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Review

A Bibliometric and Visualized Overview of Hydrogen Embrittlement from 1997 to 2022

Chilou Zhou [1,*], Yingjie Ren [1], Xinrui Yan [1], Yiran Zheng [1] and Baoqing Liu [2,*]

[1] School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510641, China
[2] Institute of Process Equipment, Zhejiang University, Hangzhou 310027, China
* Correspondence: mezcl@scut.edu.cn (C.Z.); baoqingliu@zju.edu.cn (B.L.); Tel.: +86-02022236321 (C.Z.)

Abstract: The mechanical properties of materials deteriorate when hydrogen embrittlement (HE) occurs, seriously threatening the reliability and durability of the hydrogen system. Therefore, it is important to summarize the status and development trends of research on HE. This study reviewed 6676 publications concerned with HE from 1997 to 2022 based on the Web of Science Core Collection. VOSviewer was used to conduct the bibliometric analysis and produce visualizations of the publications. The results showed that the number of publications on HE increased after 2007, especially between 2017 and 2019. Japan was the country with the highest numbers of productive authors and citations of publications, and the total number of citations of Japanese publications was 24,589. Kyushu University was the most influential university, and the total number of citations of Kyushu University publications was 7999. Akiyama was the most prolific and influential author, publishing 88 publications with a total of 2565 citations. The USA, South Korea and some European countries are also leading in HE research; these countries have published more than 200 publications. It was also found that the HE publications generally covered five topics: "Hydrogen embrittlement in different materials", "Effect of hydrogen on mechanical properties of materials", "Effect of alloying elements or microstructure on hydrogen embrittlement", "Hydrogen transport", and "Characteristics and mechanisms of hydrogen related failures". Research hotspots included "Fracture failure behavior and analysis", "Microstructure", "Hydrogen diffusion and transport", "Mechanical properties", "Hydrogen resistance", and so on. These covered the basic methods and purposes of HE research. Finally, the distribution of the main subject categories of the publications was determined, and these categories covered various topics and disciplines. This study establishes valuable reference information for the application and development of HE research and provides a convenient resource to help researchers and scholars understand the development trends and research directions in this field.

Keywords: hydrogen embrittlement; bibliometric analysis; research trends; visualization

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1. Introduction

Hydrogen is a promising secondary energy with rich sources and wide applications. During production, processing or service, hydrogen may enter the interior of metals and become locally enriched, causing hydrogen damage [1–7]. Hydrogen damage leads to the creation and propagation of microcracks in materials, which result in the decline of mechanical properties, such as toughness and plasticity, and, finally, lead to sudden brittle fracture [8,9]. Therefore, when a material is in a hydrogen environment, hydrogen damage is a very complex process, and this is usually referred to as "hydrogen embrittlement" (HE). Due to the inevitable adsorption of hydrogen by metals in the above process, coupled with the uncertain time until brittle fracture, failure accidents caused by HE are common [10–12]. HE has been extensively studied since its discovery, but no single theory can explain all HE phenomena. It is a global problem that has plagued academia for a long time. Understanding and solving the HE problem is the key to improving the reliability of hydrogen energy equipment.

Reviewing the previous research on HE can help in understanding its research status. In recent years, numerous publications have discussed the HE of different materials under various conditions. However, few studies have been conducted that assess the evolution of scientific output in this field. Bibliometric reviews can effectively capture research trends in a specific field from a relatively short period. They can help other scholars understand the development trends and research priorities in the field [13]. Therefore, it is necessary to analyze the status of research on HE from this perspective.

Bibliometric analysis, with its comprehensive quantitative statistics, intuitive information display and accurate descriptions and evaluations, has become an important tool for global analysis and investigation in various scientific fields [14]. Moreover, bibliometric analysis is a technique that can provide an overview of a large number of publications and that can be used to identify and quantify collaborations, co-citation similarities, major research themes, and research trends in a specific field [15]. In recent years, bibliometric analysis has been adopted in many fields, such as process safety and environmental protection [16], piezoelectric ceramics [17], COVID-19 vaccination [18], the circular economy [19], laboratory safety [20] and the hydrogen economy [13].

Therefore, bibliometric analysis is suitable for exploring the status of research and obtaining specific data on various aspects of a research object. Based on the data retrieved from the Web of Science (WOS), this study focused on the following questions regarding the field of HE:

(1) Annual trends and growth forecasts for global publications;
(2) Cooperation between countries, institutions and authors;
(3) Analysis of the main journal sources and their influence;
(4) The most influential publications and the main topics covered by the publications;
(5) Research hotspots and their evolution in different periods;
(6) The division of subject categories.

Using a bibliometric analysis, this article addresses the above problems and provides a macro-quantitative overview of the main features of HE publications.

2. Methodology

2.1. Retrieval Strategy and Data Source

The data used in this research were retrieved from the WOS Core Collection on 1 June 2022. In order to avoid deviations caused by data updates [21], all the literature retrievals and data downloads were completed on the same day. The search topics included "hydrogen embrittlement", "hydrogen induced cracking", "hydrogen assisted cracking", "hydrogen trapping", "hydrogen damage", "hydrogen induced fracture", "hydrogen induced embrittlement" and "hydrogen brittleness". In the WOS Core Collection, studies on the topic of hydrogen embrittlement first appeared in 1997. Hence, the period for the literature data included in this study was from 1997 to 2022, covering all relevant kinds of research on HE topics in the Core Collection of the Web of Science from the past 25 years. A total of 6676 relevant publications were collected.

Subsequently, all the records of the 6676 publications focusing on "hydrogen embrittlement" were exported in plain text and Excel formats. Plain text was used for bibliometric analysis, and Excel data were used to analyze publication characteristics.

Six types of documents were identified. Table 1 shows the document types and quantities. The most common was "article", which accounted for 81.88% of the total publications. The second and third most common document types were "proceeding paper" and "review article", respectively. This shows that the academic conference is an important medium for the exchange and display of academic achievements in and scientific and technological information on HE, accounting for a considerable proportion of the publications, and highlights it as another important academic exchange medium in addition to academic journals. Reviews, which are one of the methods used to quickly understand the research in the field of HE, also accounted for a certain proportion. Finally, document types that appeared less frequently in the database included "editorial material", "early access", and "book chapter". The publication languages included English, Japanese, Chinese, Korean, French and German, and 6388 (95.69%) publications were published in English, which accounted for the largest proportion.

Table 1. Document types and quantities for publications on hydrogen embrittlement.

Rank	Document Type	Quantity	Percentage
No. 1	Article	5466	81.88
No. 2	Proceeding paper	1430	21.42
No. 3	Review article	192	2.88
No. 4	Editorial material	35	0.52
No. 5	Early access	26	0.39
No. 6	Book chapter	3	0.04

2.2. Data Collection and Statistical Analysis

Raw data were initially downloaded from the WOS Core Collection database and then imported into Microsoft Excel 2019 to analyze publication characteristics, including the total number of annual publications, countries, research institutions, authors, journal sources and IF impact factors. The impact factor is an internationally accepted journal evaluation index that indicates the average number of citations per year of published publications [22]. We used Microsoft Excel 2019 to fit polynomial models and analyze time trends in publications. The equation $f(x) = ae^{bx}$ was used to calculate the annual number of publications, where the variable x represents the year of publication and $f(x)$ represents the number of publications per year. VOSviewer 1.6.13 was used for cooperation network analysis and visualization [23–25].

3. Results and Discussion

3.1. Annual Trends and Growth Forecasts for Global Publications

The change in the number of academic publications in a research field is an important indicator for the measurement of the development trends in this field [26,27]. Analyzing trends in the numbers of publications over time and performing statistical analyses make it easy to infer the level of and trend in research activities. Figure 1 presents the annual and cumulative numbers of publications related to HE, and the growth trend is fitted according to the annual number. According to the WOS Core Collection, although the first publication was in 1997, research on HE had already gained researchers' attention at an earlier time [28,29]. The first report on HE was published in 1874 by Johnson, which shows that research on HE has a long history [30]. However, the publication circulation of HE research was low before 2007, and the research was in a state of fluctuation with various ups and downs, which means that the research on HE during this period was in an initial development stage and had not yet formed a complete literature system. HE research entered a stage of rapid development after 2007. The number of related publications increased yearly, especially from 2017 to 2019, during which time it increased significantly compared to previous years. The increase in 2017 was the most dramatic, with a rise of 22.7% compared to 2016.

