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Review

Overview of advancement and development trend on magnesium alloy

Tiancai Xu[a,b,*], Yan Yang[b,c], Xiaodong Peng[a,b,c,*], Jiangfeng Song[b,c], Fusheng Pan[b,c]

[a] *Library, Chongqing University, Chongqing 400044, China*

[b] *College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China*

[c] *National Engineering Research Center for Magnesium Alloys, Chongqing University, Chongqing 400044, China*

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Abstract

Magnesium alloys are characterized by their low density (approximately 1.8 g/cm^3 for magnesium alloys), high strength, large modulus of elasticity, good heat dissipation, good shock absorption, greater ability to withstand impact load than aluminum alloys, good corrosion resistance to organic matter and alkalinity. According to the statistical analysis of literature data collected by Web of Science Core Collection, it can be found that the growth rate of publications on magnesium alloy during 2008–2018 is significantly higher than the overall growth rate of alloy research papers. In the past 11 years, the Web of Science Core Collection has collected 21,440 papers on magnesium alloys, averaging nearly 2000 papers annually, of which 2768 papers were collected in 2018, an increase of 206% over 2008, accounting for more than one fifth of the total literature on alloy research. Magnesium alloys have become an important lightweight metallic structural material and have been widely studied worldwide. As the only journal focusing on magnesium alloy research which devoted to the coverage and dissemination of global research on magnesium alloys. This article statistically analyzes all the academic articles published by Journal of Magnesium and Alloys (JMA) from 2013 to 2018 and compares them with all the articles containing magnesium alloy in their titles on the Web of Science during this period. The development trends of magnesium alloys are summarized based on these articles, and the influence and academic value of the articles published by JMA are summarized as well. This paper hopes to better realize the value of JMA, help better spread the academic research of magnesium alloys, and promote the development of global magnesium alloy research.

Keywords: Magnesium alloy; Developing trend; Research hotspots; Impact.

1. Introduction

Magnesium, which is considered the best alloy in the 21st century, is the lightest structural metal and has a high specific strength and stiffness [1–3]. Magnesium alloys have become very attractive for a variety of technical applications, especially in the automotive and aircraft industries and the electronics sector [4–6]. Using "Mg alloy" as the key word and searching in the world famous "Web of Science Core Collection" database, it can be concluded that the total amount of literature containing magnesium alloys in the topic is as much as 39,422 reports between 2000 and 2018. The number of documents published annually ranged from 760 in 2000 to 3735 in 2018, representing a growth rate of 491%. This growth reflects the fact that magnesium alloys have become the most common metallic structural materials in the world.

The Journal of Magnesium and Alloys (JMA) is an international journal for the publication of theoretical and experimental studies in magnesium science and engineering across the world [7]. As a specialized resource for magnesium alloys, the journal has published 272 academic articles between 2013 and 2018 and has been cited 2853 times. In this paper, we hope to reveal the research hotspots and development trends of magnesium alloys in recent years based on the above literature. The development trends of magnesium alloys are summarized based on the published articles, and the influence and academic value of the articles published by the JMA are summarized as well. This paper hopes to better realize the

* Corresponding authors at: College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China.

E-mail addresses: xtc@cqu.edu.cn (T. Xu), pxd@cqu.edu.cn (X. Peng).

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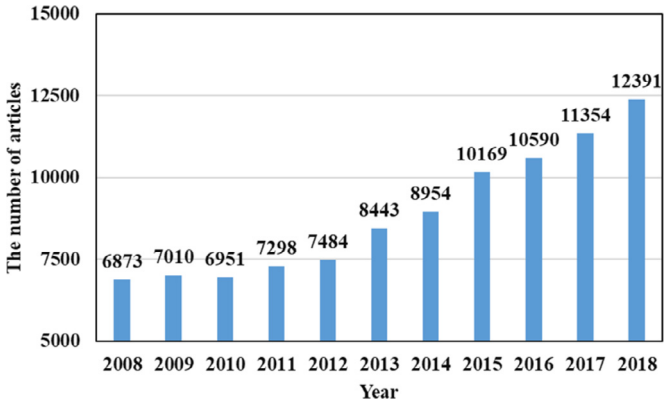

Fig. 1. The annual trend of research documents on alloy included by WOS.

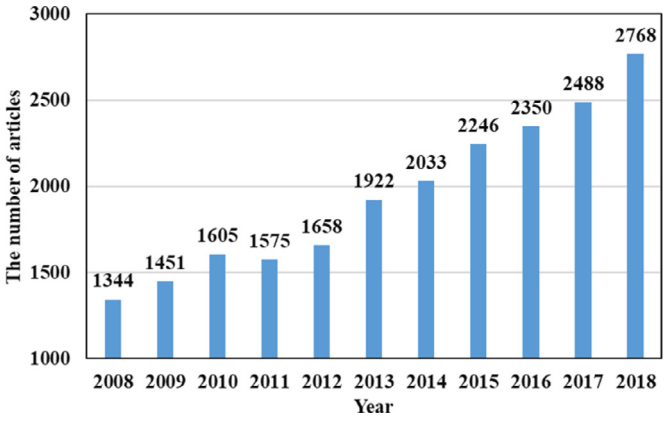

Fig. 2. The annual trend of research literature on magnesium alloy included by WOS.

