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Corrosion of Additively Manufactured Steel – A Review

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ABSTRACT

This paper performs a bibliometric and critical review on the topic “corrosion of additively manufactured steel” using RStudio software and its tools. Data for analysis is collected from the Web of Science (WoS) database. The critical review reveals mechanical behavior, corrosion mechanisms, microstructural evolution, and additive manufacturing (AM) process development, highlighting that corrosion performance is strongly influenced by AM process selection, parameter settings, alloying elements, and post-treatment methods, all of which shape microstructure, surface morphology, and passive layer formation. Based on the reviewed literature, AM techniques produce stainless steels with material properties that promote the formation of a passive oxide film significantly thicker, more electrically resistive, and more uniform than in conventionally produced counterparts. Moreover, the repeated heating and cooling cycles in AM suppress chromium-carbide precipitation along twin boundaries, thereby significantly enhancing resistance to intergranular corrosion compared to wrought counterparts. By optimizing AM parameters, it may be possible to refine grain structure, reduce process-induced defects, enhance post-processing efficiency, and stabilize passive films, enabling AM stainless steels to possibly match or even exceed the corrosion resistance of wrought steels, thus accelerating the use of AM stainless steel in marine engineering applications.

1 Introduction

Technology of additive manufacturing (AM), also known as 3D [1] printing of metals, is rising and has significant use in industrial applications like aerospace, automotive, pipeline, medicine, construction, and tools. Some advantages of AM are its lightweight design, low costs and complex designs thus reducing production time and need for additional manufacturing processes such as lathe machining and milling [2]. Application of AM metal in maritime applications could be of great significance for the repair of vessels, underwater, and offshore structures [3]. AM steels could be employed for various purposes such as the production of tools, bolts, nuts, fittings, pipeline and support repairs, housings, and as spare parts for turbines, pumps, engines, and electric motors [4], [5]. According to the standard ISO/ASTM 52900-15, metal additive manufacturing processes are categorized by how

material is added and solidified. Categories of AM processes used for manufacturing metals are Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). PBF fuses metal powder layer-by-layer with a laser or electron beam. At the same time, DED uses focused energy (laser or plasma), which melts wire or powder feedstock in a moving melt pool for deposition. Electron Beam Melting (EBM) and Laser Beam Melting (LBM) are technologies used in PBF, while Wire Laser Additive Manufacturing (WLAM) and wire arc additive manufacturing (WAAM) are technologies of DED.

Wire Laser Additive Manufacturing (WLAM) and wire arc additive manufacturing (WAAM) technologies utilize conventional arc welding equipment, and it has lower porosity levels in the product, which can reduce fatigue life compared to PBF. Limitations such as low production rate and limited space of printing chamber (part size constraints) are met in PBF processes [6].

Corrosion in metals occurs as an irreversible phenomenon in which material degradation occurs. This irreversible process can be predicted and controlled by analyzing the influence of corrosion on metals. Different types of corrosion can form on metals, like pitting, crevice, electrochemical, general or uniform, and intergranular [7]. There are several corrosion protection technologies, such as coatings, cathodic protection, and corrosion inhibitors [8] apart from that, there are also metals such as aluminum and stainless steel, which form a passive oxide film on their surface [9] when exposed to a corrosive environment. Surface passive oxide is determined by the type of metal and also by the surface finish during manufacturing and post-processing steps [10]. Additionally, the corrosion resistance of some metals is attributed to different alloying elements, which help create a protective oxide layer [11]. The influence of corrosion on AM steel has been studied since these steels have different structures, and there are various methods of AM technologies, [12] due to which corrosion characteristics are expected to differ from those in conventionally produced counterparts used in marine constructions [13]. Since there is a variety of AM methods and processes, their parameters also have an impact on corrosion resistance, along with post-treatment technologies as heat treatment and cold work [14]. All characteristics mentioned above, which result from an AM, significantly impact the corrosion resistance of metals. Manufacturing processes such as rolling, melting, or welding have a considerable influence [15] on the microstructure of metals, which also affects corrosion resistance [16].

In general, wrought material properties depend on its chemical composition and the microstructure [17]. While metals manufactured with the AM process must meet some criteria, such as good weldability to avoid cracks occurring during solidification, and raw materials available as spherical powders with a size of a few tens of microns to achieve good packing density and homogeneity of the powder deposition. In comparison with traditional metal manufacturing, metals made with AM have different microstructure and surface structure [18] which exhibits characteristic features such as weld tracks, protrusion of unmelted powder particles, ejected molten droplets, recesses, anisotropic microstructure with elongated grains, non-equilibrium microstructures, porosity due to unmelted powders, and gas entrapment. The atmosphere inside the chamber of the AM process of metal needs to be inert [19] in order to reduce oxygen reaction and entrapped gas during the solidification of the powder particles, thus decreasing porosity. Main disadvantage of AM processes is the rough surface of the manufactured part, which often requires additional machining processes and surface treatments such as milling, grinding, heat treatment, hardening, shot-peening [20], polishing or blasting.

In this paper, a bibliometric analysis has been performed; data for analysis were gathered from the Web of Science (WoS) database and analyzed in R software via the Bibliometrix tool. Data collected displays publication trends, thematic clusters and key contributors. It will also provide a view of the progress of this research area, highlights of the impactful studies, and proposed directions for future research. Content of this paper is: Methodology which describes utilization of the bibliometric tool and data collection process, the Bibliometric analysis giving insight into thematic clusters, collaborations and trends result, followed by the Critical review providing the results, conclusions, and findings presented in papers, followed by the future research proposition, and last, the Conclusion summarizing the crucial findings and giving comments on the limitations of analysis.

2 Materials and Methods

In this paper, a bibliometric and critical analysis was conducted on the topic "Corrosion of additively manufactured steel". Bibliometric analysis is a set of statistical and mathematical methods used for a literature review [21]. A critical analysis is a systematic, analytical, and evaluative approach for analyzing existing literature or other data sources to assess each work's quality, strengths, and weaknesses, or conceptual gaps, and synthesize these to guide future research. There is different software available for conducting bibliometric analysis, one of them being the open-source RStudio statistical software, which analyzes and visualizes bibliometric data collected. This software runs under the Windows 10 system. R software contains Biblioshiny, a sub-tool that is a web-based graphical interface designed for non-coders, offering visualization and bibliometric analysis. It is divided into various categories, such as overview, sources, authors, documents, clustering, conceptual structure, intellectual structure, and social structure, while it can display results as graphs or tables. Data collected from the renowned academic database of Web of Science (WoS) is exported in a supported BibTeX file, while it's imported in Biblioshiny as raw data [22].

Bibliometric analysis has the possibility of mapping a scientific field or topic through co-citation analysis, bibliographic coupling, and keyword co-occurrence [21].

Lotka's Law is one of the bibliometric measures that describes the distribution or frequency of scientific productivity between authors in a particular field. The general formula of Lotka's Law is expressed [23]:

$$f(y) = \frac{C}{b} \quad (1.1)$$

whereas:

C - researchfield - specific constant

$f(y)$ - number of occurrences of studies written by each author of a population

x – number of authors publishing documents, where the number of authors that publish only one article is about $1/x^b$.

b -value, if high indicates a higher degree of authorship concentration, while a low value indicates the absence of a dedicated group of authors in a specific scientific discipline.

Analysis and synthesis of the available documents is one of the essential things to be done while conducting a systematic review, which depends on the number of studies included in the review, the type of research method, the quality of the evidence, and the chosen analytical or visualization technique [24].

