

Article

State of the Art in Metal Matrix Composites Research: A Bibliometric Analysis

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Abstract: Metal matrix composites (MMC) are the materials of tomorrow. This paper presents an in-depth analysis of the MMC research articles published in Web of Science (WoS) during 2001–2020. The study firstly included year on year publications, publication types, sources, research directions as well as the most productive researchers, organizations and nations. Secondly, a detailed analysis of collaborations among various MMC researchers, organizations and countries has been presented. Thirdly, citations based linkages among the published articles, sources, researchers, institutions and places have been discussed relative to their respective collaborative link strengths. A co-occurrence analysis of MMC keywords was also conducted to highlight the most important keywords trending in this area. Finally, burst detection analyses of keywords and references were carried out to unearth sudden citation spikes of keywords and documents. Primary results indicate that research articles formed 80.54% of all MMC publications in WoS. The journal ‘Materials Science and Engineering A: Structural Materials, Properties, Microstructure and Processing’ published maximum MMC articles. Collaboration analysis results indicate that Zhang D, the Chinese Academy of Science and People’s Republic of China, attained topmost collaboration based total link strengths (TLS). Citations based analysis showed that Zhang D, the Shanghai Jiao Tong University (China), People’s Republic of China and the journal ‘Materials Science and Engineering A: Structural Materials, Properties, Microstructure and Processing’ received highest citation TLS values. Keyword ‘Graphene’ scored the highest citation burst strength (2018–2020). The future of MMC research lies in processing and characterization of novel nanocomposites with reinforcements such as graphene and boron carbide for various applications.

Keywords: metal matrix composites; bibliometric analysis; web of science; VoS viewer; CiteSpace; research trends



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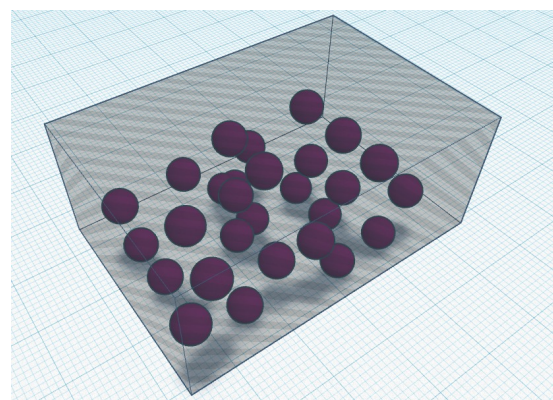
1. Introduction

Advancement in science and technology is directly correlated with the discovery, processing and applied investigations of novel materials. Modern materials are more complex, functionally efficient and commercially viable as compared to their simpler and functionally limited predecessors. Composites form a large group of new age materials that combine the positive attributes of two or more different constituents resulting in a superior combination. These materials help fulfill the conflicting requirements of maximising performance and minimising energy consumption simultaneously [1,2]. Composites typically consist of reinforcements added to base materials to make them stronger, tougher and more resilient [3–5]. The base materials can vary from metals to polymers, whereas the reinforcements may vary from ceramics to fibres and fly ash [6]. The current study focuses on the research trends pertaining to metal based composites reinforced with ceramic particles. The following subsection gives a brief overview of the properties, compositions, force/tool wear/surface generation mechanisms, machining challenges as

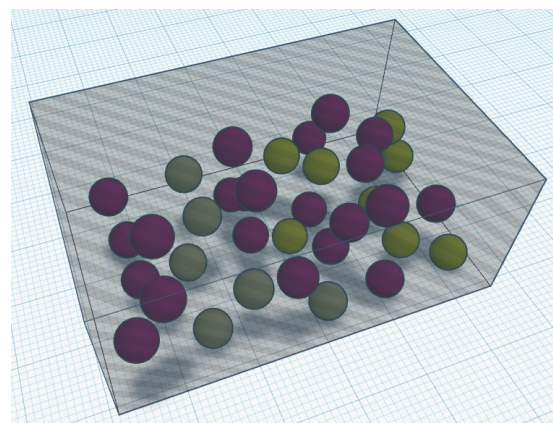
well as the simulation/modeling techniques explored by researchers to characterize these complex materials.

1.1. Metal Matrix Composites

Metal matrix composites refer to a class of new age materials consisting of base metal alloys primarily reinforced with ceramic particles for enhanced functional properties. Figure 1 shows a pictorial representation of metal matrix composite structure reinforced with (a) single and (b) multiple types of particles. The composites with multiple types of reinforcement particles are called hybrid metal matrix composites. Composites with nano sized inclusions are termed nano metal matrix composites, or simply, nano-composites. Hybrid metal matrix composites can also consist combinations of metal matrices in the form of alloys such as aluminum-magnesium, aluminum-copper and titanium based compositions [7].



(a)



(b)

Figure 1. Pictorial representations of a metal matrix composite structure with (a) single and (b) multiple types of reinforcement particles.

These materials offer superior mechanical characteristics as compared to monolithic alloys. These characteristics include strength to weight ratio, stiffness to weight ratio, wear resistance, corrosion resistance, strength, hardness and more [8]. However, these materials are difficult to prepare and to machine. One of the challenges involving these materials is to obtain uniform dispersion of the reinforcement particles in the base alloy matrix. Hence, researchers have explored various processing techniques such as stir casting and powder metallurgy to ensure the same [9]. Investigators have also studied various machining methods such as turning, milling, drilling and grinding to process these materials efficiently [10]. Others have tried different simulation and control methods towards accurate predictive modeling [11,12] and automation of the MMC machining process outcomes such as surface

roughness [13–16], tool chip interface friction [17] and more. Aluminium is a commonly preferred base metal alloy for most MMC compositions because of its good strength, light weight machinability and aerospace applications [18–21]. Common reinforcement materials include silicon carbide, boron carbide, alumina and others. Recently, nano scale reinforcement particles such as carbon nanotubes and graphene are also becoming popular among MMC researchers [13].

Metal matrix composites exhibit very unique strengthening and fracture mechanisms that make them difficult to machine. Researchers have conducted detailed experiments to understand the behavior of MMCs under quasi static as well as high strain rate processing conditions [22–24]. For instance, particle reinforcements tend to enhance the sensitivity of strain hardening to strain rate effects of machining [25], resulting in higher strain hardening rates at smaller increments in machining speeds. The hard ceramic reinforcements tend to generate higher tool wear during machining of composites [26]. Higher volume fractions of reinforcements lead to greater tool wear and damage [27]. These enhanced tool wear modes include edge chipping, grooving and notch wear [28–30]. The tool wear modes are generated during composite machining include two body and three body abrasion mechanisms caused by the mutual rubbing of the hard ceramic particles with the work surface and the tool flank face [31–34]. The abrasions between the ceramic particles and the work/tool surfaces is enhanced because of completely/partially pulled out, debonded and fractured particles leading to greater tool wear [35–38]. Additionally, the particle reinforcements improve the yield strength of the base metal alloy leading to high cutting force generation during machining. Alloy yield strength gets enhanced due to the numerous dislocations created by the particle inclusions in the matrix microstructure [26,39–46]. During machining, the dislodged and broken ceramic particles plough through the machined surface to generate higher machined surface roughness as compared to monolithic alloys [47–50]. In order to account for the various complex mechanisms active during MMC machining, the researchers categorised MMC machining forces into shearing, ploughing and particle fracture/debonding for improved force modeling and prediction [51–54]. These modeling theories are primarily based on the seminal works of Merchant (orthogonal cutting model) [55], Oxley (slip line field model) [56] and Colwell (equivalent cutting edge concept) [57]. The Johnson–Cook’s constitutive equation [58] is also widely used by researchers to model shear stress generation during MMC machining. This model incorporates strain hardening, strain rate as well as thermal softening phenomena to predict material flow stress.

The foregoing discussion gives a brief insight into the complex nature of some aspects of metal matrix composites. Similarly, researchers have extensively worked upon other MMC aspects such as preparation methods, characterisation techniques, varied applications and more. In the present study, a detailed bibliometric analysis has been carried out to understand the important contributing authors, institutions, countries as well as the current and upcoming trends of this rapidly emerging field.

1.2. Bibliometric Studies

Bibliometric analysis complements the traditional literature reviews by providing an objective evaluation of the trends and future potential of a research area [59–62]. This analysis is useful to highlight the evolution of a particular research area over a period of years or decades [61]. There are many methods to review the scientific research developments in a particular field [63]. These methods can be categorised under two broad classifications—evaluative and relational reviews [64,65]. Evaluative reviews generally deal with the quantitative analysis of the absolute research impacts of research articles, authors, organizations and nations. This analysis includes various productivity metrics such as the number of publications, publications per year, number of citations and more [66–69]. Evaluative reviews can also be conducted qualitatively based on expert opinions of research impact metrics in a particular area [70]. On the other hand, the relational review methodology focuses on inter-relationships among the above-mentioned evaluative impact metrics. These

inter-relationships are measured and expressed in terms of the number of collaborative outputs, collaborative linkages and respective link strengths. Other relational metrics include citations based linkages, co-occurrences and co-citations based analyses [71]. Co-authorship linkages are important indicators of knowledge sharing among different research groups [72]. Citation linkages are vital for understanding research relationships among productive authors and organizations [73]. Determination of linkage strengths reveals the extent of collaborations/co-citations across geographies [74]. The current study considers both evaluative as well as relational tools for a balanced bibliometric analysis of metal matrix composites research. Bibliometric surveys provide insights into the development of a research area over a time period of one or more decades [59,75]. These analyses typically yield vital information about research outputs of individual authors and respective affiliating organizations [68,69,76]; collaboration and citation networks among documents, authors, organizations and places [76–78]; trending topics and keywords [70,79]; top publishing journals, inter-journal linkages [66,80,81] and more.

The above mentioned bibliometric results can be effectively analysed and displayed by employing visual data representation tools such as VoS viewer [82], CiteSpace [83,84], ATLAS.ti [85], BiPlot [86], BibExcel [87], Network Workbench [88,89], VantagePoint [90] and many more. Data visualization tools are vital for effectively communicating the analysis results as well as for quickly arriving at useful conclusions [91,92]. In the present work, VoSviewer and CiteSpace were utilized for the quantitative data analysis and visualization of MMC research published in WoS during 2001–2020. VoSviewer generates author and journal network maps based on bibliometric analysis of the collaboration/citation data. It can also create keyword maps showing inter-linkages among various co-occurring terms related to a research area [82,93]. CiteSpace is a Java application designed to analyse and visualize citation based networks [83], co-authorship links, time series analysis of important topics and citation/reference bursts [94].

Recently, few researchers have conducted bibliometric analysis on some aspects of metal matrix composites. Laad and Ghule [95] analysed MMCs reinforced with environment friendly silica. Vencl et al. [96] studied the tribological properties and applications of composite materials with special emphasis on eastern European nations. Saxena et al. [97] used bibliometric analysis to explore the impact of friction stir processing to produce MMCs for industry 4.0 applications. Ghule and Laad [98] conducted another bibliometric survey on energy storage applications of polymer matrix composites. Koo and Jeong [99] applied bibliometric analysis to survey research conducted only on carbon nanotube reinforced composites. Costa and Moura [100] analysed the performance of and strategy for the development of polymer matrix nanocomposites with a special emphasis on Brazil. Pecas et al. [101] reviewed various natural fibre composites including their applications using the bibliometric methodology. Bibliometric studies of general areas include an analysis of knowledge maps in metallurgy [102], applications of artificial neural networks in engineering [103] and an analysis of materials research in India with a focus on international linkages [104]. The above section shows that there is a need to report an in-depth, comprehensive bibliometric analysis on the subject of metal matrix composites. The present work aims to bridge this research gap by providing multi-dimensional insights to the researchers for identifying current and future trends in this exciting field.

1.3. Data Selection and Extraction

The web of science (WoS) repository was selected as the primary database for the bibliometric analysis carried out in the current study. This database is a premium collection of high quality and high impact research articles published in the most prestigious journals across the globe. It catalogues manuscripts published in indexed journals since the year 1990. The WoS core collection includes eight citation indices viz. Emerging Science Citation Index (ESCI), Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Arts and Humanities Citation Index (AHCI), Conference Proceedings Citation Index—Social Sciences and Humanities (CPCI-SSH), Book Citation Index—Social

Sciences and Humanities (BCI-SSH), Conference Proceedings Citation Index—Science (CPCI-S) and the Book Citation Index—Science (BCI-S). This entire WoS core collection was searched for the keywords: (“nano” OR “aluminium” OR “machining” OR “fabrication” OR “characterization” OR (“mechanical” OR “electrical” OR “tribological”) OR “properties”) OR “mechanisms” OR “modeling” OR “preparation” OR “novel” OR “in situ” OR “scanning electron microscopy” OR “advanced” OR “carbon nanotube reinforced” OR “particle reinforced” OR “safety aspects of nano” OR “applications” OR “aerospace”) AND “metal matrix composites” for two decades spanning from 2001 to 2020. The search options were set to ‘full record and cited references’ with regard to the aforementioned keywords. The search yielded a total of 10,018 research articles which were exported from the database in plain text forms on 3 June 2021. The most exact records matching the specified MMC keywords were obtained from the ESCI, SCIE, CPCI-S, CPCI-SSH and BCI-S indices. The following sections present and discuss the different MMC research insights revealed by the bibliometric analysis.

2. Publication Distribution along Various Verticals

This section details upon the distribution of the searched articles on the basis of publication years, types, source titles, MMC research areas and their trends. Moreover, the top MMC research contributing nations, organizations, authors and their respective nationalities are also presented along with their respective publication counts.

2.1. Year on Year Vertical

The year on year progression of WoS research publications in the field of metal matrix composites is depicted in Figure 2. The *x*-axis of this figure shows the publication years from 2001 to 2020, whereas the *y*-axis depicts the WoS publication numbers. In addition, the exact publication counts for each year have been marked on top of the yearly publication bars. The figure shows a stagnant number of MMC publications from 2001 to 2006. These numbers started rising gradually from 2007, indicating an increasing interest in MMC research. The years 2016 and 2017 witnessed a significant jump in publication counts as compared to the previous years. In fact, the number of MMC articles published in WoS in the year 2017 tripled the number of manuscripts published in 2002. The MMC research outputs crossed 1000 WoS articles in 2018, with 2019 and 2020 registering almost similar publication levels. The year on year publications count analysis highlights the rising interest in MMC research sustained over a period of two decades.

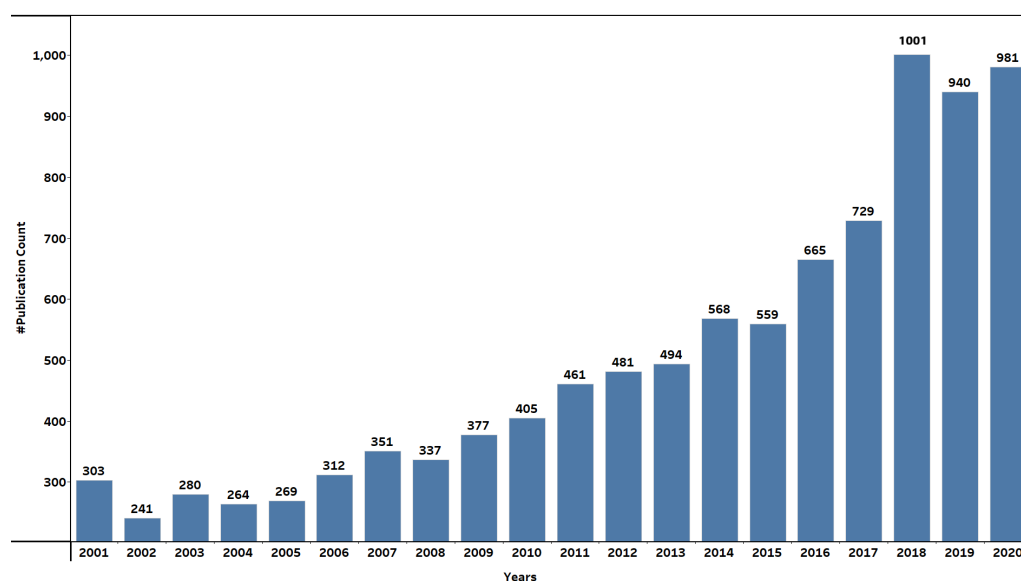


Figure 2. Annual publications from 2001 to 2020.

The primary reason behind this phenomenon is the sheer variety of metal matrix compositions that can be prepared using various combinations of base alloys, particle inclusions, reinforcement fractions and processing techniques. There is also a rising interest in the synthesis and analysis of metal matrix composites infused with various nano particles. In addition, there is an almost limitless scope for MMC modeling, application specific deployments, conventional and non conventional MMC machining and much more. Hence, the interest of researchers in this ever green topic is likely to be sustained in the future as well. The following subsection discusses the diversity of the publication types in the area of metal matrix composites.

