BIBLIOMETRIC ANALYSIS OF ADDITIVELY MANUFACTURED HIGH ENTROPY ALLOYS

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RESUMO: *High entropy alloys (HEAs) are a distinctive class of materials composed of multiple principal elements, offering unique mechanical properties and structural stability. In recent years, additive manufacturing (AM) has emerged as an innovative technology for synthesizing (HEAs), offering unique advantages over traditional methods. As research in this field expands, it becomes crucial to understand the development and trends within it. Therefore, this study conducts a bibliometric analysis of 324 publications from 2015 to 2024 to map the growth, key contributors, and emerging trends in additively manufactured HEAs research. Such analysis is important for identifying influential studies, research gaps, and guiding future investigations. The findings reveal a significant increase in publications after 2018, with key techniques like laser powder bed fusion and selective laser melting leading the fabrication methods. The analysis also shows a focus on microstructure and mechanical properties, which are essential for practical applications. Additionally, emerging topics such as machine learning and in-situ alloying are promising yet underexplored areas. This work underscores the growing importance of AM in developing HEAs and provides insights into optimizing future research efforts in this innovative field.*

KEYWORDS: *High entropy alloys, additive manufacturing, multicomponent alloys, bibliometrics*

1. INTRODUCTION

High entropy alloys (HEAs) have been developed for various special applications and are classified as novel advanced materials. According to Yeh *et al*. (2004), these alloys, also called multicomponent alloys, are generally defined as those composed of 5 or more elements in equal or near-equiatomic compositions, with a concentration between 5 and 35 atomic percent. They are easily processed, synthesized, and manipulated due to the solid solution's increased stability provided by the phase mixture's high entropy. They are characterized by specific effects that enhance mechanical strength and other properties challenging to achieve with common alloys, such as binary or ternary alloys (Xiong *et al*., 2023 and Tsai and Yeh, 2014).

The most commonly used conventional method for synthesizing HEAs is arc melting, given its relative operational simplicity and good cost-benefit ratio (Tian *et al*., 2024 and Sünbül, 2024). However, this process presents some disadvantages in the manufacture of this type of material, such as the high energy required for operation, especially for elements with significant differences and high melting points, as well as the occurrence of evaporation for elements with low melting points (e.g., Mg and Zn) (Torralba, Alvaredo and García-Junceda, 2019 and Zhang *et al*., 2024).

Therefore, in recent years, additive manufacturing has attracted attention as a promising method in developing HEAs. This is due to its benefits, such as obtaining complex geometries, efficiency, and accelerated prototyping capability due to the high heat and cooling rates during the process compared to conventional methods (Gorsse *et al*., 2017 and Xaba, 2024). Moreover, additive manufacturing is considered a new technology that allows for the creation of objects with complex geometries by printing layer by layer from raw materials, such as metal powders, based on a 3D prototype designed in CAD software (Ngo *et al*., 2018; Palaniappan *et al*., 2024). This technology encompasses various processes, broadly categorized into Powder Bed Fusion (PBF) and Direct Energy Deposition (DED).

In Powder Bed Fusion, raw material powders are melted on the substrate in a powder bed layer by layer. This category includes techniques such as Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), and Electron Beam Melting (EBM). On the other hand, Direct Energy Deposition involves melting raw metals into powders or wire forms using high-energy sources like electron beams, lasers, or electric arcs. This includes methods such as Laser Engineering Net Shaping (LENS), Direct Metal Deposition (DMD), Direct Laser Deposition (DLD), and Laser Metal Deposition (LMD) (DebRoy *et al*., 2018; Frazier, 2014; Liu *et al*., 2024).

HEAs have been synthesized using various additive manufacturing processes due to their advantages and potential in developing novel advanced materials. For instance, refractory high entropy alloy TiZrNbTa has been synthesized using PBF methods (Mooraj *et al*., 2024), while CoCrFeMnNi was produced using DED methods (Liu *et al*., 2023). Other examples include

Ti1.4Nb0.6Ta0.6Zr1.4Mo0.6 synthesized via SLM (Ishimoto *et al*., 2021), LaNiFeVMn using Laser LENS (Kunce *et al*., 2017), CrMnFeCoNi by LMD (Xiang *et al*., 2019), and AlCoCrFeNiCu using DLD (Dada *et al*., 2020).

In this scenario, with the growing interest and the wide range of applications for additive manufacturing in the synthesis of HEAs, significant literature reviews have been produced, like those by Chan *et al*. (2020), Moghaddam *et al*. (2021), and Xiong *et al*. (2023). These reviews highlight the main characteristics, advances, and systems investigated in crucial studies. However, there remains a gap in bibliometric studies related to additively manufactured high entropy alloys, which would demonstrate analyses, historical evolution, and trends in this field of study. According to VanEck *et al*. (2014), bibliometric analysis (also known as science mapping or scientometrics) is a systematic method that uses text-mining techniques to analyze and visualize various bibliometric networks. It draws on academic literature from a specific scientific area. It has been used to evaluate research performance and distribution of research funding across different levels, such as researchers, affiliations, and countries (Bornman and Leydesdorff, 2014).