This kind of analysis includes descriptive analysis and network extraction, for network extraction, there are different approaches of science mapping developed, such as:

- Citation analysis – Identifies the most influential publications within a research field where the impact is determined by the number of citations it receives.
- Co-citation analysis considers only highly cited publications, while others, like low-cited, recent, or niche publications, are left out.
- Bibliographic coupling – Recent, niche, and recent publications can become visible here since thematic clusters are formed based on citing publications.
- Co-word analysis – Words in this analysis are often extracted from author keywords when present, while in their absence, words can also be extracted from ar-

title titles, abstracts, and full text. Provides a review of the future of the research field.

- Co-atorship analysis – It also includes scholars or authors’ connection to affiliated institutions and countries [25].

2.1 Data collection

This section will give insight into the data collection method from the WoS web database. WoS can advance search queries by applying Boolean operators to set the desired parameters or boundaries in the search engine. The structure of the mentioned search query with the help of Boolean operators is presented in Table 1.

Search results in Table 1 were based on the filter options “Author Key Words” (AK), and the last result of 304 documents in total was taken for the analysis. The author keywords which are directly supplied by the authors were chosen over the “Keyword Plus” (KP) which are algorithmically generated from the titles of cited references, where KP (same as given in Table 1) gave only five papers in total compared to the selected search results. In addition, chosen results for analysis consider document types like articles, proceeding papers, review articles, and early access papers.

The time span is set from 2010-12-31 to 2024-12-31 (year-month-day) to gain insight into the thematic progress of the selected time range. The current year (2025) is excluded since documents are still being published yearly, and the database will fluctuate.

Table 1 Advanced Search query in combination with Boolean operators

Search order	Search Query	Results (number of documents)
1	AK=(corrosion) AND AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	2248
2	(AK=(corrosion) AND AK=(additive)) AND AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	29
3	(AK=(corrosion) AND AK=(additive manufacture)) AND AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	25
4	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d)) AND AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	4951
5	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	3085
6	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(materials)) OR AK=(metals) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	286331
7	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(materials)) OR AK=(metals) OR AK=(steel) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	405604
8	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(materials)) OR AK=(metals) OR AK=(steel) OR ALL=(alloys) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	842221
9	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(metals)) OR AK=(steel) OR AK=(alloys) NOT AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	264674
10	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(metals)) OR AK=(steel)) NOT AK=(alloys) NOT AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	114015
11	((AK=(corrosion) AND AK=(additive manufacture)) OR AK=(3d print)) AND AK=(metals)) OR AK=(steel)) NOT AK=(alloys) NOT AK=(materials) AND LA=(English) Timespan: 2010-12-31 to 2024-12-31	304

2.2 Research workflow

The research workflow is shown in Figure 1, step by step, for better illustration.

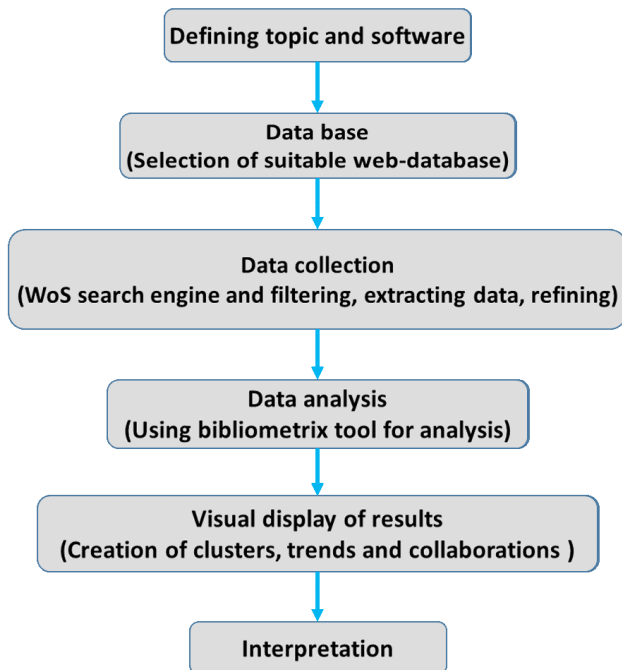


Figure 1 Review of research methodology.

The flowchart shown in Figure 1 illustrates the steps of the critical review taken:

- Defining topic and software – The Topic of interest for bibliometric analysis is “Corrosion of additively manufactured steel” while the software used for analysis is Biblioshiny.
- Database – A Suitable web database can be chosen from scientifically orientated sources, such as DOAJ (Directory of Open Access Journals), Scopus, Web of Science, and Google Scholar. For this purpose, the Web of Science (WoS) is selected, from which a BibTeX file containing collected data is extracted.
- Data collection – In the chosen web database WoS, an advanced search query is performed with the Boolean operators AND, OR, and NOT as previously given in Table 1, to refine and filter gathered results regarding the topic of interest. Advance search was based on filter option “Author Keywords” (AK) such as corrosion, additive manufacturing, 3D print, steel, alloys, metals, and materials with a timespan of selection from 2010-12-31 to 2024-12-31, resulting in a total of 304 articles.
- Data analysis – After results refinement, data extraction is made using a suitable file type, BibTeX, for analysis, which is supported by Biblioshiny software.

The database is imported as raw data from a BibTeX file; papers without complete metadata (affiliation, keywords, author, journal, title, and so on) are automatically rejected by the software, leading to a reduced number of articles in the analysis to a total of 296 articles.

- Visual display of results – In this step, results are graphically or tabularly presented via Biblioshiny on publication trends overview, relevant authors, collaborative networks, and relevant journals, clusters on keywords and papers. Results are used to display and interpret complexities, patterns, and trends within the dataset.
- Interpretation – Explanation of findings, summarizing the results, conclusions, and findings on corrosion of additively manufactured steel and providing insight into research gaps and future trends.

3 Results

In this section, summarized results are presented based on the analysis of the topic ‘corrosion of additively manufactured steel’, which includes an overview of publication trends, relevant authors, collaborative networks, leading journals, and thematic clusters and keywords.

3.1 Overview of publication trends

The application of the AM technology is rapidly growing and is attracting attention also in ship building and marine engineering industries [26]. Figure 2 shows a significant increase in the number of published papers per year on the topic ‘Corrosion of AM steel’ starting from 2020, with 19 papers per year, to 2024, with 82 papers per year. Search results indicated that the first document was published at the end of 2014 on the topic [27] published in Journal of Power Sources.