2.2. Publication Types

The complete corpus of 10,018 MMC publications obtained from the WoS database was categorized into research articles, proceedings, review papers, early access documents and more. All these publication types and their respective counts are pictorially depicted in Figure 3. Research articles (8068) make up a major chunk (80.54%) of the total publications. Proceedings' articles (2198) form the second largest group of MMC publications (21.94%), whereas review articles (309) comprise 3.08% of the entire corpus. Book chapters (111) and early access manuscripts (44) on metal matrix composites contributed 1.11% and 0.44% to the total, respectively. Remaining publication types viz. letters, corrections, editorials, data papers, reprints and others constituted less than 0.25% of the exported database.

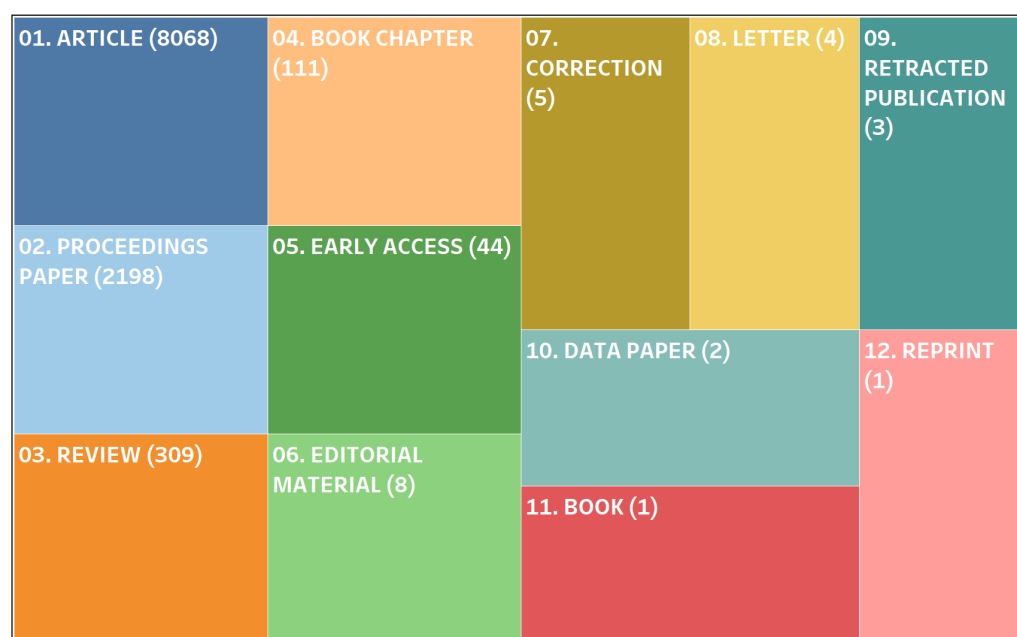


Figure 3. The top 10 publication types.

2.3. Publication Sources

This subsection provides insights into the top sources publishing metal matrix composite research indexed in WoS. Figure 4 indicates these sources and their respective published article counts through a colorful pictorial presentation. The source-wise distribution analysis shows that the journal 'Materials Science and Engineering A: Structural Materials, Properties, Microstructure and Processing' published maximum articles (640) in the field of metal matrix composites, comprising 6.39% of all published material. The 'Journal of Alloys and Compounds' stood second with 468 (4.67%) MMC publications. 'Materials Today Proceedings', 'Materials Design', 'Composites Part A Applied Science and Manufacturing' and 'Composites Part B Engineering' published the third (435, 4.34%), fourth (273, 2.73%), fifth (200, 2.00%) and sixth (199, 1.99%) biggest number of MMC papers during 2001–2020. The other journals to make it to the top ten MMC publisher list were 'Materials Science

Forum’ (seventh), Composites Science and Technology’ (eighth), ‘Journal of Composite Materials’ (ninth) and ‘Journal of Materials Processing Technology’ (tenth). These journals published 187 (1.87%), 185 (1.85%), 160 (1.60%) and 157 (1.57%) articles during the surveyed period, respectively.

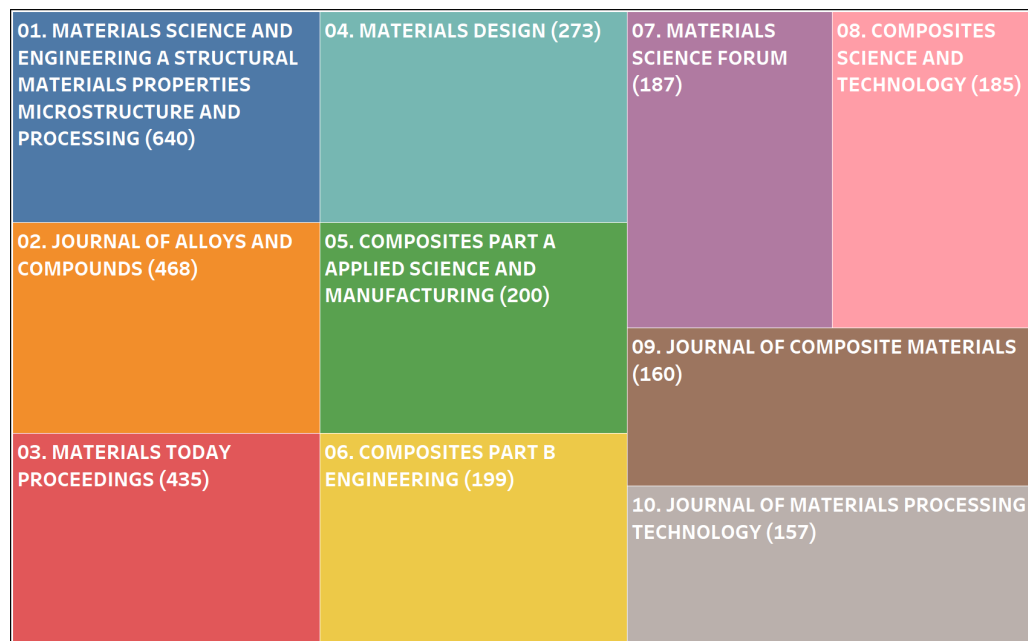


Figure 4. The top 10 publication sources.

2.4. Research Directions

After the previous subsection on the distribution of the publication sources, the present sub section throws light on the various research directions focused by investigators in the field of MMCs. Figure 5 provides these research directions with their specific article counts filtered by the WoS corpus search. The analysis results indicate that the maximum publications (7580, 75.66%) were categorized under the general topic of ‘materials science’, indicating the materials specific focus of most articles. The topic of ‘metallurgy/metallurgical engineering’ emerged as the next most investigated area (3242, 32.36%). This indicates the number of articles dedicated to the various processing methods of the metal matrix composites. The next most significant chunk of the publications (2703, 26.98%) belonged to the general area of ‘engineering’, indicating a more general engineering based approach to the problems associated with MMC fabrication, machining and testing. Similarly, ‘science technology and other topics’ included 1082 (10.80%) articles, showing the percentage of investigations into novel scientific and technological aspects of metal matrix composites. The articles dealing with the physical and chemical properties of the various particulate materials and corresponding reinforced metal matrices numbered 839 (8.38%) and 738 (7.37%), respectively. About 436 (4.35%) articles reported investigations upon the various mechanics and mechanisms involved in processing and machining these advanced materials. Researchers also published 151 (1.51%) papers aimed at the integration of MMC machining aspects in industrial control systems for automated manufacturing. In addition, 83 articles focused on the mining, extraction and treatment of micro and nano particles for imparting desirable properties to the reinforced base metal alloys. Investigators also worked on applications of metal matrix composites in the field of and fibre optics and optical instruments (72 articles). Figure 6 depicts the publication trends of each of the above-mentioned research directions during 2001–2020. These results clearly indicate the prevalence of ‘materials science’ as the highest trending general research area in the field of metal matrix composites. It is readily evident that the majority of all published MMC articles have ‘materials science’ as their central theme. The next most important trending topics

are ‘metallurgy metallurgical engineering’ and ‘engineering’, implying the ever increasing general interest in processing, machining and engineering applications of various MMCs. The related topics of ‘science technology’, ‘chemistry’ and ‘physics’ witnessed moderately incremental interest over the past two decades. Research areas such as ‘automation control systems’, ‘mining mineral processing’ and ‘optics’ do not indicate any upward publication trend. Hence, these research directions offer maximum opportunities for carrying out novel MMC investigations.

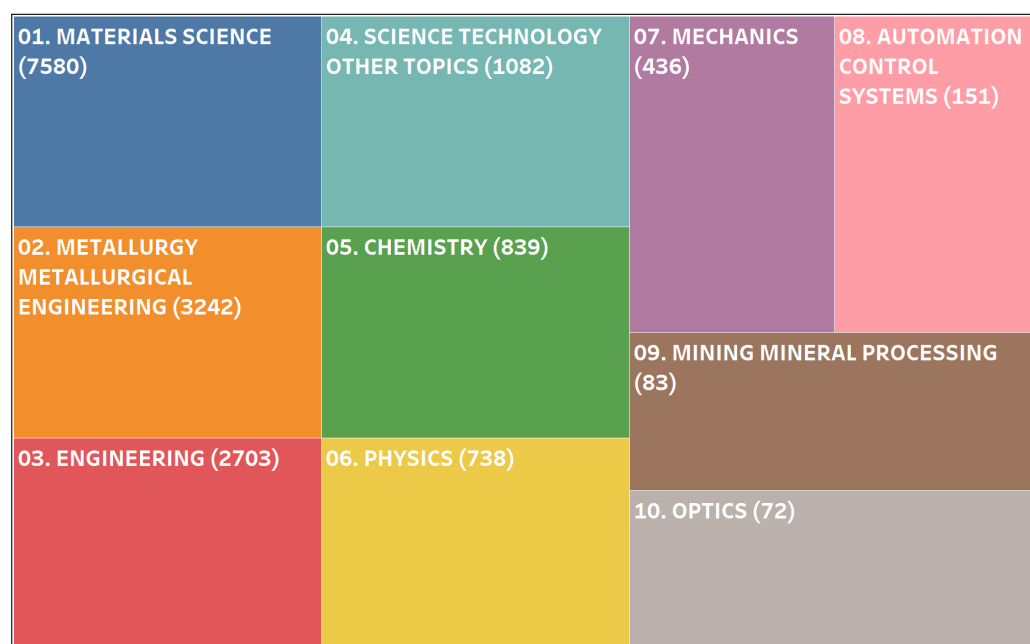


Figure 5. The top 10 research directions.

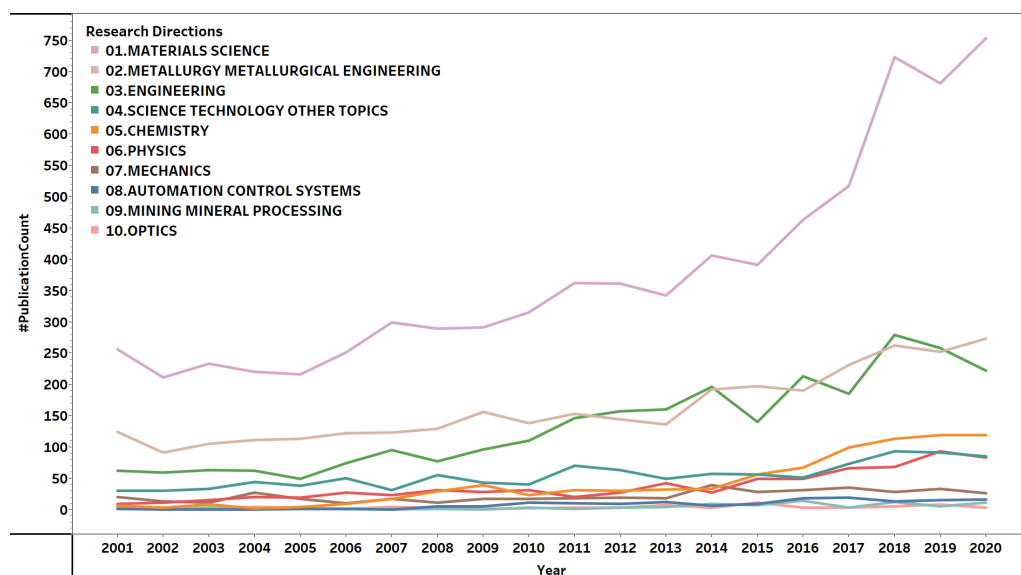


Figure 6. The publications trends of the top 10 research directions.

2.5. Popular Places Vertical

This subsection focuses on the top ten publishing nations that have contributed MMC articles in WoS—Peoples Republic of China, India, USA, Germany, Iran, Turkey, South Korea, England, Japan and France. Figure 7 depicts the publishing trends of these countries across twenty years starting 2001. It is evident from this figure that, during the initial years

(2001–2004), researchers affiliated with the USA were publishing the most MMC papers of all (60 papers published under USA affiliation in 2004). However, the Chinese authors surpassed the annual MMC research output of USA from 2005. The MMC publications of People's Republic of China witnessed a steady rise from 2001 (48 publications) to 2020 (260 articles); and Chinese authors published the maximum number of articles in WoS till the year 2012 (114 papers). However, post 2012, the MMC publication output of the Indian researchers surpassed that of their Chinese counterparts. The number of Indian author publications in MMCs soared steeply during 2015 (134 articles)—2020 (415 WoS papers); and this count is expected to continue its upward trend. In comparison, the MMC research output of the USA authors increased marginally over the last two decades (from 62 articles in 2001 to 81 articles in 2020). Similarly, the number of MMC publications of the remaining countries in the top ten remained below 50 per year with no signs of any significant upward trend to be expected in the near future. The highest annual publication counts of these countries stand as follows: Germany—41 (2014), Iran—50 (2018), Turkey—31 (2020), South Korea—25 (2011, 2017 and 2018), England—41 (2019), Japan—30 (2001) and France—38 (2018). The next subsection throws light upon the flagship institutions whose researchers have published the maximum number of MMC articles.

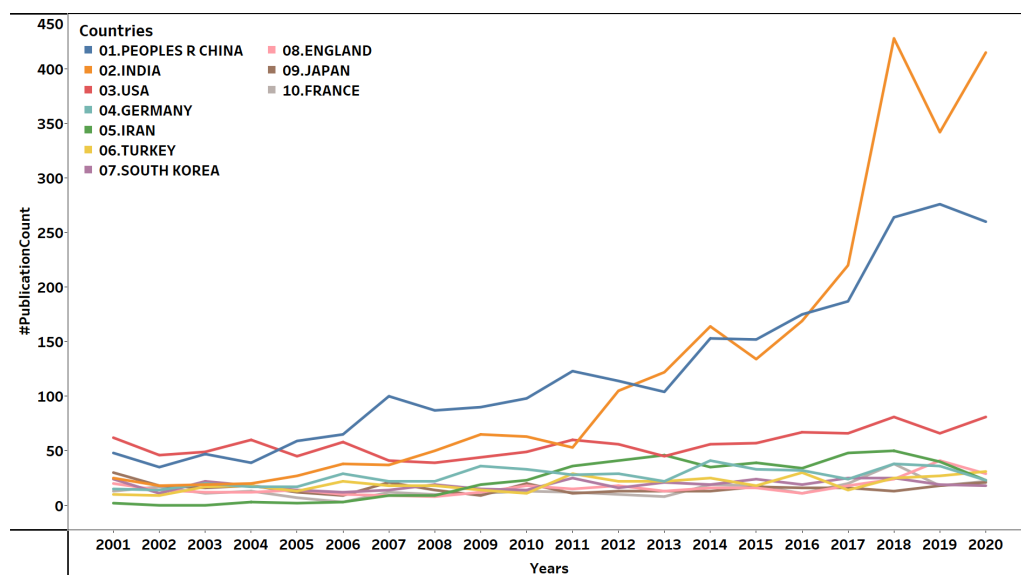


Figure 7. The top 10 productive places.

2.6. Productive Organizations and Researchers Vertical

This subsection discusses an analysis of the top ten institutes publishing MMC related articles in WoS during 2001–2020. Figure 8 shows that the Harbin Institute of Technology, China published the maximum number (335, 3.34%) of WoS papers in the field of metal matrix composites. The Shanghai Jiao Tong University, China published the second highest number (271, 2.71%) of WoS articles during 2001–2020. It was followed by the Chinese Academy of Sciences with a total of 227 (2.27%) publications in MMCs. The Indian Institutes of Technology arrived a close fourth with 225 (2.25%) publications during the same period. The National University, Singapore bagged 162 (1.62%) articles on MMCs, whereas the researchers at the National Institutes of Technology, India published 156 (1.56%) articles on MMCs. These were followed by the Northwestern Polytechnic University, China and the University of Science and Technology, Beijing, China with 132 (1.32%) and 118 (1.18%) publications, respectively. Finally, the Anna University, India and the Islamic Azad University, Iran arrived ninth and tenth on this list, wherein the affiliated researchers published 113 (1.13%) and 108 (1.08%) WoS papers on MMCs, respectively. This analysis showcases the detailed affiliations of the Chinese and Indian authors contributing significantly to the metal matrix composites research over the past two decades.