Considering this gap, this work aims to conduct a bibliometric analysis of additively manufactured HEAs using literature data from 2015 to 2024. The study will employ data refinement techniques, mapping, and visualization methods to provide a detailed assessment of advancements in this area and identify current research themes and areas requiring further investigation. This will involve examining authors, publications, affiliations, the evolution of the topic over the years, and potential promising topics for deeper exploration within this field.

2. MATERIALS AND METHODS

A database with 393 articles was obtained through a direct search on Scopus, using the following Search Query: (TITLE-ABS-KEY (("high entropy alloys" OR "multicomponent alloys" OR "multiprincipal element alloys" OR "concentrated complex alloys") AND ("additive manufacturing" OR "laser bed fusion")) AND NOT TITLE-ABS-KEY (("medium entropy alloy*" OR "medium-entropy alloy*" OR "steel*" OR "binary*" OR "ternary*" OR "glass" OR "superalloy*"))) AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND (LIMIT-TO(DOCTYPE, "ar")) AND (LIMIT-TO(LANGUAGE, "English")), meaning that titles, keywords, and abstracts including high entropy alloys and their equivalents were searched from 2014 to 2024 for articles published in English, as a way to standardize the results.

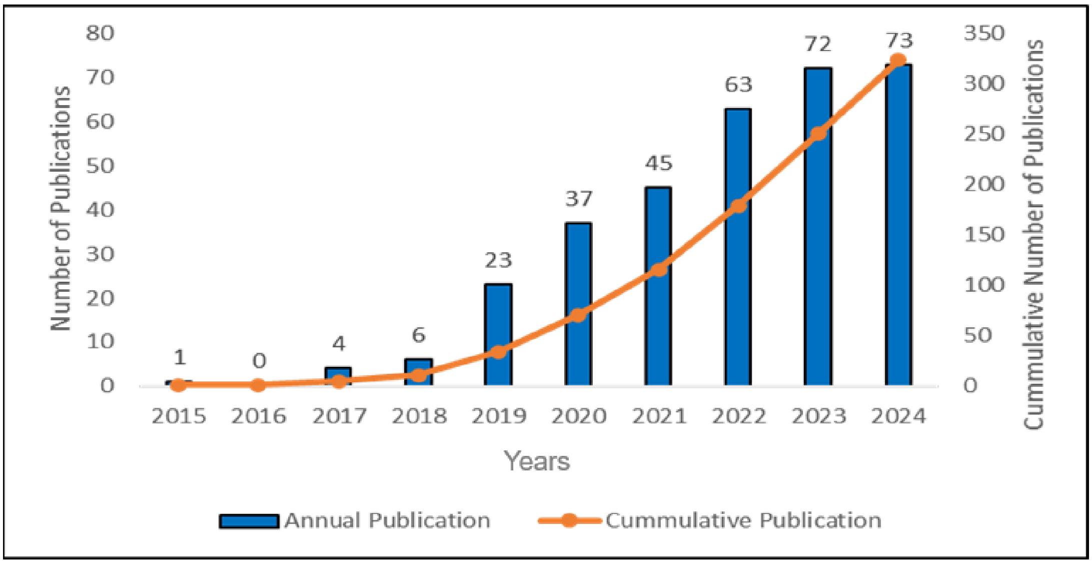
After this, the open-source software OpenRefine was used for data processing and refinement, particularly for evaluating the titles of the works to confirm their relevance to this study. It was also used to compile similar keywords, such as high-entropy alloys, multicomponent alloys, and multiprincipal element alloys, indexed as high entropy alloys. At the end of this process, 324 refined articles were obtained. Scientific production indicators by year and country were constructed using the bibliometric package Biblioshiny in R Studio. Other indicators, such as authors, affiliations, documents, and relevant keywords, were obtained using VOSviewer software. The methodology used in this work was based on the procedures presented by Akinwekomi and Akhtar (2022).

3. RESULTS

3.1. Scientific Production on Additively Manufactured HEAs Through the Years

One of the most essential bibliometric indicators is the annual scientific publications, which provide insight into the production trends over the years. This indicator reflects the field's promise by illustrating the number of research studies conducted, which indicates the level of interest in the specific area being analyzed. Figure 1 presents a graph built using Excel software based on bibliometric analysis data obtained from the Biblioshiny package of R Studio. The graph shows the annual and cumulative numbers of scientific publications related to additively manufactured high entropy alloys from 2015 to 2024. This visualization highlights the growth trajectory of research in this area, offering a clear picture of how the field has evolved.

FIGURE 1 – Annual and cumulative number of publications on additively manufactured HEAs.



Source: Author.