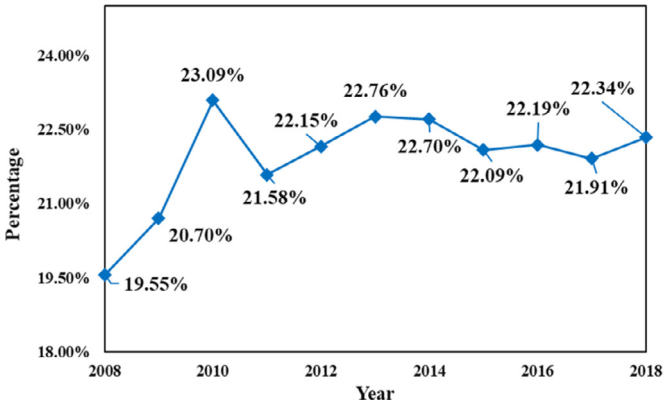

Fig. 3. The annual trend of proportion magnesium alloy in alloy literatures included by WOS.

value of JMA, help better spread the academic research of magnesium alloys, and promote the development of global magnesium alloy research.

2. Data sources and analysis principles

Data acquisition was divided into two parts. First, based on the Scopus and SciVal databases, we collected and analyzed the index data of JMA, such as the number of publications, cited frequency, publishing area and publishing organization or cooperation. Second, using the Web of Science Core Collection, we set Mg or magnesium alloy as the key word, selected literature title or topic as the retrieval range and limited the search to the time range. At the same time, we collected the important index data for JMA in the Web of Science Core Collection. In this way, the specific performance JMA periodicals in two different databases is reflected. Based on the data obtained, we analyzed the research trends and hotspots of magnesium alloys in recent years.

3. Result and analysis

3.1. Overview

Alloy is one of the most important components in material research. Alloy is used as a key word to search the Web of Science (WOS) Core Collection, which is the One of the most authoritative scientific literature databases in the world. Search conditions: 2008–2018 year, the search scope “title”, literature type is “article and review”. The annual changes in the trend of total literature included by WOS as shown in Fig. 1. In the past 11 years, the number of literatures on alloy increased by WOS from 6873 to 12,391, with an increase rate of 180%.

Magnesium alloys, as the lightest metal structural materials, have become an absolute hot spot in the global alloy research field. On the basis of the above literature search results, the annual trend of literature collection on magnesium alloy research is further retrieved by using the keyword “Mg alloy” or “magnesium alloy” as the key word, as shown in Fig. 2. Over the past 11 years, the number of literatures on magnesium alloys has increased from 1344 to 2768, with a growth rate of 206%, which is higher than the increasing ratio of literature on alloy. This undoubtedly reflects the increasing global attention of magnesium alloy related research. At the same time, the percentage change trend of magnesium alloy literature in the whole alloy literature is shown in Fig. 3.

From 2008 to 2018, the proportion of magnesium alloy literatures in alloy literatures included by WOS increased from 19.55% to 23.09% in 2010. In recent years, it has stabilized at 22% and increased by nearly 3 percentage points. The increase of nearly 3 percentage points translates into the number of literatures more than 300 articles, which shows the hot degree of magnesium alloy related research. Unfortunately, before the advent of JMA, there was no official magazine focusing on magnesium alloy research in the world.

JMA was founded in 2013 and is published four times a year. A total of 6 volumes, corresponding to 24 issues and 272 papers, had been published by December 31, 2018. The number of papers published annually in this journal is between 42 and 49 (as shown in Fig. 4). The number of publications reached its highest number of 49 in 2014 and then dropped to 42 in 2016.

The representation of JMA citations is shown in Fig. 5. The citation count of all papers published in the journal in

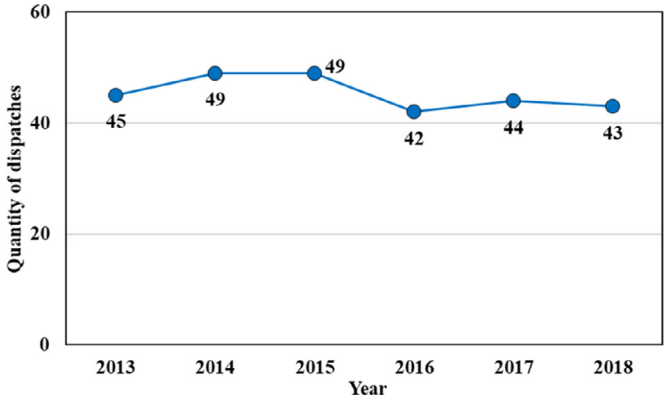

Fig. 4. The number of articles published by JMA per year (2013–2018).

2013–2018 totaled 2853 citations, and the average number of citations per paper published was to 10.49. By strictly controlling the number of articles published and ensuring the academic level of the articles, an effective guarantee for the academic value of JMA is provided.

The number of Scopus views received by publications in the JMA is shown in Fig. 6. It can be seen that the number of views publications have received in recent years has greatly improved. These data reflect the fact that the articles published in JMA are receiving increasing attention and recognition from researchers of magnesium alloys.