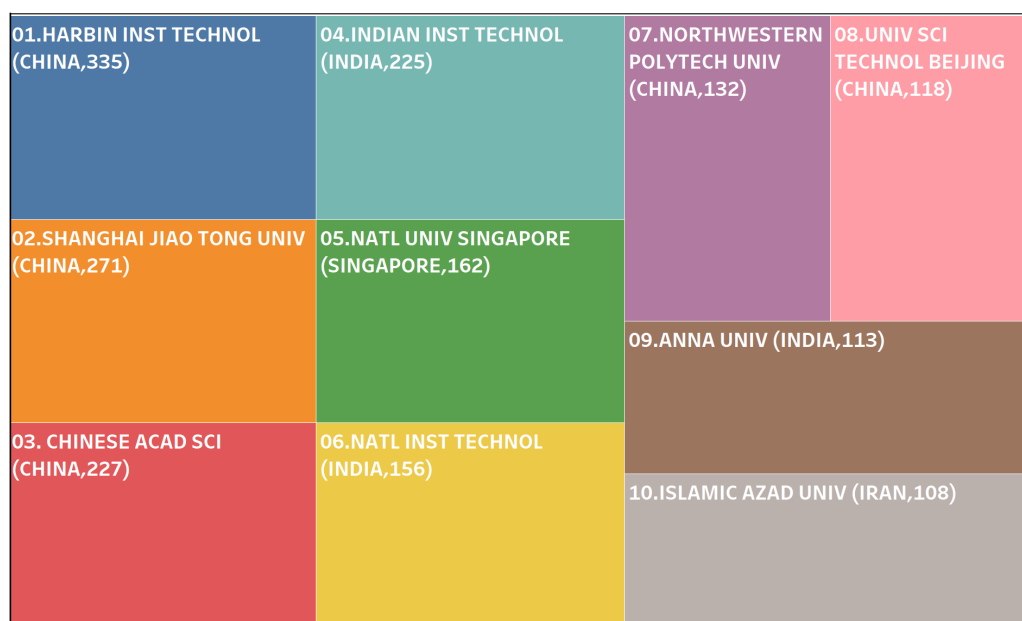


Figure 8. The top 10 productive organizations worldwide.

Figure 9 depicts the top 13 Indian institutions publishing MMC papers in WoS. Researchers affiliated with the group of Indian Institutes of Technology published the maximum articles (225) during 2001–2020. They were followed by the authors belonging to the group of the National Institutes of Technology, with 156 papers published in WoS. The Anna University arrived third with 113 papers, whereas the Council of Scientific Industrial Research (CSIR) came fourth with 75 articles in WoS. Other top publishing Indian institutions included the Indian Institute of Science, PSG College of Technology, Annamalai University, Vellore Institute of Technology, Siddaganga Institute of Technology, Amrita Vishwa Vidyapeetham, Thapar Institute of Engineering Technology and the Coimbatore Institute of Technology with 51, 47, 46, 39, 37, 32, 32 and 31 MMC papers in Web of Science, respectively.

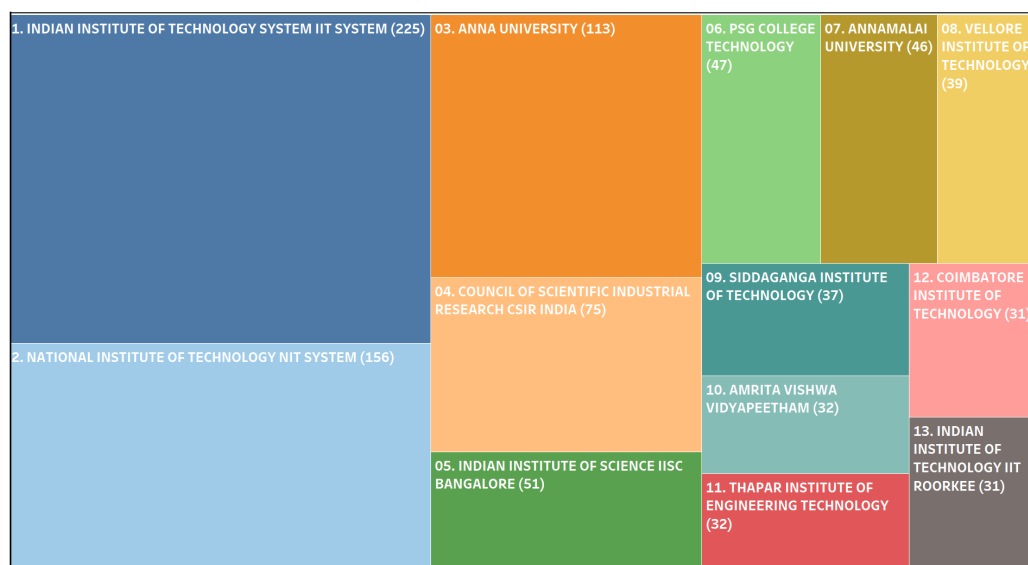


Figure 9. The top 10 productive Indian organizations.

Table 1 lists the top ten researchers worldwide with maximum MMC publications in WoS. Although the topmost contributing author hails from Singapore (Gupta M, 140 articles, 1.40% of total corpus), all of the next nine top authors are affiliated with Chinese institutions.

This analysis highlights the presence of high output MMC research groups in China. The next section showcases an analysis of the various research collaborations in the field of MMCs.

Table 1. The 10 productive authors.

Rank	Author	Country	Record	% of 10,018
1	Gupta, M.	Singapore	140	1.40%
2	Zhang, Di	China	97	0.97%
3	Wu, Gouhua	China	86	0.86%
4	Li, Zhiqiang	China	65	0.65%
5	Geng, L.	China	64	0.64%
6	Ma, Z. Y.	China	58	0.58%
7	Wang, H. W.	China	57	0.57%
8	Liu, Ying	China	55	0.55%
9	Xiao, B. L.	China	51	0.51%
10	Guo, Qiang	China	48	0.48%

3. Collaboration Analysis

Collaboration is very important for useful sharing of knowledge, ideas and resources among the national/international research community. Collaborative teams tend to be more productive, efficient and innovative. The following subsections present analyses of MMC research collaborations at various levels, viz. researchers, organizations and countries. In the present work, VOSviewer software was utilised for obtaining the MMC collaboration insights.

3.1. Collaboration among Researchers

For researcher–collaboration analysis, the VoSviewer threshold was set at a minimum of five documents and zero citations per author. This criteria was met by 1616 authors out of a total of 16,735. These 1616 authors were examined for mutual co-authorship links and the researchers with the greatest total link strengths (TLS) were ranked. The VOSviewer revealed that these authors produced 1429 WoS articles through their mutual collaborations! The top ten collaborative researchers in the field of metal matrix composites are listed in Table 2. The column ‘P’ refers to the number of MMC articles published by the respective authors in WoS during 2001–2020. ‘Links’ column refers to the total number of investigators in collaboration with each of these authors (appearing as co-authors in ‘P’ publications). Thus, each link represents a collaboration between two researchers. The strength of this link is determined on the basis of the number of published articles featuring these two researchers. The total link strength of a researcher is computed as the sum of the strengths of all his/her links.

Table 2. The top 10 researchers with maximum TLS values.

Rank	Author	Country	P	Links	TLS
1	Zhang, D	China	113	108	499
2	Li, Z	China	93	110	443
3	Li, J	China	117	184	421
4	Liu,	China	94	161	319
5	Guo, Q	China	50	57	317
6	Wang, H	China	90	112	300
7	Fan, G	China	46	48	288
8	Wang, X	China	80	133	286
9	Zhang, Y	China	85	133	276
10	Li, Y	China	85	149	273

Tables 3 and 4 clearly depict the difference between the scale of co-author linkages of Fan G and Wang X. The top six collaborators of Fan G have many more joint publications with Fan G (minimum 22 articles) as compared to the number of joint publications of the top most collaborator of Wang X (17 papers). Therefore, higher research outputs may not always correspond with higher collaboration strengths. In fact, some authors, like Gupta, M with high research outputs (Table 1) are not even mentioned in the top ten TLS rankings because of their lower collaboration linkages (60) and corresponding link strengths (TLS 223). Figure 10 shows the collaboration network map of the 1616 researchers with their respective inter-linkages. This map highlights different network groups in different colors and shows link thicknesses based on the respective link strengths. Moreover, Figure 11 depicts the collaboration network of the author with the highest TLS as per Table 2, i.e., Zhang D. This figure provides information of the collaborative linkages and the relative link strengths of this author at a glance. Herein, the respective author ‘nodes’ are depicted with varying sizes depending on their individual TLS values. It is evident from the link ‘thicknesses’ that Zhang D. has more publications with co-authors such as Li Z, Su Y, Tan Z, Fan G and Guo Q relative to the number of articles produced with Ji G, Zhang J, Li S, Guo X and others. On the other hand, Figure 12 shows the collaboration network of Gupta M, the author with the most MMC publications in WoS. It may be noted that this author does not figure in the list of researchers with the top ten TLS values. This occurrence is readily understood on mutual comparison of the two author’s (Gupta M and Zhang D) collaboration networks. Figure 12 shows that both the collaboration authors’ nodal weights (TLS of co-authors) as well as the collaboration link strengths (number of articles published in every collaboration) of Gupta M are lesser in comparison to those of Zhang D.

Table 3. The top 10 co-author linkages of Fan G.

Sr. No.	Linked Author	Link Strength
1	Li, Z	41
2	Zhang, D	39
3	Guo, Q	33
4	Tan, Z	28
5	Xiong, Db	26
6	Su, Y	22
7	Ji, G	11
8	Xu, R	10
9	Zhang, J	8
10	Guo, C	7

Table 4. The top 10 co-author linkages of Wang X.

Sr. No.	Linked Author	Link Strength
1	Zhang, H	17
2	Zhang, Y	17
3	Li, J	14
4	Wang, L	8
5	Kim, Mj	7
6	Wang, J	7
7	Che, Z	6
8	Wu, K	5
9	Zhang, X	5
10	Hu, X	5

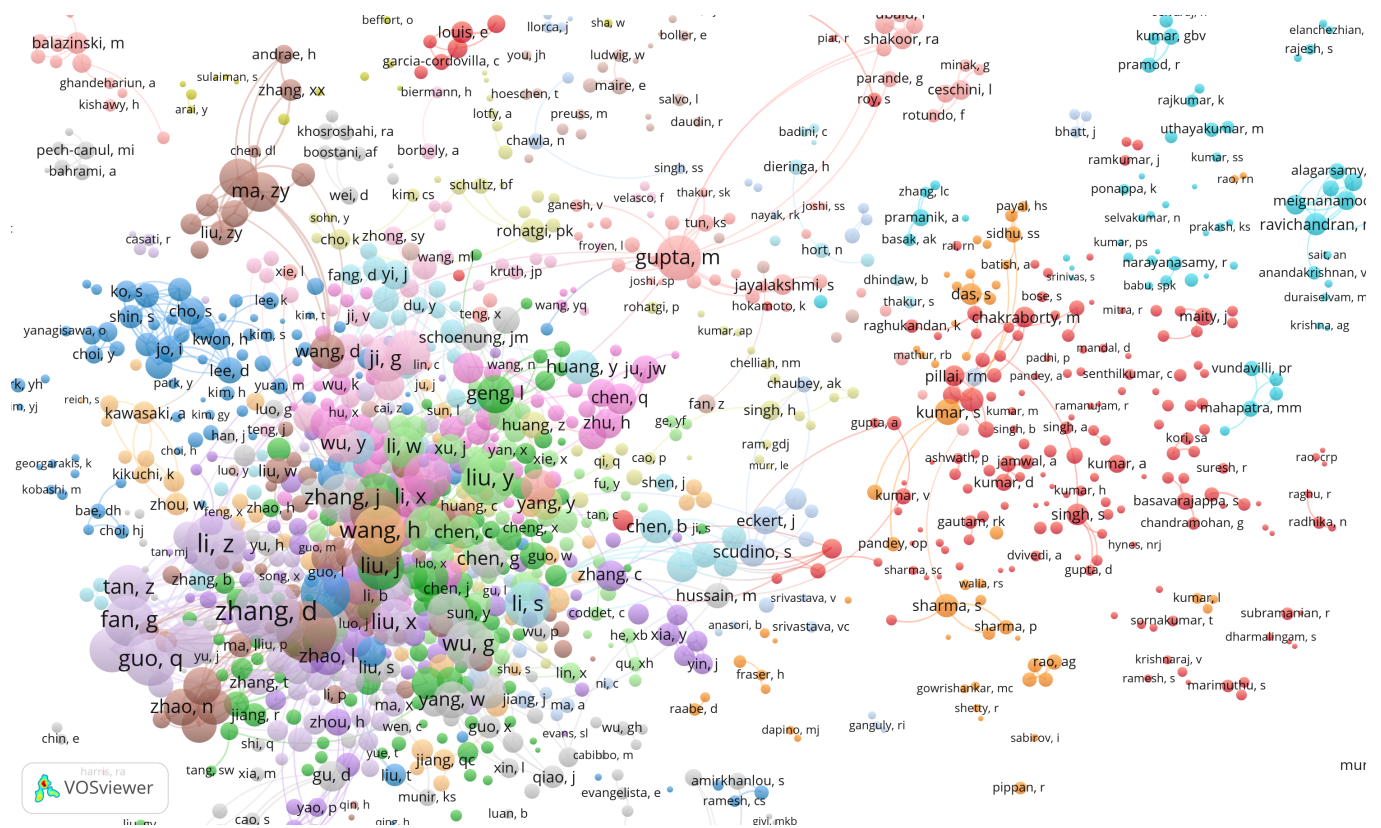


Figure 10. The collaboration networks of MMC researchers.

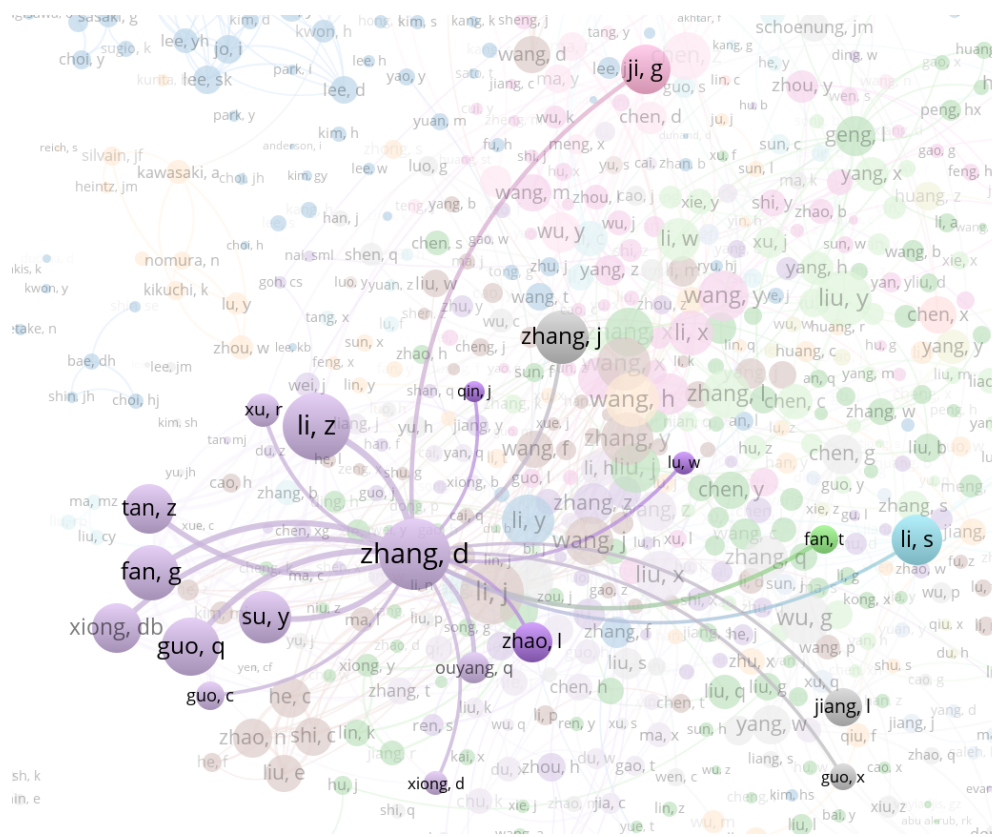


Figure 11. The collaboration network of Zhang D.