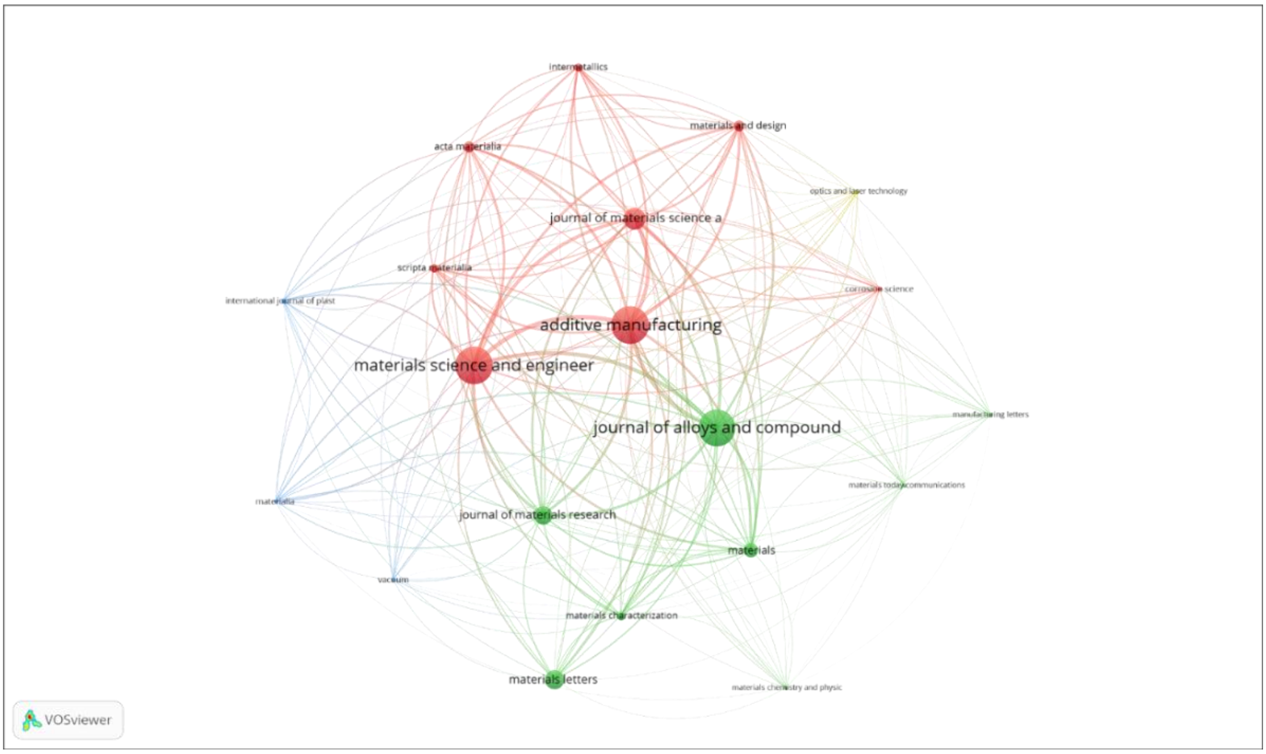
Based on the results presented in Figure 1, the interest in additively manufactured high entropy alloys (HEAs) has steadily increased over the years. The cumulative number of publications reached 324 from 2015 to 2024, reflecting growing research activity in this area. The first significant work in this field appears to have been conducted by Sistla *et al*. (2015), studying AlFeCoCrNi alloys synthesized by LMD at the Missouri University of Science and Technology in the United States.

This field of study is relatively recent, considering that initial studies on HEAs began in 2004 (Yeh *et al*., 2004). The broader HEAs field has since seen over 200 publications per year. Although the current number of works on additively manufactured HEAs is close to 70 publications per year, the upward trend in research, as indicated by the curve's slope, suggests a promising future for this area. Furthermore, given the total number of publications so far, it is evident that much remains to be explored in this field. The steady increase in research activity indicates that additively manufactured HEAs are gaining traction, and the area is likely to see further development and innovation in the coming years.

3.2. Most Relevant Sources of Additively Manufactured HEAs Publications

When analyzing a research field, looking for and reading papers from reliable sources is fundamental. Reliable sources usually have many publications and citations within the field of interest, which can help gain an accurate understanding of current and relevant studies. Figure 2 presents a map highlighting the twenty most relevant sources of publications on additively manufactured HEAs obtained from VOSviewer. This map was generated by considering the number of publications and citations from 2015 to 2024, as shown in Table 1. These sources provide a comprehensive view of the advancements and research trends in this rapidly growing field.

FIGURE 2 – Map of the most relevant sources of publications on additively manufactured HEAs.



Source: Author.

Table 1 – List of the twenty most relevant sources of publications on additively manufactured HEAs.

