10	7	0.2%

The authors’ local impact in the field of titanium AM is summarized in Table 6, which ranks key researchers based on their respective h-index, g-index, m-index, total citations (TC), number of publications (NP), and the year they began publishing (PY_start). Matthews, M. leads with the highest h-index (17), total citations (1787), and number of publications (20), indicating substantial influence in the field. Close competitors like L. Chen and K. Fezzaa also demonstrate high impact, with notable citation counts and publication productivity. The collaboration network in Figure 9 visually maps the relationships between these leading researchers, revealing a dense central cluster where authors like Matthews, Fezzaa, and Chen exhibit high connectivity, reflecting extensive collaboration. Distinct groups are formed around these central figures, with authors like Roehling, Guss, and Wen showing peripheral, yet notable, collaborations. This network indicates that knowledge production in this field is driven by a tightly connected core group of researchers, facilitating the dissemination of expertise and advancements across the community.

Table 6. Authors’ local impact.

Author	h_index	g_index	m_index	TC	NP	PY_start
Matthews, M.	17	20	2.125	1787	20	2017
Chen, L.	16	21	2	1742	21	2017
Fezzaa, K.	13	18	1.625	1630	18	2017
Rollett, A.	13	15	1.625	1719	15	2017
Sun, T.	12	16	1.5	1774	16	2017
Li, Y.	11	17	2.2	608	17	2020
Roehling, T.	11	11	1.833	702	11	2019
Guss, G.	10	11	1.25	1341	11	2017
Wang, J.	10	16	1.111	785	16	2016
Wen, P.	10	13	1.667	662	13	2019

The most relevant affiliations and countries by corresponding author are presented in Table 7 and Table 8, respectively, highlighting the institutions and nations leading research in titanium additive manufacturing. Table 7 shows that *RMIT University* in Australia tops the list with 73 articles, accounting for 12% of the total output among the top institutions. In the United States, *Lawrence Livermore National Laboratory* and *Carnegie Mellon University* contribute significantly, with 66 and 55 articles, respectively, demonstrating the strong presence of American research. Chinese universities, such as *Shanghai Jiao Tong University* and *South China University of Technology*, have also made impactful contributions, each with 55 and 46 articles, respectively, emphasizing China’s growing influence. Table 8 complements this by listing the United States as the most prolific country, producing 303 articles, 94.4% of which are single-country publications (SCPs). China follows with 174 articles, supported by its leading institutions from Table 7. Germany, with 137 articles, and Italy, with 89, also show substantial contributions, appearing in both tables. The MCP (Multiple Country Publication) ratios reveal that Australia and the United Kingdom have

higher international collaboration rates, with MCP ratios of 16.1% and 10.7%, respectively. This pattern suggests a globally distributed and collaborative research effort, driven by key institutions in these leading countries.

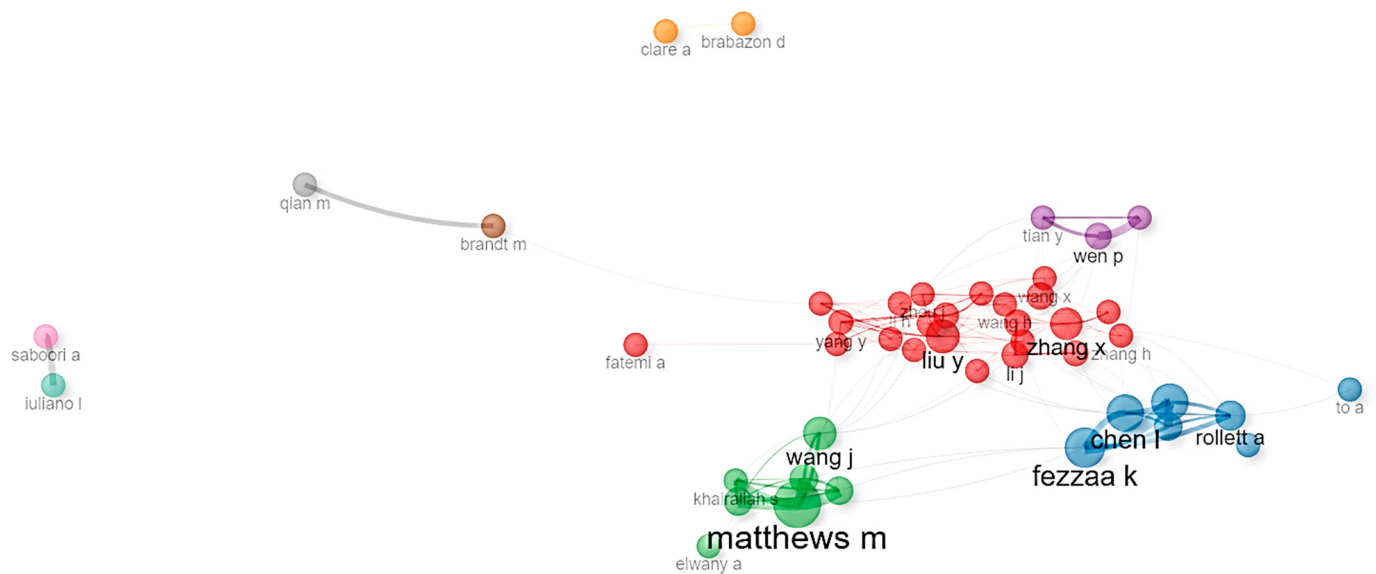


Figure 9. Collaboration network.