In general, a steady growth in the volume of published papers can be noticed, with a significant jump in the last year, indicating a growth of interest in the analyzed topic over the years. The most significant research areas of the published papers are in Material Science and Engineering, followed by Metallurgy Metallurgical Engineering, Construction Building Technology and Physics for timespan given in Figure 2. One paper can be published in more than one research area. If the term “corrosion” is used in each research area to filter papers related to the term, results are Material Science, counting 113 papers out of the overall 192, Engineering, 29/127, Metallurgy and Metallurgical Engineering 58/88, Construction and Building Technology 2/47, and Physics 17/34. Relevant 10 papers in the timespan 2014 – 2024 on the topic of corrosion of AM steel are [28] published 2019 in Journal of Nuclear Materials,

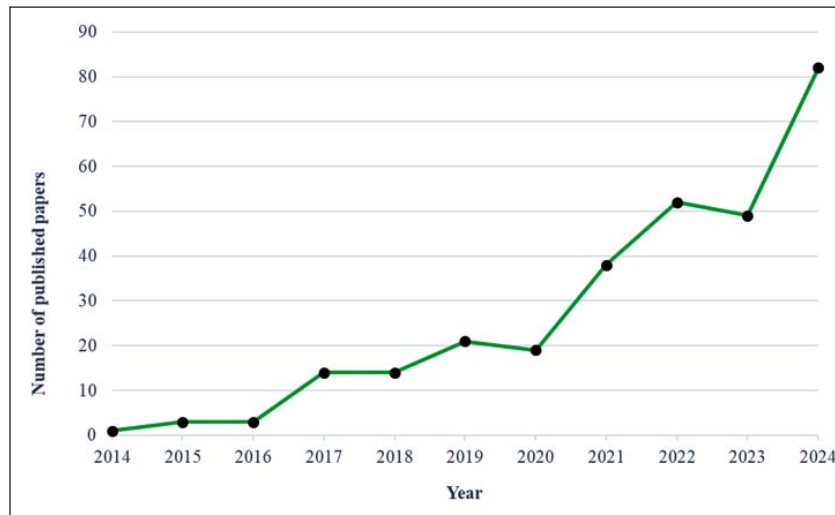


Figure 2 Annual scientific production per year on the topic of the corrosion of AM steel.

[29] published in 2022 in Corrosion Science, [18] 2021 International Materials Review, [11] 2018 Additive Manufacturing, [30] 2022 Corrosion Science, [31] 2022 Materials Letters, [32] 2024 Acta Materialia, [33] 2021 Corrosion, [34] 2018 Powder Metallurgy and [35] 2021 Materials Performance and Characterization.

3.2 Relevant authors

Besides providing an overview of the publication trends, an overview of the relevant authors is provided as well. This includes the authors in the research field who contributed most to the topic through their studies, as well as those who have the most published papers and whose research or papers gained the most citations, reflecting their impact, significance, and contribution to the scientific community.

Figure 3 displays the top 10 most productive authors based on the number of their published papers. Gardner

Leroy and Salahi Salar have the highest number of published papers within the time span 2010 to 2024, followed by Nemani Alireza Vahedi and Wang with seven documents, Ghaffari Mahya and Ron Tomer with six documents, while the rest have five or fewer documents. Relevant papers given by the analysis from the most productive and corresponding authors are [36] and [37] by Gardner Leroy, then [38] and [39] by Salahi Salar, [40] and [41] by Nemani Alireza Vahedi, [42] and [9] by Ron Tomer.

Research areas of the mentioned papers differ, where most of them come from Materials Science and the rest are from Metallurgy and Metallurgical Engineering, Construction & Building Technology, and Engineering. Figure 3 doesn't give insight into the authors' productivity over the years, or in other words, when each document is published or how many of them were published throughout the year; instead, it gives insight only into the overall number of published documents of each author.

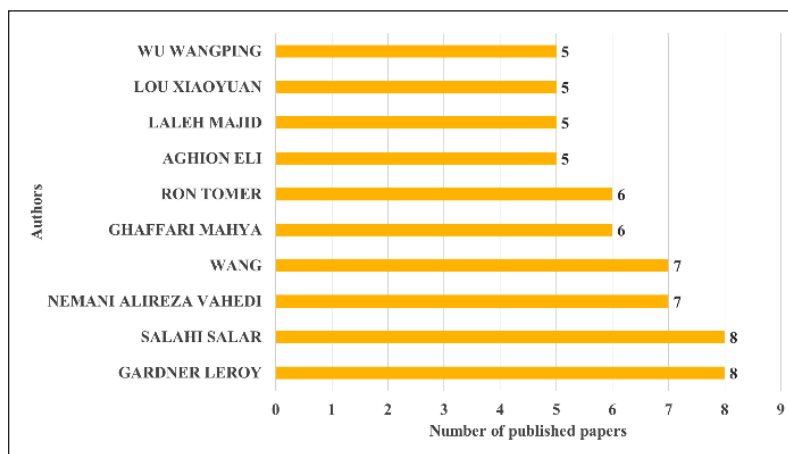


Figure 3 Most productive authors by the number of publications in the period 2010-2024.

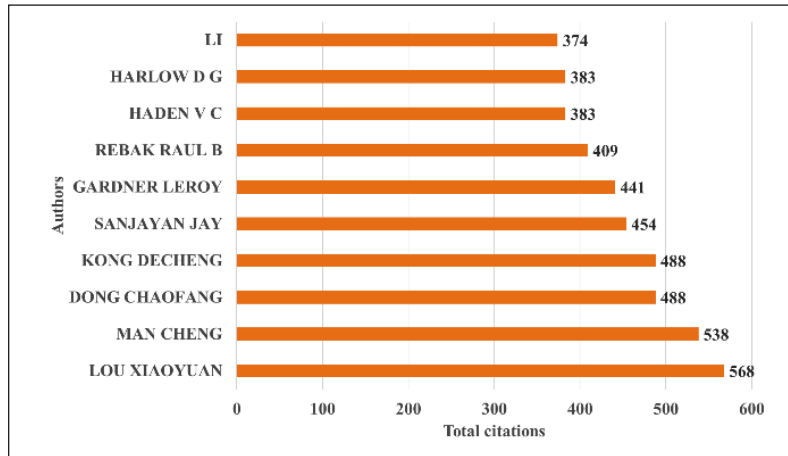


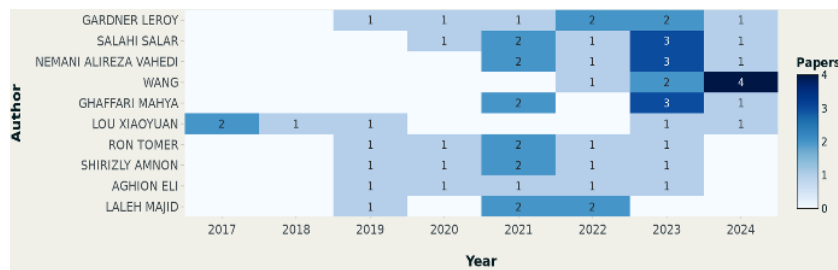
Figure 4 Most cited authors and their papers in the period 2010-2024.

Figure 4 displays the top 10 authors who are the most cited through their documents. The highest cited authors are Lou Xiaoyuan with a score of 568 with overall six papers and Man Cheng with score of 538 with overall three papers, followed by Dong Chaofang 488 with three papers and Kong Decheng with two papers, Sanjayan Jay 454 citations with four papers and Gardner Leroy 441 with nine papers while others have around 400 or less.

Most cited papers of the given corresponding authors are as follows: Lou Xiaoyuan: [43] 220 citations, [44] 129 citations and [28] 118 citations, Man Cheng: [45] 300 citations and [46] 191 citations, Dong Chaofang and Kong

Decheng share the same mentioned papers along with Man Cheng, since they are also one of the corresponding authors in papers, which can be noticed in this case from the same total citation number; Sanjayan Jay [47] 217 citations and [48] 200 citations, which are related more to Civil Engineering, and the last Gardner Leroy [36] 172 citations and [37] 175 citations.

