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Review Article

Current Status and Way Forward of Microwave Hybrid Heating in India: A Bibliometric Analysis

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Automotive and aerospace industries are keen to employ unique techniques and novel materials to reduce weight and cost and improve part performance. The application of microwave technology in the processing of metallic materials is a relative breakthrough in this direction. Recently, microwave hybrid heating (MHH) has evolved to extend the technique's utility further. Several studies on MHH have been carried out worldwide in the last three decades, and India is the prime contributor. This article documents a systematic and bibliographic review of MHH (between 1998-2022) in the Indian scenario. For this purpose, 125 documents are chosen from Scopus Core Collection and analyzed using a bibliometric analysis tool. The research status is examined based on the time distribution of articles, geography, top-cited documents, citation mapping of journals and researchers, mapping of co-occurrence, analysis of authors' keywords, country-wise publications, and cluster assessment. The result establishes that India is dominating, followed by theUSA. Moreover, there is an increasing trend in the number of publications. A guideline is also included to revive the research community's interest to mature the process further.

Keywords: Bibliometric Analysis, Joining, Microwaves, Microwave hybrid heating, Scopus

1 Introduction

New innovative lightweight materials are being developed to improve automobile and aircraft fuel efficiency. The use of traditional joining processes to join such materials results in a weak junction. It necessitates the creation of one-of-a-kind connecting processes for sophisticated materials. Furthermore, multi-material models are commonly employed in the automotive industry to reduce vehicle weight. However, combining dissimilar materials using traditional joining procedures is problematic because of physical and chemical properties variances. The strength of the weld joint is substantially reduced due to the production of brittle, hard, and crack-sensitive intermetallic compounds and transition zone in the joint region[1]. Prevailing joining procedures have disadvantages in terms of processing time, connecting materials, and higher heat input. Factors including processing ease, equipment cost, energy usage, and environmental hazards must also be considered. As a result, a more adaptive, faster, and cleaner procedure have a considerable impact on production. Given the limits, establishing a one-of-a-kind approach to connect dissimilar metals to address the difficulties mentioned above is crucial.

In recent years, material processing using microwave radiation has emerged as a new field. Microwave energy is ecologically safe and much faster; requires a modest initial investment for materials processing[2]. Microwaves are non-ionizing electromagnetic waveforms with frequencies between 300 MHz and 300 GHz and wavelengths between 1 m and 1 mm. Frequency 2.45 GHz and 0.915 GHz, with wavelengths of 12.2 cm and 13.5 cm, respectively, are the most extensively used frequencies for material processing. Microwave materials processing can replace high-energy-use heating methods commonly used in industries. Since the last decade, researchers have been drawn to microwave material processing because of its inherent advantages over traditional processing, such as superior mechanical characteristics, fine grain structure, faster process time, environmental friendliness, and cost-effectiveness. Furthermore, the technique reduces temperature gradients within the material, resulting in uniform heating; this gives the process an extra edge[3]. The interaction of electromagnetic waves with

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molecules during microwave processing transmits energy directly to the substance, resulting in volumetric heating. Microwaves transmit thermal energy through the interaction of electromagnetic fields at the molecular level. The molecule dipoles of the specimen material spin at 180 degrees, or back and forth, under the influence of an electromagnetic field. This back-and-forth motion is determined by the interplay between the material's dielectric properties and the resultant electromagnetic field[4]. The collision of these molecules produces a significant quantity of heat in the substance. In microwave heating, heat is produced internally within the material and transferred outward rather than coming from outside sources as in conventional heating. As a result, the heating profile is inverted, 'inside-out,' as opposed to the typical heating profile, 'outside-in'[5-6]. Several parameters influence microwave penetration through a material's surface, including magnetic, dielectric constant, microwave frequency and wavelength, volume, temperature, power, conductivity, size, and so on. The degree of interaction of the work material with the microwave is primarily determined by its dielectric property, such as dielectric constant ($\epsilon^{'}$), dielectric loss factor (ϵ), and loss tangent($\tan\partial$). The material's complex permittivity, ϵ^{*} (F/m), and energy loss tangent of a material ($\tan\partial$)is presented by equations (1) and (2).

$$\epsilon^{*} = \epsilon^{'} - j\epsilon \ldots (1)$$

$$\tan\partial = \epsilon/\epsilon^{'} \ldots (2)$$

$\epsilon^{'}$indicates the permittivity, which represents the material's energy storage capacity. The dielectric loss factor (ϵ) defines a material's ability to disperse microwave radiation as heat.The greater the loss factor, the higher the temperatures of the materials[7].