Table 7. Most relevant affiliation.

Affiliation	Country	Articles
RMIT University	Australia	73
Lawrence Livermore National Laboratory	United States of América	66
Technical University of Munich	Germany	60
Carnegie Mellon University	United States of América	55
Shanghai Jiao Tong University	China	55
South China University of Technology	China	46
Dublin City University	Ireland	45
Politecnico di Milano	Italy	45
Texas Aandm University	United States of América	44
Huazhong University of Science and Technology	China	44

Table 8. Most relevant countries by corresponding author.

Country	Articles	SCP	MCP	Freq	MCP_Ratio
United States of America	303	286	17	0.23	0.056
China	174	157	17	0.132	0.098
Germany	137	133	4	0.104	0.029
Italy	89	84	5	0.068	0.056
Australia	56	47	9	0.043	0.161
United Kingdom	56	50	6	0.043	0.107
Japan	40	40	0	0.03	0
Canada	39	36	3	0.03	0.077
India	30	28	2	0.023	0.067

Table 9 shows the most cited countries in titanium AM research, with the United States leading at 12,400 total citations (53.5% of the total) and an average of 40.9 citations per article, indicating its dominant influence. China ranks second with 3455 citations (14.9%), though its average is lower at 19.9. The United Kingdom and Singapore exhibit high impact per article, averaging 42.2 and 44.8 citations, respectively. South Africa stands out with an average of 80 citations per article, indicating high significance despite fewer total citations

(1679). The Netherlands also shows a strong impact with an average of 62.5 citations per article, while Ireland maintains a respectable average of 28.4 citations.

Table 9. Most cited countries.

Country	TC	Average Article Citations
United States of America	12,400	40.90
China	3455	19.90
United Kingdom	2365	42.20
Germany	1812	13.20
South Africa	1679	80.00
Australia	1650	29.50
Italy	1554	17.50
Singapore	1120	44.80
Netherlands	813	62.50
Ireland	768	28.40

Regarding the most cited papers (Table 10), there is a clear concentration of citations among a small number of key articles. Lewandowski et al. lead with 1148 citations, accounting for approximately 23.4% of the total citations among the 10 papers listed. Blakey-Milner et al. follows closely with 1054 citations, representing 21.5% of the total. These two papers together make up 44.9% of all citations, indicating a significant influence within the field. In terms of citations per year, Blakey-Milner et al. stands out with an average of 263.50 citations per year, far surpassing the other works, indicating its rapid impact. Additionally, M. Salmi shows a notable Normalized TC of 8.20, the highest in this metric, suggesting a strong influence adjusted for publication time, even with fewer total citations. These high citation numbers highlight that while some papers dominate in total citations, others like Salmi and Zhao et al. (with a Normalized TC of 7.75) show significant ongoing influence despite fewer overall citations. This suggests a concentration of impactful research, where a few studies drive most attention in the field.

Table 10. Most cited papers.

Authors	Ref.	Total Citations	TC per Year	Normalized TC
Lewandowski, J. J. et al.	[48]	1148	127.56	4.27
Blakey-Milner, B. et al.	[49]	1054	263.50	31.09
Zhao, C. et al.	[50]	547	68.38	2.99
Martin, A. et al.	[50]	425	70.83	6.23
Yuan, Li. et al.	[51]	421	70.17	6.18
Zhao, C. et al.	[52]	387	77.40	7.75
Ly, S. et al.	[53]	323	40.38	1.77
Bayat, M. et al.	[54]	310	51.67	4.55
Salmi, M.	[55]	278	69.50	8.20
Galarraga, H. et al.	[56]	271	33.88	1.48

The word cloud in Figure 10 prominently features terms like “powder bed”, “metals”, “additives” and “laser powders” underscoring a strong emphasis on materials and fusion techniques, particularly those involving lasers. “Titanium alloys” is notably highlighted, reflecting their significance in the field, while “aluminum alloys” and “ternary alloys” indicate ongoing research into diverse alloy compositions. Furthermore, terms such as “microstructure”, “porosity”, and “mechanical properties” stress the importance of understanding material behavior and performance for optimizing AM processes. The inclusion of “3D printers” further reinforces the crucial role of technology in this area.

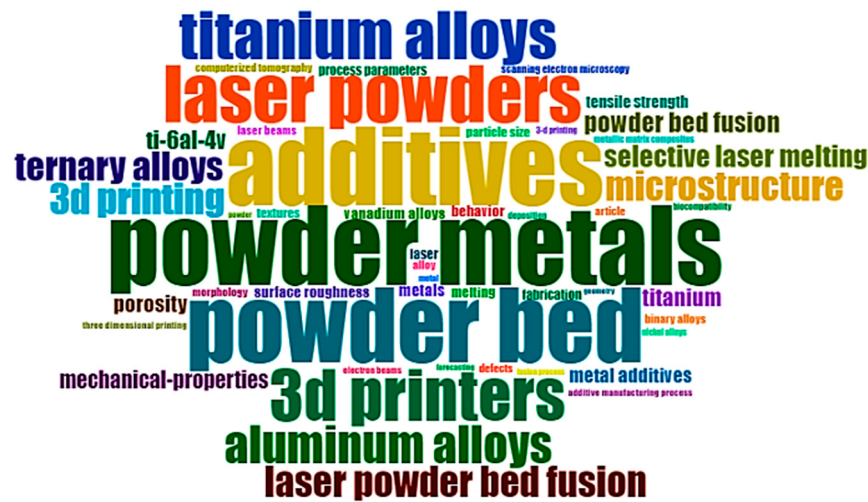


Figure 10. Word cloud.