In recent years, growing demand related to the hydrogen energy industry has led to support from hydrogen energy policies in many countries and regions. The development of research on HE is inseparable from the support provided by these policies. Before 2006, the global hydrogen energy policy layout was imperfect, and there was less relevant policy support. The USA released the National Hydrogen Energy Development Roadmap in 2002 [31], aiming to achieve a full-scale hydrogen economy by 2040. The research on HE was then still in its infancy, and the number of publications was relatively small. In 2006, the USA released the Advanced Energy Initiative, which may have had a certain connection with the growth in the number of HE publications in the following years. In 2014, Japan released the Strategic Roadmap for Hydrogen Energy and Fuel Cells, which clarified the three-stage development goals for 2025, 2030 and 2040 [32]. In 2015, the US Department of Energy proposed a major push for the large-scale production and application of solar and hydrogen energy [33]. In 2017, Japan became the first country to issue a national hydrogen energy strategy when it released the Basic Strategy for Hydrogen Energy, which proposed specific goals for supplying and utilizing hydrogen energy [34,35]. By 2019, more than 20 countries and regions, including the USA, Japan and South Korea, had formulated strategies for national hydrogen energy development, actively fostering the development of the hydrogen energy industry [36]. Many countries released national-level hydrogen energy development strategies during this period, so the number of corresponding publications proliferated. After 2019, the number of publications was more than 500 each year, which shows that the research on HE entered a stage of rapid development. In 2022, China released the Medium and Long-Term Plan for the Development of Hydrogen Energy Industry (2021~2035) in order to formally incorporate hydrogen into the energy system, which will continue to accelerate the development of research on HE in China. The issuance of these policies is closely related to the development of research on HE.

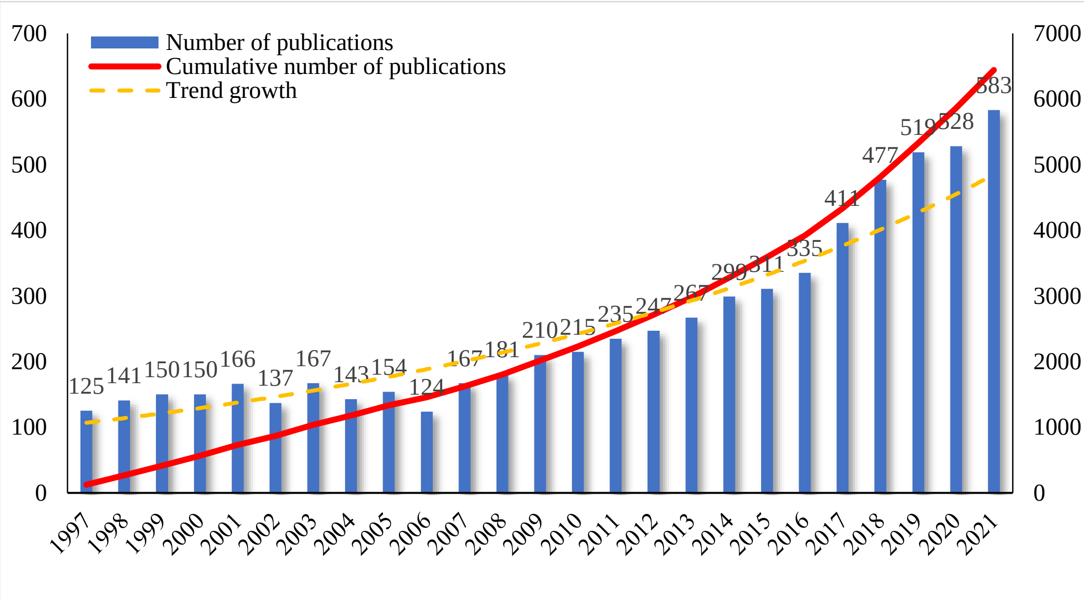

Figure 1. Growth trend, annual number and cumulative number of publications related to hydrogen embrittlement.

Overall, the annual number of publications related to HE has increased exponentially, from 125 in 1997 to 583 in 2021, and the growth shows that research on HE has become more and more important during the past 25 years.

3.2. Quantitative Analysis of Prolific Countries

According to the retrieval results, publications related to HE have been published in 87 countries (or regions). Table 2 lists the top ten countries with the highest numbers of publications, the total of which amounted to 5787, 86.68% of the total publications. Figure 2 shows a bubble chart of the numbers of publications by country. Most of these publications were published by developed countries in East Asia, North America and Europe. China, a developing country, has the largest number of publications on HE, ranking first with 1464 publications, which account for 21.93% of the total, and its research is in a stage of rapid development. Japan ranks second with 1183 publications, accounting for 17.72%. The USA was the first developed country to propose the concept of the "hydrogen economy" [37], and its related research was also carried out earlier; it ranks third with 938 publications, accounting for 14.05%. Germany and South Korea, which rank fourth and fifth, accounted for 7.71% and 5.75% of the total, respectively; the number of publications in other countries accounted for less than 5%. Most countries with a large number of publications have issued national hydrogen energy development strategies. They are economically developed or in a rapid development stage and pay more attention to research on HE than other countries.

Table 2. Top ten countries for the number of publications related to hydrogen embrittlement from 1997~2022.

Rank	Countries	Region	Documents	Percentage	Citations
No. 1	China	East Asia	1464	21.93	18,256
No. 2	Japan	East Asia	1183	17.72	24,589
No. 3	USA	North America	938	14.05	22,243
No. 4	Germany	Central Europe	515	7.71	12,751
No. 5	South Korea	East Asia	384	5.75	5906
No. 6	France	Western Europe	295	4.42	5878
No. 7	UK	Western Europe	291	4.36	6366
No. 8	India	South Asia	259	3.88	3279
No. 9	Spain	Southern Europe	241	3.61	2532
No. 10	Canada	North America	217	3.25	5197

Figure 2. Bubble chart of the number of hydrogen embrittlement publications distributed by country.

In VOSviewer, the analysis module was applied to generate a cooperation network for the main countries in the field of HE research. Each country in Figure 3 had at least five publications, and 60 countries met the threshold, excluding countries with no partnerships with other countries in the network. The size of the nodes represents the number of publications, the thickness of the connecting lines represents the tightness of the cooperation and the colors represent the main cooperation clusters. The network can be divided into seven significant clusters, among which the representative ones are the following.

The first cluster is China (purple cluster, top right), which has many publications co-authored with authors from the USA, Japan, Germany and Australia. The second cluster is Japan (orange cluster, right); as one of the countries with the longest histories in the hydrogen energy industry, its publications have the highest total number of citations at 24,589 and the most significant influence. The color of the German cluster is the same as that of the Japanese cluster, which means that their research on HE is similar. The next cluster is the USA (red cluster, middle), which has a certain degree of cooperation with almost all the countries in the network. The total number of citations of its publications is second only to Japan, with 22,243 citations; it also has a significant influence in the field of HE. As one of the few developed countries in East Asia, South Korea also has many publications, ranking fifth with 384 publications. The cluster on the left is mainly composed of several countries in Europe. The numbers of publications published in Germany, France and the UK are also included in the ranking. These countries cooperate more frequently and closely with other European countries.

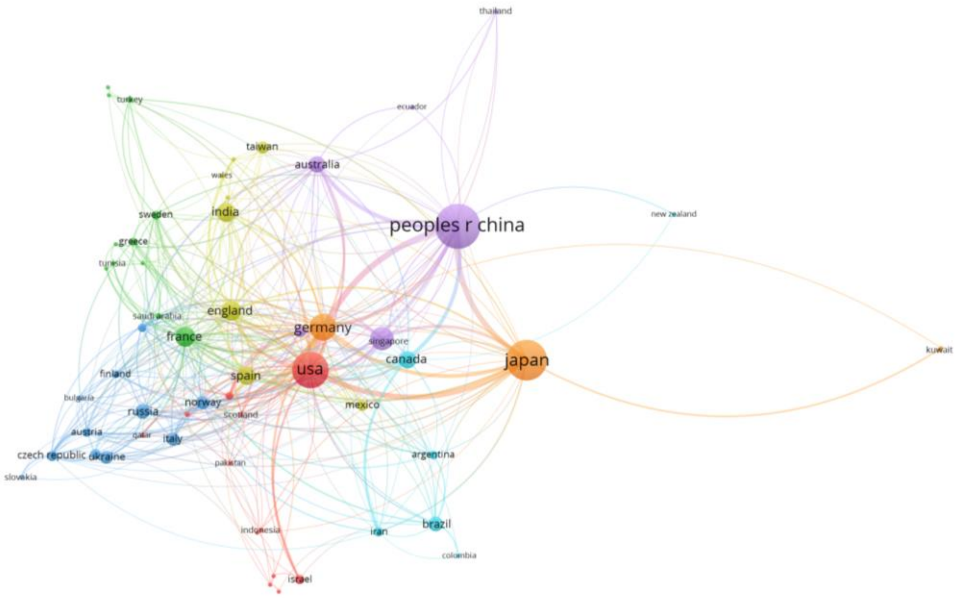

Figure 3. Cooperation network for main countries' research on hydrogen embrittlement.