The papers mentioned above focus mainly on corrosion mechanisms and their effects on the mechanical behavior of steels under different conditions. Most cited papers by authors such as Man Cheng and Dong Chaofang are related to the field of medicine. However, Man Cheng and Dong Chaofang do have a relevant pa-



a)



b)

Figure 5 Author's production over the time period 2010-2024 based on: a) number of the papers published, b) Total citation per year

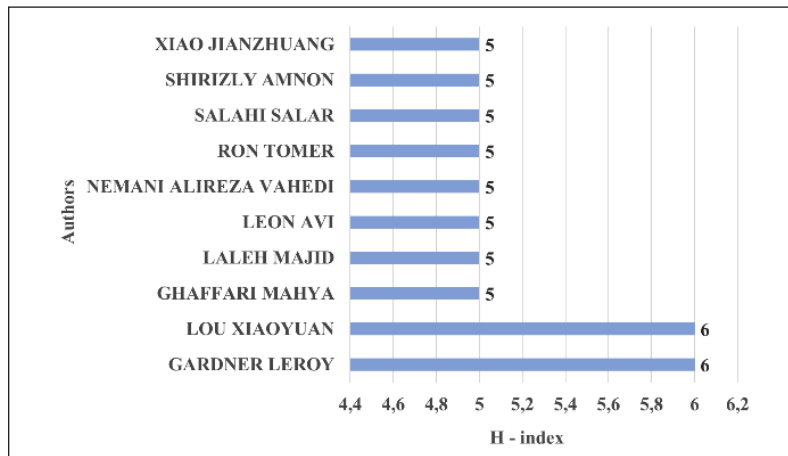


Figure 6 Author’s local impact based on H-index in the timespan 2010-2024.

per [10], although it is not among their most cited works. When comparing Figures 3 and 4, it’s clearly indicated that the most productive authors aren’t also the most cited authors. As mentioned above, from prior Figure 3, it wasn’t able to examine author productivity over the year based on published documents, while Figure 5 gives insight into authors’ productivity over the time period from 2010 to 2024. Based on the top 10 productive authors, Figure 5 a) takes into account the author’s first year of his first published paper regarding the analyzed topic, as in this case, the starting year is 2017 and not 2014 when the first paper was published.

The author’s productivity over time is represented by number of papers published throughout the whole year Figure 5 a) and total citations per year (TCpY) Figure 5 b). Gardner Leroy in 2023 with two published papers [36] and [49] with a total citation per year of 59.33 over time till 2024. Lou Xiaoyuan started publishing her first papers in 2017 among these 10 authors, [44] and [50] with a high TCpY of 22.33. It is also worth mentioning the year 2018, with the publication of 1 paper [43] with a total citation of 219 and TCpY of 27.38. Salah Salar, Nemani Alireza Vahedi, Wang, and Ghaffari Mahya were more productive in certain years (from 2021 to 2024), but on average, all of them published two papers per year. Wang published four papers in 2024 [12], [51], [52], and [53] with TCpY of 5.5, where Salah Salar and Nemani Alireza Vahedi published three papers in 2023 [41], [54], and [55], both with TCpY of 6 since they both worked on same papers. Laleh Majid had published two papers in 2021 [18] and [56] with a TCpY of 22.4.

In addition, Figure 6 displays the results of the author’s local impact based on H-index.

H-index is a value that determines an author’s impact and importance based on the number of documents published and the number of citations those documents have received [57]. Leading authors with the

highest H-index of 6 are Gardner Leroy and Lou Xiaoyuan, although Lou Xiaoyuan has fewer papers with higher citation numbers in comparison with Gardner Leroy, while both have maintained consistency of publishing on average one paper per year. First papers of Lou Xiaoyuan [44] and [50] had a high impact in the research field of Materials Science and Metallurgy & Metallurgical Engineering, whereas Gardner Leroy’s papers in 2023 [36] and [49] had a high impact on the research field of Engineering. Other authors who follow the leading authors have an H-index of 5, which does not diminish their significance due to certain individual papers. Ghaffari Mahya [58], Laleh Majid [59], Leon Avi, Ron Tomer and Shirizly Amnon [6].

Table 2 Lotka’s law results analysis.

Documents written	Number of authors	Proportion of authors
1	1195	85.20%
2	133	9.50%
3	42	3.00%
4	18	1.30%
5	7	0.50%
6	4	0.30%
7	2	0.10%
8	2	0.10%

Table 2 results indicate changes regarding the increase/decrease in the number of authors, relative to the number of published documents. Meaning, that a large percentage of 83% or 1195 of authors have at least published 1 document regarding the analyzed topic, while on the other hand, only a very small percentage, 0,10% or two authors, have published a total of 8 documents.

3.3 Collaborative networks

Collaboration networks display correlations between authors, sources, institutions, countries, keywords, and cited documents. Correlations between different entities or institutions can provide and display data on influential authors, contributions, and cooperation among authors, countries, institutions, and sources, focus and direction of research fields, as well as research trending topics and their authors within a certain field [60]. It indicates trends in the collaboration of research groups. Figure 7 displays cluster coupling based on published papers, the connection between shared references and different journals in which they are published.

Every dot in the cluster coupling from Figure 7 represents a paper by a certain author, and the bond between dots is made based on the number of shared references used in the same document. The size of each dot corresponds to the number of references in the respective paper; papers with more references are displayed with larger dots. In addition, the cluster also considers papers that are most frequently cited from reputable publications, which are highlighted along with authors in Figure 7, thus receiving greater weighting values and emphasizing key contributors. Highlighted authors as Ghonchen M.H., Zhang Di, Lou Xiaoyuan, Andreacola Francesca Romana, Santamaria Ricardo, Salahi Salar, Al-Mamun Nahid Sultan and including Etefagh Ali Hemmasian are some of authors with high number of references in their papers. This gives insight that papers with high number of references are often review papers where leading is author is Ghonchen M.H. [61] containing 403 references and only 10 citations, published in Critical Reviews in Solid State

and Materials Sciences of 8.9 impact factor, then Etefagh Ali Hemmasian [62] 318 references and citations 170, published in Additive Manufacturing of 11.1 impact factor, Zhang Di [63] 158 references and 121 citations, Journal of Manufacturing Process of 6.8 impact factor while rest papers aren't review papers such as Lou Xiaoyuan [44] has smaller number of references 46 but citation number is high 129, published in Corrosion Science of 8.5 impact factor, Salahi Salar [55] 53 references, five citations, Materials, Chemistry and Physics of 4.7 impact factor, Santamaria Ricardo [64] 80 references, four citations published in Materials of 3.2 impact factor, Andreacola Francesca Romana [65] 84 references, 10 citations, Helyon of impact factor 3.6. Papers' connection to different journals provides insight into topics covered in different research areas. Worth mentioning is Ocean Engineering, which has one paper [66] regarding the application of AM technology in Marine Engineering.

Figure 8 displays the collaboration network of different scientific institutions.

Each dot represents a different scientific institution that shares a connection with other institutions based on the number of shared published papers and collaboration among them. Dot size implies that a certain scientific institution is relevant and significant in their research. The weight of the connection between universities is based on cooperation through projects or organizations, thereby contributing to the growth of the published documents and their citations, making a higher impact in the academic society, which, on the other hand, could have benefits such as financial support for conducting research or needed equipment.