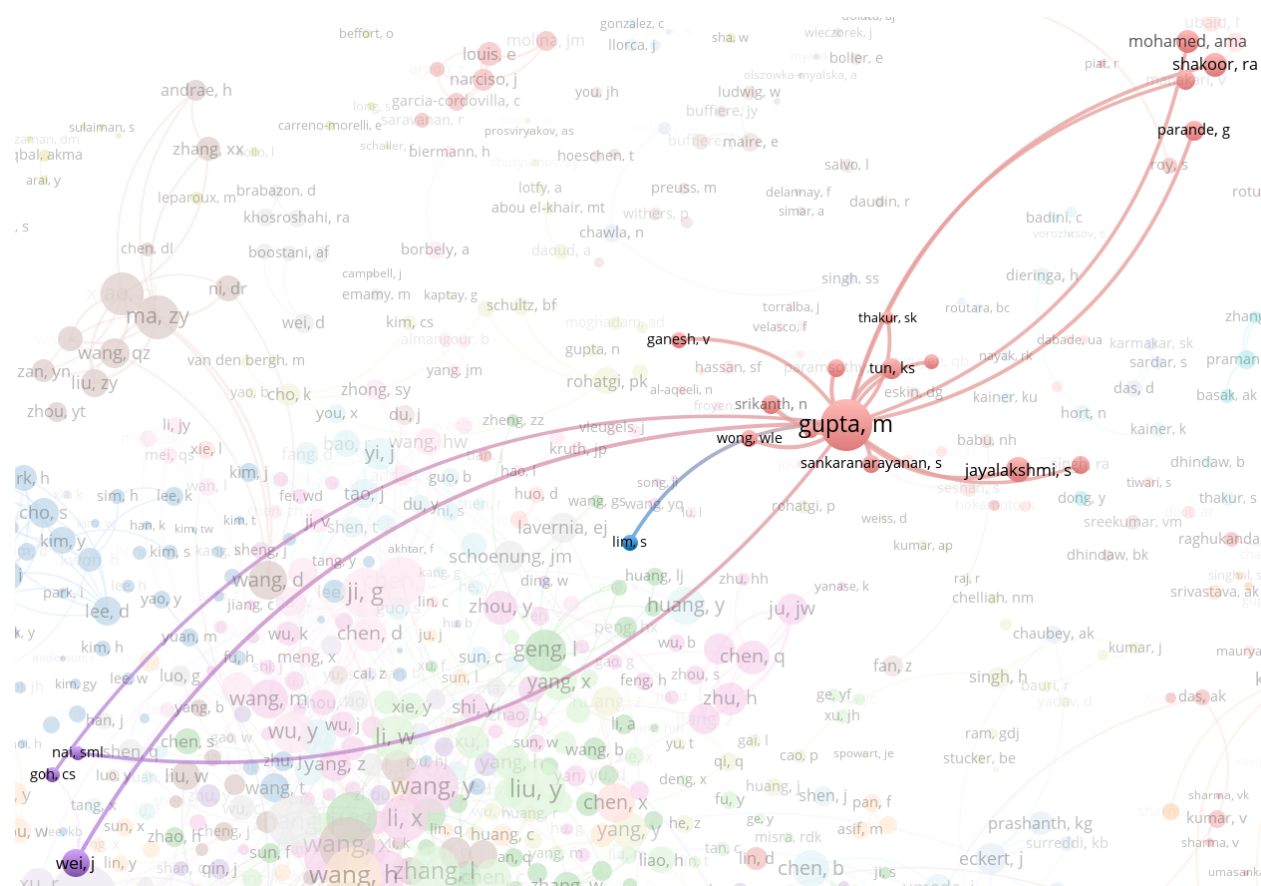


Figure 12. The collaboration network of Gupta, M.

As is evident from Table 2, all MMC researchers with the top ten TLS hail from China. Together, these researchers were able to publish a comparatively larger number of WoS articles. It may be observed that some researchers with lesser number of publications/links have higher TLS values over some of their colleagues with more WoS articles. This is due to the higher number of co-authors collaborated by these researchers in a comparatively lesser number of articles. For instance, Fan G has 46 articles and 48 links in comparison to the 80 papers and 133 links of Wang X. Still, Fan G has higher TLS of 288, whereas the TLS of Wang X is 286. This implies that Fan G included many more co-authors per paper as compared to Wang X.

3.2. Collaboration among Organizations

This subsection discusses the analysis results pertaining to the collaboration networks among various organizations involved in the metal matrix composites research. For this analysis, the VoS viewer thresholds were set at a minimum of five documents and zero citations per organization. About 801 institutes met these criteria out of a total of 4462 organizations. At the outset, the analysis revealed a total 765 articles penned through inter-institute collaboration networks. This number is far lesser than the total number of articles (1429) published through researcher networks, highlighting the scope to improve cross organizational research networking. Table 5 depicts the top thirteen institutes with the highest TLS values. Five of these institutions hail from China, three from India and one each from Singapore, Afghanistan, USA, Germany and Japan. These numbers indicate higher inter-institute collaboration environment present in Chinese organizations over others. It is interesting to note how Anna University, India scores slightly better TLS of 95 in comparison to the National Institutes of Technology, India (TLS 91, links 45, papers 155) despite having less WoS publications (112). This observation highlights the higher number of co-authors from different institutes collaborating per paper published

by the Anna University researchers over those of the National Institutes of Technology. Tables 6 and 7 list the top collaborators of these two organizations for a deeper analysis of their respective link strengths. The Anna University researchers have collaborated with those from Sri Sivasubramaniya Nadar College of Engineering, University College of Engineering Kancheepuram and the University of Witwatersrand (South Africa), among others. On the other hand, the MMC investigators affiliated with the National Institutes of Technology have scored joint publications with their collaborators at the Indian Institutes of Technology, Jadavpur University (India), Indian Institute of Science and the National University Singapore among others. A similar observation may be made (Table 5) with regard to the Leibniz Institute for Solid State and Materials Research, Germany (TLS 68, links 25, papers 33) and the Nanjing University of Aeronautics and Astronautics, China (TLS 63, links 22, papers 78), wherein the former institute has better inter-institute collaborations in lesser publications as compared to the latter organization.

Table 5. The top 13 organizations with the maximum TLS.

Rank	Organization	Country	P	Links	TLS
1	Chinese Academy Science	China	227	73	212
2	Harbin Institute of Technology	China	335	70	162
3	Indian Institutes of Technology	India	223	71	154
4	Shanghai Jiao Tong University	China	270	71	151
5	National University of Singapore	Singapore	160	47	102
6	Islamic Azad University	Afghanistan	108	36	97
7	Anna University	India	112	45	95
8	National Institutes of Technology	India	155	45	91
9	Northwestern Polytechnic University	USA	132	45	85
10	University of Science and Technology Beijing	China	118	39	72
11	Leibniz Institute for Solid State and Materials Research	Germany	33	25	68
12	Nanjing University of Aeronautics and Astronautics (NUAA)	China	78	22	63
13	Osaka University	Japan	51	21	61

Table 6. The top 10 institutional collaboration links of Anna University.

Sr. No.	Linked Organization	Country	Link Strength
1	Sri Sivasubramaniya Nadar College of Engineering	India	10
2	University College of Engineering Kancheepuram	India	7
3	University of the Witwatersrand	South Africa	6
4	K Ramakrishnan College of Engineering	India	5
5	Sri Sairam Institute of Technology	India	5
6	Sri Sairam Engineering College	India	4
7	Thiagarajar College of Engineering	India	4
8	Annamalai University	India	3
9	National Institutes of Technology	India	3
10	Sri Venkateswara College of Engineering (SVCE)	India	3

Table 7. The top 10 institutional collaboration links of the National Institutes of Technology.

Sr. No.	Linked Organization	Country	Link Strength
1	Indian Institutes of Technology	India	12
2	Jadavpur University	India	6
3	Chendhuran College of Engineering and Technology	India	5
4	Amrita Vishwa Vidyapeetham University	India	4
5	Indian Institute of Science	India	4
6	National Metallurgical Laboratory	India	4
7	Visvesvaraya Technological University	India	4
8	National University of Singapore	Singapore	3
9	Amrita Vishwa Vidyapeetham University	India	3
10	Anna University	India	3

Figure 13 shows a pictorial representation mapping the inter-institute research networks in the field of metal matrix composites. This figure shows collaborative networks of the top TLS institutes (Table 5) in different colored nodes and linkages. For instance, the light blue colored network headed by the Indian Institutes of Technology depicts the various partner universities like the Indian Institute of Sciences, Siddaganga Institute of Technology, Amrita University and Visvesvaraya Technological University, among others. Similarly, the red colored network of Amrita University is joined by institutions such as the National Institute of Technology Tiruchirapalli, Thiagarajar College of Engineering, Covenant University and the University of Johannesburg among many more.

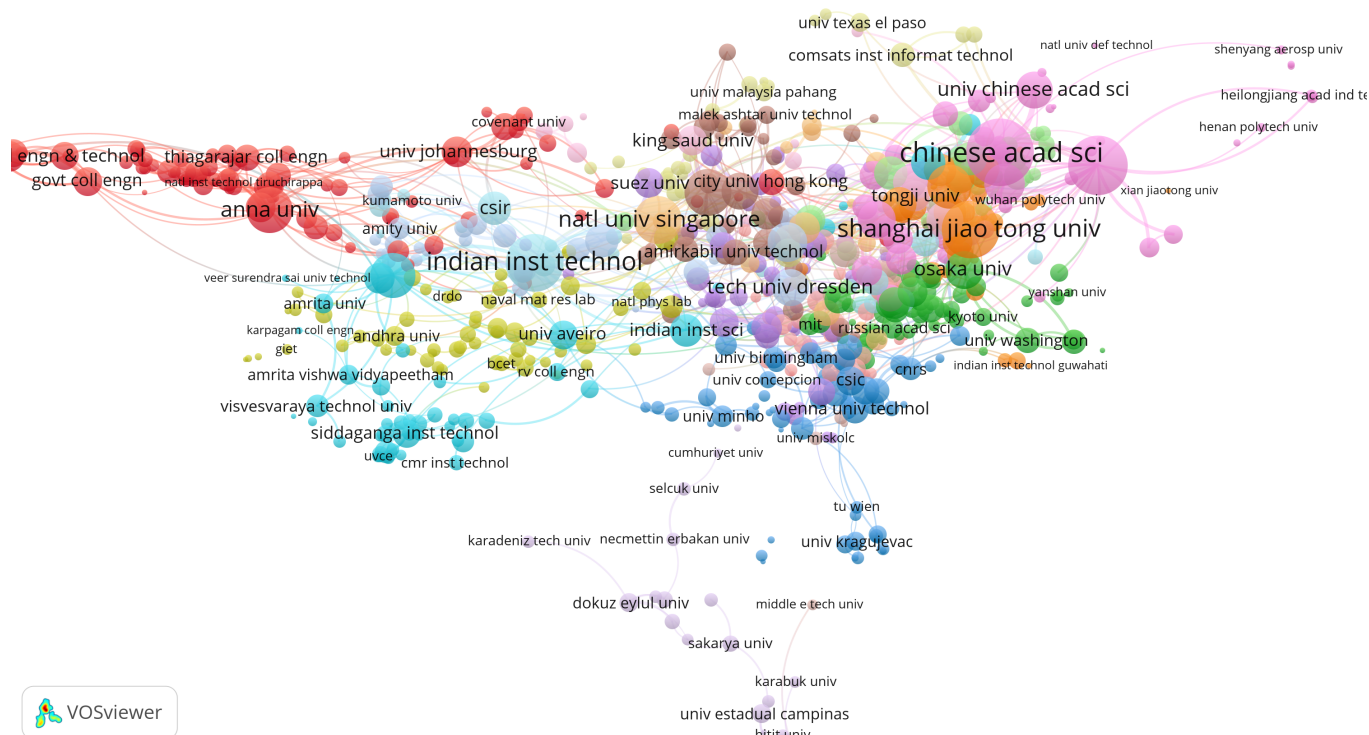


Figure 13. The collaboration networks of organizations.

3.3. Collaboration among Places

For a macro perspective of MMC research collaborations amongst various nations, the VoS viewer thresholds were set at five documents and zero citations per country. These conditions were met by 67 countries out of a total of 93. Table 8 lists the top thirteen countries with the highest TLS values. Once again, the People's Republic of China tops the list with a TLS of 681, featuring 2475 WoS publications and 42 linkages with international co-authors. Interestingly, Indian authors published the maximum number of articles (2509) in WoS during 2001–2020. However, Indian researchers feature neither in the list of top ten publishing authors (Table 1) nor in the list of the top ten TLS researchers (Table 2). This unique observation provides insights into a large number of Indian researchers publishing less MMC articles per author with relatively lesser collaborations. Another remarkable observation is with respect to the comparison of MMC research outputs of USA and India. The researchers affiliated with the USA scored higher international co-author linkages (47) and greater publications via these linkages (TLS 537) despite publishing much fewer WoS articles (1104) as compared to India (links 45, TLS 350, papers 2509). This observation also highlights the greater international collaboration oriented research environment prevalent in the USA as compared to India. Tables 9 and 10 depict the international co-author linkages of these two nations. The MMC investigators of USA have a large number of co-authored publications with Chinese authors. In comparison, their collaboration with Indian authors is far less. The Indian authors, on the other hand, have their maximum collaborations with

the researchers based in the USA. Their collaborations with other nationals are still lesser in quantity. Similarly, the French researchers exhibit better international links (36) and TLS (259) over their Japanese counterparts (links 28, TLS 186, papers 312) despite having lesser publications (282). The same trend is evident among the Canadian (TLS 155, links 27, papers 259) and the Iranian (TLS 145, links 26, papers 463) researchers working on metal matrix composites. This pattern is repeated by the researchers located in Australia (TLS 142, links 23, papers 172) over their colleagues situated in Spain (TLS 130, links 26 and papers 245). Thus, the researchers of India, Japan, Iran and Spain need to improve international collaborative linkages in proportion to their respective MMC publication outputs.

Table 8. The top 13 countries with the maximum TLS.

Rank	Country	P	Links	TLS
1	Peoples Republic of China	2475	42	681
2	USA	1104	47	537
3	India	2509	45	350
4	Germany	525	43	332
5	England	325	40	274
6	France	282	36	259
7	Japan	312	28	186
8	Canada	259	27	155
9	Iran	463	26	145
10	South Korea	372	25	143
11	Australia	172	23	142
12	Spain	245	26	130
13	Egypt	157	17	124

Table 9. The top 10 international collaboration links of USA.

Sr. No.	Linked Country	Link Strength
1	People Republic of China	171
2	India	50
3	South Korea	26
4	Japan	24
5	France	23
6	Egypt	19
7	Canada	18
8	Turkey	16
9	England	15
10	Germany	15

Table 10. The top 10 international collaboration links of India.

Sr. No.	Linked Country	Link Strength
1	USA	50
2	England	30
3	Singapore	28
4	Germany	25
5	South Africa	22
6	Australia	19
7	Portugal	16
8	South Korea	16
9	People Republic of China	13
10	Oman	9

Figure 14 shows a colorful representation of the various international MMC research collaboration networks. This figure depicts international networks of the top TLS nations like the People's Republic of China, USA, India, England, Canada and Spain using distinct colors. Figure 15 shows the international collaboration network of the People's Republic of China, the country with the maximum TLS. This figure reveals strong collaborations of Chinese researchers with their colleagues in Japan, Australia and South Korea. There is also a strong linkage among the networks of Chinese and USA investigators. Furthermore, this figure indicates relatively minor inter linkages of Chinese authors with international collaborators from India, Egypt, England, Canada, Iran, Spain, Denmark and North Ireland. Similarly, Figure 16 depicts international linkages from the perspective of MMC researchers located in India. The Indian authors' led network includes participants from Singapore, Egypt, Saudi Arabia, Qatar, Oman, United Arab Emirates, Norway and others. Indian researchers have also collaborated with the investigators of other international networks such as Germany, Austria, Poland, Sweden, Brazil, Spain, Chile, Mexico, South Africa and Japan. Lastly, Figure 17 showcases the diverse network span of USA led MMC research. The USA researchers have international collaborations with MMC investigators from Germany, Austria, Hungary, Turkey, Slovenia, Taiwan, Ethiopia and South Africa. Their cross network linkages include India, England, Spain, Canada, Poland and Japan. With regard to the relatively smaller networks, researchers of England published MMC articles in collaboration with their contemporaries located in Wales, Portugal, Romania, Brazil, Malaysia, Iraq and others (Figure 14). Lastly, the researchers of Canada and Spain worked together on MMCs with partners from Chile and others (Figure 14).