It can be seen from the network that countries with partnerships tend to be geographically related to each other, such as China, Japan and South Korea, as well as some countries in North America and Western Europe. This means that the publications are mainly concentrated in developed countries with relatively mature hydrogen energy development. However, there are also some publications concentrated in developing countries, such as China.

3.3. Quantitative Analysis of Major Research Institutions

The most productive organizations and groups in the field of HE were determined by analyzing cooperation between research institutions. According to the retrieval results, 3477 different research institutions published 6676 publications related to HE, and 54 institutions were included in the cooperation network, each with at least 30 publications. Table 3 presents the details for the top ten institutions with the highest total link strengths, including five universities, three institutes, one company and one academy of science. Six institutions were from Japan, with the top-ranking institution being Kyushu University, which has published 245 publications. The other five institutions were JFE Steel Corporation, Tohoku University, the National Institute of Materials Science, Kyoto University and the National Institute of Advanced Industrial Science and Technology. Two institutions in China were in the top ten; namely, the University of Science and Technology Beijing and the Chinese Academy of Sciences, ranking second and tenth, respectively. The University of Science and Technology Beijing had 283 publications, the largest number of publications. Germany's Max Planck Inst Eisenforsch ranked seventh with 86 publications. One organization in the USA was in the top ten, the University of Illinois, which published 72 publications.

Universities and institutes are the major sources of countries' research output, and they often represent a country's scientific and innovation capabilities. As shown in Table 3, among the top ten institutions, five universities published 808 publications, accounting for 12.10% of the total, and three institutes published 254 publications, accounting for 3.80%. Several specific institutions in Japan were major contributors to the research on HE, and Japanese universities and institutes published 694 publications in total, accounting for 10.40% of the total. Two Chinese organizations also had many publications, with a total of 462 publications, accounting for 6.92% of the total. Among the 3477 research institutions, 2156 institutions published only one publication, accounting for 62.01%; 519 institutions had at least five publications, accounting for 14.93%; 254 institutions had at least ten publications, accounting for 7.31%; and 111 institutions had at least 20 publications, accounting for 3.19%. It can be seen that most institutions had relatively few publications, and more than 90% of institutions had fewer than ten publications. However, there was no effect on the total production of publications because the main contributors to HE publications were the productive organizations.

Table 3. Top ten institutions with the highest total link strengths for hydrogen embrittlement research.

Rank	Institution	Country	Total Link Strength	Documents	Citations
No. 1	Kyushu University	Japan	176	245	7999
No. 2	University of Science and Technology Beijing	China	96	283	4856
No. 3	JFE Steel Corporation	Japan	92	73	2272
No. 4	Tohoku University	Japan	86	115	1948
No. 5	National Institute for Material Science	Japan	80	102	3740
No. 6	Kyoto University	Japan	74	93	1141
No. 7	Max Planck Inst Eisenforsch	Germany	66	86	3693
No. 8	University of Illinois	USA	64	72	4888
No. 9	National Institute of Advanced Industrial Science and Technology	Japan	54	66	1993
No. 10	Chinese Academy of Sciences	China	51	179	3137

In VOSviewer, the cooperation network for the main research institutions for HE research was generated through co-author analysis. Figure 4 shows the distribution of research intensity, the classification of institutions and the degree of cooperation between institutions, as found through the analysis. In Figure 4, each node represents an institution, and the node size represents the number of publications. The connections between nodes represent the cooperative relationships, and a denser line indicates more instances of cooperation.

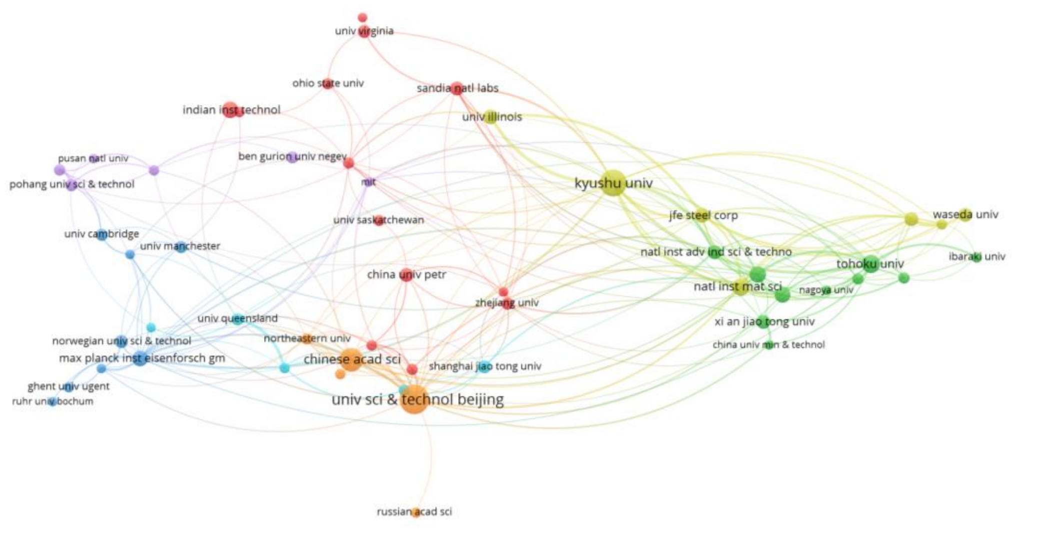

Figure 4. Cooperation network for main research institutions' publications on hydrogen embrittlement.

In the generated cooperation network, 54 institutions, 7 clusters and 218 connections were selected and displayed using automatic clustering. The geographical relationship between the clusters is also indicated. The yellow and green clusters on the right are mainly Japanese institutions, the orange and red clusters below are mainly Chinese institutions, the red clusters above are mostly US and Indian institutions, the purple ones on the upper left are mainly Korean institutions and the blue ones in the lower left are mainly European institutions. The cooperation network for the various institutions shows the cooperation links and proximity. The network shows that institutions in the same country tended to cooperate more closely, and their research themes were relatively similar, such as Japan and China. However, from a global perspective, research institutions in different countries demonstrated relatively less cooperation. Regarding total link strength, Kyushu University had the highest total link strength (176), followed by the University of Science and Technology Beijing (96) and then Japan's JFE Steel Corporation (92) and Tohoku University (86). The total link strength shows that Japan, as a pioneer in HE, has a high level of overall cooperation between research institutions. In recent decades, research institutions in China have rapidly developed HE research, demonstrating high total link strength and an increasing influence.

3.4. Cooperation Analysis of Major Research Groups

The 6676 publications related to HE were written by 15,760 authors, with an average of 2.36 authors per publication. In total, 11,420 authors published only one publication about HE, accounting for 72.46% of the total with the most significant proportion. In addition, 2116 authors published three or more publications, accounting for 13.43% of the total; 851 authors published five or more publications, accounting for 5.40%; and there were 230 authors with ten or more published publications, accounting for 1.46%, and only a small percentage were productive or influential authors.

Due to the highly interdisciplinary nature of HE research, many researchers from different branches in the same field have their own focus, such as materials science, electrochemistry and metallurgical engineering. Thus, cooperation can produce complementary advantages and a win–win situation.

Table 4 lists the top 12 authors with the most publications on the topic of HE. The ranking is based on the numbers of publications by the authors of the 6676 selected publications. Akiyama was the most prolific and influential author on the topic of HE with 88 published publications, followed by Koyama and Tsuzaki, who published 67 and 62 publications, respectively. Their publications were cited relatively often, and their total link strengths ranked in the top three. These authors are very influential in the field of HE.

Table 4. Top 12 authors with the highest numbers of publications related to hydrogen embrittlement.