Source	Documents	Citations	Total Link Strength
additive manufacturing	36	1607	11015
materials science and engineering: a	36	1290	10122
journal of alloys and compounds	35	955	9085
journal of materials science and technology	21	681	7247
materials letters	19	438	1454
journal of materials research and technology	18	100	4965
materials	14	301	3840
acta materialia	11	420	3949
materials and design	11	819	4309
intermetallics	8	200	2859
materials characterization	8	57	1960
scripta materialia	8	289	2811
international journal of plasticity	5	46	1306
corrosion science	4	209	1280
materialia	4	63	1492
vacuum	4	46	610
manufacturing letters	3	72	403
materials chemistry and physics	3	149	231
materials today communications	3	50	415
optics and laser technology	3	101	753

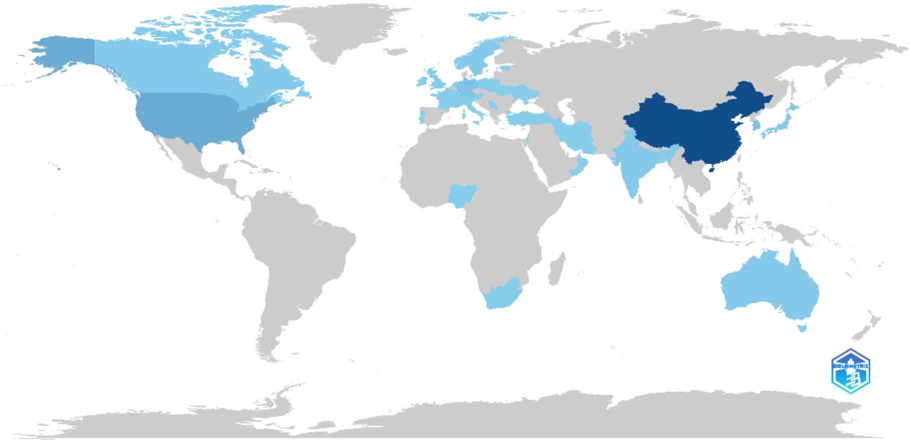
Source: Author.

The Additive Manufacturing journal is the most relevant source, with 36 publications and 1,607 citations related to additively manufactured HEAS. It is followed by Materials Science and Engineering, which has 36 publications but 1,290 citations. Completing the top three is the Journal of Alloys and Compounds, with 35 publications and 955 citations. As presented in Table 1 and Figure 2, these sources encompass a significant portion of the published work on additively manufactured HEAs. They are considered reliable sources, contributing substantially to advancing studies in this field.

3.3. Country's Scientific Production on Additively Manufactured HEAs

Interest in developing studies related to a specific field is directly connected to regional needs and investments, which reflect the demands and priorities of each area worldwide. The leading regions that dominate practical and specialized knowledge are those with significant opportunities and interests in investigating that topic. Figure 3 maps the central countries that have researched additively manufactured HEAs. This map was created using the Biblioshiny library in R Studio based on the bibliometric data shown in Table 2. The data were obtained from the Scopus database covering 2015 to 2024. The map illustrates the global distribution of research in this field, highlighting regions with the most significant scientific activity and contributions.

FIGURE 3 – Country's scientific production on additively manufactured HEAs.



Source: Author.

TABLE 2 – List of relevant countries based on their production on additively manufactured HEAs.

Country	Documents	Citations	Total Link Strength
China	179	4169	58914
United States	56	1957	24557
Germany	27	1333	14152
South Korea	23	703	14062
Singapore	19	1027	14391
India	17	508	8795
United Kingdom	13	440	7449
Japan	10	472	7326
Australia	10	260	6034
France	9	534	5035
Sweden	9	339	4968
Estonia	7	183	5178
Austria	7	181	5110
Norway	6	292	5565
Nigeria	5	101	1181
Switzerland	3	50	2760
Israel	3	115	1904
Taiwan	3	178	1281