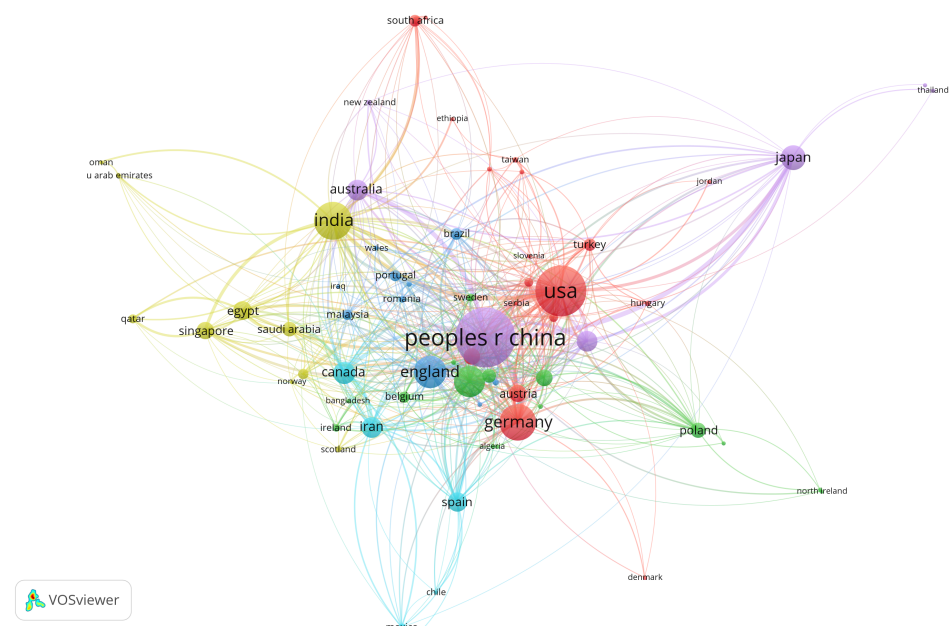


Figure 14. The collaboration networks among nations.

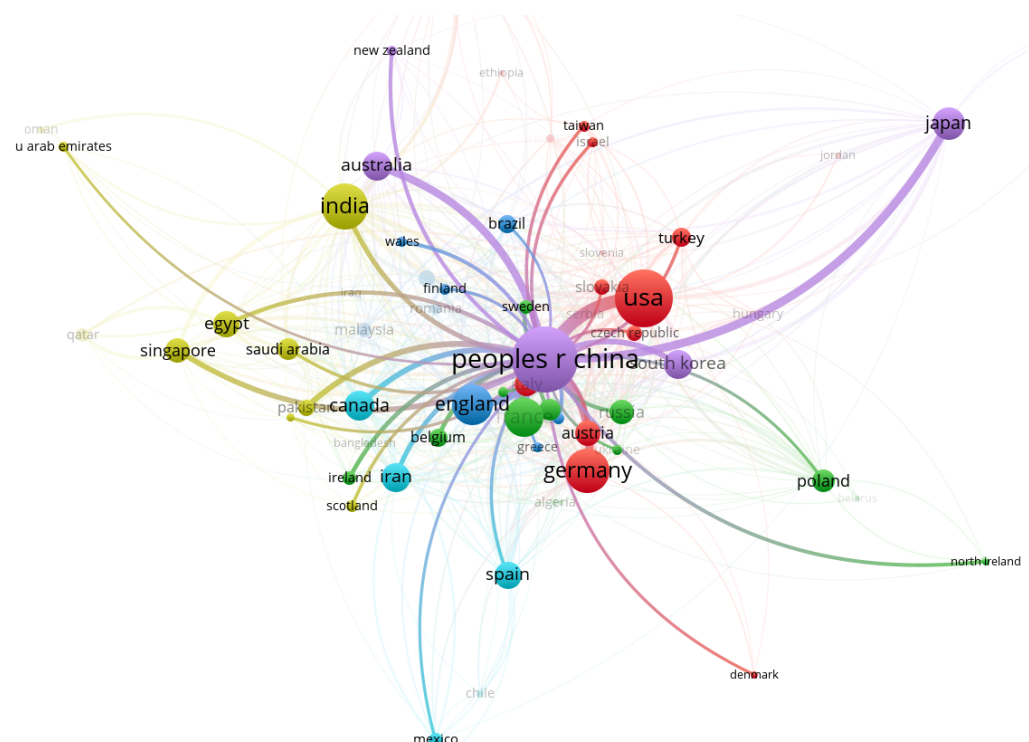


Figure 15. The international collaboration network of the People's Republic of China.

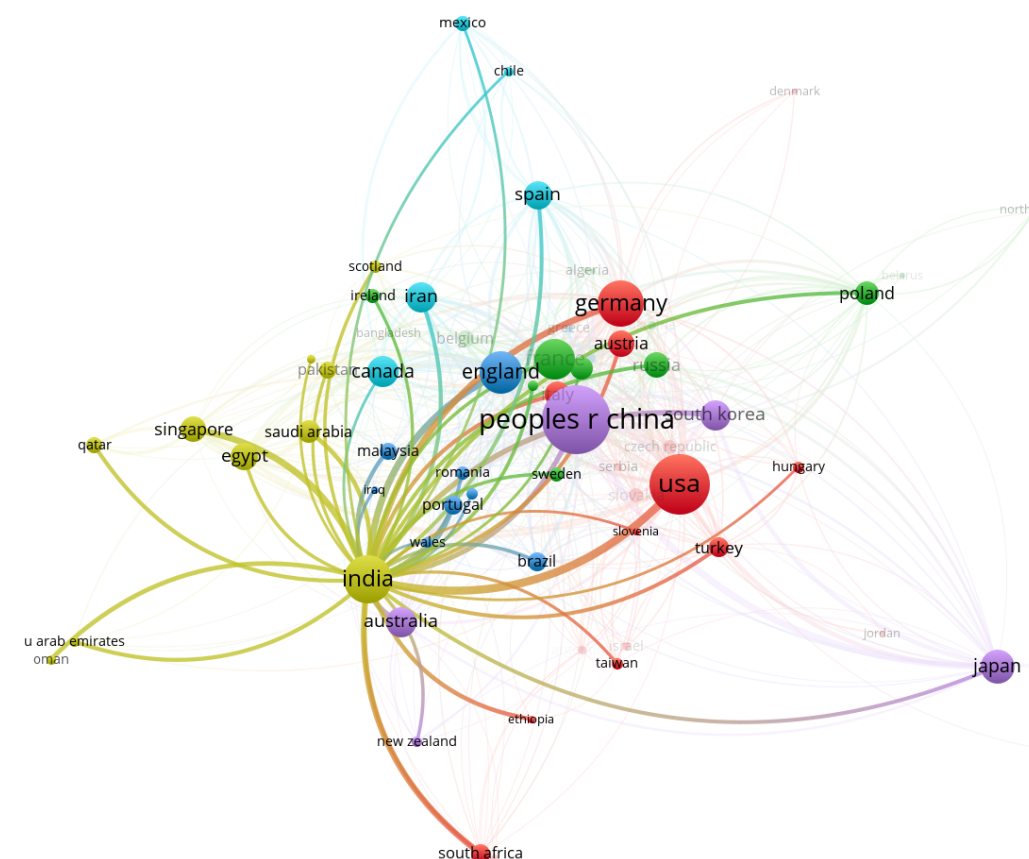


Figure 16. The international collaboration network of India.

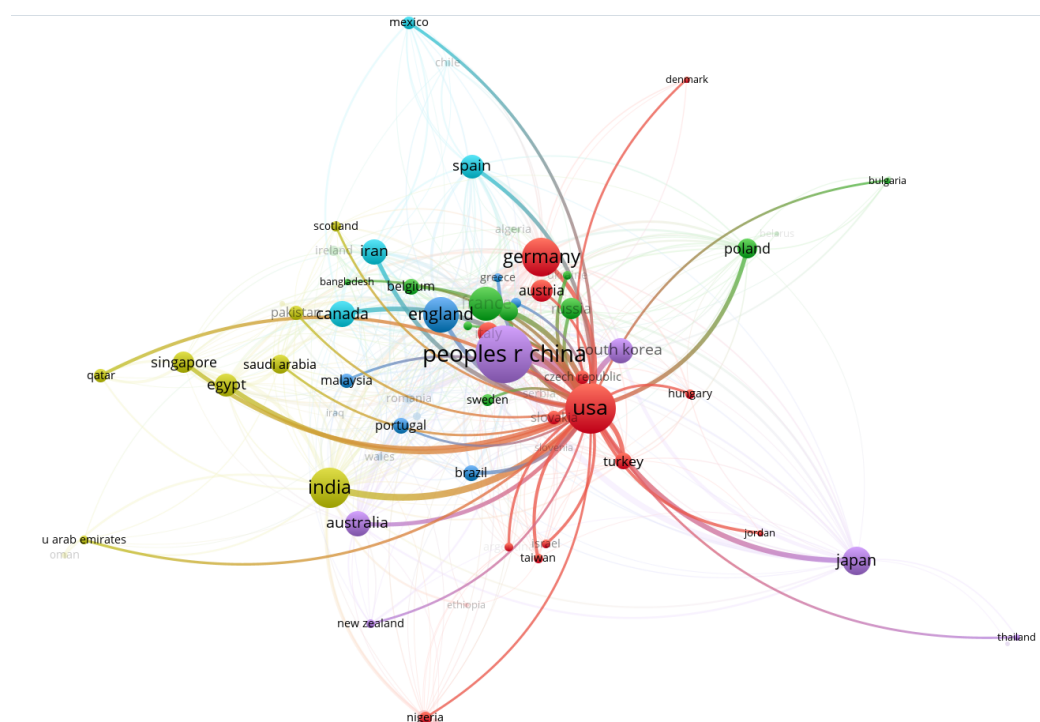


Figure 17. The international collaboration network of the USA.

4. Citation Landscapes

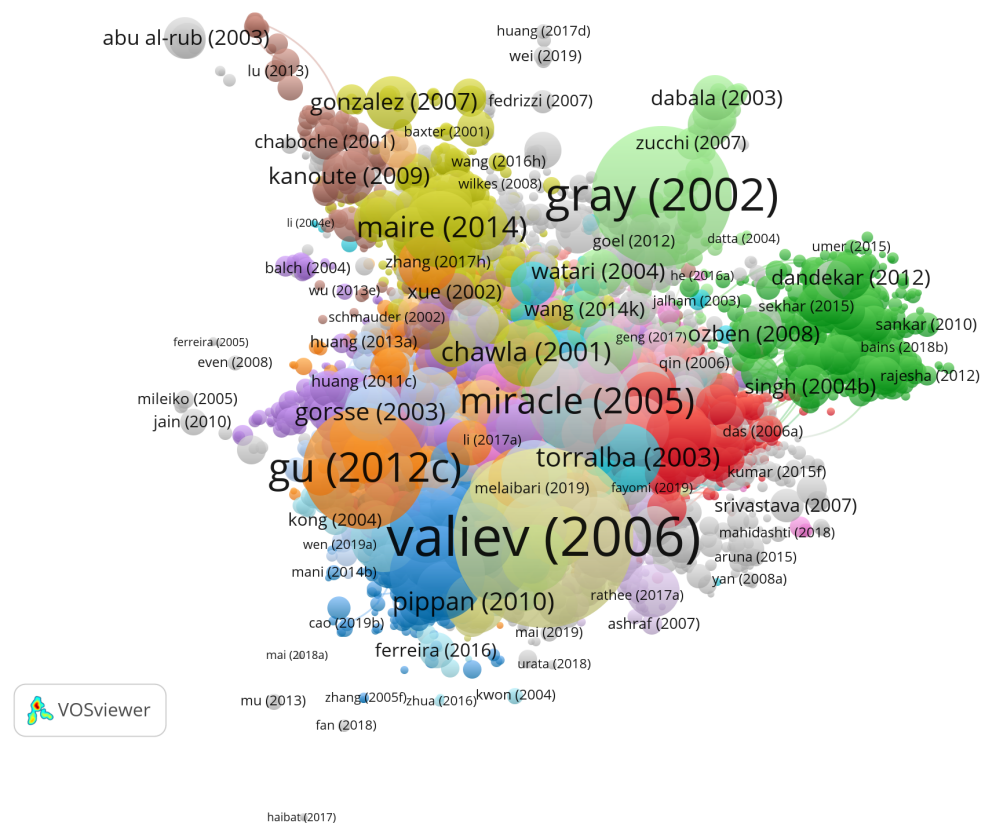
Citations are an important indicator of the actual research impact of a published article. This section presents an analysis of the MMC articles' citations and citations based linkages during 2001–2020. The MMC article citation analysis has been categorized as per the cited papers, associated/linked researchers, organizations, countries, publishing sources and keywords to understand the relative impacts of MMC research outputs under these classifications.

4.1. Citation Landscape of Published Articles

The first subsection of citation landscapes is concerned with the MMC publications having topmost citation based linkages with other WoS documents in the same field. The VoS viewer threshold was set at a minimum of five citations per document. Out of a total of 10,018, 5796 documents fulfilled this criterion. Of these, 5381 number of documents were found to be linked together by mutual citations. Table 11 shows the top ten WoS documents having the highest number of citations based links with other MMC articles of the selected database. Of these, three articles (Bakshi et al., 2010; Tjong, 2013; Tjong, 2007) [105–107] are concerned with the review, processing and properties of the nano particle reinforced metal matrix composites. Another three papers (Kok, 2005; Torralba et al., 2003; Chawla et al., 2001) [108–110] are related to the production and mechanical properties of particle reinforced MMCs. Two articles (Hashim et al., 2002 and Shorowordi et al., 2003) [111,112] deal with the microstructural analysis of processed metal matrix composites that includes the study of particle distribution and particle–matrix interface characteristics. The remaining two papers (Miracle, 2005 and Mortensen, 2010) [113,114] address general review of metal matrix composites and associated science, technology and application aspects. Figure 18 shows the mutual citation network graphs of the MMC articles published in WoS during 2001–2020.

Table 11. The top 10 MMC articles with maximum citation links.

Rank	Title of Article	Authors	Year	Journal	Citations	Links
1	Metal matrix composites—from science to technological significance [113]	D.B. Miracle	2005	Composites Science and Technology	1006	333
2	Carbon nanotube reinforced metal matrix composites—a review [105]	S. R. Bakshi, D. Lahiri and A. Agarwal	2010	International Materials Reviews	879	212
3	Recent progress in the development and properties of novel metal matrix nanocomposites reinforced with carbon nanotubes and graphene nanosheets [106]	S.C. Tjong	2013	Materials Science & Engineering R: Reports	552	200
4	Production and mechanical properties of Al ₂ O ₃ particle-reinforced 2024 aluminium alloy composites [108]	M.Kok	2005	Journal of Materials Processing Technology	407	130
5	P/M aluminum matrix composites: an overview [109]	J.M. Torralba, C.E. da Costa and F. Velasco	2003	Journal of Materials Processing Technology	458	130
6	Mechanical behavior of particle reinforced metal matrix composites [110]	N. Chawla and Y.L. Shen	2001	Advanced engineering materials	436	128
7	Novel nanoparticle-reinforced metal matrix composites with enhanced mechanical properties [107]	S.C. Tjong	2007	Advanced engineering materials	348	122
8	Metal Matrix Composites [114]	A. Mortensen and J. Llorca	2010	Annual Review of Materials Research	207	116
9	Particle distribution in cast metal matrix composites—Part I [111]	J. Hashim, L. Looney and M.S.J. Hashmi	2002	Journal of Materials Processing Technology	287	114
10	Microstructure and interface characteristics of B ₄ C, SiC and Al ₂ O ₃ reinforced Al matrix composites: a comparative study [112]	K.M. Shorowordi, T. Laoui, A.S.M.A. Haseeb, J.P. Celis and L. Froyen	2003	Journal of Materials Processing Technology	397	110

**Figure 18.** The citation network graph of MMC research articles.

4.2. Citation Landscape of Researchers

To determine the citations based links among various MMC researchers, the VoS viewer threshold was set at a minimum of five documents and zero citations per author. Of the total of 16,735 authors, only 1616 met this criterion. Together, these 1616 authors cited each other in 1612 WoS articles. Table 12 lists the top thirteen authors sorted as per their TLS values. The table also lists their nationalities, number of publications in WoS, citations and mutually cited author links. This list is primarily dominated by Chinese authors, with an author each from Singapore and Australia. It may be observed that Gupta M has the highest citations (3546) for 140 documents published in WoS. In comparison, Zhang D has 3278 citations for 113 published articles. Nevertheless, Zhang D has more mutually cited author linkages (777) than those of Gupta M (738). Similarly, Zhang D has a higher sum of mutual citations with all network links (TLS 7016) as compared to that of Gupta M (TLS 3287). Interestingly, Gupta M does not figure in the top ten co-author TLS listings (Table 2) but attains the eighth spot in the citations based TLS rankings. This indicates that this author may not have a high number of co-authored works but has a good number of mutually cited articles in WoS. Analyzing the Tables 2 and 12 further, it is evident that six researchers feature in both of these lists—Zhang D, Li Z, Li J, Guo Q, Fan G and Wang X. All of these authors are from China. This analysis provides insights into the level of collaboration and mutual citations based linkages among the MMC authors of China. There are some authors having high collaborative linkages but not having enough citation linkages—Liu, Wang H, Zhang Y and Li Y. Conversely, authors such as Su Y, Gupta M, Tan Z, Ji G, Xiong Db, Wu G and Chen Z have very good citation networks but moderate collaborative linkages. Tables 13 and 14 list the top ten mutually cited author links of Zhang D and Gupta M along with their respective link strengths for a comparative analysis. For instance, Zhang D and Li Z have cited each other's WoS articles 334 times, whereas Zhang D and Li J have cited each other's papers only 70 times. On the other hand, Gupta M and Tun Ks have cited each other's article 112 times, whereas Gupta M and Adeva P referenced each other's articles in only 31 instances. Figure 19 shows the network map of mutually cited authors in the field of metal matrix composites.