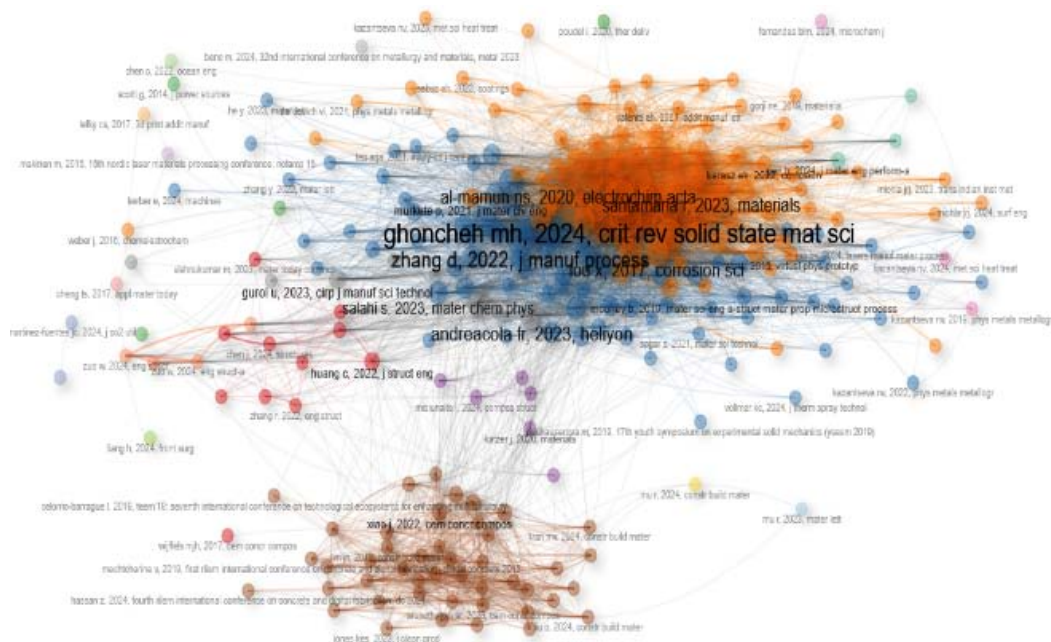


Figure 7 Cluster coupling based on papers and their connection to references and the journal's impact.

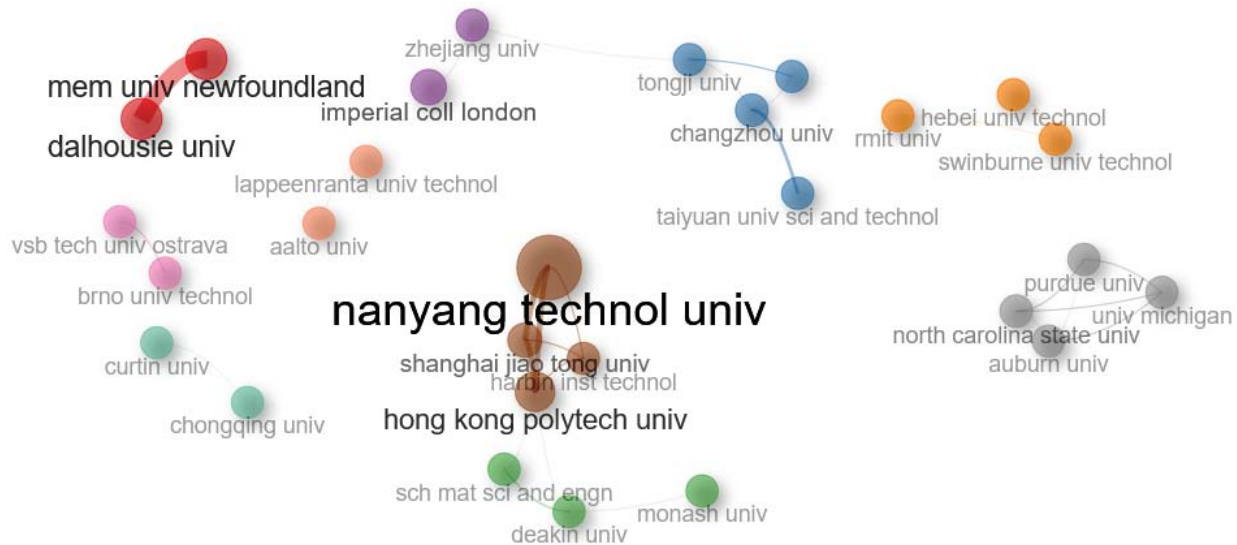


Figure 8 Collaboration network of scientific institutions.

Highlighted universities are Nanyang Technological University (Singapore) with an overall of 15 published papers, Hong Kong Polytechnic University (China) with five papers, Memorial University of Newfoundland (Canada) and Dalhousie University (Canada) with eight papers, and Imperial College London (United Kingdom) with 10 papers. Nanyang Technological University (Singapore) is a leading institution in the field of additively manufactured steels and is notable for its extensive collaboration with other institutions, mostly with Chinese institutions, Hong Kong Polytechnic University, Shanghai Jiao Tong University, and Harbin Institute of Technology. Shared papers between these mentioned institutions are [67], [68] and [69] but these papers are related to the mechanical properties and behavior of AM steels which makes their connection strong. In addition, relevant papers on the corrosion of AM steels are from Hong Kong Polytechnic University [56] and Nanyang Technological University [32] and [70], which were already mentioned in this review paper. Hong Kong Polytech University has also collaborated with the Australian institution Deakin University, with a shared paper [56]. Memorial University of Newfoundland and Dalhousie University both in Canada which have the most collaboration through jointly published papers [39], [40], [41], [54], [55], [58] and [71] based on combination of corrosion mechanisms, mechanical properties and post-processing treatments, corrosion test are conducted in different solutions. Purdue University, North Carolina State University, Auburn University, and the University of Michigan share paper [72] based on the effects of corrosion cracking on the microstructure and mechanical properties.

Regional clusters can be made from Figure 8 based on collaboration:

- Asian cluster – Nanyang Technological University (Singapore), Hong Kong Polytechnic University, Harbin Institute of Technology, Tongji University, Taiyuan University of Science and Technology, Zhejiang University.
- European cluster – Aalto University, Lappeenranta University of Technology, VSB – Technical University of Ostrava, Brno University of Technology, Imperial College London.
- North American cluster – Purdue University, North Carolina State University, Auburn University, University of Michigan.
- Oceanian cluster – Monash University, Deakin University, Curtin University, RMIT University, Swinburne University of Technology.
- Canadian cluster – Memorial University of Newfoundland and Dalhousie University.

3.4 Leading journals analysis

Analysis of the journals provides insight into quality of the journals and its productivity in academic society [73]. Usually journals are related to their field of interest. Impact factor determines the influence of the journal and their reputation. The Journal Impact Factor (JIF) is a metric calculated at the journal level using data (in this case) from the Web of Science Core Collection while considering multiple factors that affect citation rates, including the publication volume and citation patterns specific to the subject area and journal type. Journals have an important role because by publishing documents they point out current trends and thematic in science research by high citation scores and thus affecting its quality and impact factor [74].

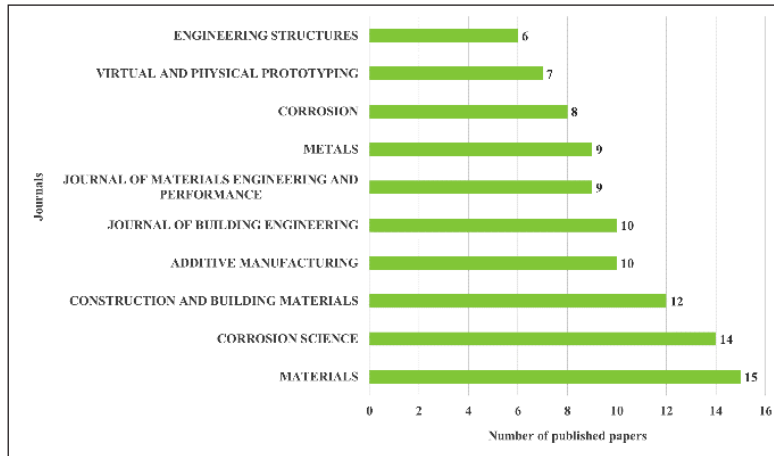


Figure 9 Most relevant journals on corrosion of AM steel.