4. Discussion

By examining the frequency and evolution of key terms in the scientific literature, it becomes clear that research has significantly intensified over the past decade, particularly in areas related to material optimization, process advancements, and the influence of manufacturing parameters on the final product's properties. This section discusses the most prominent research themes identified through this analysis and explores their implications for the development and application of PBF technology in the context of titanium alloys.

Figure 11 presents a frequency chart of the most common terms in the scientific literature on titanium AM using PBF. The most frequent terms, such as “Powder Metals” (8.32%), “Additives” (8.17%) and “Powder Bed” (7.83%), reflect that a significant field of the research is centered on the manipulation of metallic powders and the use of additives in the powder bed process. This dominance suggests a clear focus on optimizing the raw materials and enhancing the fundamental processes involved in PBF technology [4,57]. Other notable terms include “Laser Powders” and “3D Printers”, indicating that laser optimization and AM technologies are also critical areas of study that have been studied in different works [58–60]. Furthermore, the presence of “Aluminum Alloys” underscores that aluminum is the most used alloying element, which is consistent with the state of the art [31,61]. The appearance of terms like “Microstructure” suggests a strong interest in how the AM process influences the internal structure of the material, affecting the final product’s performance. Additionally, the term “Selective Laser Melting” highlights a greater focus on this technology for titanium printing compared to electron beam melting, another PBF technology, as discussed in the Section 1. Another frequently mentioned term is “Porosity”, which represents a significant challenge in PBF technology. In some cases, however, controlled porosity is necessary for biomedical applications, where specific pore sizes can enhance biocompatibility and promote tissue integration [62,63]. The presence of both terms, “porosity” and “microstructure”, in most frequent words highlights critical issues in the structural integrity of produced components. Porosity, characterized by tiny voids within the material, can significantly compromise the structural health of a part, potentially leading to premature failure under stress. Similarly, the formation of fragile microstructures during the fusion process can result in brittle components unsuitable for many applications. To address these challenges, post-processing has become an integral part of the AM workflow. Common post-processing techniques include heat treatment, hot isostatic pressing, surface finishing methods (such as grinding, polishing, and shot peening), and additional machining [64,65]. These processes aim to reduce porosity, refine the microstructure, relieve internal stresses, and improve surface quality. By implementing appropriate post-processing strategies, manufacturers can significantly enhance the me-

chanical properties, durability, and overall performance of manufactured parts, making them suitable for even the most demanding applications.