Table 12. The top 13 researchers with the highest citation TLS values.

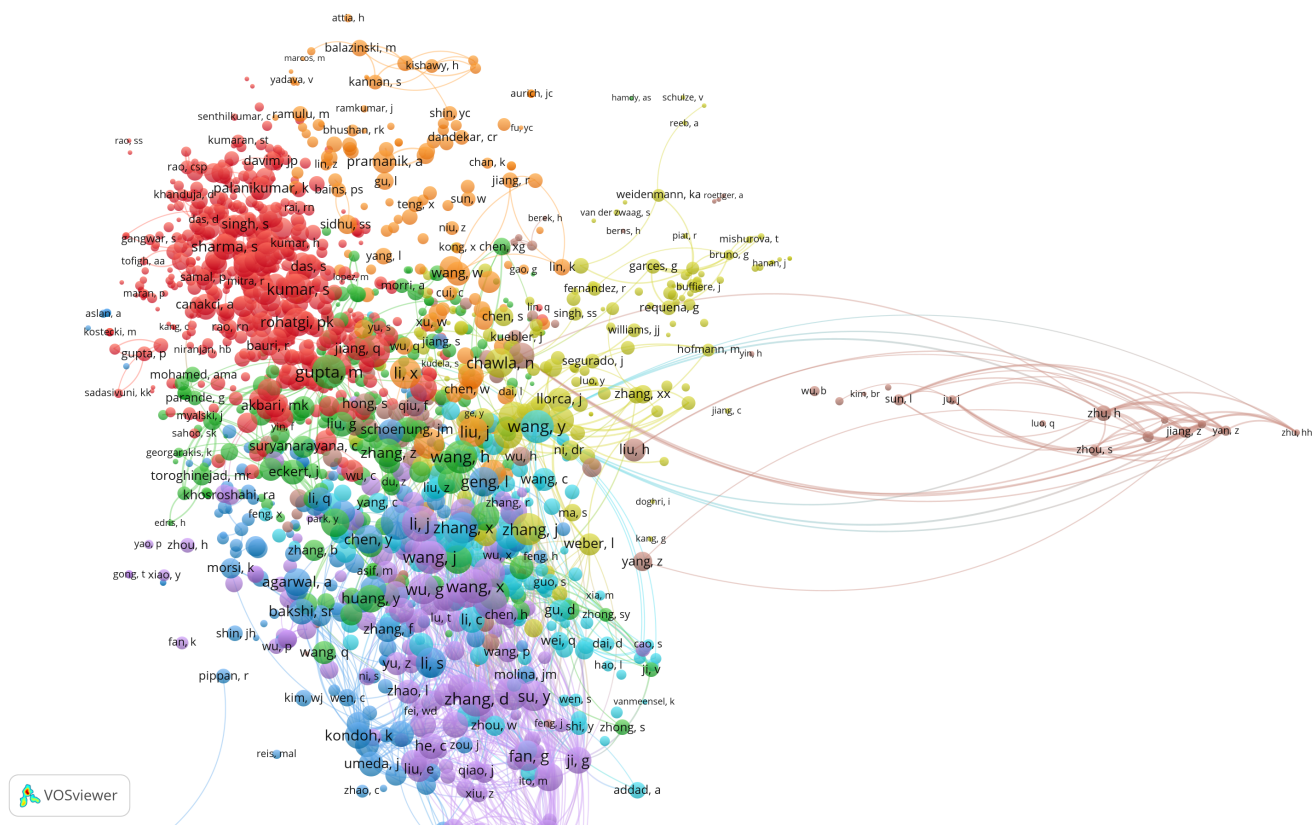
Rank	Author	Country	P	Citations	Links	TLS
1	Zhang, D	China	113	3278	777	7016
2	Li, Z	China	93	2617	733	5921
3	Fan, G	China	46	2168	581	4662
4	Guo, Q	China	50	1536	525	4230
5	Li, J	China	117	1903	815	3936
6	Wang, x	China	80	2088	740	3622
7	Su, Y	China	46	1244	567	3330
8	Gupta, M	Singapore	140	3546	738	3287
9	Tan, Z	China	34	1064	423	3233
10	Ji, G	China	40	927	459	3164
11	Xiong, Db	China	34	1028	427	3091
12	Wu, G	China	70	1185	591	2805
13	chen, z	Australia	50	1443	634	2804

Table 13. The top 10 citation links of Zhang D.

Sr. No.	Linked Author	Link Strength
1	Li, Z	334
2	Guo, Q	283
3	Fan, G	259
4	Xiong, Db	209
5	Su, Y	207
6	Tan, Z	184
7	Ji, G	97
8	Zhang, J	93
9	Zhao, L	87
10	Li, J	70

Table 14. The top 10 citation links of Gupta M.

Sr. No.	Linked Author	Link Strength
1	Tun, Ks	112
2	Wong, Wle	62
3	Sankaranarayanan, S	61
4	Jayalakshmi, S	60
5	Habibi, Mk	51
6	Nguyen, Qb	47
7	Paramsothy, M	41
8	Shakoor, Ra	34
9	Perez, P	31
10	Adeva, P	31

**Figure 19.** The citation network graph of MMC authors.

4.3. Citation Landscape of Organizations

This subsection analyses the citation based links among the various organizations of the MMC researchers. For this analysis, the VoS viewer thresholds were set at a minimum of five documents and zero citations per organization. About 801 organizations qualified this criterion from a total of 446. These organizations cited each other's WoS articles 800 times. Table 15 lists the top thirteen organizations having maximum mutually cited TLS values in their respective networks. It may be observed that the Nanjing University of Aeronautics and Astronautics (NUAA) is missing from this list. This university was listed at number 12 in the top co-authored TLS list (Table 5). On the other hand, the University of Wisconsin-Madison, featuring at number thirteen in Table 15, did not appear at all in the top co-authored TLS list (Table 5). This observation delineates the difference between the co-authored and mutually cited linkages. For instance, the Chinese Academy Science is the top listed co-authored TLS institution (Table 5), whereas it only has the fourth highest TLS of mutual citations (Table 15). Conversely, the Shanghai Jiao Tong University is only the fourth highest co-authored TLS scoring institution in Table 5, whereas it has the highest mutual citations among its links making it the topmost TLS university (Table 15). Similarly, in Section 3.2, it was pointed out that the Anna University attained higher co-authored TLS over the National Institutes of Technology (India) despite having relatively less publications in WoS. This scenario is reversed in the case of citations based TLS rankings, wherein the National Institutes of Technology has much higher TLS value (2187) as compared to that of the Anna University (1602). These observations indicate higher mutual citation linkages for lower co-authored linkages or vice versa in the case of the above-mentioned institutions. Other organizations like the Indian Institutes of Technology, National University of Singapore and Northwestern Polytechnic University maintained their respective positions viz. third, fifth and ninth spots in both of the top co-authored as well as citations based TLS listings. These organizations exhibited balanced levels of collaborative as well as citation linkages amongst their network institutions. Taking a macro view of the co-authored and citation TLS lists, it is evident that mostly the same organizations feature in both of these top rankings. Hence, it may be inferred that inter-institute research collaborations lead to inter-institute citation links as well. In addition, the citation TLS values tend to be much higher than the co-authored TLS numbers. For example, the highest mutually cited TLS value is 4463 (of Shanghai Jiao Tong University), whereas the greatest co-authored TLS values is just 212 (of Chinese Academy Science). Tables 16 and 17 show the top ten citations based organizational links of the National Institutes of Technology and Anna University, India. It is evident that the MMC researchers of the National Institutes of Technology and the Indian Institutes of Technology have cited each other 73 times. On the other hand, MMC investigators at the Anna University and the National Institutes of Technology have cited each other's MMC WoS papers on 49 occasions. The Harbin Institute of Technology has equal citations link strength of 29 with both the National Institute of Technology as well as the Anna University. However, Gazi University (Turkey) has varying citation link strengths of 30 and 15 with the National Institutes of Technology and the Anna University, respectively. Figure 20 shows the citation based inter-institutional networks in different colors.

Table 15. The top 13 organizations with the highest citation TLS values.

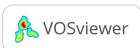
Rank	Organization	Country	P	Citations	Links	TLS
1	Shanghai Jiao Tong University	China	270	5323	544	4433
2	Harbin Institute of Technology	China	335	5659	565	3938
3	Indian Institutes of Technology	India	223	5109	592	3272
4	Chinese Academy Science	China	227	3925	498	3010
5	National University of Singapore	Singapore	160	4185	456	2277
6	National Institutes of Technology	India	155	2499	461	2187
7	University of Science and Technology Beijing	China	118	3199	341	1822
8	Islamic Azad University	Afghanistan	108	2249	433	1816
9	Northwestern Polytechnic University	USA	132	1780	395	1715
10	Anna University	India	112	2124	424	1602
11	Osaka University	Japan	51	2223	297	1584
12	University of Tehran	Iran	72	2389	403	1509
13	University of Wisconsin-Madison	USA	60	2524	417	1337

Table 16. The top 10 citation links of the National Institutes of Technology.

Sr. No.	Linked Organization	Country	Link Strength
1	Indian Institutes of Technology	India	73
2	Anna University	India	49
3	National University of Singapore	Singapore	43
4	Amrita Vishwa Vidyapeetham University	India	42
5	Council of Scientific and Industrial Research	India	32
6	Gazi University	Turkey	30
7	Jadavpur University	India	30
8	Harbin Institute of Technology	China	29
9	University of Tehran	Iran	26
10	Annamalai University	India	23

Table 17. The top 10 citation links of Anna University.

Sr. No.	Linked Organization	Country	Link Strength
1	National Institutes of Technology	India	49
2	Indian Institutes of Technology	India	36
3	Harbin Institute of Technology	China	29
4	K Ramakrishnan College of Engineering	India	20
5	PSG College Of Technology	India	20
6	Sri Krishna College of Engineering and Technology	India	19
7	Annamalai University	India	17
8	University of Wisconsin-Madison	USA	16
9	Gazi University	Turkey	15
10	Kongu Engineering College	India	15



4.4. Citation Landscape of Places

To determine the citation based linkages for MMC research among various countries, the VoS viewer threshold was set at a minimum of five WoS documents and zero citations per nation. Only 63 countries met this criterion out of a total of 97. Table 18 shows the top thirteen countries having the best citations based TLS values. Compared with the collaboration TLS rankings given in Table 8, it may be observed that the People's Republic of China has topped both the lists. The authors of this country have maximum co-authored links (681) in MMC papers as well as the highest number of mutual citations (20,878) in these WoS articles. India, listed as the nation with the third highest co-authored linkages (350), bagged the second spot in international citation linkage rankings (17,501). Conversely, the USA attained the third highest citation linkages (13,112), although it has the second highest co-authored links (537) in its MMC articles. Similarly, nations like Germany, England, France, Japan, Canada and Spain also attained relatively lower citation based TLS ranks as compared to their respective co-authored works based TLS rankings. However, some countries improved their citation rankings over collaboration ranks. These countries included India, Iran and South Korea. Australia maintained the same rank in both listings. The biggest rankings difference is observed in the case of Iran. Iran has the fourth highest mutually cited TLS (5938), whereas it is ranked only ninth in the co-authored MMC research linkages based TLS (145). This analysis shows that Iranian researchers have relatively higher mutual citations with their international colleagues as compared to other top TLS nations; and lesser internationally co-authored publications against the rest of the top linked countries. Table 19 lists the top ten countries having MMC articles' citation based linkages with the Iranian authors. The top three linked nations are India, People's Republic of China and the USA having their mutual MMC citation link strengths with Iran at 1407, 988 and 568, respectively. Figure 21 depicts the citation network graph among the various countries engaged in MMC research, whereas Figure 22 shows the international citation linkages of Iranian authors.

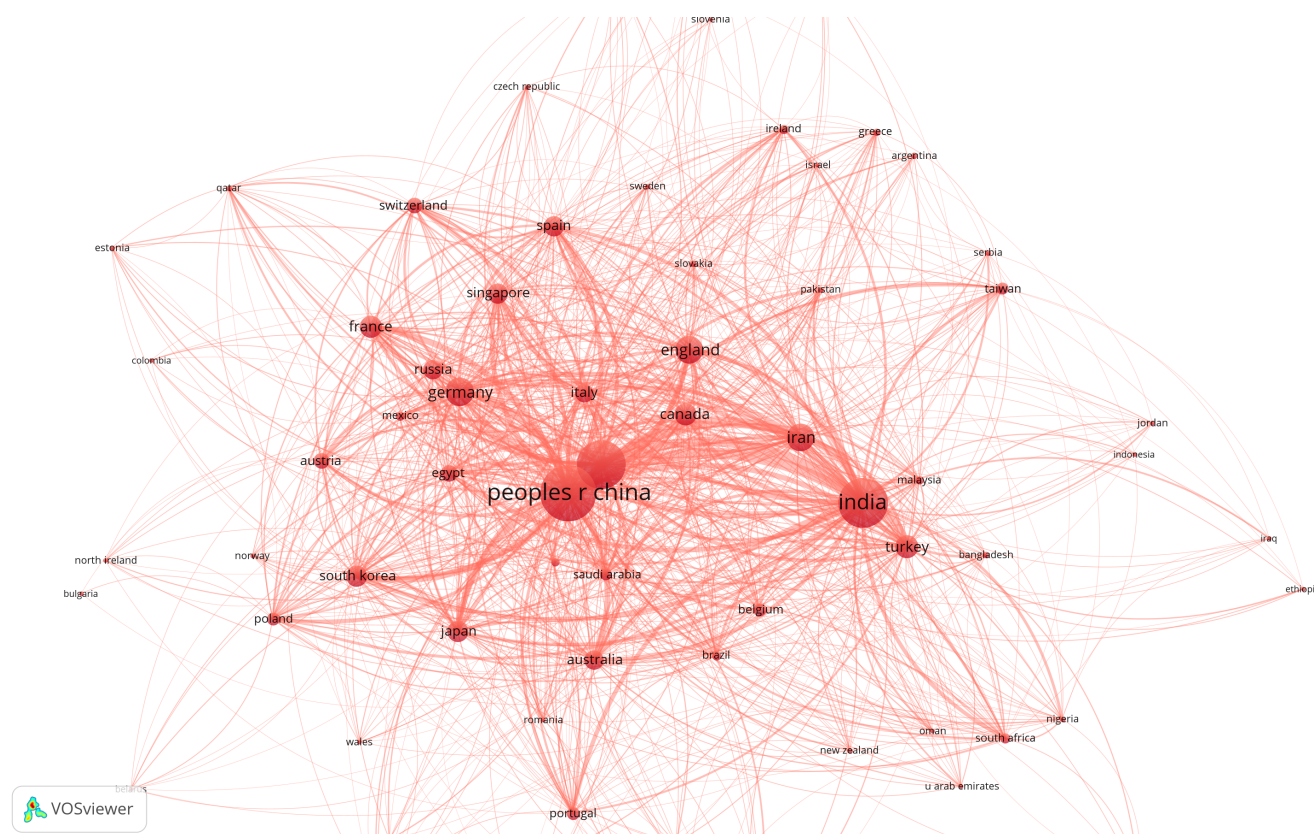


Figure 21. The citation network graph of countries.