Rank	Author Name	Country of Author	Documents	Citations	Total Link Strength
No. 1	Akiyama, E.	Japan	88	2565	198
No. 2	Koyama, M.	Japan	67	1828	143
No. 3	Tsuzaki, K.	Japan	62	2512	105
No. 4	Li, X. G.	China	58	1112	108
No. 5	Verbeken, K.	Belgium	45	1503	67
No. 6	Takai, K.	Japan	44	680	39
No. 7	Matsunaga, H.	Japan	41	690	93
No. 8	Chu, W. Y.	China	41	447	89
No. 9	Barnoush, A.	Germany	40	1375	53
No. 10	Yamabe, J.	Japan	40	817	83
No. 11	Hojo, T.	Japan	39	239	68
No. 12	Liu, Z. Y.	China	39	707	86

Creating and analyzing an author-level cooperation network can provide a reference to help new scholars learn about influential scholars and their teams more quickly. It can also serve as a reference to help existing research teams find cooperative groups. Figure 5 shows the author cooperation network for HE publications. The authors in the network each published at least nine publications related to HE. Authors are represented as nodes, and those with no ties to other authors in the network were excluded. The node size represents the number of publications, and lines between two authors indicate their cooperation. More lines indicate more cooperation and different colors indicate different cooperation clusters.

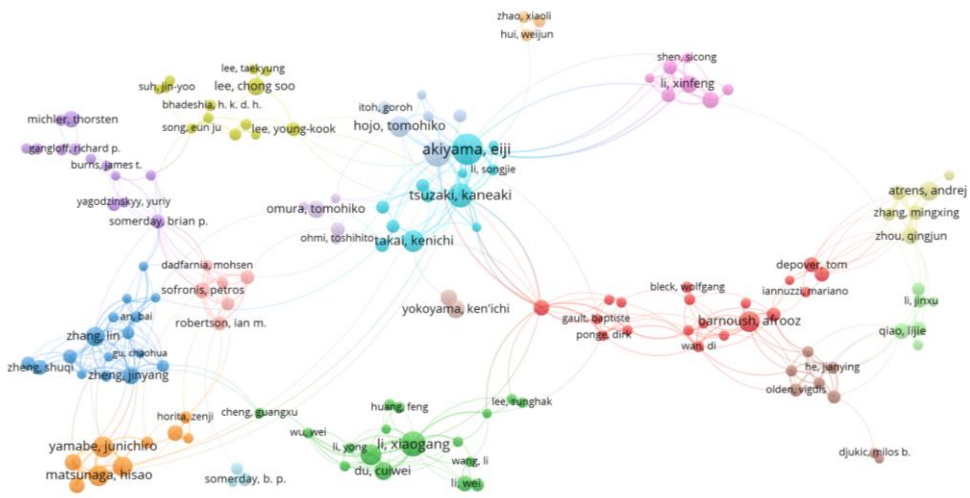

Figure 5. Co-authorship network for research on hydrogen embrittlement.

The cooperation network is divided into 17 author clusters. In general, cooperation between prolific authors was not very close; they all have their specific research directions and collaborating groups. The more representative ones were the indigo blue cluster with professor Akiyama as the core, the green cluster with professor Li as the core, and the red cluster with professor Barnoush as the core. There were also small clusters that were not closely related to others, often dominated by independent authors or authors with a small number of co-authors. These clusters accounted for a certain proportion, but this cooperation was small-scale and unstable, demonstrating a lack of effective international exchanges and cooperation [14].

3.5. Analysis of Major Journal Sources

Academic journals are used as a medium to disseminate academic information and publish academic achievements, and they are also an important symbol indicating academic level and scientific ability. Journals are essential carriers for the transmission of academic achievements [38]. The journal source analysis was used to confirm the distribution of core journals in the field. The 6676 publications were published in 1064 different journals covering research fields such as energy and fuels, thermodynamics, materials science, metallurgical engineering, characterization testing and physical chemistry, which indicates that HE research covers a wide range and has a multidisciplinary nature. Among the 1064 journals, 614 journals published only one publication, accounting for 57.71%; 154 journals published only two publications, accounting for 14.47%; 186 journals published no less than five publications, accounting for 17.48%; and 101 journals published no less than 10 publications, accounting for 9.49%.

Table 5 lists the 15 most active journals that published relevant publications in the field of HE from 1997 to 2022. These 15 journals accounted for 1.41% of all journals, but the number of publications was 40.41% of the total. Figure 6 shows the citation network for publication sources for work on HE. It can be seen from Table 5 and Figure 6 that the most important journal in the field of HE was the *International Journal of Hydrogen Energy* with 455 publications published, followed by *Materials Science and Engineering A—Structural Materials: Properties, Microstructure and Processing* and *Corrosion Science*, in which 396 and 357 publications were published, respectively. In the subject categories of these 15 journals, 13 were related to materials science, seven to metallurgical engineering, two to chemical engineering and one to nuclear science and technology. The core journals of HE research were generally multidisciplinary or interdisciplinary. HE is a multidisciplinary and interdisciplinary science with multi-mechanism coordination, including the characteristics of many other disciplines, such as materials science, mechanics, electrochemistry and mechanical engineering.

Table 5. Top 15 main sources for publications on hydrogen embrittlement from 1997~2022.

Rank	Journal	Number	Impact Factor [1]	Subject Category
No. 1	*International Journal of Hydrogen Energy*	455	5.242	Chemistry, physical; energy and fuels
No. 2	*Materials Science and Engineering A—Structural Materials: Properties, Microstructure and Processing*	396	5.266	Materials science, multidisciplinary; nanoscience and nanotechnology
No. 3	*Corrosion Science*	357	7.687	Materials science, multidisciplinary
No. 4	*Engineering Failure Analysis*	181	3.233	Engineering, mechanical; materials science, characterization and testing
No. 5	*Acta Materia*	178	9.277	Materials science, multidisciplinary
No. 6	*Corrosion*	157	2.056	Metallurgy and metallurgical engineering
No. 7	*ISIJ International*	153	1.985	Materials science, multidisciplinary; metallurgy and metallurgical engineering
No. 8	*Scripta Materialia*	136	5.898	Metallurgy and metallurgical engineering
No. 9	*Metallurgical and Materials Transactions A—Physical Metallurgy and Materials Science*	123	2.602	Materials science, multidisciplinary; metallurgy and metallurgical engineering
No. 10	*Journal of Alloys and Compounds*	122	4.631	Materials science, multidisciplinary; metallurgy and metallurgical engineering
No. 11	*Journal of Nuclear Materials*	111	2.841	Materials science, multidisciplinary
No. 12	*Journal of Materials Engineering and Performance*	87	1.895	Chemistry, physical
No. 13	*Metals*	85	2.487	Materials science, multidisciplinary; nuclear science and technology
No. 14	*Materials Science*	79	0.665	Materials science, multidisciplinary
No. 15	*Materials*	78	3.920	Materials science, multidisciplinary; metallurgy and metallurgical engineering

[1] Impact factor and subject category source: Journal Citation Reports ™ 2020.

3.6. Citation Analysis

Citation consists of two processes: citing and being cited. Referencing one publication in another publication is called citing, and the use of a publication as a reference in other publications is called being cited [39]. It is generally accepted that the total number of citations reflects the impact, popularity and quality of a publication [40–42]. However, some authors think that the number of citations by others is a measure of a publication's visibility instead of a comprehensive indicator of publication quality [43,44].

The citation relationships between pairs of publications can be seen from the citation network, and the size of the node indicates the frequency of the citation of the publication. Figure 7 shows the citation network for publications cited more than 80 times among the 6676 publications. The citation network depicts the historical evolution of publications in this field, and the connections between pairs of nodes represent citations. Publications from earlier years are cited by later publications, and the publications in the citation network cite each other to form a citation network. However, since the citation network only involves the retrieved publication data, it also has certain limitations.