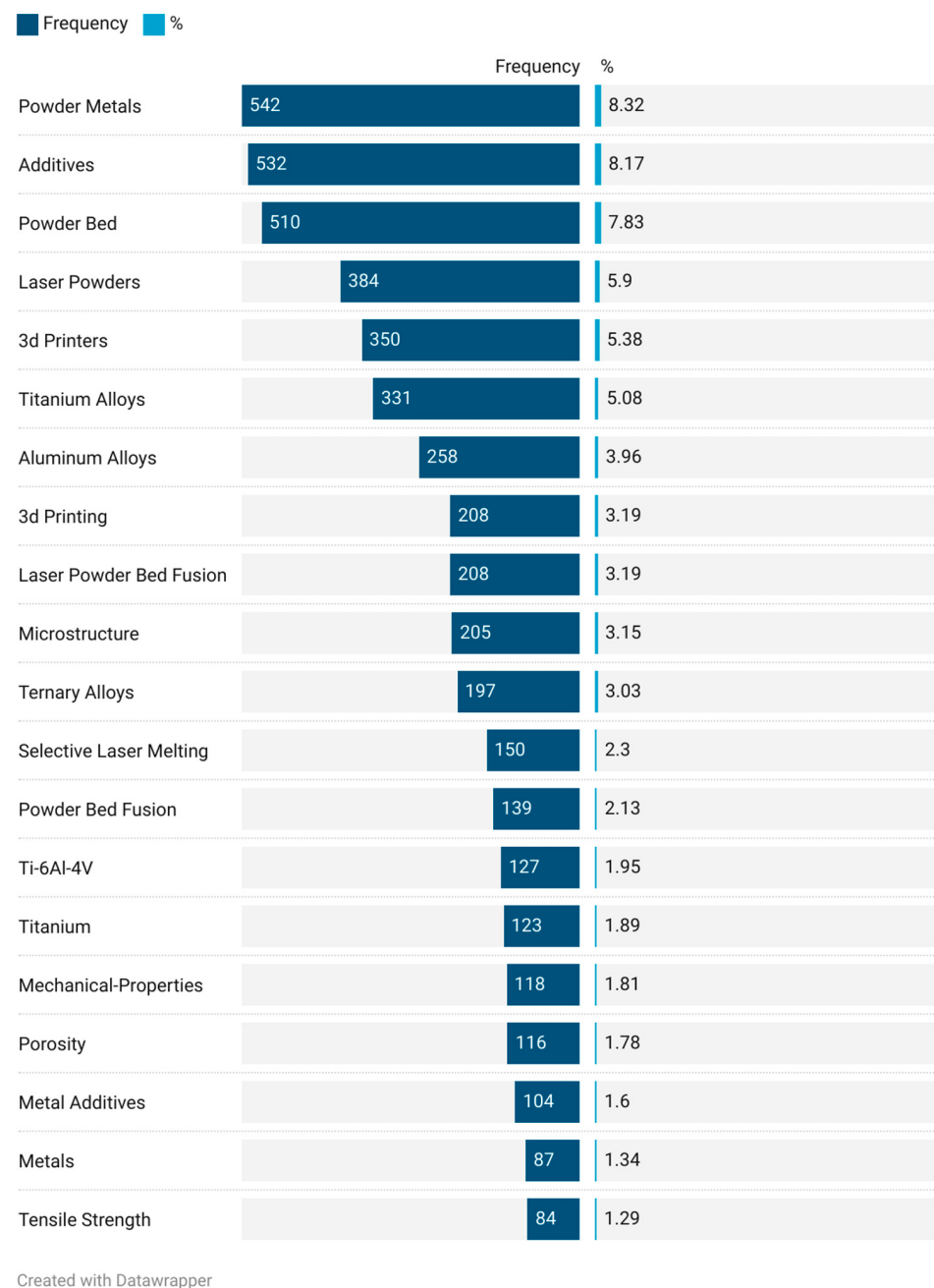


Figure 11. Frequency distribution of key words in titanium AM with the PBF literature.

Figure 12 presents a line chart depicting the temporal evolution of the key terms identified in Figure 11 from 2015 to 2025, revealing several significant trends. From 2018 onward, there is a marked increase in the frequency of publications mentioning these terms, reflecting a surge in research activity related to titanium AM with PBF. This growth continues steadily until 2023, when many of the terms seem to plateau or reach a peak. “Powder Metals” and “Additives” emerge as the most frequently mentioned terms since 2020, highlighting that advancements and a comprehensive understanding of these base materials are essential for enhancing the PBF process. Similarly, “3D Printers” and “Laser Powders” follow similar trends, suggesting that technological improvements in machinery and laser systems have been pivotal during this period. “Microstructure” is another term

that shows rapid growth starting in 2021, reflecting a rising interest in understanding how manufacturing processes influence material properties, which is essential for optimizing the printed material for different applications. “Titanium Alloys” and “Aluminum Alloys” show parallel growth trends, with titanium remaining the primary focus but some interest in aluminum alloys as well. In this regard, these results demonstrate that research in titanium AM using PBF has grown exponentially over the past several years, with a clear emphasis on improving powder materials, additive processes, and the resulting microstructures to enhance the overall quality and efficiency of this technology.