Table 18. The top 13 countries with the maximum citation TLS values.

Rank	Country	P	Citations	Links	TLS
1	Peoples Republic of China	2475	43,374	66	20,878
2	India	2509	34,715	66	17,501
3	USA	1104	33,038	66	13,112
4	Iran	463	10,830	63	5938
5	Germany	525	11,654	64	5042
6	Turkey	392	7784	62	4678
7	England	325	10,849	64	3799
8	South Korea	372	6264	62	3598
9	Japan	312	6452	64	3489
10	France	282	7011	61	3397
11	Australia	172	5240	64	3077
12	Canada	259	6846	59	2922
13	Spain	245	5763	61	2797

Table 19. The top 10 citation links of Iran.

Sr. No.	Linked Country	Link Strength
1	India	1407
2	Peoples Republic of China	988
3	USA	568
4	Turkey	261
5	South Korea	184
6	Australia	160
7	Germany	153
8	England	150
9	Egypt	145
10	Japan	140

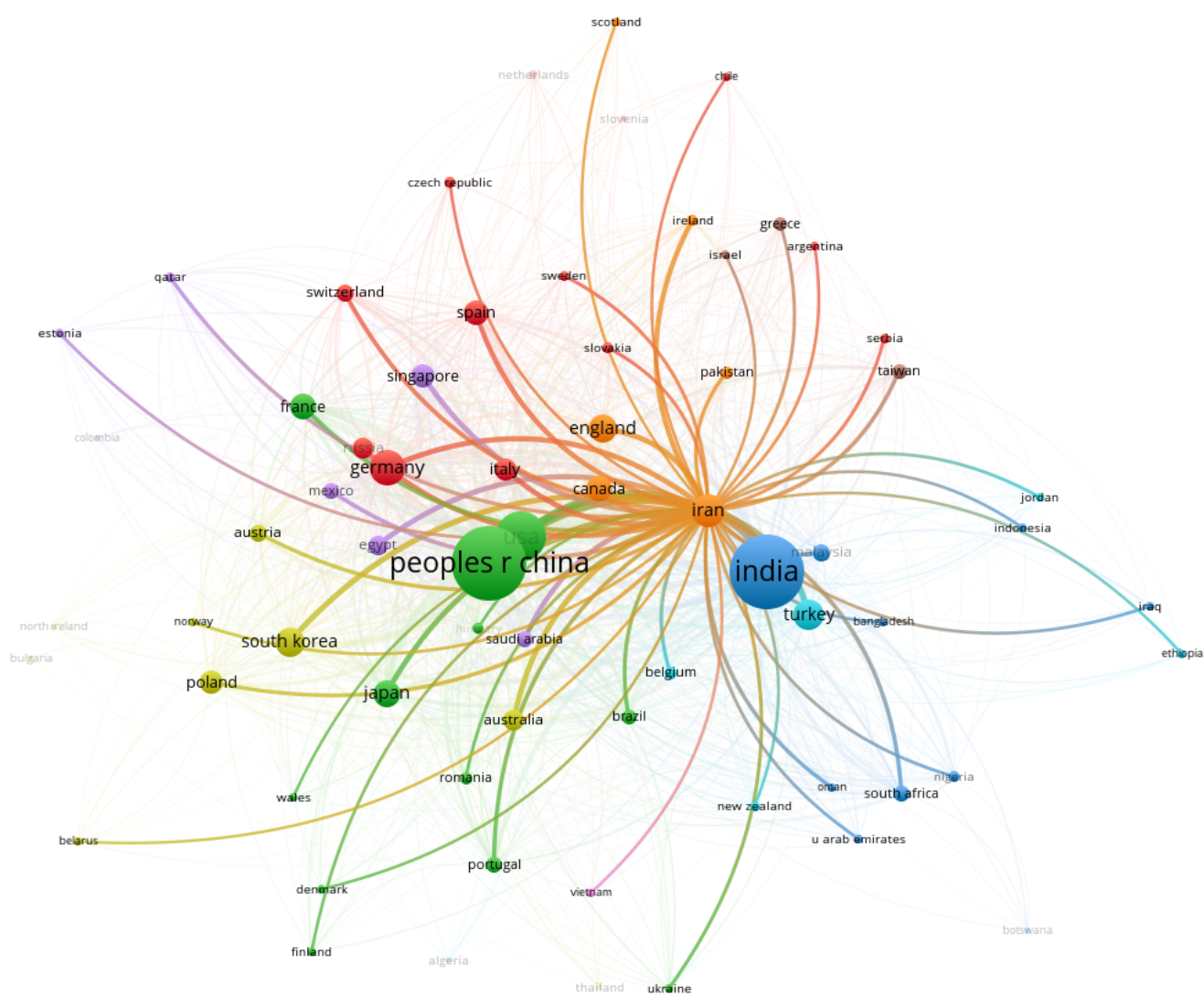


Figure 22. The international citation network of Iran.

4.5. Citation Landscape of Sources

The citation landscape of publication sources was determined using the VoS viewer threshold of a minimum of five WoS documents and zero citations per source. Out of a total of 1471 sources, only 270 made it to the threshold limit. Table 20 shows the list of journals having the highest citations based TLS values. This table gives source-wise numbers of MMC papers published in WoS, their citations, number of journals linked via mutual citations and the total strengths (TLS) of these linkages. Considering the relative metrics of the International Journal of Advanced Manufacturing Technology (TLS rank 11) and Scripta Materialia (TLS rank 12), it may be observed that the former source has higher publications, lower citations, lower links and higher TLS as compared to the latter journal. This observation indicates that, in case of International Journal of Advanced Manufacturing Technology, the number of mutual citations per link is much greater than that of Scripta Materialia. Tables 21 and 22 show the top ten citation based links of these two journals. The Journal of Materials Processing Technology is the strongest citation link for the International Journal of Advanced Manufacturing Technology with 187 mutual citations in WoS. Similarly, the Materials Science and Engineering: A—Structural Materials: Properties, Microstructure and Processing is the link with the highest strength, i.e., having the maximum number of mutual citations with the MMC articles published in Scripta

Materialia during 2001–2020. A similar analysis shows that the Acta Materialia (rank 9, articles 131, citations 7726, links 172, TLS 1983) has more publications, citations and TLS despite having lesser linkages as compared to the journal Wear (rank 10, articles 129, citations 6007, links 191, TLS 1883). Figure 23 shows the citation based linkages between the various sources publishing MMC papers in the WoS. Figure 24 shows citation linkages of the top ranked TLS source—Materials Science and Engineering: A—Structural Materials: Properties, Microstructure and Processing.

Table 20. The top 13 sources with the maximum TLS values.

Rank	Source	P	Citations	Links	TLS
1	Materials Science and Engineering: A-Structural Materials: Properties, Microstructure and Processing	640	18,715	242	6634
2	Journal of Alloys and Compounds	468	12,992	213	4377
3	Materials & Design	273	11,299	229	4364
4	Composites Science and Technology	185	10,482	225	3109
5	Composites Part A: Applied Science and Manufacturing	200	8708	222	2987
6	Journal of Materials Processing Technology	157	8198	218	2895
7	Composites Part B: Engineering	200	7212	194	2254
8	Materials Today: Proceedings	435	2024	160	2155
9	Acta Materialia	131	7726	172	1983
10	Wear	129	6007	191	1883
11	The International Journal of Advanced Manufacturing Technology	133	2755	146	1575
12	Scripta Materialia	100	5105	161	1397
13	Journal of Materials Science	139	2667	158	1257

Table 21. The top 10 citation links of sources: The International Journal of Advanced Manufacturing Technology.

Sr. No.	Linked Journal	Link Strength
1	Journal of Materials Processing Technology	187
2	International Journal of Machine Tools & manufacture	111
3	Materials and Manufacturing Processes	87
4	Wear	67
5	Materials & Design	52
6	Materials Science and Engineering a-structural Materials Properties	50
7	Materials Today-proceedings	46
8	Composites Science and Technology	44
9	Advances in Manufacturing	41
10	International Journal of Mechanical Sciences	38

Table 22. The top 10 citation links of source: Scripta Materialia.

Sr. No.	Linked Journal	Link Strength
1	Materials Science and Engineering: A-Structural Materials: Properties, Microstructure and Processing	172
2	Journal of Alloys and Compounds	138
3	Materials & Design	95
4	Composites Part a-applied Science and Manufacturing	80
5	Acta Materialia	67
6	Composites Part b-engineering	52
7	Composites Science and Technology	46
8	Advanced Engineering Materials	37
9	Carbon	34
10	Journal of Materials Science	33

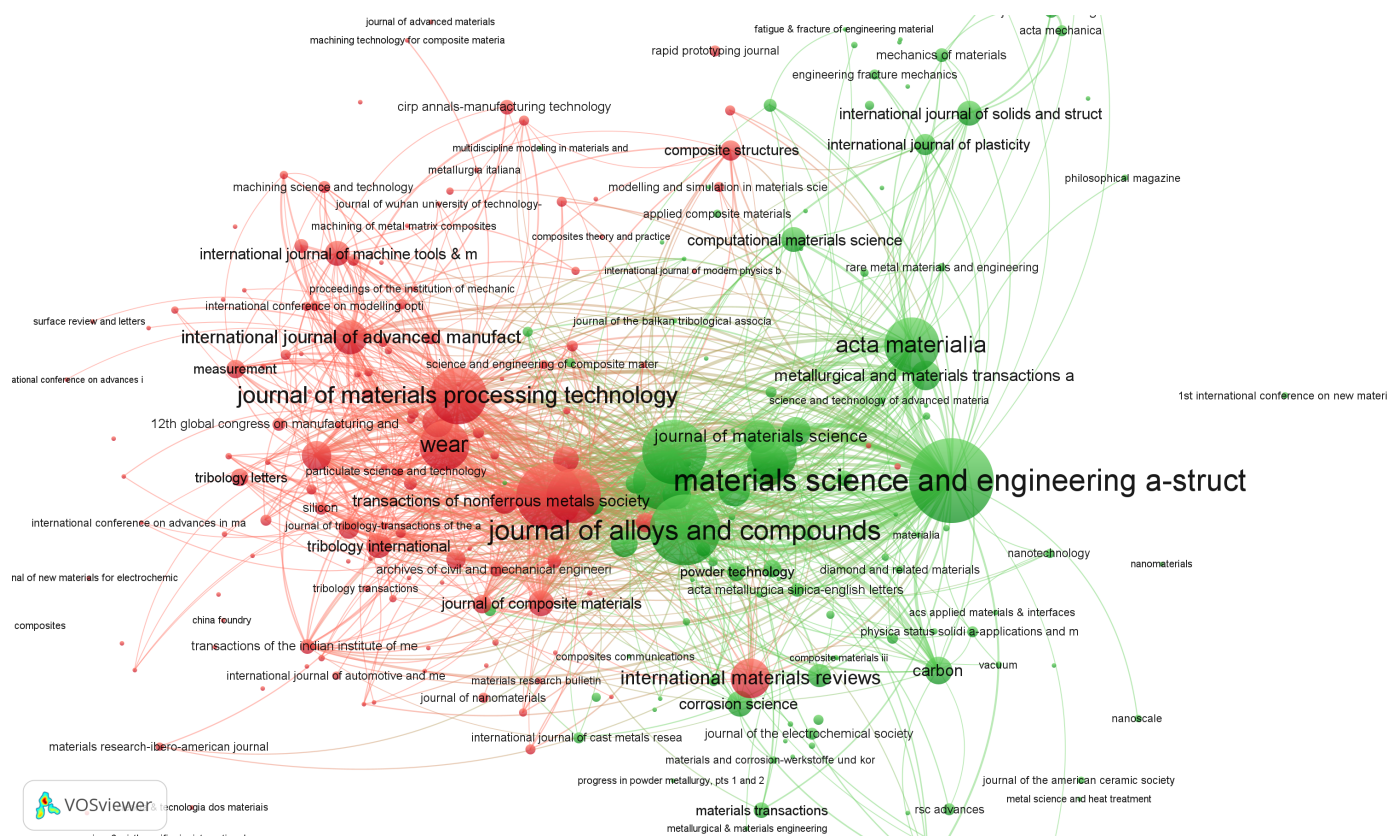


Figure 23. The citation network graph of sources.

4.6. Co-Occurrence Landscape of Keywords

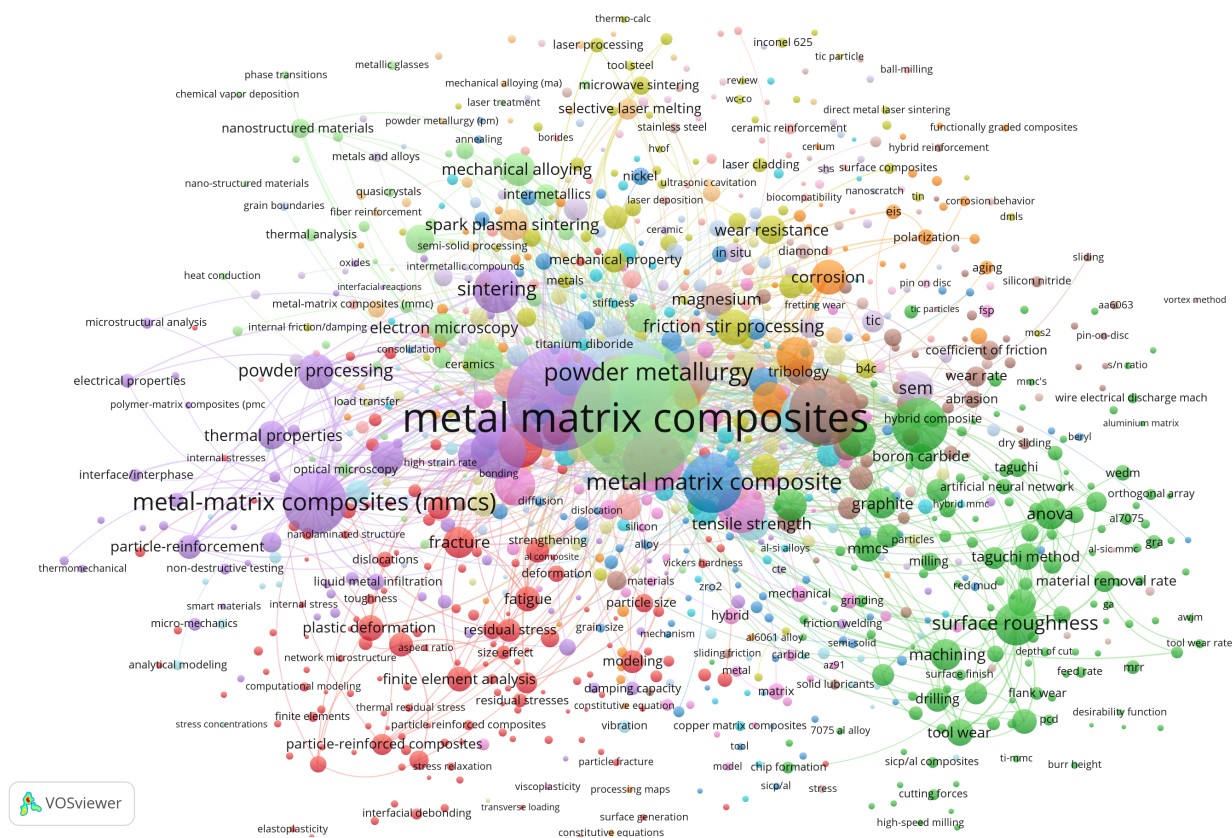
This subsection describes the co-occurrence based analysis of the technical keywords most quoted by the MMC researchers in their WoS articles. For this analysis, the WoS viewer threshold was set at a minimum of five occurrences per keyword. From a total of 11,569 keywords, only 1068 could qualify for this condition. Table 23 lists thirteen keywords with top TLS values based on co-occurrence links with other keywords appearing in MMC publications. It is evident that the keyword ‘Metal Matrix Composites’ is the top TLS keyword having 2135 occurrences in WoS documents. It has co-occurred with 845 other keywords, with a total strength of such linkages at 5566. It is interesting to note that the fifth, eighth and the tenth ranked keywords, viz. ‘Metal-Matrix Composites (mmcs)’, ‘Metal Matrix Composite’ and ‘Metal-Matrix Composites’ are instances of the top TLS keyword itself. Similarly, the sixth and the thirteenth ranked keywords—‘Composites’ and ‘Composite’ are also generalized versions the keyword with the highest TLS. Thus, six out of the thirteen top co-occurred keywords refer to the same term. The second ranked keyword ‘Mechanical Properties’ indicates the focus of most WoS articles on investigating the physical properties of the MMCs for varied applications. The fourth and ninth ranked keywords—‘Wear’ and ‘Hardness’ reveal the most important mechanical properties considered by researchers during MMC performance tests. Similarly, the keywords ranked seventh and eleventh—‘Powder Metallurgy’ and ‘Stir Casting’ indicate the most important techniques explored by various researchers for preparing MMCs of various compositions. After mechanical properties, the next most widely studied aspect of MMCs is ‘Microstructure’, listed as the third highest TLS keyword in WoS articles. Lastly, the twelfth ranked keyword—‘Aluminium’ indicates the favorite base metal alloy material used most widely by the researchers for processing MMCs with different micro/nano particulate inclusions. Figure 25 shows the network map of these and other keywords co-appearing in WoS articles during 2001–2020. These figures show inter-linkages among keywords belonging to various MMC materials, methods of preparation, characterization, testing, analyses, processing/machining and applications. Figures 26–28 showcase the

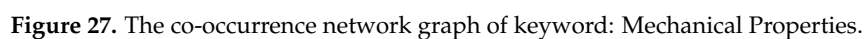
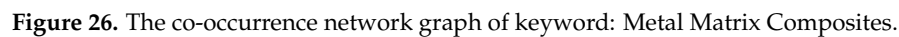
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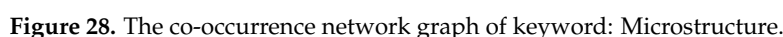
Figure 24. The citation network graph of source: Materials Science and Engineering: A—Structural Materials: Properties, Microstructure and Processing.