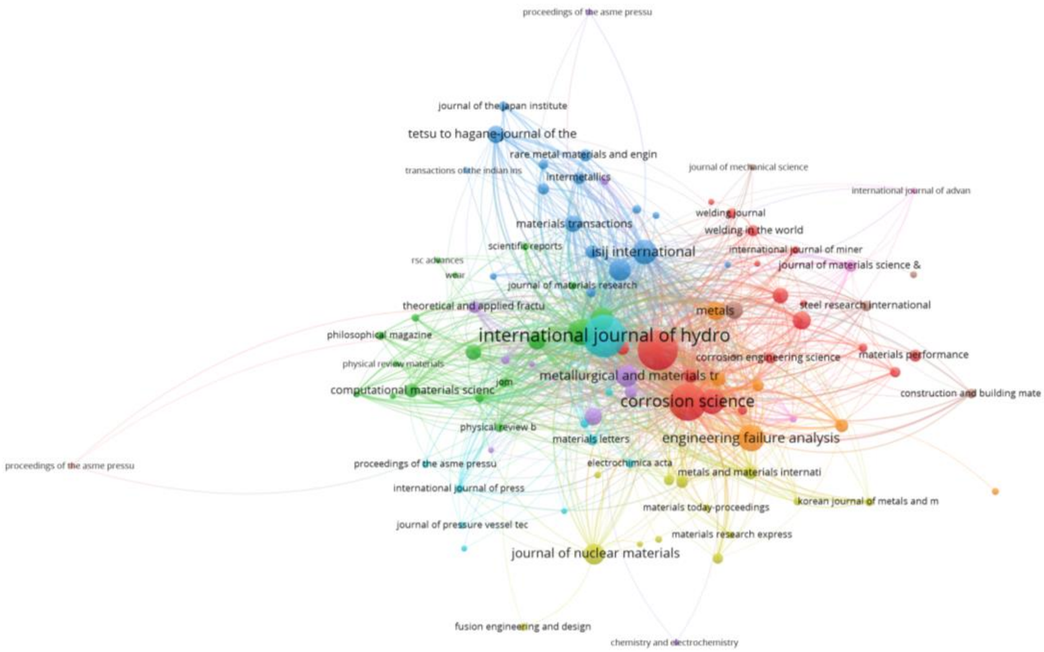

Figure 6. Citation network for publication sources for work on hydrogen embrittlement.

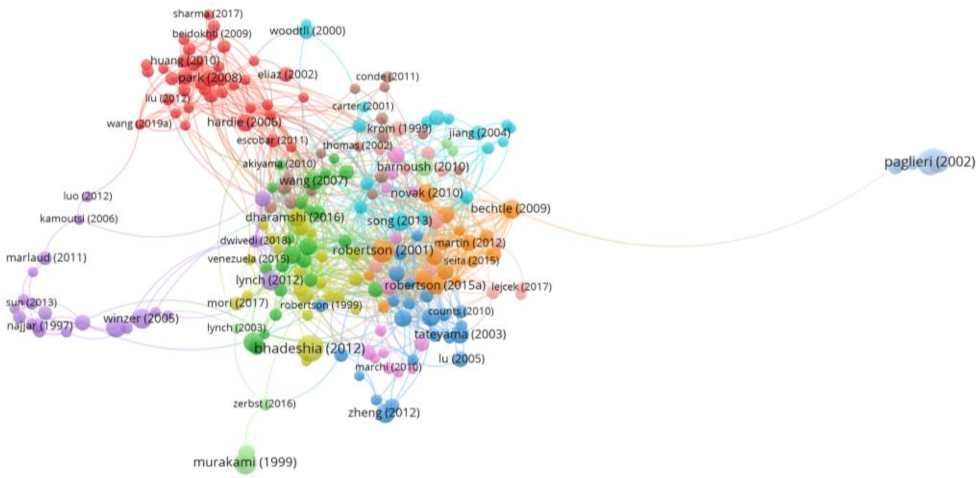

Figure 7. Citation network for highly cited references used in publications on hydrogen embrittlement.

In the retrieved data, 18.29% of the publications were cited zero times, 55.60% were cited more than five times and 39.22% were cited more than ten times. Table 6 shows the top nine most cited publications. The most cited publication was "Innovations in palladium membrane research" [45] by Paglieri et al.; it has been cited 523 times since it was published in 2002. The publication with the highest average number of citations per year was "Correlations in palladium membranes for hydrogen separation: A review" [46] by Yun et al.; it has been cited an average of 39.7 times per year since 2016. The average citations per year in other publications also exceeded 30, including "Atomic mechanism and prediction of hydrogen embrittlement in iron" [47] by Song et al. (35.38 citations), "Hydrogen embrittlement phenomena and mechanisms" [1] by Lynch et al. (30.78 citations) and "Development of high pressure gaseous hydrogen storage technologies" [48] by Zheng et al. (30.33 citations). This ranking was calculated based on the total citations, so some highly cited publications published in recent years were not included. However, this did not affect the ranking of the high-quality publications published in recent years. For instance, the total citations of "Development of high pressure gaseous hydrogen storage technologies" [48] (30.33 citations), published by Zheng et al. in 2012, were included in the ranking.

Table 6. Top nine most frequently cited publications on hydrogen embrittlement.

Rank	Title	Author(s)	Country of First Author	Published Year	Citations	Average Citations per Year
No. 1	Innovations in palladium membrane research	Paglieri, S. N. et al.	USA	2002	523	27.53
No. 2	Test environment and mechanical properties of Zr-base bulk amorphous alloys	Liu, C. T. et al.	USA	1998	503	21.87
No. 3	Correlations in palladium membranes for hydrogen separation: A review	Yun, S. et al.	USA	2011	397	39.70
No. 4	Factors influencing the mechanism of superlong fatigue in steels	Murakami, Y. et al.	Japan	1999	384	17.46
No. 5	The effect of hydrogen on dislocation dynamics	Robertson, I. M. et al.	USA	2001	384	19.20
No. 6	Atomic mechanism and prediction of hydrogen embrittlement in iron	Song, J. et al.	Canada	2013	283	35.38
No. 7	Hydrogen embrittlement phenomena and mechanisms	Lynch, S. et al.	Australia	2012	277	30.78
No. 8	Grain-boundary engineering markedly reduces susceptibility to intergranular hydrogen embrittlement in metallic materials	Bechtle, S. et al.	USA	2009	277	23.08
No. 9	Development of high pressure gaseous hydrogen storage technologies	Zheng, J. Y. et al.	China	2012	273	30.33

Among the top nine most cited publications, authors in the USA wrote five and the rest were written by authors in Japan, Canada, Australia and China, which reflects the great influence of experts in some developed countries, such as the USA and Japan.

The high numbers of citations of these publications reflect their research's general applicability and importance. The research content of these publications included: (1) palladium membranes for hydrogen blocking technology; (2) the HE of zirconium-based bulk amorphous alloys; (3) palladium membranes for hydrogen separation technology; (4) the factors influencing the super-long fatigue mechanism of steel; (5) the effect of dislocations on HE; (6) the atomic mechanism of HE in iron; (7) HE and its mechanism in steel and other materials; (8) the susceptibility to intergranular HE of metallic materials; and (9) the development of high-pressure hydrogen storage technology. Among these nine highly cited publications, six were related to HE and its mechanism, two were related to palladium membrane hydrogen blocking technology and one was related to hydrogen storage technology. Due to the characteristics of hydrogen atoms and the diverse applications of hydrogen energy, HE exists widely in materials, which is reflected in the focuses of the research. Hydrogen blocking technology can efficiently reduce the susceptibility of materials to HE, and research on hydrogen separation technology is becoming more and more popular. Hydrogen storage technology involves the three processes of hydrogen storage, production and transportation, providing the foundations for the utilization of hydrogen energy. Therefore, publications on the above topics are highly cited.

3.7. Co-Citation Analysis

Two publications may be similar in content if other publications cite them simultaneously [49,50]. Co-citation analysis focuses on the relationship or interaction between two publications and highlights publications on similar topics that are cited together in other publications. The more times two publications are cited together, the more similarities they can be assumed to share [51]. Co-citation analysis is mainly used to analyze the references of publications.

A total of 106,705 references were cited, and the number of references cited only once was 79,807, accounting for 74.79% of the total. VOSviewer was used to analyze and visualize co-cited publications. Due to the large number of publications, to make the co-citation network more centralized, only publications that were cited together more than 60 times were included in the network, and 225 of the 106,705 publications met the requirements.

The results of the co-citation analysis are shown in Figure 8. Different nodes represent different publications. The node size represents the number of times the publication was cited; the larger the node, the more citations. The distance between two nodes indicates the similarity of the topics; the smaller the distance between two publications, the closer the relationship. As can be seen from the co-citation network, there are five clusters with different colors, and the same color represents a cluster with similar topics. These five clusters represent several main topics covered in the field of HE: yellow cluster (top), red cluster (right), purple cluster (bottom right), green cluster (bottom left) and blue cluster (middle). The yellow cluster covers a wide range and has certain connections with the blue, green and red clusters. The blue and green clusters are closely related and mixed, while the purple cluster is smaller but closely related to the red cluster.