According to statistical analysis of all the authors, there are 849 authors in total, of which 459 are from China, accounting for 54%, and 390 are from outside China, accounting for 46% (as shown in Fig. 7). According to the statistical analysis of the institutions with authorship, there are 175 institutions that had publications in JMA. Statistical analysis is conducted on the data for the regional distribution of institutions. The results show that the total number of countries involved is 36, and the top three countries based on the number of institutions are China (138), India (58) and the United States and Iran (15 each), as shown in Fig. 8.

Of all the authors, the most published scholar is Pan, Fusheng from Chongqing University, China, who has published 11 papers, for which the total number of citations is 219 from 2013–2018. The most articles published by a foreign scholar were for Kainer, Karl U. from Helmholtz-Zentrum Geesthacht Center for Materials and Coastal Research, Germany, who has published 7 papers, for which the total number of citations is 143. The institution with the highest number of published articles is the Chinese Academy of Sciences, which has published 24 papers, for which the total number of citations is 292, and the total number of authors is 45 from 2013–2017. The foreign institution with the highest number of published articles is Helmholtz-Zentrum Geesthacht Center for Materials and Coastal Research, Germany, which has published 8 papers, the total number of citations for which is 150 and the total number of authors is 15. The article “Magnesium casting technology for structural applications”, written by Luo, A.A., Department of Materials Science and Engineering, Ohio State University, Columbus, OH, United States, is the highest cited paper, having been cited 272 times [8].

Statistical analysis of the authors and institutions of the JMA articles revealed the amount of international, national and institutional collaboration involved in JMA publications. The specific results can be seen in Table 1.

The number of international collaboration articles was 40, accounting for 14.8%, the number of cooperation between different institutions in the same country articles was 79, accounting for 29.3%, and the number of cooperation within the same institution articles was 141, accounting for 52.2%. More than half of the articles in JMA involved institutional collaboration. Therefore, the journal attaches greater importance to academic achievements resulting from cooperation

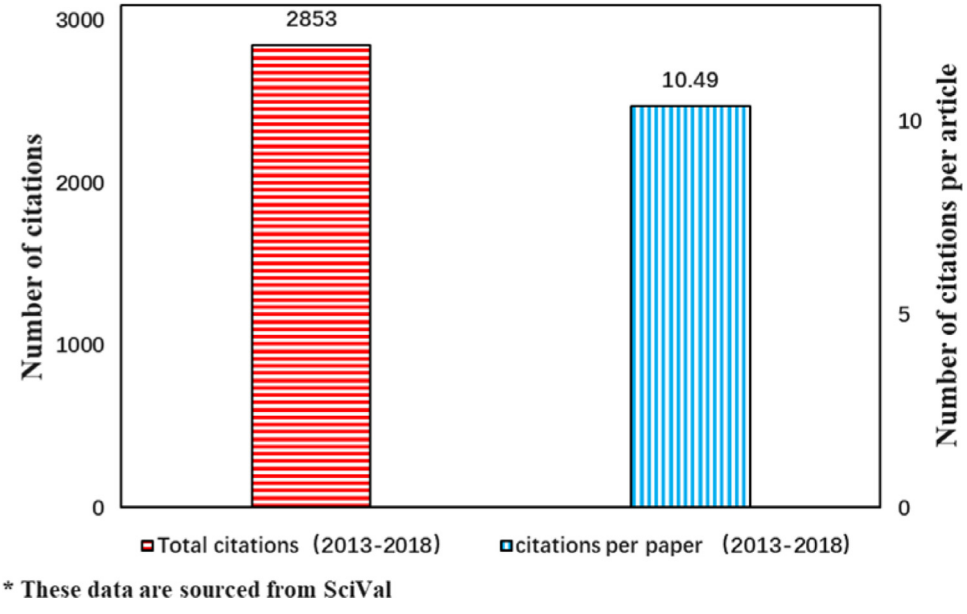

Fig. 5. Representation of JMA citations (2013–2018).