Skin depth is another material feature that is important in microwave heating. It is defined as the microwave penetration into a sample from the material's surface where the microwave field intensity decreases to 1/e of its strength on the surface[8]. Skin depth (δ) is represented as follows (equation 3).

$$\delta = 1/\sqrt{\pi f \mu_{\circ} \mu^{'} \sigma} \ldots (3)$$

Where,

σ = electrical conductivity (S/m)

f = microwave frequency (Hz)

$\mu_{\circ}$= 4π x 10^{-7} H/m (permeability of free space)

μ' = permeability of material (H/m)

However, microwave processing of metal at room temperature has long been a source of consternation for experts. Because microwave radiation penetrates less deeply due to the thinner skin depth. Further, an electron cloud accumulates at sharp edges, and this cloud of electrons causes plasma and arc generation[9]. Moreover, at normal temperatures, microwaves are reflected by metallic material. Furthermore, pure microwave heating of high dielectric loss materials induces overheating, leading to thermal deterioration[10]. An enhanced microwave procedure for metals known as microwave hybrid heating (MHH) has been developed to circumvent these constraints. The MHH first increases the metal's temperature to a critical temperature, and at elevated temperature, metals start absorbing microwave to a greater extent[11]. This type of heating can be performed in two ways:

a) A combination of traditional and direct microwave heating includes induction, resistance, and infra-red heating combined with direct microwave heating.

b) Heating is accomplished with the assistance of a susceptor powder. The susceptor powder is a powerful microwave absorber with increased dielectric losses at room temperature. They can absorb microwave radiation and convert it to heat. They use conduction, convection, or radiation to heat materials to critical temperatures. Metals readily absorb microwave radiation at this elevated temperature. Susceptor powder warms the metal to a critical temperature and works as a heat-loss barrier[12].

As a susceptor, charcoal with a loss tangent of 0.14–0.38 and a 6–11 cm skin depth is commonly utilized. Depending on the purpose, other susceptor media can be employed, including silicon carbide (SiC), graphite powder, etc. A schematic diagram of MHH for joining is depicted in Fig. 1. Fig. 1 highlights the specimens to be joined, the interface substance, which is a precise mix of metallic powder and epoxy resin, and susceptor powder that absorbs microwaves and raises the temperature of the specimens[13]. The epoxy resin helps the powder particles adhere together. During the heating process, this resin evaporates. A separator sheet is also used to separate the susceptor powder and the samples to be combined. Metal surfaces are not permitted to close contact with microwaves to narrow the heat-affected zone. It is ensured by encasing it in graphite sheets or refractory bricks that function as a masking material. Only the joint contact is exposed to microwave radiation [14-15].

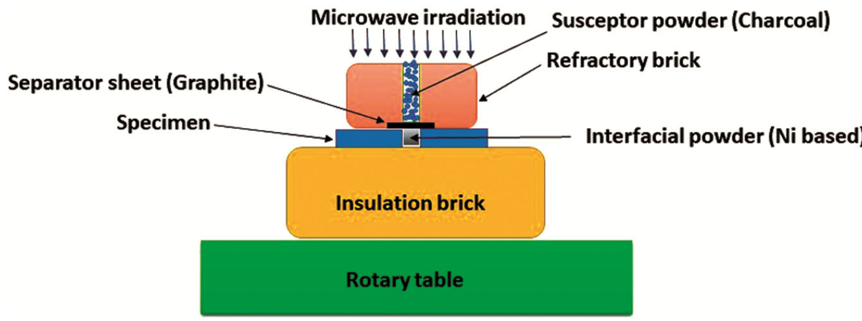

Fig. 1 — Schematic diagram of microwave hybrid heating for joining.