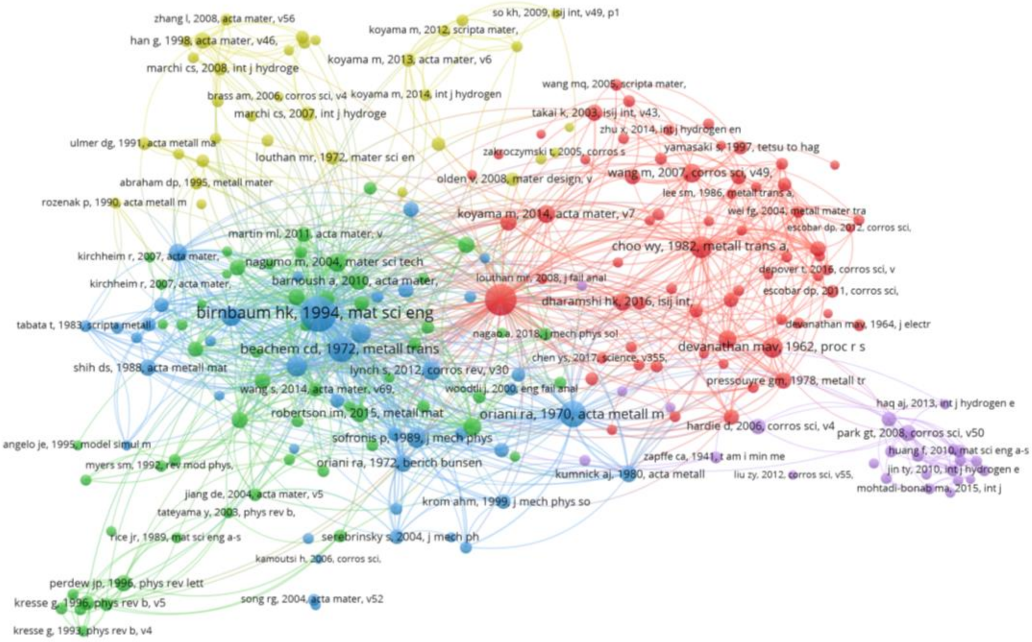

Figure 8. Co-citation network for highly cited references used in publications on hydrogen embrittlement.

Cluster 1 (yellow): HE in different materials.

In this cluster, the most cited publication in the selected database was "Effect of strain-induced martensite on hydrogen environment embrittlement of sensitized austenitic stainless steels at low temperatures" by Han et al. [52]. The number of co-citations was 169 and the total link strength was 1163, which shows that this paper occupies an important role in the yellow cluster.

This paper investigated the hydrogen environment embrittlement (HEE) of 304, 316 and 310S austenitic stainless steels after solution annealing, sensitization and desensitization heat treatment. The electron emission spectra of strain-induced martensite and carbide during HEE were studied. Both structures were found on the grain boundaries of the sensitized materials. HEE greatly affected the 304 and 316 metastable austenitic stainless steels but had no significant effect on 310S stable austenitic stainless steel. The test temperature had the greatest effect on the HEE of the 304 and 316 stainless steels, and the maximum HEE occurred at about 220 K. The heat treatment had no significant effect on the HEE. Sensitization could enhance the susceptibility of materials to HE, and strain-induced martensite and carbide could be observed along the grain boundary of the sensitized material. Desensitization could inhibit the formation of martensite along the grain boundary, which indicated that the strain-induced martensite along the grain boundary led to the HEE of the sensitized material rather than the carbide.

Cluster 2 (red): Effect of hydrogen on mechanical properties of materials.

In this cluster, the most cited publication in the selected database was "Effect of hydrogen on the properties of iron and steel" by Hirth et al. [53]. The number of co-citations was 613, and the total link strength was 5442.

In this paper, a new mechanism for the optimal performance of iron in hydrogen at low temperatures was proposed. Internal friction and mechanical properties were found to explain the effect of hydrogen on iron at different temperatures, and it was shown that hydrogen deteriorates iron by enhancing the mobility of screw dislocation at room temperature. However, iron can be strengthened through core interaction at low temperatures. The authors state that a single theory cannot explain the degradation of steel properties by hydrogen; many HE mechanisms are often involved, and the combination of various mechanisms can explain most hydrogen-induced degradation phenomena.

Cluster 3 (purple): Effect of alloying elements or microstructure on HE.

In this cluster, the most cited publication in the selected database was "Effect of microstructure on the hydrogen trapping efficiency and hydrogen-induced cracking of line pipe steel" by Park et al. [54]. The number of co-citations was 174, and the total link strength was 1631.

This paper compared the hydrogen trapping efficiency of different microstructures, and the critical hydrogen flux leading to hydrogen-induced cracking of API X65 pipeline steel was determined. Ferrite/degenerated pearlite (F/DP), ferrite/acicular ferrite (F/AF) and ferrite/bainite (F/B) were obtained using different processes. It was found that microstructures, such as DP, AF, BF and martensite/austenite (M/A), can affect hydrogen capture and hydrogen diffusion. Among these microstructures, AF was found to have the highest hydrogen capture efficiency. When the steel contains microstructures, such as F/AF and F/B, hydrogen-induced cracking preferentially spreads and expands in areas where martensite and austenite are locally concentrated. Bainite was found to be more susceptible to HE than AF.

Cluster 4 (blue): Hydrogen transport.

In this cluster, the most cited publication in the selected database was "Hydrogen-enhanced localized plasticity—A mechanism for hydrogen-related fracture" by Birnbaum et al. [55]. The number of co-citations was 780, and the total link strength was 8395.

In this paper, some of the main HE mechanisms were briefly reviewed. The mechanisms underlying stress-induced hydride formation and debonding and hydrogen-promoted local plastic deformation were evaluated. The failure mechanism underlying hydrogen-enhanced dislocation mobility was further discussed. The hydrogen shielding theory for the interaction between dislocation and the elastic stress center was discussed and summarized. The results showed that this theory could explain hydrogen-enhanced dislocation mobility.

Cluster 5 (green): Characteristics and mechanisms of hydrogen-related failures.

In this cluster, the most cited publication in the selected database was "Hydrogen related failure of steels—A new aspect" by Nagumo et al. [56]. The number of co-citations was 222, and the total link strength was 2791.

This paper systematically discussed the characteristics and mechanism of, as well as the recent research progress in, hydrogen-induced failure in steel. After analyzing hydrogen states in steel, a new hydrogen-induced failure mechanism was proposed. Hydrogen can reduce ductile crack growth resistance, which may be caused by an increase in the vacancy during strain. The vacancy density is increased by the interaction between hydrogen and the vacancy, which can be used to explain the crack growth in some amorphous phenomena.

3.8. Co-Occurrence Analysis of Keywords

Analyzing the keywords in the titles and abstracts of publications can provide insight into a field's main topics and research trends [57]. These keywords were analyzed and visualized using VOSviewer. Figure 9 shows the keyword hotspot density map for HE research over different periods. It is very useful for understanding the overall structure of research and focusing on the most critical areas [58].