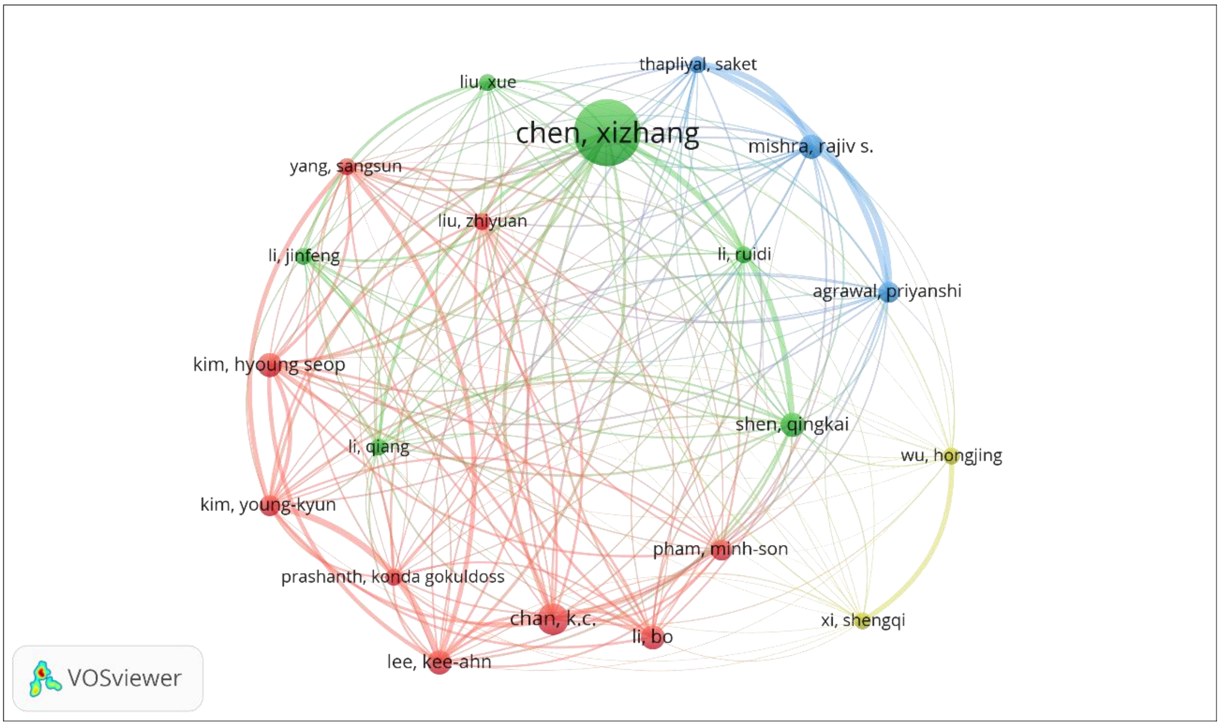
Source: Author.

Figure 3 and Table 2 show that China is the leading country to research and develop studies on additively manufactured HEAs, with 179 publications and 4,169 citations associated with Chinese affiliations from 2015 to 2024. This highlights China's significant potential in this field, aligning with primary research and interest in applying advanced processes for novel classes of materials. Following China, the United States ranks second with 56 documents and 1,957 citations associated with American affiliations. Completing the top three, Germany has 27 publications with 1,333 citations related to German affiliations.

3.4. Most Relevant Authors on Additively Manufactured HEAs and Their Affiliations

A research field can be understood and characterized by its leading authors, who become key references. These authors demonstrate expertise and produce results that contribute to the advancement of the study in a particular topic. The most relevant authors guide and shape the field's fundamental principles, showcasing their authority and developing key topics and prospects. Figure 4, created using VOSviewer software based on data from the Scopus database, as presented in Table 3, displays the top twenty authors who investigate and contribute to advancing additively manufactured high entropy alloys. The map is based on the number of publications and citations from 2015 to 2024.

FIGURE 4 – Mapping of most relevant authors on additively manufactured HEAs.



Source: Author.

The author Xizhang Chen, affiliated with Wenzhou University in China, has the highest number of publications and citations related to additively manufactured HEAs, with 25 publications and 382 citations. Chen represents the most relevant author actively contributing to the development of this field. Following Chen is K. C. Chan, affiliated with Hong Kong Polytechnic University in China, with 9 publications and 280 citations. Rajiv S. Mishra, affiliated with the University of North Texas in the United States, completes the top three with 8 publications and 247 citations.

The authors and their respective affiliations, presented in Table 3, align with the main findings from Figure 2 and Table 1, which show the leading countries' research on additively manufactured HEAs. China is the top contributor, followed by the United States in both analyses. This reaffirms the importance of these countries in the global landscape of research in additively manufactured high entropy alloys, as evidenced by the leading authors' affiliations who dominate the field.

TABLE 3 – List of the twenty most relevant authors on additively manufactured HEAs and their affiliations.