Table 23. The top 13 keywords with the maximum citation TLS values.

Rank	Keyword	P	Links	TLS
1	Metal Matrix Composites	2135	845	5566
2	Mechanical Properties	1255	599	3643
3	Microstructure	962	597	2922
4	Wear	511	429	1701
5	Metal-Matrix Composites (mmcs)	485	280	1383
6	Composites	437	425	1284
7	Powder Metallurgy	423	360	1272
8	Metal Matrix Composite	457	466	1222
9	Hardness	295	338	1081
10	Metal-Matrix Composites	403	374	1060
11	Stir Casting	328	309	1026
12	Aluminum	256	300	852
13	Composite	264	327	794

**Figure 25.** The co-occurrence network graph of keywords.





Burst detection analysis reveals the specific time periods wherein particular keywords and/or sources witnessed sudden increase in research interest (indicated by the number of citations) [63]. In the current study, burst detection analyses of keywords and references related to MMCs were carried out based on the research published during 2001–2020.

Burst detection for the MMC keywords used by WoS articles during 2001–2020 was analysed using the CiteSpace software tool. Table 24 shows the top MMC research related keywords ranked as per their relative burst strengths, i.e., the degrees of sudden increase in their respective citation frequencies. As per this list, the keyword ‘graphene’ witnessed the highest spike in citations as compared to all other keywords related to MMC research. CiteSpace determined the strength of ‘graphene’ keyword burst at 33.6453. Moreover, this burst assumes additional significance because of its latest burst duration, i.e., 2018–2020. This particular citation spike indicates a sudden increase in nano-scale particle reinforced metal matrix composites research in the last two years. During the first decade of this century, keywords like ‘fracture’, ‘damage’, ‘deformation’, ‘creep’, ‘flow’, ‘residual stresses’ and ‘particulate composites’ witnessed citation bursts with respective strengths of 24.5309, 24.1626, 22.9149, 20.4049, 16.3026, 15.6975 and 15.6215. These citation bursts indicate

an initial interest in the investigation of various mechanical properties of the developed composite materials. Later on, this focus gradually started shifting towards the novel processing techniques, indicated by the citation bursts of keywords like ‘powder processing’, ‘metal matrix composites (mmc)’ and ‘pressureless infiltration’ with burst strengths of 15.1708 (2007–2016), 14.8633 (2006–2011) and 14.2745 (2006–2011), respectively. During the last four years, MMC researchers have favored keywords (including ‘graphene’) like ‘strengthening mechanism’, ‘stir casting’, ‘nanocomposite’ and ‘B4C’ having burst strengths of 20.45 (2017–2020), 19.9426 (2018–2020), 16.9666 (2016–2018), and 13.6994 (2018–2020), respectively. These citation bursts indicate a renewed emphasis on mechanisms and methods of preparing different metal matrix composites. In addition, the recent keyword bursts also indicate a lot of researchers exploring various kinds of nanocomposites reinforced with particulate materials like graphene and boron carbide for various applications.

Table 24. The top 15 keywords with the strongest citation bursts.

Rank	Keywords	Year	Strength	Begin	End	2001–2020
1	Graphene	2001	33.6453	2018	2020	
2	Fracture	2001	24.5309	2001	2009	
3	Damage	2001	24.1626	2001	2009	
4	Deformation	2001	22.9149	2001	2008	
5	Strengthening Mechanism	2001	20.45	2017	2020	
6	Creep	2001	20.4049	2001	2010	
7	Stir Casting	2001	19.9426	2018	2020	
8	Nanocomposite	2001	16.9666	2016	2018	
9	Flow	2001	16.3026	2001	2010	
10	Residual Stresses	2001	15.6975	2001	2008	
11	Particulate Composite	2001	15.6215	2001	2010	
12	Powder Processing	2001	15.1708	2007	2016	
13	Metal Matrix Composites (mmc)	2001	14.8633	2006	2011	
14	Pressureless Infiltration	2001	14.2745	2006	2011	
15	B4C	2001	13.6994	2018	2020	

5.2. Reference Burst Detection

References burst detection analysis was also carried out using the CiteSpace software to gain insights into the top MMC articles that received the highest citation bursts during 2001–2020. Table 25 lists fifteen publications having the highest burst strengths based on citations in WoS. Three of these articles (ranked 1, 2 and 15) are review papers dealing with the different particle reinforced metal matrix composites [115,116], associated preparation techniques and characteristics [117]. The remaining papers (ranked 3 to 14) reported investigations into specific mechanical properties of MMCs such as deformation [118], tensile strength [119,120], creep [121], fracture [122,123], dislocation generation [41,124], ductility [125], elastic energy [126] and others [127]. It may be observed that all of these articles were published before 2001. Seven of them were published during 1991–2000 and six articles were published during 1981–1990. Two papers were published as far back as 1973 and 1957! This analysis shows that researchers have been working on metal matrix composites for the last five decades. All of the fifteen strongest citation bursts have been attained by the articles published before 2001, with zero instances of the MMC articles published during 2001–2020. In fact, all of these citation bursts have been recorded during

the initial period of 2001–2005. Referring to Figure 2, it may be observed that relatively fewer MMC papers were published in WoS in that period. Hence, the documents with top burst strengths were cited at high frequencies by the MMC papers published during 2001–2005. In addition, none of the top cited articles listed in Table 11 have made it to the top citation burst list. This observation implies that the top cited MMC articles did not receive their respective citations in the form of short-term high frequency bursts.

Table 25. The top 15 references with the strongest citation bursts.

Rank	References	Year	Strength	Begin	End	2001–2020
1	LLOYD DJ, 1994, INT MATER REV, V39, P1 [115]	1994	72.1562	2001	2005	
2	IBRAHIM IA, 1991, J MATER SCI, V26, P1137 [116]	1991	38.8436	2001	2005	
3	CHRISTMAN T, 1989, ACTA METALL MATER, V37, P3029 [118]	1989	33.77	2001	2005	
4	Clyne TW, 1993, INTRO METAL MATRIX C, V0, P0 [119]	1993	33.2064	2001	2005	
5	ESHELBY JD, 1957, PROC R SOC LON SER-A, V241, P376 [128]	1957	32.0793	2001	2005	
6	BAO G, 1991, ACTA METALL MATER, V39, P1871 [121]	1991	29.2619	2001	2005	
7	LLOYD DJ, 1991, ACTA METALL MATER, V39, P59 [122]	1991	26.4452	2001	2005	
8	ARSENAULT RJ, 1986, MATER SCI ENG, V81, P175 [41]	1986	26.4452	2001	2005	
9	MCDANELS DL, 1985, METALL TRANS A, V16, P1105 [125]	1985	22.5029	2001	2005	
10	MORI T, 1973, ACTA METALL MATER, V21, P571 [126]	1973	21.9398	2001	2005	
11	NARDONE VC, 1986, SCRIPTA METALL MATER, V20, P43 [120]	1986	21.9398	2001	2005	
12	VOGELSANG M, 1986, METALL TRANS A, V17, P379 [124]	1986	19.6878	2001	2005	
13	TJONG SC, 2000, MAT SCI ENG R, V29, P49 [127]	2000	19.628	2002	2005	
14	BRECHET Y, 1991, ACTA METALL MATER, V39, P1781 [123]	1991	18.7652	2001	2004	
15	ROHATGI P K, 1986, INTERNATIONAL METALS REVIEWS, V31, P115 [117]	1986	17.999	2001	2005	

6. Conclusions

This paper presents a comprehensive bibliometric analysis of metal matrix composites research articles published in the web of science database during the last two decades. The MMC related keywords generated a corpus of 10,018 articles from indices such as SCIE, ESCI, CPCI-S, CPCI-SSH and BCI-S. The bibliometric analysis was carried out under four major categories—publications distribution along different verticals, collaboration analysis, citation landscapes and burst detection. The first category of publication distribution was comprised of verticals such as year on year number of articles, publication types, sources, research directions, productive places, organizations and researchers. The second category included analysis of collaboration among various MMC researchers, affiliating organizations and countries. The third category dealt with mutual citation based linkages among MMC articles, researchers, organizations, places and sources. This section also included a co-occurrence based analysis of MMC related keywords quoted by researchers in their WoS articles. The fourth category provided insights into the top keywords and documents that witnessed strongest citation bursts during the last two decades. Following are the primary findings of the entire bibliometric analysis of metal matrix composites research presented in the current study.

1. The MMC related keywords' search yielded a total of 10,018 articles from the WoS database.
2. The number of MMC publications in WoS started rising after 2005. In 2018, 1001 articles were published as compared to just 269 in 2005.

3. Research articles comprised 80.54% of all publications. Other publication types include proceedings (21.94%), review articles (3.08%), book chapters (1.11%) and early access manuscripts (0.44%).
4. The journal 'Materials Science and Engineering A: Structural Materials, Properties, Microstructure and Processing' published the maximum MMC articles (640 papers) in WoS (6.39% of total corpus). The 'Journal of Alloys and Compounds' published 468 (4.67%) articles whereas 'Materials Today Proceedings' contributed 435 (4.34%) papers in WoS.
5. 'Materials science' emerged as the most significant research direction with 7580 (75.66%) WoS publications. 'Metallurgy/metallurgical engineering' was the second most important research direction with 3242 (32.36%) articles. The third highest number of MMC articles (2703, 26.98%) were categorized under the general research direction of 'engineering', dealing with the various engineering aspects of MMCs. These three research directions witnessed steadily increasing publication trends during 2001–2020.
6. There is a lot of scope in the MMC research directions pertaining to 'automation control systems', 'mining mineral processing' and 'optics'.
7. Researchers affiliated with the USA published the most MMC articles during 2001–2004 (60 papers in 2004). From 2005 to 2012, Chinese authors published the maximum number of WoS papers (114 papers in 2012). Post 2012, Indian investigators contributed maximum articles in WoS (415 papers in 2020).
8. Globally, the Harbin Institute of Technology, China published the maximum number of WOS papers (335, 3.34%) in the field of metal matrix composites. The Shanghai Jiao Tong University, China (271 papers, 2.71%) and the Chinese Academy of Sciences (227 papers, 2.27%) contributed the second and third highest number of MMC articles in WoS.
9. Among Indian organizations, the Indian Institutes of Technology published the maximum articles (225) followed by National Institutes of Technology (156 papers) and Anna University (113 papers).
10. Gupta M (Singapore) published the most MMC papers (140, 1.40%) followed by Zhang D (China) and Wu Gouhua (China) with 97 (0.97%) and 86 (0.86%) publications, respectively.
11. Zhang D, Li Z and Li J emerged as the MMC researchers with the topmost collaboration based total link strength (TLS) values of 499, 443 and 421, respectively. They published 113, 97 and 117 papers with 108, 110 and 184 co-authors, respectively. Gupta M did not make it to the top ten collaborative TLS list despite having maximum MMC publications due to less co-author linkages and respective link strengths.
12. The top three organizations with the maximum inter-institute collaborative TLS values are the Chinese Academy of Science (papers 227, links 73, TLS 212), Harbin Institute of Technology, China (papers 335, links 7, TLS 162) and the Indian Institutes of Technology (papers 223, links 71, TLS 154).
13. Among the Indian organizations, Anna University attained better inter-organizational collaborative TLS value of 95 as compared to the National Institutes of Technology (TLS 91) despite publishing fewer MMC papers in WoS.
14. The People's Republic of China, the USA and India attained the highest international collaborative TLS values of 681, 537 and 350, respectively. The authors affiliated with these countries published 2475 (links 42), 1104 (links 47) and 2509 (links 45) articles, respectively.
15. The MMC researchers of India, Japan, Iran and Spain need to improve international collaborative linkages in proportion to their respective MMC publication outputs.
16. The review articles published by Miracle DB [113], Bakshi et al. [105] and Tjong SC [106] were determined to have the highest citations based link strengths of 333, 212 and 200, respectively. These papers obtained 1006, 879 and 552 WoS citations, respectively.

17. Zhang D, Li Z, Fan G (all from China) were the top ranked MMC researchers with the highest mutual citations based TLS values of 7016, 5921, 4662 with 3278 (links 777), 2617 (links 733) and 2168 (links 581) citations, respectively. Gupta M figured at rank 8 of this list despite having maximum citations (3546) due to lesser mutual citations with the documents of other MMC researchers.
18. The Shanghai Jiao Tong University, Harbin Institute of Technology and the Indian Institutes of Technology attained the maximum citations network based TLS of 4433, 3938 and 3272, respectively. The authors affiliated with these organizations bagged 5323, 5659 and 5109 citations with 544, 565 and 592 links, respectively.
19. The top three countries with the highest international linkage based TLS rankings are the People's Republic of China (TLS 20878), India (TLS 17501) and the USA (13112). These nations have citations based linkages with 66 countries each. Their authors have obtained 43,374, 34,715 and 33,038 WoS citations, respectively.
20. Iran obtained the fourth highest TLS (5938) based on its international citation linkages (63), whereas it was ranked only ninth in the international co-authored MMC research linkages (links 26, TLS 145).
21. The top three MMC publication sources with the highest citations based TLS values are the 'Materials Science and Engineering: A—Structural Materials: Properties, Microstructure and Processing' (TLS 6634), 'Journal of Alloys and Compounds' (TLS 4377) and 'Materials & Design' (TLS 4364). Their WoS articles have received 18,715 (links 242), 12,992 (links 2313) and 11,299 (links 229) citations, respectively.
22. The top three MMC related keywords with the highest co-occurrence based TLS are 'Metal Matrix Composites' (TLS 5566), 'Mechanical Properties' (TLS 3643) and 'Microstructure' (TLS 2922). These keywords have occurred in 2135, 1255 and 962 documents with 845, 599 and 597 co-occurrence based links with other MMC keywords, respectively. The other MMC keywords (with high co-occurrence based TLS) are related to MMC materials, processing techniques, properties and analyses.
23. Keyword burst detection analysis revealed that 'graphene', 'stengthening mechanism', 'stir casting' 'nanocomposite' and 'B4C' have witnessed significant citation bursts in the last four years. The citation burst strengths of these keywords are 33.6453 (2018–2020), 20.45 (2017–2020), 19.9426 (2018–2020), 16.9666 (2016–2018) and 13.6994 (2018–2020), respectively. This analysis indicates that the current research trend is related to processing and characterisation of nanocomposites with special emphasis on graphene reinforced MMCs.
24. Reference burst detection analysis showed that all of the top fifteen documents with the highest citation burst strengths were published before 2001. All of these documents witnessed their respective citation bursts during 2001–2005, when the annual number of MMC publications in WoS was the lowest! None of the top cited MMC articles featured in the top fifteen citation burst strength rankings. These top fifteen citation burst documents dealt with a general review of MMCs, methods of preparation, characterisation as well as investigations into their specific functional properties and applications.

Thus, the bibliometric analysis presented in this paper provides deep insights into the various aspects of metal matrix composites' research articles published in WoS sources during 2001–2020. The researchers affiliated with the institutions and universities of China, the USA and India are expected to continue leading investigations into newer composite materials with nano scale inclusions such as graphene for enhanced functional properties. The collaboration and citations based linkages among various MMC researchers are also expected to increase in terms of numbers and strengths in the near future.

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