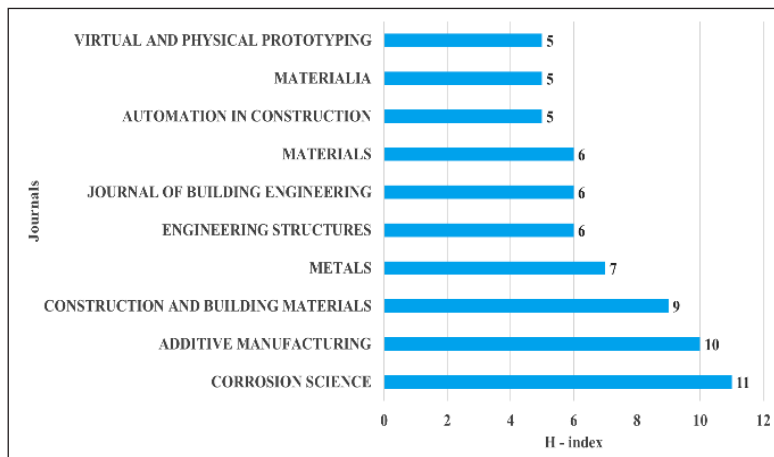


Figure 10 Journals impact based on H-index.

In Figure 9 are 10 most relevant journals, journals with different names usually referring to the field of research. Leading journal is Materials numbering 15 papers with impact factor 3.2, then followed by Corrosion Science with 14 papers and impact factor 8.5, Construction and Building Materials with 12 papers and impact factor 8, Additive Manufacturing with 10 papers and impact factor 11.1, Journal of Building Engineering with 10 papers and impact factor 7.4, Journal of Materials Engineering and Performance with 9 papers and impact factor 2, Metals with 9 papers and impact factor 2.5 and Corrosion with 8 papers and impact factor 1.3 while rest have less than 7 papers with impact factor varying from 8.8 to 6.4. Materials journal covers wide research areas such as Chemistry, Materials Science, Metallurgy & Metallurgical Engineering and Physics which has influence on its impact factor, where a high volume of published papers does not guarantee that each paper will receive many citations. In contrast, Corrosion Science journal covers specific research areas such as Materials Science and Metallurgy & Metallurgical Engineering where pa-

pers contain high reference number and high citations thus increasing its impact factor: Construction and Building Materials journal covers Construction & Building Technology, Engineering and Materials Science research area, Journal of Building Engineering covers areas of Construction & Building Technology and Engineering, Journal of Materials Engineering and Performance covers area of Materials Science, Metals journal covers areas of Materials Science and Metallurgy & Metallurgical Engineering, Virtual and Physical Prototyping covers areas of Engineering and Materials Science and last Engineering Structure journal covers area of Engineering.

Relevant papers in Materials journal [9] 9 citations, [75] 22 citations and [12] 4 citations. Corrosion Science journal relevant papers [29] 17 citations, [30] 20 citations, and [59] 107 citations while [44] not on top but scores highest citation of 129. Additive Manufacturing journal [62] 170 citations, [11] 72 citations, [76] 94 citations. Journal of Materials Engineering and Performance [77] 13 citations, [40] 10 citations, [78] 3 citations. Metals [79] 66 citations, [6] 44 citations and [42] 8 cita-

ies are focused on the additive manufacturing of metals such as duplex stainless steel, austenitic stainless steel, and 316L stainless steel, including various alloys, as indicated by the network connections. All these metals can be produced using different additive manufacturing processes, such as PBF and DED. The research predominantly investigates changes and behavior in the microstructure of these steels during the development of various types of corrosion, such as pitting corrosion, as well as the mechanisms of corrosion initiation. Additionally, the studies examine alterations in the metal's microstructure and surface following various post-processing treatments, including heat treatment, shot peening, and polishing, different solutions (fluids) in electrochemical processes, such as sodium chloride NaCl, ammonium chloride NH_4Cl , thiosulfate $\text{Na}_2\text{S}_2\text{O}_3$, potassium chloride KCl, and zinc chloride ZnCl_2 . There is also a focus on the impact of corrosion on the mechanical properties of the metals, the influence of AM process parameters on corrosion resistance, and the relationship between microstructural changes and mechanical properties in relation to both manufacturing and post-processing conditions, and alloying steel.

Figure 12 displays a thematic map regarding keywords from which important and influential themes are based on their centrality and density. It is divided into four quadrants, the upper right quadrant is motor themes with high centrality and density, the lower right is basic themes with high centrality and low density, the upper left is niche themes with high density and low centrality, and last one lower left is emerging or declining themes with low both centrality and density. On the x-axis is the development degree (density), and on the y-axis is the relevance degree (centrality), whereas high density and centrality indicate the most influential and crucial themes. Centrality is a measure of how strongly

a theme interacts with other themes, and density gives insight into the internal relationships among keywords [57].

Nods with keywords additive manufacturing (129 paper occurrence), microstructure (109 paper occurrences), corrosion (71), along with 3D printing (96), mechanical properties (82), and behavior (78) are the foundation of the motor themes with high centrality and high density. Niche themes and their focus are specific fields such as civil engineering and construction, regarding nods with keywords 3D printed concrete occurring in 17 papers, 3D concrete printing and cement 7 papers, along with metallic 3D printing four papers, bolted connections three papers, and bearing two papers. These themes are often isolated from other fields due to low centrality, while emerging or declining themes regarding wire arc additive manufacturing (WAAM) occurring in 5 papers are both low in density and centrality, but in order to confirm that, their progress should be observed in the future. Basic themes keywords strength occurring in 29 papers, performance in 28 papers, and design represent general in 19 papers. Basic themes are important for the research field, but are not sufficiently developed.

3.6 Literature-based analysis

The analysis of corrosion research in additively manufactured steel reveals distinct patterns of research focus. The most cited authors led by Lou Xiaoyuan, Man Cheng, Dong Chaofang, Kong Decheng, Sanjayan Jay, and Gardner Leroy differ from the most productive researchers, which include Gardner Leroy, Salahi Salar, Nemani Alireza Vahedi, Wang, Ghaffari Mahya, and Ron Tomer. Notably, these authors' papers are focused on AM metals, their mechanical properties, microstructur-

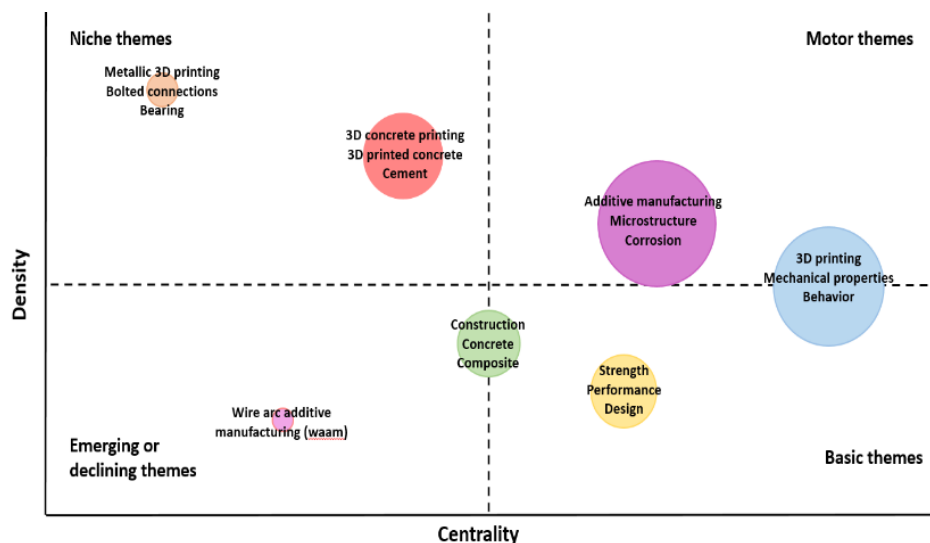


Figure 12 Thematic map of keywords.

al effects, and post-processing treatment influences, providing insight into corrosion mechanisms. All corrosion studies were conducted under controlled laboratory conditions using various test solutions.