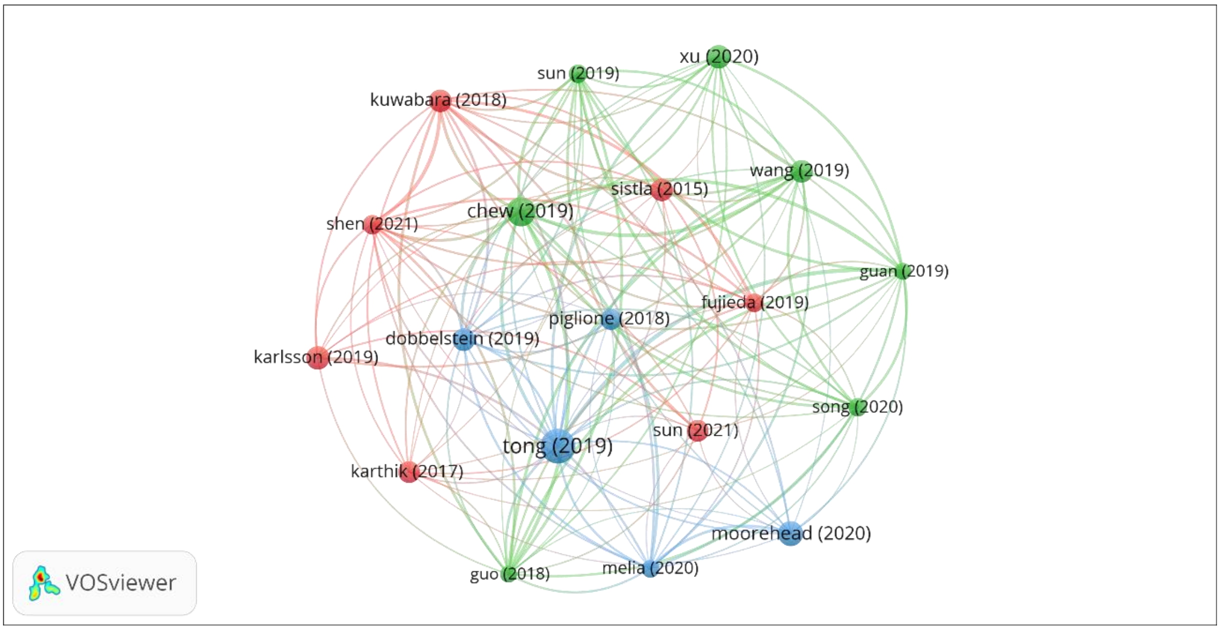
Author	Affiliation	Country	Documents	Citations	Total Link Strength
chen, xizhang	Wenzhou University	China	25	382	2560
chan, k.c.	Hong Kong Polytechnic University	China	9	280	1822
mishra, rajiv s.	University of North Texas	United States	8	247	2125
lee, kee-ahn	Inha University	South Korea	7	259	2487
kim, hyoung seop	Pohang University of Science and Technology	South Korea	7	174	1929
shen, qingkai	South China University of Technology	China	7	248	1706
li, bo	East China University of Science and Technology	China	7	231	1226
kim, young-kyun	Inha University	South Korea	6	259	2486
agrawal, priyanshi	University of North Texas	United States	6	203	2034
pham, minh-son	Imperial College London	London	6	98	938
thapliyal, saket	University of North Texas	United States	5	182	1842
yang, sangsun	Nanchang Hangkong University	China	5	139	1719
liu, zhiyuan	University of Chinese Academy of Sciences	China	5	246	1252
prashanth, konda	Vellore Institute of Technology	India	5	130	882
li, qiang	Suzhou University	China	5	141	873
li, jinfeng	China Academy of Engineering Physics	China	5	300	764
liu, xue	China Academy of Engineering Physics	China	5	297	745
wu, hongjing	Xi'an Jiaotong University	China	5	122	659
xi, shengqi	Xi'an Jiaotong University	China	5	122	659
li, ruidi	Central South University	China	5	103	602

Source: Author.

3.5. Most Relevant Publications on Additively Manufactured HEAs

To understand a subject thoroughly, identifying and understanding its important publications is crucial. Therefore, when conducting a study on a specific topic, researchers should build upon initial studies, identify gaps, and create a comprehensive database encompassing all the field's characteristics and possibilities. Seminal documents, or the most important articles that provide foundational studies and indispensable information, are considered the most relevant for the subject. Figure 5 presents a map of the twenty most relevant papers in the study of additively manufactured HEAs. This map was created using VOSviewer software based on bibliometric data shown in Table 4 obtained from the Scopus database.

FIGURE 5 – Map of the most relevant publications on additively manufactured HEAs.



Source: Author.

Figure 5 and Table 4 highlight that the most relevant document is the study by Tong *et al*. (2019), which focuses on developing high entropy alloys in the FeCrCoMnNi system through additive manufacturing. This paper is the most cited, with 232 citations among all the evaluated works from 2015 to 2024. Its relevance stems from the promising results, including mechanical properties and the effects of thermal treatments on HEAs synthesized by additive manufacturing. In second place is the article by Chew *et al*. (2019), which presents important results on the microstructure and enhanced strength of laser-aided additive manufactured CoCrFeNiMn high entropy alloy, with 194 citations. The top three is the study by Moorehead *et al*. (2020), which discusses the high-throughput synthesis of Mo-Nb-Ta-W high-entropy alloys via additive manufacturing, with 164 citations.

Notably, the three most cited articles were published between 2019 and 2020. It suggests that this period represents a maturation of the topic within the scientific community, with more precise results that complement earlier studies. This aligns with the significant increase in publications starting in 2019, as shown in Figure 1, suggesting a deeper understanding and viable synthesis of HEAs via additive manufacturing, as evidenced by these seminal studies.

TABLE 4 – List of the twenty most relevant publications on additively manufactured HEAs.