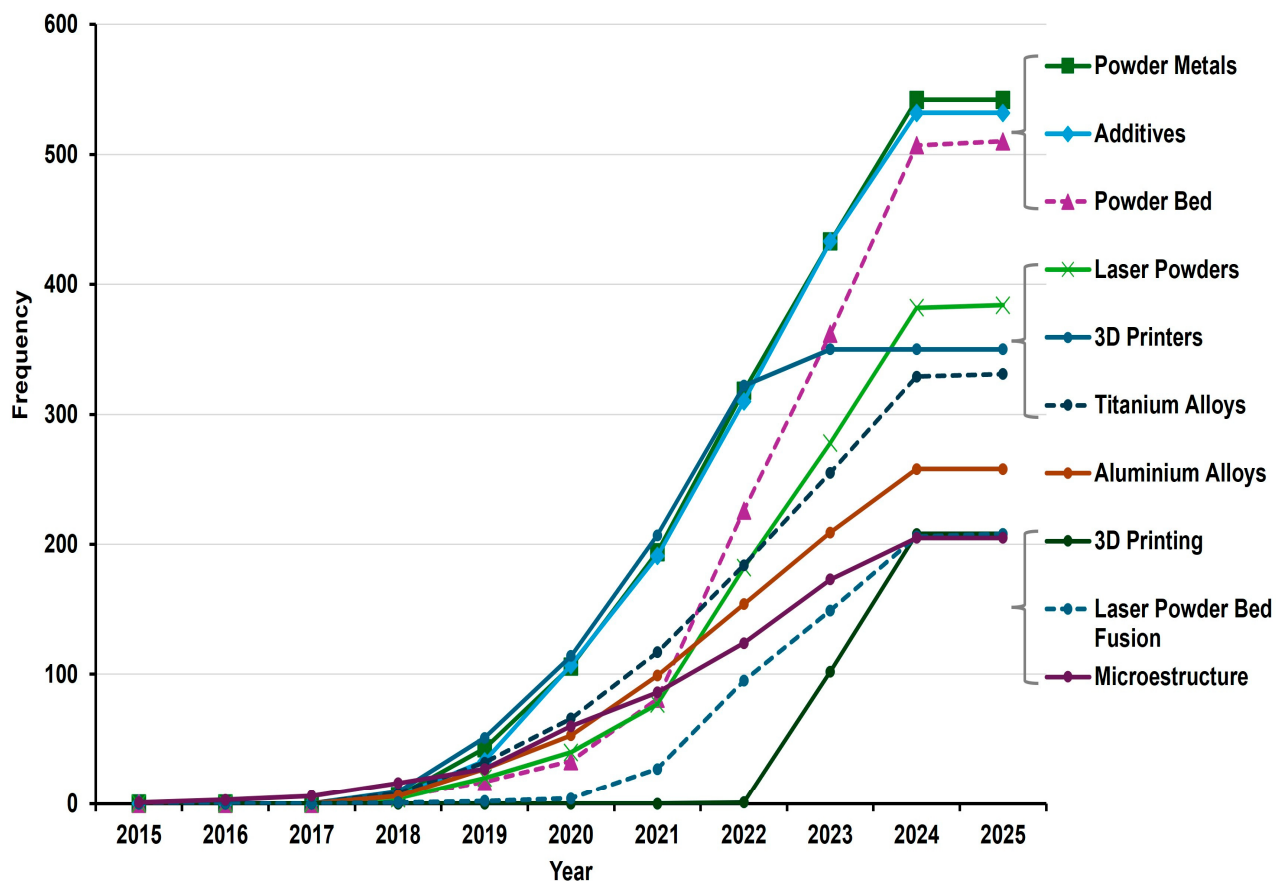


Figure 12. Annual growth trends in titanium AM with PBF research from 2015 to 2024.

The co-occurrence network map presented in Figure 13 reveals the thematic structure of proposed research that illustrates how frequently specific terms appear together across research papers related to titanium AM by PBF. By clustering keywords that often appear in the documents, the map highlights key thematic areas and their interconnections within the field. Moreover, the proximity and connections between clusters provide insights into how different research areas intersect. In this work, two clusters are distinguished.

On the one hand, the blue cluster is centered around materials and additive processes, highlighting key terms such as “powder metals”, “additives”, and “powder bed”. This cluster underscores the importance of nature and manipulation of metallic powders, specifically focusing on aspects like laser powders and titanium alloys [66–68], as commented above.

On the other hand, the red cluster, in contrast, focuses on process parameters and their impact on the final material properties, with terms like “process parameters”, “microstructure” and “porosity” indicating a research emphasis on the influence of fabrication settings on the microstructure and mechanical performance of titanium components [69–71]. The connections between these clusters illustrate the interdisciplinary nature of PBF research, linking studies on material properties and composition with investigations into process optimization and mechanical outcomes.

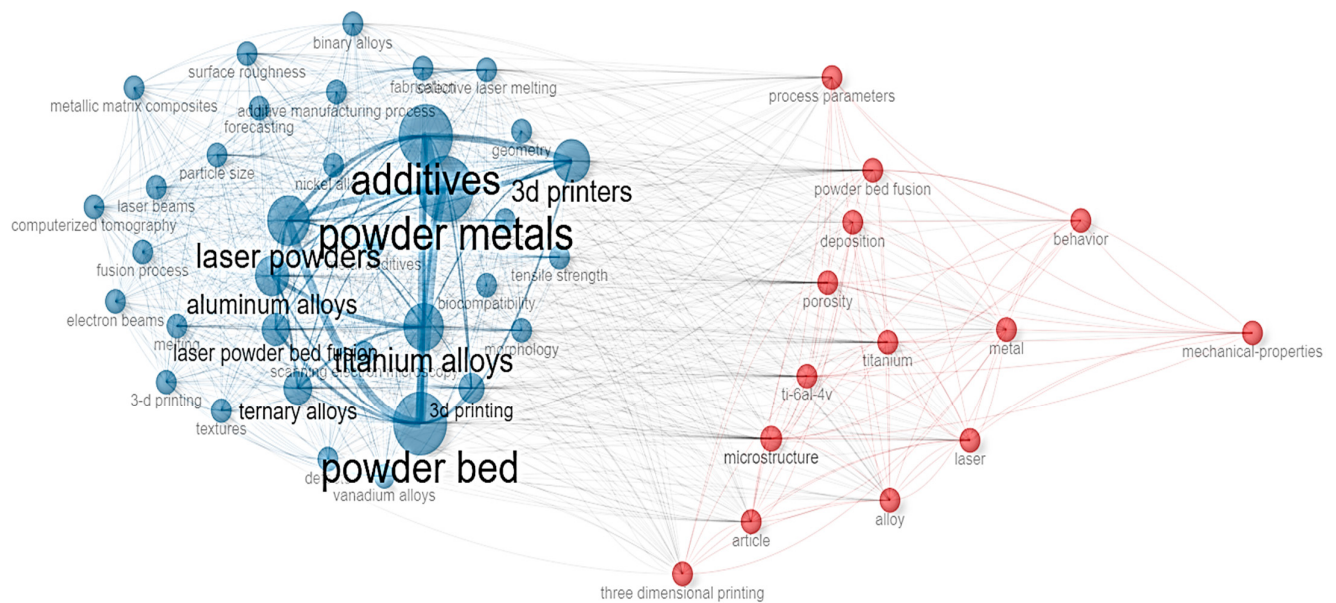


Figure 13. Co-occurrence network: thematic clustering of keywords in titanium AM with PBF research, highlighting distinct research focuses.