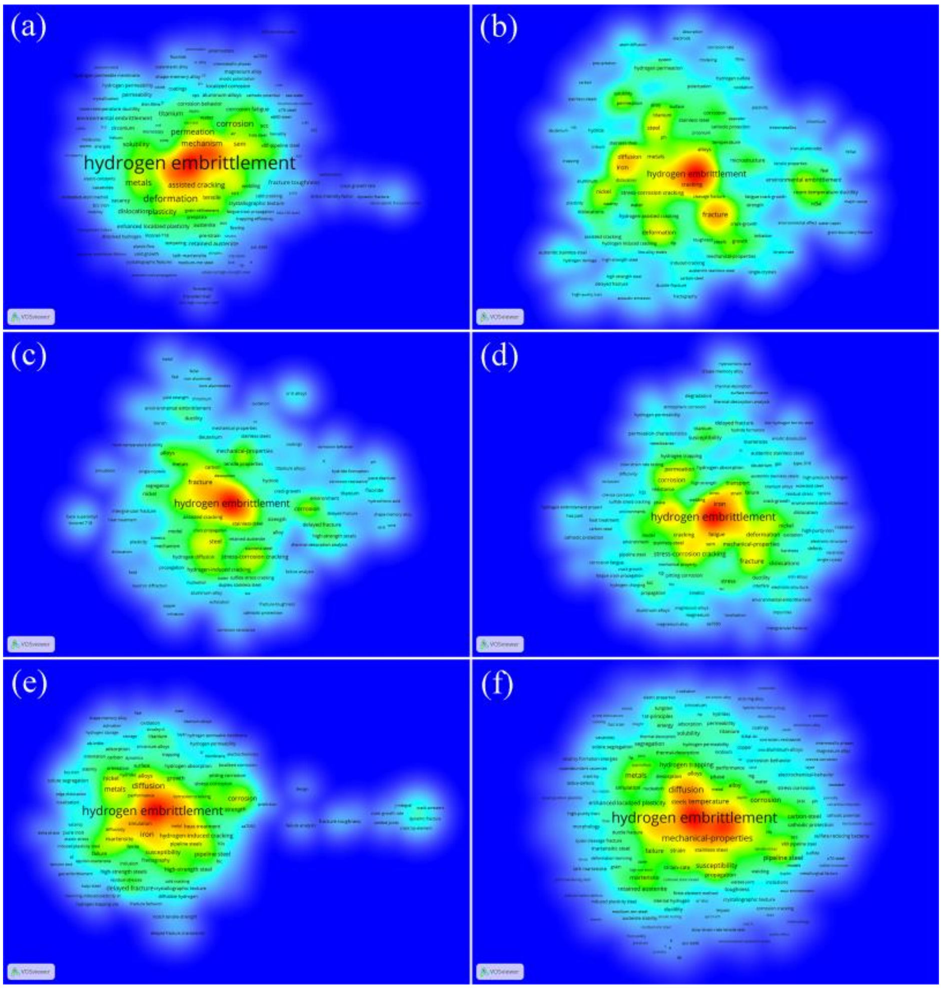

Figure 9. Research hotspots for hydrogen embrittlement research during different periods: (**a**) 1997~2022; (**b**) 1997~2001; (**c**) 2002~2006; (**d**) 2007~2011; (**e**) 2012~2016; (**f**) 2017~2022.

There were 12,370 keywords in the 6676 publications. Figure 9a shows a hotspot density map for keywords from 1997 to 2022, and Figure 9b–f show the maps in different periods. Each keyword in the maps had to occur at least five times in the publications. The node colors depend on the number of occurrences. The frequency increases from blue to red, and the closer the two keywords are, the tighter the connection is. Table 7 lists the top 20 keywords in different periods.

From 1997 to 2001, 144 of the 1783 keywords reached the threshold. This period can be regarded as the early stage of HE research. During this period, “Fracture failure behavior and analysis”, “Stress corrosion cracking”, “Steel and its alloys”, “Hydrogen diffusion”, “Microstructure” and “Environment embrittlement” were the main research topics.

From 2002 to 2006, 182 of the 2110 keywords reached the threshold, as shown in Figure 9c and Table 7. “Fracture failure behavior and analysis”, “Hydrogen diffusion”, “Stress cracking corrosion”, “Steel and its alloys”, “Microstructure” and “Mechanical properties” were the main research topics. Scholars also gradually began to pay attention to “Hydrogen permeation”, “Effect of nickel content”, “Delayed fracture”, “Hydrogen assisted cracking” and so on.

Table 7. Distribution of top 20 research hotspots for work on hydrogen embrittlement during different periods.

Rank	1997~2001		2002~2006		2007~2011		2012~2016		2017~2022		1997~2022	
	R [2]	F [2]	R	F	R	F	R	F	R	F	R	F
No. 1	Hydrogen embrittlement	215	Hydrogen embrittlement	326	Hydrogen embrittlement	451	Hydrogen embrittlement	733	Hydrogen embrittlement	1563	Hydrogen embrittlement	3288
No. 2	Fracture	88	Fracture	82	Behavior	123	Behavior	235	Behavior	549	Behavior	1022
No. 3	Stress corrosion cracking	63	Behavior	65	Iron	95	Microstructure	223	Microstructure	540	Microstructure	913
No. 4	Iron	57	Diffusion	59	Fracture	85	Diffusion	206	Diffusion	391	Fracture	794
No. 5	Behavior	50	Iron	58	Steel	81	Fracture	184	Mechanical properties	381	Diffusion	759
No. 6	Deformation	44	Corrosion	49	Microstructure	79	Iron	147	Fracture	355	Mechanical properties	579
No. 7	Steel	43	Stress corrosion cracking	84	Stress corrosion cracking	136	Stress corrosion cracking	170	Stress corrosion cracking	324	Deformation	563
No. 8	Diffusion	42	Steel	46	Diffusion	61	Deformation	136	Deformation	287	Iron	560
No. 9	Nickel	39	Microstructure	45	Corrosion	61	Steel	130	Steel	218	Steel	518
No. 10	Environmental embrittlement	32	Deformation	43	Metals	53	Metals	114	Strength	205	Stress corrosion cracking	786
No. 11	Metals	32	Cracking	42	Assisted cracking	46	Mechanical properties	106	Iron	203	Corrosion	412
No. 12	Cracking	31	Mechanical properties	35	Growth	46	Corrosion	100	Resistance	193	Metals	396
No. 13	Microstructure	26	Alloys	35	Cracking	46	Transport	94	Susceptibility	182	Cracking	370
No. 14	Corrosion	25	Hydrogen permeation	30	Permeation	43	Cracking	86	Corrosion	177	Cracking	370
No. 15	Hydrogen-induced cracking	25	Delayed fracture	27	Transport	40	Permeation	81	Temperature	170	Transport	323
No. 16	Room-temperature ductility	22	Nickel	27	Stress	39	Stress	72	Metals	169	Permeation	322
No. 17	Mechanical properties	21	Assisted cracking	25	Alloys	39	Mechanism	72	Cracking	165	Strength	317
No. 18	Temperature	21	Growth	24	Nickel	37	Delayed fracture	72	Permeation	163	Resistance	294
No. 19	Permeation	21	Transport	23	Susceptibility	36	Susceptibility	71	Hydrogen-induced cracking	152	Temperature	292
No. 20	Dislocations	18	Stress	21	Mechanical properties	36	Nickel	59	Transport	148	Stress	282

R indicates the research hotspots, F indicates the occurrence frequency of each research hotspot.

From 2007 to 2011, 272 of the 2816 keywords reached the threshold, as seen from the data in Figure 9d and Table 7. The research focused on topics such as "Fracture failure behavior and analysis", "Iron and steel", "Hydrogen diffusion and transport" and "Hydrogen permeation". Steel and its alloys are commonly used materials in the research on HE. In addition, topics such as "Crack initiation and propagation in hydrogen environment", "Hydrogen assisted cracking" and "Hydrogen embrittlement susceptibility" begun to receive more attention.

From 2012 to 2016, 501 of the 4167 keywords reached the threshold. From Figure 9e and Table 7, it can be seen that "Fracture failure behavior and analysis", "Microstructure", "Hydrogen diffusion and transport" and "Mechanical properties" were still the main research topics. Among them, the frequency of the occurrence of the keyword "Microstructure" increased yearly, indicating that microscopic characterization technology was becoming more and more mature with time. In addition, "Hydrogen permeable membrane", "Fatigue" and "Welded joints" gradually became hot topics, and there was also more and more related research on high-strength steel and pipeline steel.

Between 2017 and 2022, 862 of the 7287 keywords reached the threshold. From Figure 9f and Table 7, it can be seen that, in addition to several major research topics, such as "Fracture failure behavior and analysis", "Microstructure", "Hydrogen diffusion and transport", "Mechanical properties", "Hydrogen permeation" and "Stress corrosion cracking", "Hydrogen resistance" and "Temperature effect" have also become popular research topics in recent years.

As shown in Figure 9a and Table 7, although the research hotspots continually changed over the 25 years, the main research hotspots, such as "Fracture failure behavior and analysis", "Microstructure", "Hydrogen diffusion and transport", "Mechanical properties" and so on, did not change much. These are the basic methods used to investigate the HE of materials. In addition, there were relatively more studies on topics such as "Hydrogen permeation", "Hydrogen embrittlement susceptibility", "Temperature effect" and "Hydrogen resistance".

The keyword hotspot density map shows that HE was the main concern in these studies. While many new research topics have emerged over the past 25 years, there are still many areas that have not been fully explored, such as hydrogen diffusion in metal under external loading [59,60], hydrogen atom characterization [61,62], the interaction of hydrogen with various microscopic defects [63,64] and hydrogen-induced crack nucleation and propagation [65,66]. These research topics are important in HE, but they were not explored deeply in the current study. These issues should be given more attention in the future.

3.9. Subject Category

Each journal in the WOS Core Collection is assigned at least one subject category, and each subject category represents a specific research area. The information for each publication in the WOS Core Collection contains the subject category of its source journal. The 6676 publications retrieved belonged to 94 different subject categories. Among these 94 subject categories, 46 subject categories contained fewer than 10 publications, and 29 subject categories contained 11~60 publications. Figure 10 shows the distribution of the subject categories with more than 60 publications and indicates that the subject category most related to HE was "Materials Science Multidisciplinary" with 3732 publications, followed by "Metallurgy Metallurgical Engineering" with 3155 publications and "Engineering Mechanical" and "Chemistry Physical" with 884 and 822 publications, respectively.