Author	Title	Citations	Total Link Strength
Tong *et al.* (2019)	Laser additive manufacturing of FeCrCoMnNi high-entropy alloy: Effect of heat treatment on microstructure, residual stress and mechanical property	232	82
Chew *et al.* (2019)	Microstructure and enhanced strength of laser aided additive manufactured CoCrFeNiMn high entropy alloy	194	118
Moorehead *et al.* (2020)	High-throughput synthesis of Mo-Nb-Ta-W high-entropy alloys via additive manufacturing	165	30
Haase *et al.* (2017)	Combining thermodynamic modeling and 3D printing of elemental powder blends for high-throughput investigation of high-entropy alloys – Towards rapid alloy screening and design	159	0
Xu *et al.* (2020)	Corrosion resistance enhancement of CoCrFeMnNi high-entropy alloy fabricated by additive manufacturing	157	46
Karlsson *et al.* (2019)	Elemental segregation in an AlCoCrFeNi high-entropy alloy – A comparison between selective laser melting and induction melting	154	26
Dobbelstein *et al.* (2019)	Laser metal deposition of compositionally graded TiZrNbTa refractory high-entropy alloys using elemental powder blends	152	55
Kuwabara *et al* . (2018)	Mechanical and corrosion properties of AlCoCrFeNi high-entropy alloy fabricated with selective electron beam melting	149	83
Wang et al. (2019)	Additively manufactured CoCrFeNiMn high-entropy alloy via pre-alloyed powder	148	78
Sistla *et al.* (2015)	Effect of Al/Ni ratio, heat treatment on phase transformations and microstructure of AlFeCoCrNi high entropy alloys	148	21
Sun *et al* . (2021)	Reducing hot tearing by grain boundary segregation engineering in additive manufacturing: example of an AlCoCrFeNi high-entropy alloy	147	22
Karthik *et al.* (2017)	Additive manufacturing of an aluminum matrix composite reinforced with nanocrystalline high-entropy alloy particles	142	22
Piglione *et al.* (2018)	Printability and microstructure of the CoCrFeMnNi high-entropy alloy fabricated by laser powder bed fusion	139	7
Shen et *al.* (2021)	Significant transitions of microstructure and mechanical properties in additively manufactured Al–Co–Cr–Fe–Ni high-entropy alloy under heat treatment	127	69
Song *et al.* (2020)	Nitrogen induced heterogeneous structures overcome strength-ductility trade-off in an additively manufactured high-entropy alloy	125	55
Fujieda *et al.* (2019)	Mechanical and corrosion properties of CoCrFeNiTi-based high-entropy alloy additive manufactured using selective laser melting	123	42
Sun *et al* . (2019)	Revealing hot tearing mechanism for an additively manufactured high-entropy alloy via selective laser melting	122	72
Melia *et al* . (2020)	High-throughput additive manufacturing and characterization of refractory high entropy alloys	115	63
Guan *et al* . (2019)	Additive manufacturing of fine-grained and dislocation-populated CrMnFeCoNi high entropy alloy by laser engineered net shaping	112	87
Guo *et al* . (2018)	On the machining of selective laser melting CoCrFeMnNi high-entropy alloy	112	84

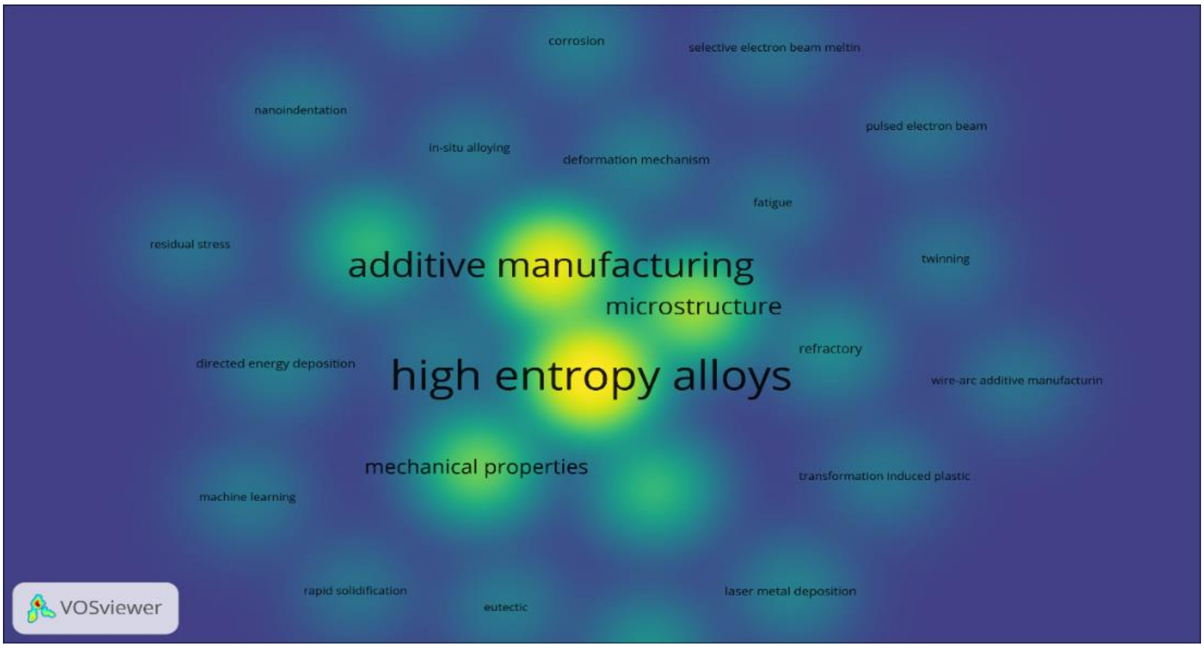
Source: Author.