To illustrate the level of development and significance of current research, as well as to highlight emerging research trends, a thematic map (Figure 14) is produced to illustrate the level of development and relevance of current research, to highlight the lines of research in and relevance of current research, as well as to highlight the lines of research on the rise. In this map, each bubble symbolizes a set of key words (themes), their names being the names of the key words (themes) which are most significant according to their combined frequency of joint occurrence [72].

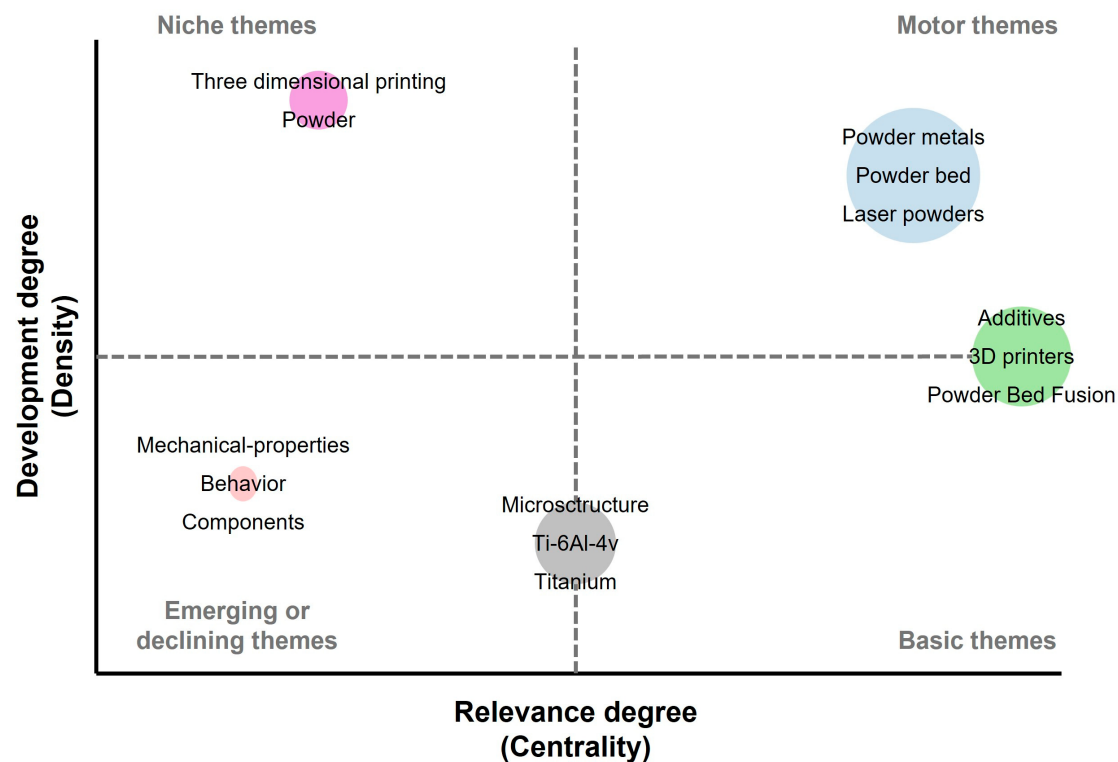


Figure 14. Thematic map: distribution of research themes by centrality and density, illustrating core and emerging topics in the field.

The map is divided into four quadrants: (i) driving themes, characterized by high density and high centrality; (ii) key themes, with low density but high centrality; (iii) specialized themes, which show high density but low centrality; and (iv) emerging or receding themes, marked by both low density and low centrality [73]. In the case of research on titanium additive manufacturing with powder bed fusion, in the niche themes quadrant are three-dimensional printing and powder; however, in the intersection between the basic themes and the emerging themes are the terms microstructure and titanium.

Figure 15 shows the correspondence analysis plot that illustrates the distribution and relationships of key terms within the literature. Dimension 1, which explains 58.6% of the variance, separates studies focusing on process parameters and mechanical properties (e.g., “mechanical properties”, “process parameters”, “microstructure”) on the left from those emphasizing technological aspects and material characteristics (e.g., “powder bed”, “laser beam”, “3d printers”) on the right. Dimension 2, accounting for 21% of the variance, distinguishes more general topics related to AM (“three-dimensional printing”, “powder”) from more specialized studies focusing on powder properties and biocompatibility (“biocompatibility”, “particle size”) at the bottom. This plot highlights the thematic diversity within the field, illustrating how research spans across broad technological themes and specific material properties.