At room temperature, the skin depth of most metals ranges between 1 and 5 μm. It can be seen from equation 3 that skin depth is inversely proportional to electrical conductivity. As conductivity decreases, skin depth increases. This characteristic is exploited to make MHH possible. When the metallic powder size equals or less than the skin depth, microwave radiation equally heats it up. In contrast, MHH is used to heat metal powders with particle sizes bigger than the skin depth. When the temperature of the susceptor rises owing to microwave irradiation, it transfers its heat to metallic powder. The specimen's conductivity decreases as its temperature rises, increasing the skin depth. As a result, MHH allows for the heating of metals larger than their skin depth. Accordingly, the materials are heated directly by microwaves and indirectly through heat transmitted by the susceptor[16-17]. Besides joining[18-43], MHH has also been utilized for cladding[44-61], melting[62-66], casting [67-71], sintering [72-76], heat treatment[77-80], surface modification[81, 82], coating [83-86] and brazing[87]purposes. Further, MHH has also been employed to alter the phase microstructure and thermoelectric properties of Cu_2Se material[88].

A bibliometric analysis is usually employed to investigate articles' influence within a particular research field and determine the impact of certain research areas or researchers. It has been used in many academic fields, including materials, chemistry, computer science, economics, social science, art and humanities, environmental science, medicine, energy, psychology, and so on. Engineering disciplines have not properly utilized this tool in their research application compared to other disciplines. Moreover, to the authors' best knowledge, this is the first attempt to report a systematic and bibliographic analysis of MHH, emphasizing the Indian scenario. Bibliometric studies are straight forward techniques for measuring and defining trends in research output, top organizations, renowned authors and journals, highly cited papers, and other key bibliometric indices. Such information can help researchers improve their understanding and standardize their bibliographic information. Bibliometric analysis has been employed to expose statistical trends and provide a useful sketch of major significant viewpoints on MHH. In contrast, earlier studies sought to investigate this issue through narrative and traditional literature reviews. The evaluation is carried out to address the following important research concerns:

- What are the major journals and publications in India?
- India's status among countries at the forefront of this field of study?
- Who are the most prominent researchers in India?
- What are India's primary research foci and domains and the research directions?

To accomplish this, bibliometric literature reviews reveal 125 publications reported over 24 years from 1998 to 2022 from Indian scholars, which are then examined to understand the current status and identify the future direction.The remarkable contributions of this article are:

- A distinct idea of the impact of research publications, authors, and study areas based on bibliometric assessment.
- Underline the importance of microwave joining in modern multi-material advanced joining techniques in the Indian automobile and aerospace industries.

2 Materials and Methods

Figure 2 shows the methodology in greater detail. The bibliometric information for the study is extracted from the Scopus database. Scopus is the largest abstract and citation database for peer-reviewed papers, book chapters, and conference reviews globally. It provides a comprehensive overview of