In Figure 10, three subject categories are multidisciplinary fields (3883 publications), four subject categories are related to materials science (4955 publications), three subject categories are related to chemistry (1540 publications) and two subject categories belong to the field of mechanical engineering (1200 publications). There are also subject categories belonging to the fields of metallurgical engineering (3155 publications), energy fuels (522 publications) and nuclear science and technology (240 publications).

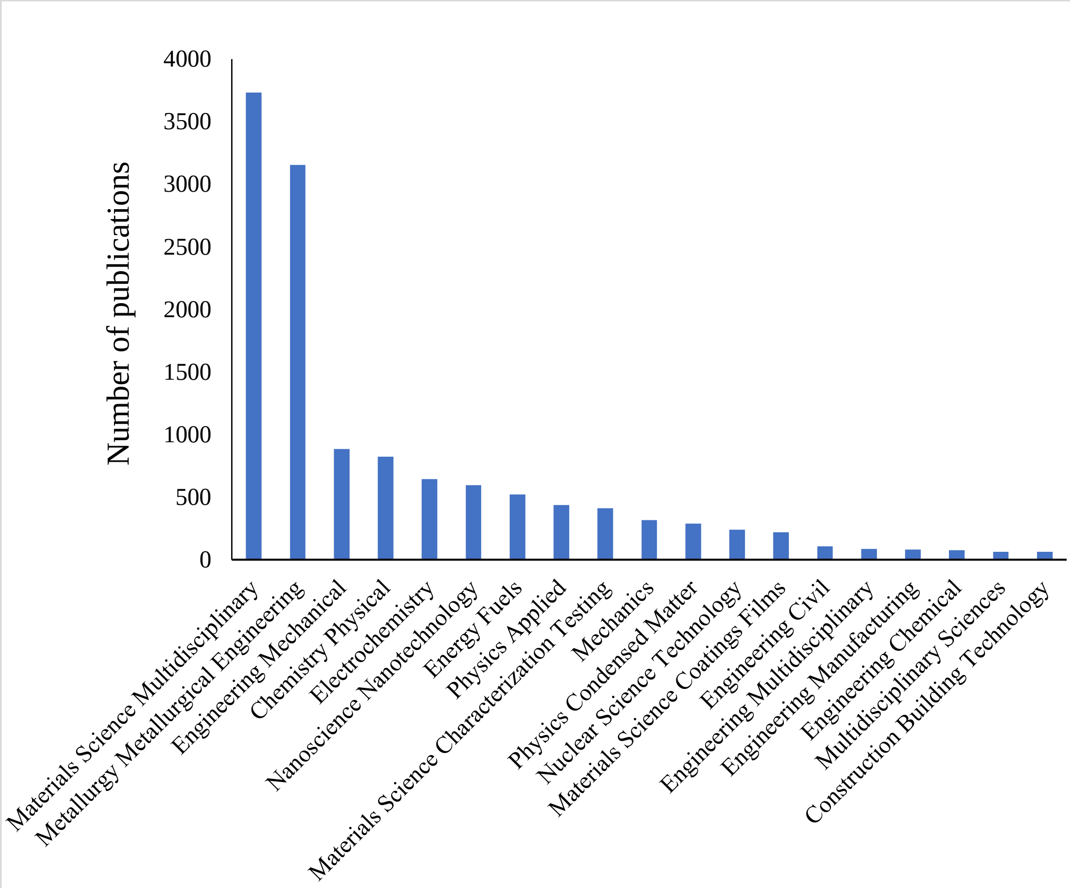

Figure 10. The subject categories with more than 60 publications on hydrogen embrittlement.

Therefore, the research on HE covers a wide range of subjects. The most popular subjects were "Materials Science Multidisciplinary" and "Metallurgy Metallurgical Engineering". In addition, the research also involved topics such as chemical physics, mechanical engineering and electrochemistry.

4. Conclusions

In this study, we retrieved 6676 publications related to HE from the WOS. Based on the data from these publications, bibliometric analysis of the publications in the field of HE from 1997 to 2022 was conducted and visualizations were produced to assess the global research trends. It should be noted that the analysis in this research was limited to data retrieved from the WOS, which is a more widely accepted and used database for the analysis of scientific publications compared to other international databases, such as Scopus [67]. Therefore, publications that are also related to HE research but not included in the WOS may result in deviations from the results. According to the bibliometric analysis, the following conclusions can be drawn:

(1) From 1997 to 2022, the annual number of publications related to HE showed an exponentially increasing trend. From 1997 to 2006, the number of publications per year was relatively low and fluctuated. After 2007, the number of publications showed an increasing trend, and HE research entered a stage of rapid development. The development of HE research is inseparable from the support of policies. The attention and support given by various countries to hydrogen energy have accelerated the development of the field;

(2) In the field of HE, Japan had the highest numbers of productive authors and citations of publications. The USA, South Korea and some developed European countries were also leading countries in these aspects. China had the most significant number of

publications. As a developing country, although it started slowly, it has provided much policy support at the national level in recent years. Its research on HE is developing rapidly;

(3) Kyushu University was the most productive and influential university regarding the number of publications and the total number of citations. Publications from the University of Illinois, the University of Science and Technology Beijing and the Max Planck Inst Eisenforsch had high total numbers of citations, attracting much attention from scholars in the field of HE;

(4) Akiyama was the most prolific and influential author with 88 publications, followed by Koyama and Tsuzaki with 67 and 62 publications, respectively. In the cooperation network, the cooperation between prolific authors was not very close; they all have their specific research directions and cooperation groups. The representative groups were the research groups centered on Akiyama from Tohoku University and the research groups centered on Li from the University of Science and Technology Beijing. Compared with cooperation between institutions in the same country, the cooperation between institutions in different countries was generally weaker. A clear geographic distinction could be seen from the cooperation networks for research institutions, as cooperation between institutions was mainly carried out within the institutions' own countries;

(5) The most important journal in the field of HE was *the International Journal of Hydrogen Energy* with 455 publications, followed by *Materials Science and Engineering A—Structural Materials: Properties, Microstructure and Processing* and *Corrosion Science* with 396 and 357 publications, respectively. The core journals of HE research were generally multidisciplinary or interdisciplinary. HE is a multidisciplinary and interdisciplinary science that involves the coordination of multiple mechanisms and includes the characteristics of many other disciplines, such as materials science, mechanics, electrochemistry and mechanical engineering;

(6) Citation analysis showed that the most cited paper was "Innovations in palladium membrane research" by Paglieri et al., which has been cited 523 times since it was published in 2002. The paper with the highest average number of citations per year was "Correlations in palladium membranes for hydrogen separation: A review" by Yun et al., which has received an average of 39.7 citations annually since 2016. The publications related to HE mainly covered five topics: "HE in different materials", "Effect of hydrogen on mechanical properties of materials", "Effect of alloying elements or microstructure on HE", "Hydrogen transport" and "Characteristics and mechanisms of hydrogen related failures";

(7) The research hotspots in the field of HE changed over different periods. However, the main research hotspots, such as "Fracture failure behavior and analysis", "Microstructure", "Hydrogen diffusion and transport", "Mechanical properties" and so on, did not change much. These are the primary methods for studying the HE of materials. In recent years, "Hydrogen permeable membrane", "Fatigue", "Welded joints", "Hydrogen resistance", "Hydrogen permeation" and "Temperature effect" have gradually become hotspots, and there has been more and more related research focusing on high-strength steel and pipeline steel. These are important research directions in the field of HE, and related research should be continued in the future;

(8) The 6676 HE publications retrieved belonged to 94 different subject categories. The subject category most relevant to HE was "Materials Science Multidisciplinary" with 3732 publications, followed by "Metallurgy Metallurgical Engineering" with 3155 publications. The research on HE covered a wide range of subject categories. The most popular subjects were "Materials Science Multidisciplinary" and "Metallurgy Metallurgical Engineering". In addition, the subjects also involved topics such as chemical physics, mechanical engineering and electrochemistry.

This study can help researchers gain an in-depth understanding of the research priorities, research trends and development trends in the field of HE. Through this study, scholars can conveniently obtain information on the influential author groups and research institutions in this field, as well as the main journals. It can serve as a reference for cooperation between different scholars and research institutions and for the selection of journals when submitting manuscripts.

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