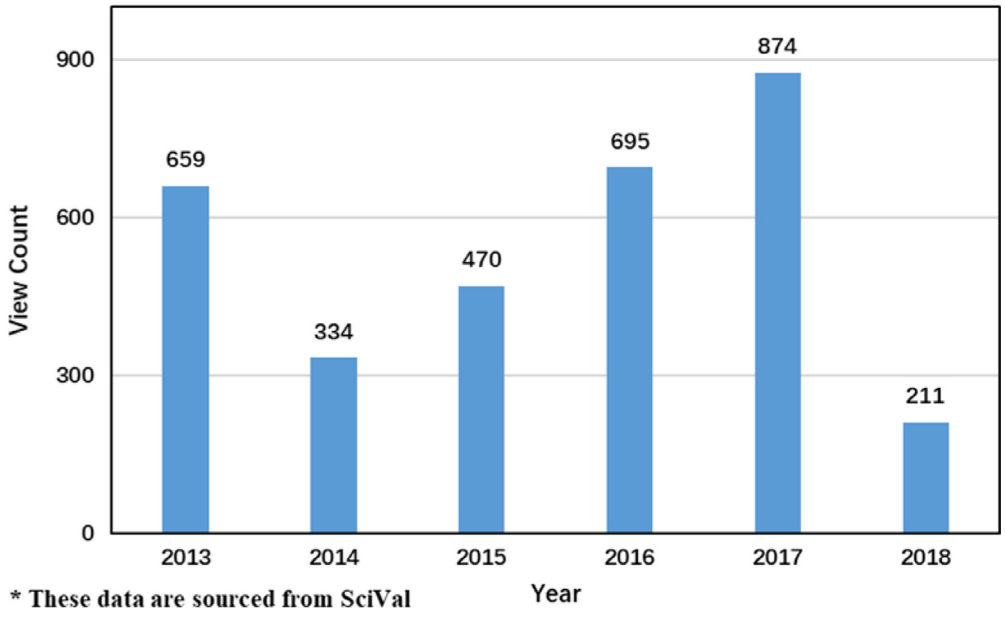

Fig. 6. Annual changes in the view count of JMA publications.

Table 1
Publications in JMA, by amount of international, national and institutional collaboration.

Type of collaboration	Percentage	Number of Publications	Number of Citations	Citations per Publication	FWCI
International collaboration	14.8%		557	13.9	1.4
Only national collaboration	29.3%		638	8.1	1.2
Only institutional collaboration	52.2%		1323	9.4	1.4

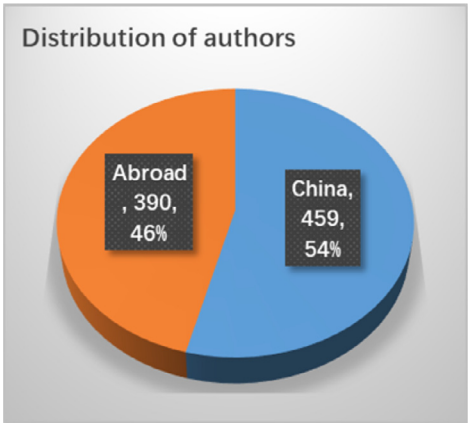

Fig. 7. The distribution of authors and institutions published in JMA.

between researchers. Using the data of Table 1 for comparative analyses, it can be seen that the citations per publication and field-weighted citation impact of articles involving international collaboration are higher than those of articles involving only national collaboration. International collaboration between institutions is conducive to the dissemination and enhanced impact of academic achievements.

The Web of Science Core Collection includes all the papers published by JMA from 2015 to 2018. According to the analysis of WOS citation reports, a total of 175 publications have been included, the sum of times cited was 1120, the without self citations was 1041, the citing articles was 785, and without self citing articles was 739. Statistical analysis of the citing articles from source journals is carried out. According to the number of citation source journals, the top 25 journals are listed in Fig. 9. According to journal citation report (JCR), the number of articles from journals above Q2 level reached 365, accounting for more than 85%.the ACTA MATERIALIA,ELECTROCHIMICA ACTA,CORROSION SCIENCE,MATERIALS SCIENCE AND ENGINEERING A STRUCTURAL MATERIALS PROPERTIES MICROSTRUCTURE AND PROCESSING,MATERIALS DESIGN,MATERIALS LETTERS,JOURNAL OF ALLOYS AND COMPOUNDS and so on, the articles published above authoritative journals all cited articles published by JMA. These results directly reflect the significance of the research papers on magnesium alloys published by JMA for the development of magnesium alloys research, and have been recognized by many experts in the same field.

According to the calculation method of journal impact factors in simulated Journal Citation Reports, the published and cited data of JMA in Web of Science Core Collection from 2015 to 2019 are collected in Table 2. The impact factors (IF) of JMA journals in 2017–2019 can be obtained in Table 3. The simulation IF of JMA journals in 2018 are as high as 4.59, which confirms the value of JMA journals in the field of material research again.