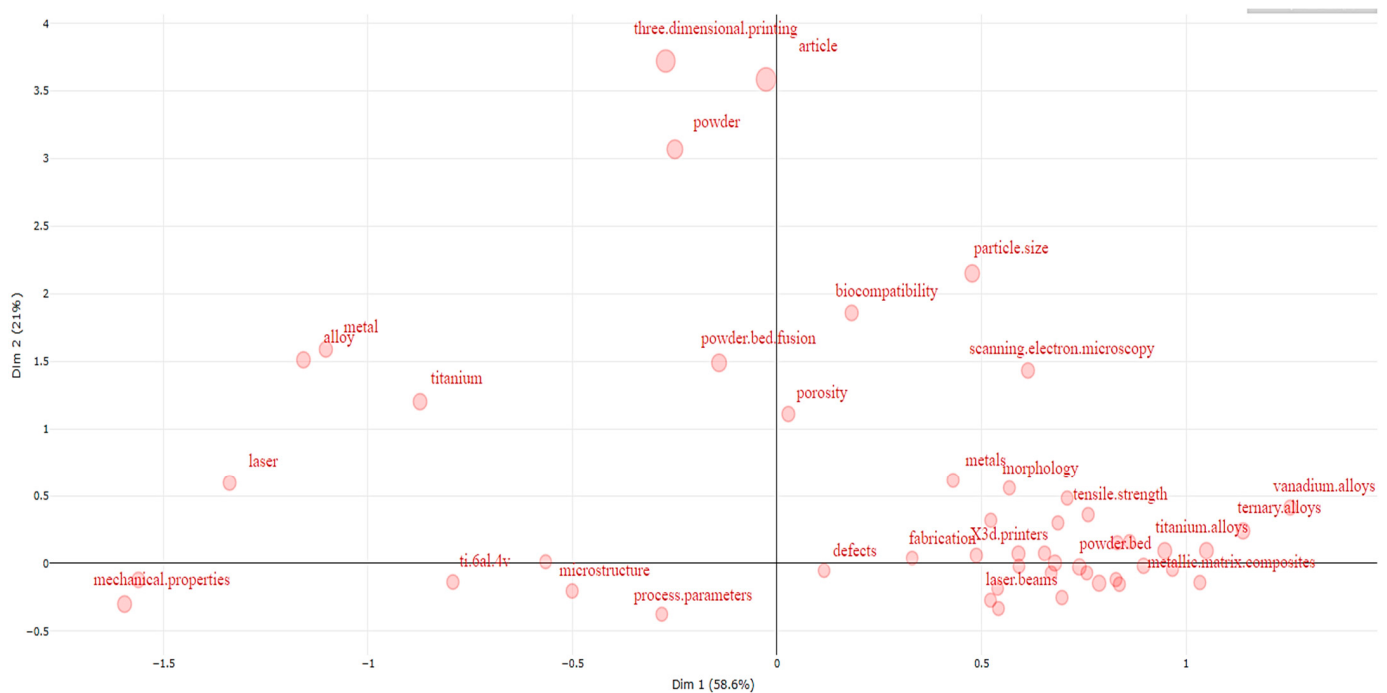


Figure 15. Factorial analysis: plot showing relationships among key terms, categorizing studies by focus on material properties versus technological processes.

Considering the most cited and recent articles on titanium additive manufacturing, particularly in PBF, as indicated in Table 10 in the Section 3, significant advancements have been made in understanding and optimizing the process.

Researchers have utilized advanced in situ characterization techniques, such as high-speed X-ray imaging and diffraction, to observe critical phenomena in real time, including melt pool dynamics, powder ejection, rapid solidification, and phase transformations. [74]. On the other hand, Lewandowski and Mohsen, in their article “Metal Additive Manufacturing: A Review of Mechanical Properties”, provide a comprehensive overview of the mechanical properties of metallic materials produced through AM. The study focuses on two primary AM techniques: (i) powder bed fusion (including EBM, SLM, and DMLS) and (ii) directed energy deposition (such as LENS and EBF3) [48]. Here, the authors analyze how the build direction can influence the final material properties and discuss

the possible sources of anisotropy, such as texture, microstructural changes, and defects. This information is crucial for understanding how to optimize AM processes to achieve parts with consistent and predictable mechanical properties. The article concludes with recommendations for future research in this field, highlighting areas that require further study to enhance our understanding and application of metal additive manufacturing.

Various studies have revealed crucial details about defect formation, such as porosity and spatter, and have enabled the quantification of key parameters like solidification and cooling rates [66–68]. The formation of micro-metal vapor jets has been observed to play an important role in the redistribution of material and the surface quality of the manufactured parts [75,76]. Furthermore, researchers have characterized the evolution of phases and residual stresses during the PBF process, providing valuable insights for controlling the microstructure and the resulting mechanical properties [77–79].

Blakey-Milner et al. provide a comprehensive review of metal AM in the aerospace industry [49]. This technology has transformed the sector by offering new design freedoms, lightweight structures, and improved component performance. The review focuses on key aspects of metal AM, analyzing the most used processes, such as PBF (including SLM and EBM) and DED. It also examines the metallic materials frequently employed in aerospace applications, including titanium, aluminum, nickel, and stainless-steel alloys. The article highlights significant applications of titanium, including components for propulsion systems, aircraft structures, and the repair and maintenance of aircraft parts.