Regional collaboration patterns show strong cooperation among Asian institutions, primarily Chinese with Singapore as the most productive, alongside Oceanic clusters dominated by Australian institutions these collaborations emphasize mechanical properties and behavior of AM steels. Canadian institutions demonstrate significant inter-institutional collaboration, focusing on the effect of process parameters and heat treatments on the microstructure and corrosion performance of steels and their alloying elements, while corrosion tests are conducted in different solutions. Similarly, North American universities including Purdue University, North Carolina State University, Auburn University, and University of Michigan collaborate on research that combines corrosion cracking aspects (corrosion mechanisms) on the microstructure and mechanical properties and overall material behavior.

Most of the papers are published in journals including Corrosion Science, Additive Manufacturing, Journal of Materials Engineering and Performance, Metals, and Corrosion. Under the term corrosion research, a variety of themes emerge: effect of the production parameters on corrosion resistance, impact of different environments (electrochemical solutions) and post-processing treatment effects, corrosion mechanisms, alloying element impacts, comparative effects of different AM technologies, and the relationships between corrosion mechanisms and both mechanical properties and microstructural characteristics of steel.

4 Discussion

In this section, a systematic literature analysis is given regarding the selected papers by bibliometric research on the corrosion of the AM steels, where the results, conclusions, and findings are presented. This review is divided into four sections: different solutions' impact on the corrosion performance of AM steels, corrosion impact on different AM steels and alloying elements, AM parameters' impact on the corrosion resistance of AM steels, and post-process treatment impact on the corrosion resistance of AM steels.

4.1 Different solutions' impact on the corrosion performance of AM steels

Studies on additively manufactured (AM) steels demonstrate consistently superior corrosion resistance compared to their wrought counterparts across diverse aggressive environments. Research on AM 316L steel in ammonium chloride and variable thiosulfate concentrations reveals that the highly refined microstructure with

very fine cellular grains provides four to six times higher pitting potential than wrought material, primarily due to the absence of Cr depleted zones and formation of high-quality passive films [82]. In high-temperature molten salt environments, comparative studies show that while PBF-LB IN718 exhibits greater corrosion resistance than DED-LB SS316L due to higher Ni and lower Cr content, the segregation of δ ferrite at grain boundaries in DED-LB SS316L promotes localized corrosion attack through Cr and Fe enrichment [29]. Further investigation of PBF-LB 316L in molten sodium chloride, potassium chloride, and zinc chloride salts demonstrates that increased defects such as dislocations and grain boundaries facilitate Cr diffusion pathways, enabling surface Cr enrichment and protective Cr_2O_3 layer formation that prevents the Cr depletion observed in wrought alloys, resulting in 13% and 6% better corrosion resistance at elevated temperatures respectively [83]. Marine exposure testing confirms these findings, with AM 304L and 316L steels exhibiting shallower corrosion pits, reduced crystallographic attack, and superior resistance to deep penetration compared to wrought steels, attributed to their unique microstructure and inclusion distribution, though localized attack at melt pool boundaries remains characteristic of AM samples [80]. Additionally, nickel-free AM steels in high temperature water environments show significantly different electrochemical behavior including substantially lower oxidation rate constants and diffusion coefficients, a notably higher field strength in the barrier layer, and thinner barrier layer thickness compared to conventional AISI 316L, demonstrating the broad applicability of AM processing advantages across various steel compositions and corrosive environments [84].

4.2 Corrosion impact on different AM steels and alloying elements

The corrosion behavior of additively manufactured (AM) stainless steels is governed by a complex connection of microstructural refinement and processing-induced defects, with several key mechanisms controlling long-term stability [12]. First, AM techniques produce stainless steels with ultrafine, uniformly shaped grains, high dislocation densities, and extensive networks of twin and low-angle grain boundaries. These features promote the formation of a passive oxide film that is significantly thicker, more electrically resistive, and more uniform than in conventionally produced counterparts, enabling comparable corrosion resistance in neutral chloride environments [12], [18]. However, AM technology unavoidably introduces defects such as lack of fusion porosity, spatter-induced cavities, oxide inclusions, and microcracks [71]. These micro crevices locally disrupt the passive film, increase passive current density, and narrow the anodic passive window, especially in

acidic media, where molybdenum segregation further impedes oxide stability [17], [78]. Achieving near full material density through increased energy input, process optimization, or hot isostatic pressing leads to the elimination of manganese sulfide inclusions and improvement of localized corrosion resistance, although remaining microscopic fusion defects can still initiate metastable pitting [12], [85]. Despite their increased hardness and superior general passivity, AM stainless steels often show inferior erosion-corrosion resistance under dynamic flow or jet impingement due to a slower repassivation rate compared to cast or HIP-treated alloys [17], [62]. Moreover, the repeated heating and cooling cycles in AM suppress chromium-carbide precipitation along twin boundaries, thereby significantly enhancing resistance to intergranular corrosion compared to wrought counterparts [12], [18]. Stress corrosion cracking (SCC) and corrosion fatigue behavior are also strongly affected by internal stresses, porosity, and grain structure. Post-build heat treatments and HIP can relieve residual tensile stress, close internal voids, and improve electrochemical passivity [62], although component orientation and cyclic loading frequency still modulate crack propagation behavior. Under cathodic hydrogen charging, AM stainless steels exhibit reduced austenite to martensite transformation and enhanced resistance to hydrogen-induced degradation. Importantly, nano-scale silicate or Mn-Si-O inclusions frequently formed during AM do not act as pit initiation sites, in stark contrast to MnS inclusions in wrought steels [18], [71]. Changing microstructure, controlling process defects, improving post-processing, and enhancing film stability, AM stainless steels can not only match but sometimes surpass the corrosion resistance of conventionally manufactured alloys [17], [18].

4.3 AM parameters impact on the corrosion resistance of AM steels

Optimizing PBF parameters, most critically the hatch distance, laser power, scan speed (volumetric energy density), and scan strategy, enables precise control over both the density and localized corrosion resistance of 316L stainless steel. Varying the hatch distance changes solidification from severe elemental segregation at cell boundaries, which drives intergranular attack, to a more uniform Cr-Ni-Mo distribution that yields near full density and minimal corrosion [86]. Adjusting laser power alters both grain and cell dimensions and melt pool dynamics: higher power with energy rich scans causes stronger fluid (molten metal) flow in the melt pool (caused by thermal gradients), leading to alternating low chromium bands that act as pit initiation sites, whereas lower power refines the microstructure, reduces porosity, and stabilizes the passive oxide [87]. Changing the scan speed affects surface roughness and pore formation: faster speeds cause more pores and turbu-

lent flow, which increase corrosion risk, while slower speeds lead to more even chromium distribution and fewer spots where corrosion can start [86]. Maintaining volumetric energy density within an optimal window induces beneficial compressive residual stresses that reinforce the native passive film, whereas deviations promote a lack of fusion and gas pores that readily initiate pits [79]. Employing a rotated "island" scan pattern balances thermal gradients, refines uniformity, and imparts compressive stresses that prevent chloride entry [79], [86]. Similar approaches in other AM methods, such as heat input control in (DED) to minimize fusion porosity or pulsed current wire-arc deposition to enhance alloy homogeneity, similarly enhance corrosion resistance [79], [88]. Through a combination of tuning each key parameter, one can achieve a densely fused, chemically uniform microstructure enveloped by a robust passive film, significantly reducing pitting-sensitive regions and extending the service life of AM 316L components in aggressive chloride or nitric environments [33].