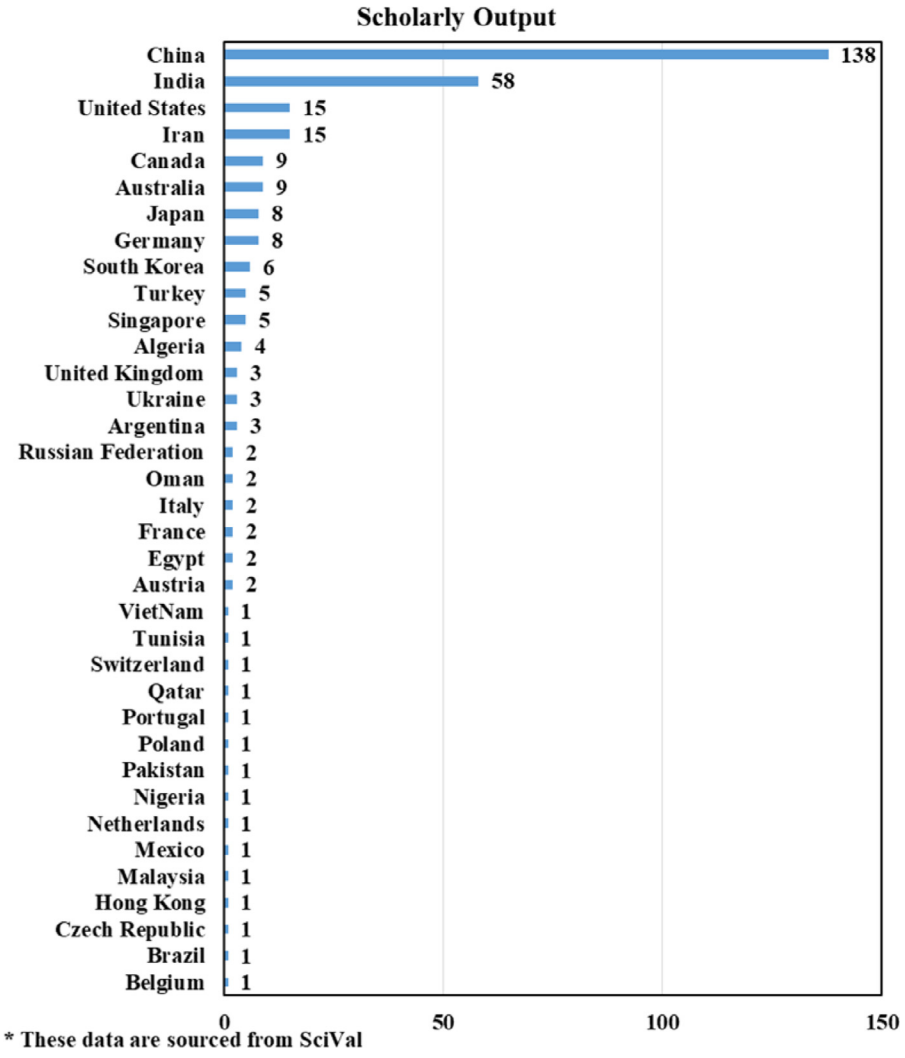

Fig. 8. The regional distribution of published institutions in JMA.

Table 2
The data of publications and citations by JMA in WOS (data acquisition deadline April 15, 2019).

	Count of article	Citation in 2015	Citation in 2016	Citation in 2017	Citation in 2018	Citation in 2019	Subtotal
2015	46	8	58	110	154	52	382
2016	42		11	116	191	58	376
2017	44			13	204	90	307
2018	43				23	32	55

Table 3
The annual simulated impact factors of JMA (data acquisition deadline April 15, 2019).

	Citation	count of article	IF
IF2017	226	88	2.57
IF2018	395	86	4.59
IF2019	122	87	1.40

As of June 20, 2019, the latest InCites Journal Citation Reports shows that the impact of JMA in 2018 is 4.523, which is almost the same as the simulated impact in this paper. JMA rank in the category of METALLURGY & METALLURGICAL ENGINEERING is 5 of 76 and quartile in category is Q1, details are shown in Fig. 10.

3.2. Trends

The top 50 key phrases by relevance, based on the 272 articles in JMA are shown in Fig. 11. By classifying the key words and analyzing the related literature, the research on magnesium alloys can be grouped into the following categories.

3.2.1. Microstructure

The microstructure of magnesium alloys has always been the foundation of magnesium alloy research. The microstructure directly determines the properties and applications of magnesium alloys. Examples of microstructural studies include grain refinement, dynamic recrystallization, twinning, textures, and intermetallics. The above microstructural changes have become the research foundation and a research hotpot for magnesium alloys.