Research has also focused on the development of new materials and structures for biomedical applications. Titanium, magnesium, and iron alloys have been explored for the fabrication of bone implants with optimized properties [80]. Studies have shown that micro- and nanometer-scale surface topography significantly influences the adhesion, proliferation, and differentiation of bone cells, enabling the design of implants with improved tissue integration [81].

Advances in the fundamental understanding of the PBF process are facilitating the development of strategies to optimize manufacturing parameters, minimize defects, and control the resulting microstructure. This is leading to the production of components with enhanced mechanical properties and greater reproducibility. Additionally, the ability to manufacture complex porous structures and functional gradients is opening new possibilities in the design of customized biomedical implants. Together, these advancements are accelerating the adoption of metal AM in critical industrial and medical applications.

5. Prospects and Limitations

The bibliometric analysis of titanium AM using powder PBF reveals both the rapid evolution of this field and its high potential for future advancements. However, further research is needed to address the remaining challenges and explore new applications.

- Current research trends, as indicated by the prominence of keywords such as “process parameters” and “microstructure”, suggest that optimization of PBF parameters remains a critical focus area. Advances in real-time monitoring technologies, including high-speed imaging and in situ melt pool analysis, offer potential for dynamic control of process parameters, thereby reducing defects such as porosity and anisotropy. Developing adaptive PBF systems that respond to real-time feedback may significantly enhance the reliability and mechanical integrity of titanium components.
- The increasing demand for high-performance titanium components across industries, especially in aerospace and biomedical applications, underscores the need for titanium alloys with tailored properties. Bibliometric analysis identified considerable interest in alloys such as Ti-6Al-4V, but expanding the range of alloys specifically optimized for AM could drive further innovation. Alloys that exhibit enhanced thermal stability, biocompatibility, or corrosion resistance could broaden the application of PBF technology in sectors where traditional alloys fall short.
- Post-processing remains essential for achieving the desired surface finish and mechanical properties in PBF-produced components. The absence of relevant studies

on post-processing in this review highlights a gap in the literature that future research could address. Techniques such as laser polishing, heat treatments, and hot isostatic pressing show potential to refine microstructural features and mitigate surface defects. A comprehensive understanding of these methods, alongside PBF, could facilitate more precise control over the final properties of titanium parts, aligning with industry requirements.

- Sustainability has emerged as a central theme in manufacturing industries. In PBF, this involves minimizing waste through efficient powder reuse, reducing energy consumption and improving the overall lifecycle impact of manufacturing. Studies focused on optimizing material usage and recycling strategies for titanium powders could make PBF more cost-effective and environmentally sustainable. Additionally, reducing emissions and exploring renewable energy sources for PBF processes aligns with broader industrial goals of reducing environmental impact.
- While PBF has established its viability for producing high-precision, small-scale parts, scaling up for mass production remains challenging. Future research may focus on developing larger, more efficient PBF systems and integrated workflows that address scalability. A transition from prototyping to large-scale manufacturing could unlock new applications and economic efficiencies for titanium AM in the high-performance sectors identified.

To overcome the limitations of this bibliometric review and provide a deeper understanding of titanium AM by PBF research, future analyses could incorporate advanced techniques such as topic modeling and the use of the Latent Dirichlet Allocation (LDA) algorithm. Topic modeling can automatically identify underlying themes within large datasets, while LDA is effective for uncovering hidden patterns in textual data, enabling the identification of emerging research areas and the evolution of academic discourse. Such approaches would enrich the current analysis and offer a dynamic view of ongoing developments in titanium AM research.

6. Conclusions

This bibliometric analysis of titanium additive manufacturing research using powder bed fusion (PBF) technologies underscores a rapidly expanding field, driven by rising global interest. This growth is particularly notable in high-performance applications across aerospace, biomedical, and automotive sectors. Since 2015, the surge in research publications reflects the growing importance of this technology for producing complex, high-strength titanium components with enhanced material efficiency and design flexibility.

Key research areas focus on metallic powder manipulation, laser technologies, and process optimization, particularly for selective laser melting, which has emerged as the dominant technique over electron beam melting. Terms like “microstructure” and “porosity” indicate ongoing efforts to understand and improve the internal properties of titanium parts, with controlled porosity playing a vital role in biomedical applications.

The collaboration between institutions, especially in Germany, the United States, and China, is driving innovation and accelerating the development of PBF technologies. However, there remains a need for increased international cooperation to address the complex challenges of scaling up titanium AM for industrial use. As research continues to evolve, the focus should shift toward optimizing PBF processes for more cost-effective, sustainable, and scalable production, while exploring new titanium alloy compositions that offer superior performance in diverse applications.

In summary, titanium additive manufacturing via powder bed fusion is poised to make transformative contributions to the future of manufacturing. Addressing current challenges through targeted innovation and increased collaboration will be essential for maximizing its potential impact across diverse industries.

Author Contributions: Conceptualization, A.d.B. and D.V.; methodology, P.F.-A.; formal analysis, A.d.B., P.F.-A. and D.V.; data curation, P.F.-A.; writing—original draft preparation, A.d.B., and P.F.-A.;

writing—review and editing, A.d.B., P.F.-A. and D.V.; supervision, A.d.B., P.F.-A. and D.V.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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