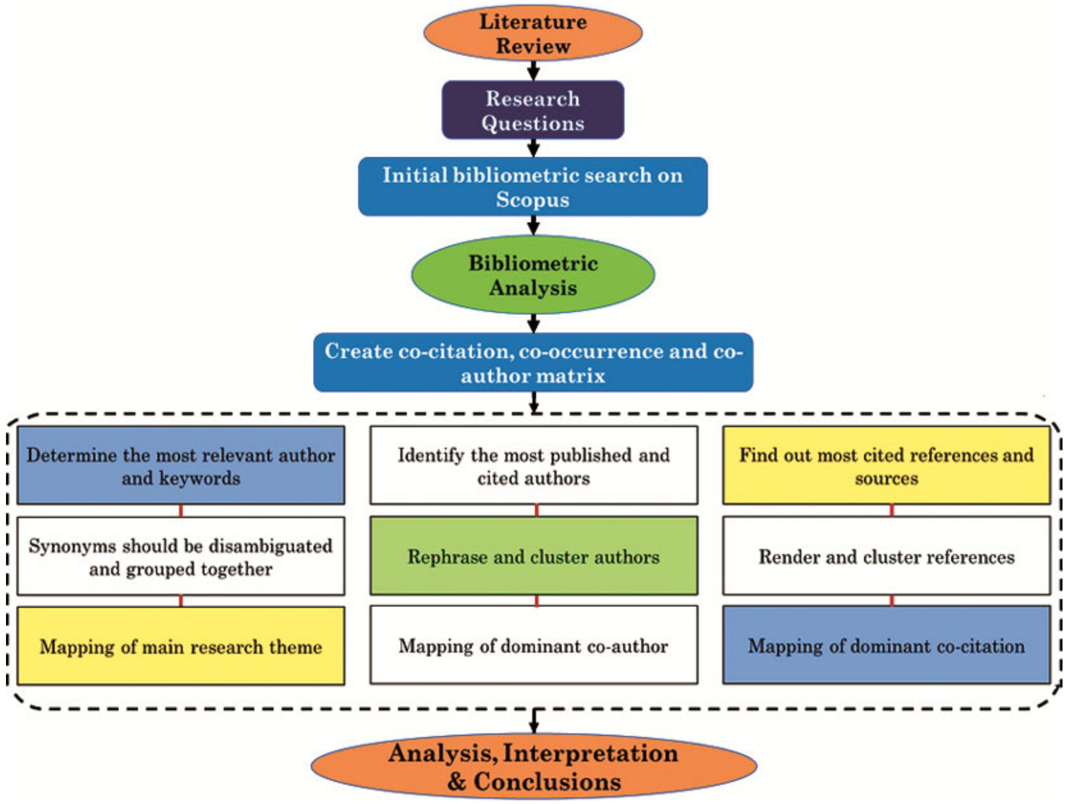

Fig. 2 — Flowchart of methodology employed for bibliometric analysis.

global research output in science, technology, medicine, philosophy, and psychology and robust tracking, analysis, and visualization capabilities. Because bibliometric indicators and literature mapping are difficult to implement on documents obtained from databases, bibliometric investigations frequently use a single database. Scopus contains almost all of PubMed and has twice as many indexed journals as Web of Science. Therefore, it is regarded as thorough and inclusive of papers included in both PubMed and Web of Science[89]. Scopus' advanced search tool generates detailed search queries that include several Boolean operators. The keyword "microwave hybrid heating" is used to search the database for the study to ensure that no potentially relevant articles are overlooked. To consider the contribution and current status of Indian researchers, the Scopus search is limited to India. Finally, 125 publications are deemed relevant and included in the final bibliometric analysis after a thorough examination and exclusion of irrelevant research based on abstract and scope. The following data elements are extracted: the research title, the year of publication, the journal name, the author's name, the keywords, the organizations, and the country. The total search string utilized to extract the data is: TITLE-ABS-KEY ("microwave hybrid heating") AND (LIMIT-TO (AFFILCOUNTRY, "India")) AND (LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English")).

Bibliometrics is used to dig deeper into the data from the Scopus database[90]. For co-occurrence analysis (country, institution, and author), keyword co-occurrence, and co-citation analysis, VOSviewer freeware version 1.6.18 for Windows is used (such as journal, author, and citation). Keyword co-occurrence analysis networks have nodes representing important phrases, such as nations, organizations, or keywords, and the larger the node, the more frequently the term appears. Co-citation analysis describes the relationship between two writers (journals, references) whom the same author quotes simultaneously (journals, references). The co-authorship nations' total link strength (TLS) is calculated for each displayed country. The TLS attribute represents the total strength of a country's author/researcher relationships with other countries. Furthermore, each colour represents a distinct cluster. The minimum cluster size is determined to be ten.

3 Results and Discussion

3.1 International Scenario

The Scopus database is searched, and 183 publications, including journal papers, conference papers, and scientific reports, are found. The global study on MHH shows a rising tendency. It is identified that 18 countries are currently conducting MHH research. The overall strength of co-authorship relationships with other countries has been assessed for each of these countries. It has been shown that India (125) is the leading country in terms of published articles, followed by the USA (18) and Malaysia (12). Malaysia is regarded as the most potent country based on total link strength (TLS), with a TLS of 6, followed by the USA and Italy with a TLS of 3. TLS indicates the total strength of a component's connections with other variables. Total link strength is a weighted characteristic with a constant weight. In terms of influential nations, this statistic shows the overall strength of a country's citation ties with other countries in terms of publications and contributions.

Table 1 shows the number of documents and citations for each country (based on authors' institutions). The amount of published documents in a geographical area indicates adaption and acknowledgment of the research topic. The position of the top-ranked nations in this field of study is shown in Table 1. It comprises both developed and developing countries, suggesting that the region is recognized as critical regardless of its economic status. The data also indicates that developing countries, such as India, contribute significantly to microwave hybrid heating research, but developed countries' research outputs are relatively modest.