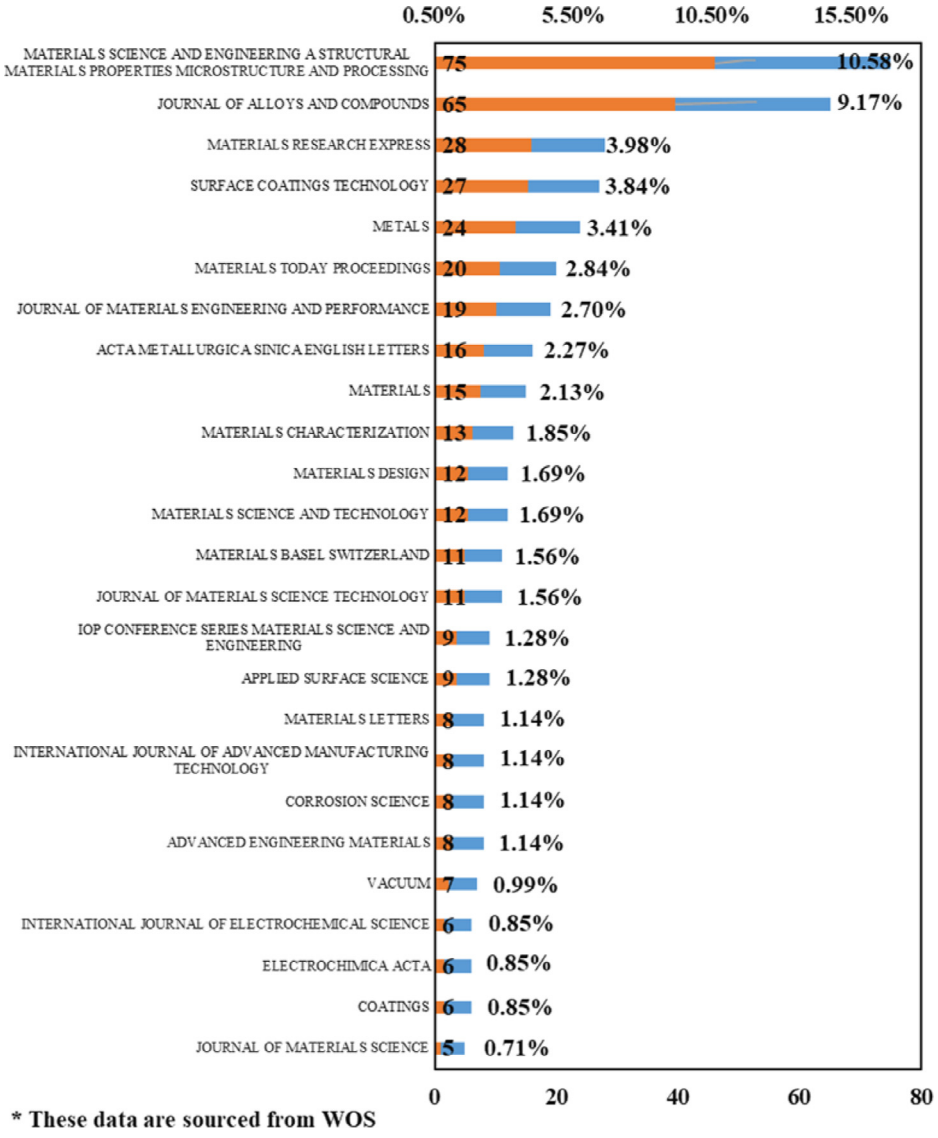

Fig. 9. The performance of JMA published papers cited by various journals.

3.2.2. Mechanical properties

As a typical metallic structural material, the alloying of magnesium has a direct impact on its mechanical properties. Therefore, research on the mechanical properties of magnesium alloys has never stopped. Methods to effectively strengthen the mechanical properties of magnesium alloys has become a common research topic for scientists. Researchers have refined the grains of magnesium alloys by plastic deformation techniques, such as extrusion, rolling, and equal channel angular pressing, to improve the mechanical properties. Alloying, heat treatment and solidification have also been used to enhance the mechanical properties of magnesium alloys.

3.2.3. Corrosion

The weak corrosion resistance of magnesium alloys also limits their application. The corrosion behavior and corrosion resistance properties of magnesium alloys are also a research focus. For example, in a study on the surface treatment (coating) technology of magnesium alloys, corrosion-resistant magnesium alloys were obtained.

3.2.4. Composite materials

The composite materials prepared from magnesium alloys not only have the advantages of low densities and high specific strengths but can also compensate for the magnesium alloy disadvantages of low strength and poor corrosion resistance.

3.2.5. The fabrication of new types of magnesium alloy

According to the articles of JMA, optimizing the preparation process of alloys and regulating and controlling the alloy composition have become important technologies for developing new magnesium alloys.

Statistically, the scientific research output of each topic can be found for each year. More than half of the articles

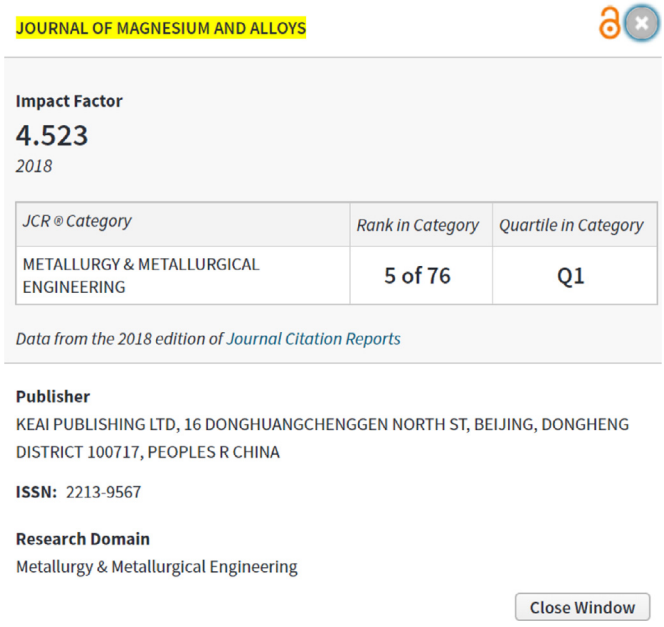

Fig. 10. Journal impact of JMA.

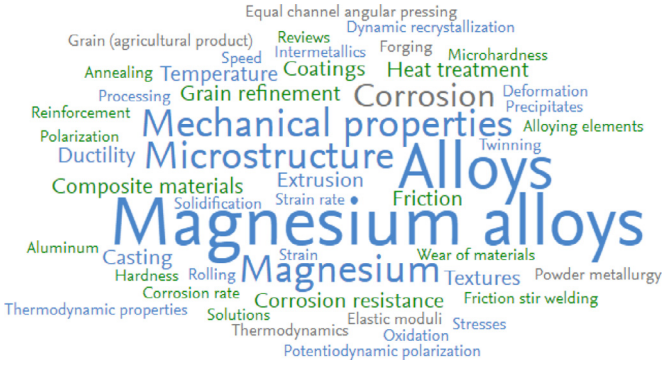

Fig. 11. Analysis of the key phrases in JMA articles.

concern the microstructures of magnesium alloys, and nearly half of the articles concerned the mechanical properties of magnesium alloys. Therefore, the microstructure and mechanical properties are still the main focus of research on magnesium alloys in recent years. Most technical innovations and research applications seek to improve the mechanical properties of magnesium alloys and understand the reasons and theoretical support for microstructural evolution. Nearly 1/3 of the articles concerned the study of the corrosion of magnesium alloys, which indicates that the corrosion behavior of magnesium alloys is another research hotspot, second only to the mechanical properties of magnesium alloys.