4.4 Post-process treatment impact on the corrosion resistance of the AM steels

Shot peening with ceramic beads at elevated pressure significantly refines the surface and subsurface microstructure of PBF-LB 17-4PH stainless steel by transforming retained austenite into martensite and reducing surface roughness, thereby increasing grain boundary density and promoting the formation of a dense, uniform passive film; this modification shifts the corrosion potential toward positive values and lowers the corrosion current density in chloride environments, resulting in minimal pitting and the lowest post-test roughness compared to steel shot or nutshell peening [20]. A high temperature anneal and a quenching and tempering cycle both reduce residual stresses and stabilize the passive film in WAAM 420 martensitic stainless steel: quenching-and-tempering fully dissolves δ -ferrite and heals microcracks to maximize austenite content, producing the most positive open circuit potential, highest charge transfer resistance, lowest corrosion current, and longest projected service life, whereas annealing yields moderate gains but remains less effective [40]. Post annealing of AISI 316L whether additively manufactured or wrought combines stress relief with the reversion of deformation induced martensite into tempered austenite, leading to decreased corrosion current density, a positive change in corrosion potential, a broader active to passive transition range, and pronounced increases in passive layer and charge transfer resistances, collectively slowing the overall corrosion rate [11]. A two-step heat treatment for AM 17-4PH initial homogenization at an elevated temperature followed by austenitization most notably benefits powders atomized in nitrogen by moving free-corrosion poten-

tials into more positive regions across neutral to acidic pH, raising pitting limits to match those of wrought counterparts, and positioning corrosion potentials within thermodynamically stable oxide domains, concurrently, it homogenizes chemistry, eliminates microgalvanic cells, and enables gradual release of dissolved nitrogen to elevate local pH at the metal oxide interface, thereby delaying passive-film breakdown and supporting the development of a robust passive film [89]. In PBF-LB 15-5PH stainless steel, solution treatment restores the ferrite austenite balance and slightly improves corrosion parameters, but peak aging delivers the greatest benefits relaxing martensitic stress and precipitating fine copper for self-passivation, nearly eliminating corrosion current, and maximizing polarization resistance whereas over aging reverses some gains through the formation of incoherent particles that undermine passive film integrity [77]. Similarly, for PBF-LB 2205 duplex stainless steel, solution treatment dissolves chromium nitride particles and restores an equal ferrite/austenite microstructure to raise corrosion potential and reduce current density, subsequent peak aging achieves the highest polarization resistance, the lowest corrosion rate, and an elevated critical pitting temperature comparable to conventionally hot rolled material, while over aging diminishes protection through re-austenitization and incoherent particles formation confirming peak aging as the optimal post-build treatment for superior passive film stability and minimal corrosion susceptibility [56].

5 Conclusions

After bibliometric study a literature based analysis revealed that additively manufactured (AM) stainless steels achieve superior corrosion performance through a combination of ultrafine, defect-controlled microstructures, optimized process parameters, and targeted post-processing treatments [12], [18], [62]. Their exceptionally fine cellular grains, high dislocation densities, and extensive low angle and twin boundaries have impact on the rapid formation of thick, uniform passive oxide films [82], [83] that resist chloride attack [80], [84], while careful adjustment of hatch spacing, laser power, scan speed, and energy density minimizes porosity and elemental segregation to further reduce localized corrosion [79], [86], [87]. Although AM process introduces fusion defects, post processes such as hot isostatic pressing, shot peening, solution annealing, and quenching and tempering relieve residual stresses, close internal voids, restore phase balance, and eliminate inclusions, improving pitting resistance, corrosion resistance, and electrochemical resistance [20], [40], [56], [77], [89]. As a result, AM steels not only match but often surpass the corrosion resistance of wrought alloys across chloride, molten salt, and high-temperature aqueous environments, extending component durabili-

ty and reliability in the harshest conditions [12], [29], [40].

At the end of the analysis, the noted research gaps are given:

Research gaps:

- Lack of AM-specific standards or procedures for corrosion testing regarding surface preparation, sample preparation, porosity, or post-process treatments, and testing methodologies uniquely for AM parts [67],
- A narrow range of corrosive environments was studied, but there were also limited corrosion studies in natural marine environments where multiple factors have an impact on corrosion, such as microorganisms, salinity, temperature differences, fouling, and UV [90], [91],
- Lack of multi-environment testing of AM steels and their alloys, which is the case in the Maritime industry on the chemical vessels carrying different aggressive liquids in tanks or transferring different liquids through pipelines, which can cause severe corrosion [79], [86],
- Impact of cryogenic processes on corrosion process of AM steels and their alloys, which is a case on the vessels carrying LNG (liquid natural gas) where temperatures go down to -162°C in the tank, or in case of pipelines transferring that kind of cargo [92],
- Incomplete understanding of how microstructures affect corrosion and the need for fundamental models linking AM microstructure to corrosion behavior [64],
- Comparative studies of different AM techniques to investigate pros and cons regarding corrosion performance and choose a suitable technique for AM metals [36],
- Environmental impact on recycling and reuse of metal powders in additive manufacturing and their effect on the corrosion performance, mechanical properties, and service life of such produced components [65],
- Lack of failure analyses and application in field service studies of AM components in combination with the time-resolved analysis of corrosion damage evolution in order to create a maintenance plan for such components [28], [50],
- Optimal or standard AM parameters framework of each AM process for steel and its alloys to achieve acceptable corrosion resistance and mechanical properties in order to meet minimum quality criteria for industrial application [69],
- Study on the combined effects of the multiple post-process sequences and their impact on the corrosion resistance and protective layer formation [62], [70].

In addition, there is a need for long-term (>5 years) exposure studies under different corrosive environments and real service conditions since most studies are usually limited to 1-2 years [80].

Future trends from analysis on the emerging themes are going towards Wire-Arc Additive Manufacturing (WAAM), but their progress should be observed in the future:

- Comparison with other AM processes in terms of corrosion resistance, microstructural, and mechanical behavior [34],
- Post-process treatments and their impact on the corrosion performance and microstructure [11],
- Impact of different corrosive environments on the corrosion and mechanical properties [79],
- Process parameters impact on the mechanical properties and corrosion behavior [65],
- Study on the optimization process parameters to meet acceptable criteria for corrosion resistance and mechanical properties [62],
- Influence of gas protective atmosphere and wire feed material on the microstructure and formation of protective corrosion layer [69],
- In addition, the application of artificial intelligence (AI) is becoming increasingly prevalent and widespread across diverse fields. The ability to train AI systems further enhances their use for the development of various systems and adaptive models, such as digital twins, as well as various simulations, assessments, and analyses [36].

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