Table 1 — Most contributing countries on MHH

Country	Documents	Citations	TLS
India	125	1896	2
United states	18	155	3
Malaysia	12	90	6
China	12	47	0
Italy	3	68	3
Japan	3	10	2

Figure 3 displays the level of international collaboration based on a single document criterion. There are just 11 connections, showing a lack of networking. It is deduced that countries work together to perform additional research in the domain. The network comprises nine countries organized into four clusters, with each country represented by a distinct hue. The thickness of the link between the two countries demonstrates the power of partnership. Japan and Malaysia form the most significant collaboration, with a total link strength of two.

3.2 Indian Scenario

Amazingly, India is the leading contributor to the domain, with 125 articles. Fig. 4 shows the number of documents published in India over the last ten years. The orange-colored dotted line illustrates the growing trend of publishing from 1998 to 2022. These documents have been cited a total of 1896 times, with each document receiving an average of 15.16 citations. Nonetheless, the rate of growth is inconsistent. It has a negative slope at the beginning of 2011 and 2012, then rapidly rises until 2018. It has a negative slope in 2018, falls until 2020, then rapidly climbs. With 29 documents, 2021 has been rated first in terms of publications. It shows that research in MHH is becoming a trending topic among researchers. Figure 4 also reveals the year-wise article published in the last decade.

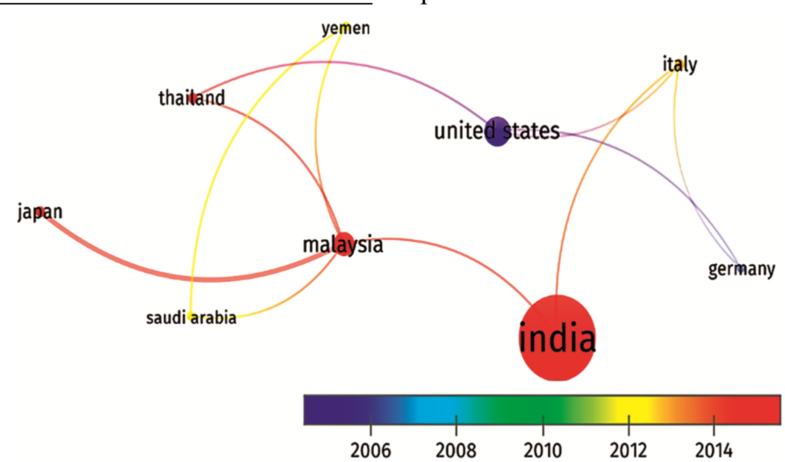

Fig. 3 — Co-authorship countries overlay visualization based on published documents.

3.2.1 Most Contributing Indian Authors

In the MHH domain, 139 Indian scholars have authored 125 papers. However, in the bibliometric study, the minimum number of publications necessary for each author is limited to three, resulting in 40 writers exceeding the limitations. This is done to avoid overlapping multiple authors with fewer papers in the network visualization study. The criteria is determined after several rounds, with three papers producing sufficient clarity. Furthermore, publications with multiple authors are tallied in full rather than proportionally to avoid misunderstandings in connection strength. The overall strength of co-authorship relationships with other writers has been computed for each of the 40 authors. The authors with the most publications are selected. Figure 5 depicts overlay visualization of highly productive authors.