Composite materials and new types magnesium alloys have become a new hotspot in recent years. The number of related documents maintains a consistent growth trend. The annual output of papers in JMA can be found in Table 4.

From further refinement of the research direction of journal publishing, it can be concluded that corrosion resistance, textures, grain refinement, extrusion, coatings, ductility, dynamic recrystallization, strain rate, rolling, intermetallics, heat

Table 4
The amount of research output per year for each topic.

	2013	2014	2015	2016	2017	2018	Total
Microstructure	26	32	28	26	21	19	152
Mechanical properties	22	26	28	23	19	25	143
Corrosion	12	17	14	9	15	13	80
Composite materials	2	5	9	7	7	7	37
New types of magnesium alloys	3	5	4	6	8	7	33

Table 5
The amount of research output per year for each topic (JMA 2013–2017).

	2013	2014	2015	2016	2017	2018	Total
Corrosion resistance	8	12	6	3	9	10	48
Textures	9	7	4	7	6	2	35
Grain refinement	6	8	5	2	7	2	30
Extrusion	6	4	9	2	5	2	28
Coatings	3	6	3	2	5	7	26
Ductility	7	7	2	2	6	1	25
Dynamic recrystallization	6	2	5	5	2	1	21
Strain rate	4	3	5	5	1	3	21
Rolling	3	3	4	5	2	2	19
Intermetallics	4	3	4	2	3	3	19
Heat treatment	2	1	2	7	5	1	18
Reinforcement	1	1	3	3	5	3	16
Potentiodynamic polarization	4	3	3	1	2	3	16
Twinning	3	1	4	2	1	3	14
Equal channel angular pressing	2	2	1	0	2	0	7

treatment, reinforcement, potentiodynamic polarization, twinning, and equal channel angular pressing are the key focal points of magnesium alloy research in the past six years. The annual output of JMA publications per year for each research topic are shown in Table 5.

Searched for topic in "Web of Science Core Collection" with "magnesium alloy" as the key words, there are 16,291 papers revealed magnesium alloy published from 2013 to 2018 year. In addition, the top 10 journals by scholarly output on magnesium alloy are shown in Table 6.

According to the statistical analysis of these 16,291 articles, we find that the research directions are essentially the same as those of the JMA. The number of papers per year for each research topic, based on the 16,291 papers found in the Web of Science database for magnesium alloy, is shown in Table 7.

The paper "Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions", published in Progress in Materials Science in 2013 by Taku et al. [9], is the most cited paper out of the 16,291 Web of Science articles, having been cited 536 times. Taku et al. elaborated on the evolution of new microstructures produced by two types of dynamic recrystallization. The conventional dynamic recrystallization, continuous dynamic recrystallization and severe plastic deformation postdynamic recrystallization–annealing behaviors after dynamic and postdynamic recrystallization are discussed in detail, taking the AZ31 magnesium alloy as an example. The paper "Enhanced strength and

Table 6
The quantity and impact factors of the top ten journals on magnesium alloys in the Web of Science Core Collection.

	Name	Number of Publications	Impact Factor (2017)
1	MATERIALS SCIENCE AND ENGINEERING A STRUCTURAL MATERIALS PROPERTIES MICROSTRUCTURE AND PROCESSING	1200	3.414
2	JOURNAL OF ALLOYS AND COMPOUNDS	842	3.779
3	MATERIALS DESIGN	483	4.525
4	SURFACE COATINGS TECHNOLOGY	421	2.906
5	RARE METAL MATERIALS AND ENGINEERING	397	0.29
6	TRANSACTIONS OF NONFERROUS METALS SOCIETY OF CHINA	313	1.795
7	CORROSION SCIENCE	300	4.862
8	JOURNAL OF MATERIALS ENGINEERING AND PERFORMANCE	297	1.34
9	ACTA MATERIALIA	277	6.036
10	APPLIED SURFACE SCIENCE	273	4.439

Table 7
The amount of research output per year for each topic.