3.6. Author's Keywords and Trends on Additively Manufactured HEAs

There are various possibilities for investigation within a research field, defined by gaps in preliminary studies or hypotheses raised during new research. Promising results lead to increased trends of further investigations and studies to elucidate and explore better applications and pathways within the field. Therefore, the keywords authors use in their papers represent the different avenues and areas of investigation associated with their research.

Figure 6 presents a mapping of the primary keywords used by authors, constructed in VOSviewer based on data from Scopus, as shown in Table 5. This mapping covers the period from 2015 to 2024 and highlights the key research areas and trends in the field of additively manufactured high entropy alloys.

FIGURE 6 – Map of authors Keywords and trends on additively manufactured HEAs.



Source: Author.

The most commonly used keywords are “high entropy alloys” and “additive manufacturing,” with 205 and 156 occurrences, respectively. This is expected, given that the field of interest is high entropy alloys processed via additive manufacturing. Following these, the main keywords are “microstructure” and “mechanical properties,” with 82 and 60 occurrences, respectively. These terms reflect key characteristics investigated in the alloys, as microstructure is closely linked to the mechanical properties of a material, and both are critical for assessing the viability of the process and the material’s suitability for desired applications.

The most frequently used processing methods for HEAs via additive manufacturing are “laser powder bed fusion” and “selective laser melting,” with 36 and 34 occurrences, respectively. This indicates a significant interest and extensive investigation into these processes, suggesting their potential viability. On the other hand, less frequently used processes include “wire-arc additive manufacturing” and “selective electron beam melting,” each with 5 occurrences. This may indicate limited viability for these methods in synthesizing HEAs, with few studies conducted, presenting opportunities for future research to better understand the properties and characteristics of these processes.

Additionally, the keywords "machine learning" and "in-situ alloying" are used 6 times each. This represents a recent area of interest, reflecting the trend of employing computational methods based on preliminary studies to optimize and design new materials and processes, as seen in studies by Oh *et al*. (2024) and Wen *et al*. (2019). This approach helps reduce the costs and time required for experimental evaluations of initial hypotheses. Furthermore, understanding the microstructural transformations occurring in high entropy alloys during synthesis is a significant challenge due to the high heating and cooling rates of additive manufacturing processes, which favor rapid consolidation of the raw material, explaining the interest in the "in-situ alloying" topic. Therefore, these topics remain as future approaches and opportunities to explore further additively manufactured HEAs.

TABLE 5 – List of authors Keywords and trends on additively manufactured HEAs.

Keyword	Occurrences	Total Link Strength
high entropy alloys	205	340
additive manufacturing	156	255
microstructure	82	161
mechanical properties	60	128
laser powder bed fusion	36	60
selective laser melting	34	65
heat treatment	14	33
refractory	12	30
laser metal deposition	9	21
corrosion	8	18
deformation mechanism	8	20
directed energy deposition	8	10
eutectic	7	18
nanoindentation	7	11
precipitation strengthening	7	14
in-situ alloying	6	12
machine learning	6	9
transformation induced plasticity	6	12
wear	6	11
fatigue	5	13
pulsed electron beam	5	7
rapid solidification	5	7
residual stress	5	6
selective electron beam melting	5	8
twinning	5	12
wire-arc additive manufacturing	5	9

Source: Author.

4. CONCLUSIONS

Based on the bibliometric analysis conducted in this study, it is possible to conclude that the synthesis of HEAs via additive manufacturing route is a relatively new field, with 324 consolidated publications to date. The earliest publications began in 2015, with a possible maturation of the topic starting around 2018. This is supported by seminal articles published in 2019 and 2020, significantly influencing this field of study. Additionally, there is a noticeable growth trend in research on this topic, as indicated by the increase in annual publications since its inception in 2015.

The main processes used in the studies to manufacture high entropy alloys via additive manufacturing are laser powder bed fusion and selective laser melting. The key characteristics investigated are the microstructures and mechanical properties obtained. Finally, topics such as “machine learning” and “in-situ alloying” suggest potential trends and research opportunities in this field. Despite their relevance and growing prominence in various research areas, these terms have relatively low occurrences. They may indicate room for further exploration and integration into studies on additively manufactured high entropy alloys.

DECLARATION OF RESPONSIBILITY

Only the author is responsible for this work.

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