	2013	2014	2015	2016	2017	2018	Total
Corrosion resistance	500	481	585	627	694	702	3589
Coatings	474	459	544	590	625	610	3302
Textures	322	336	394	377	434	443	2306
Extrusion	273	280	313	278	347	368	1859
Twinning	273	291	287	319	308	308	1786
Grain refinement	222	230	291	266	332	323	1664
Strain rate	244	235	277	259	252	280	1547
Ductility	218	214	221	234	290	265	1442
Rolling	203	208	261	222	241	241	1376
Dynamic recrystallization	184	166	197	191	212	247	1197
Heat treatment	167	151	191	194	233	200	1136
Intermetallics	146	163	168	194	195	192	1058
Potentiodynamic polarization	108	119	120	127	157	125	756
Equal channel angular pressing	48	45	42	49	68	54	306

ductility of Mg–Gd–Y–Zr alloys by secondary extrusion", published in JMA in 2013 by Li et al. [10] is a highly cited paper in JMA regarding dynamic recrystallization, and the number of times this paper has been cited is 43 according to Scopus. Li et al. elaborated on an as-cast Mg-12Gd-3Y-0.6Zr (GW123, wt.%) alloy treated with single and secondary hot extrusion techniques. The dynamic recrystallization behavior of the Mg-12Gd-3Y-0.6Zr magnesium alloy during deformation and the relationship between the microstructure and the mechanical properties of the alloy were analyzed and discussed.

Although the number of articles published by JMA is small, the research is focused on magnesium alloys. Furthermore, the articles published in JMA cover the research hotspots in the field of magnesium alloys. The average field-weighted citation impact value of articles published in JMA is 1.45, which shows that JMA has more influence than similar research journals in the world. JMA reflects the current research status and development trends of magnesium alloy in the world.

4. Conclusions

Based on the statistics of magnesium alloy research literature collected in two authoritative databases of WOS and SCOPUSE in recent years, we can draw the following trends of magnesium alloy research.

(1) According to the statistical analysis of literature data collected by Web of Science Core Collection, it can be found that the growth rate of publications on magnesium alloy during 2008–2018 is significantly higher than the overall growth rate of alloy research papers. In the past 11 years, the Web of Science Core Collection has collected 21,440 papers on magnesium alloys, averaging nearly 2000 papers annually, of which 2768 papers were collected in 2018, an increase of 206% over 2008, accounting for more than one fifth of the total literature on alloy research. These data directly reflect that magnesium alloy research has become an absolute hot spot in the world. Unfortunately, before the advent of JMA, there was no journal focusing on magnesium alloy research in the world.
(2) As the only journal focusing on magnesium alloy research, Web of Science Core Collection has collected JMA published papers since 2015. Publications of JMA had been cited by many authoritative journals such as Q1 and Q2 journal in JCR. The total number of cited journals in Q1 and Q2 is more than 50% of all cited by JMA. As of June 20, 2019, the latest InCites Journal Citation Reports shows that the impact of JMA in 2018 is 4.523. JMA rank in the category of METALLURGY & METALLURGICAL ENGINEERING is 5 of 76 and quartile in category is Q1. JMA's report on the high-level frontier research literature of magnesium alloys is of great value to the research and development of magnesium alloys and even metal materials.
(3) Through the above articles published in JMA and the literature on magnesium alloys collected by WOS in recent years, it can be concluded that the development trends of magnesium alloy research are mainly concentrated on the following aspects.
(4) The microstructures of alloys are the basis for analyzing the changes in the properties of alloys. Magnesium alloys are typically deformed alloys. The effects of the deformation process on the microstructural evolution of magnesium alloys, such as their dynamic

recrystallization behavior, texture and twinning, have been hot research topics in recent years. On the other hand, the grain refinement and regulation of the alloying elements in the microstructure of magnesium alloys are also research trends in magnesium alloys.

(5) As the lightest metallic structural material, magnesium alloys are indispensable for the study of mechanical properties. Performance enhancement by alloying, deformation strengthening and heat treatment has attracted much attention from researchers. Representative alloying elements include Al, Zn, Ca, Mn, Sn, Sr and the rare earth elements. Deformation processing technology includes extrusion, rolling, asymmetric deformation, and equal channel angular pressing. Heat treatment studies are mainly focused on solid-solution aging treatments.

(6) The corrosion resistance of magnesium alloys has always been an important defect limiting their wide application. The corrosion resistances of these alloys can be improved by adding alloying elements, but the effects are not ideal. Increasingly, research has focused on methods to improve the corrosion resistance of magnesium alloys by coating their surface. Therefore, the choice of coating materials and the methods for binding to coating to the alloy matrix have become a focus of magnesium alloy research.

(7) Magnesium alloy composites are mainly divided into two types. On one hand, the mechanical properties of magnesium alloys can be greatly improved by adding nanoparticles (SiC, GNPs, B4C, Al2O3, etc.) or long and short fibers (glass fiber, carbon fiber, etc.) with the premise being to maintain the low weights of magnesium alloys. On the other hand, integral bonding of two or more materials, such as magnesium alloy composite plates, by means of welding, diffusion and bonding different materials with magnesium alloys has been used to prepare composite materials, which meet the application requirements. For these processes, surface treatment technology of the materials has become a research hotspot.

(8) The research and development of new magnesium alloys and processing technologies are also of concern to researchers. With the addition of various alloying elements and the melting and preparation of new grades of magnesium alloys, the variety of multielement magnesium alloys is constantly expanding. Superlight Mg–Li alloys, high-strength Mg–Gd–Y–Zn alloys, high-ductility Mg–Zn–Mn–Re alloys, asynchronous rolling, asymmetric extrusion, multistage aging, new series of alloys and unconventional processing technologies have all become trends of magnesium alloy research and innovation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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