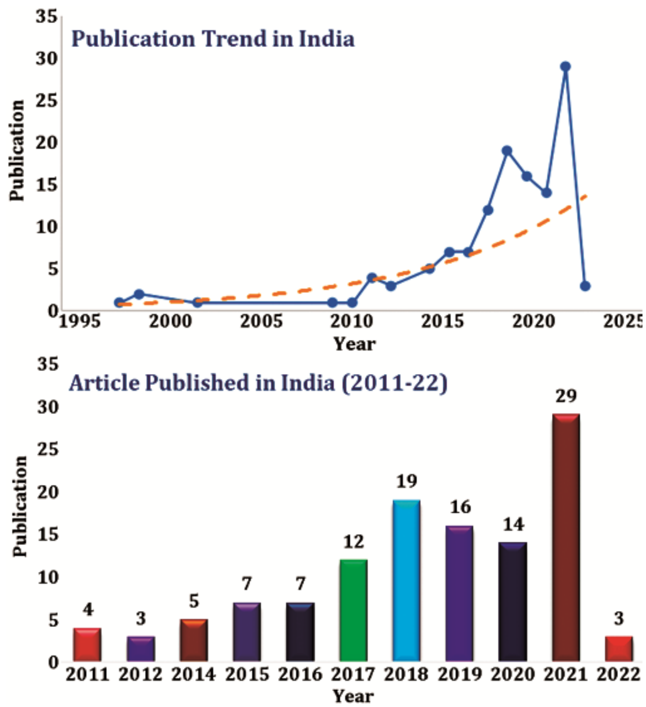

Fig. 4 — Publication trend of microwave hybrid heating in India and year wise article published in last decade.

The map shows 34 circles, each representing one researcher, with close circles reflecting author collaborations. These circles are divided into six clusters, each representing one of six research communities. The lines on the map symbolise a link identifying a connection between two scholars, signifying the number of co-authored works. With such skills in current scientific collaboration networks, access to specialisations, money, knowledge, and research productivity can all be increased. Such knowledge is also useful in broadening cooperation in academics and conveyance by decreasing segregation in research by communicating with scholars from many fields.

Table 2 presents the top 10 most influential authors of MHH research field. The TLS characteristic is utilized to assess the total strength of a researcher's co-authorship ties with other researchers. Sharma, A

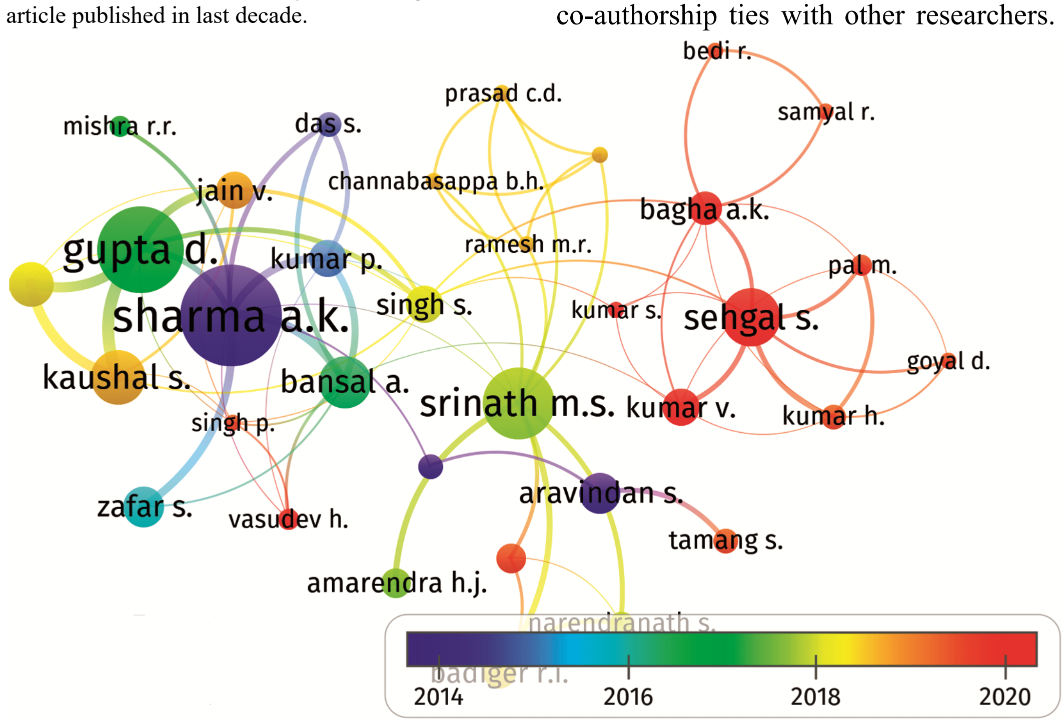

Fig. 5 — Overlay visualization of most contributing authors.

K of IIT Roorkee authored the most articles (28), collaborating with other authors, and the second-highest total link strength (39). He is also the most influential author in MHH, with the most significant number of citations (904). Gupta, D of Thapar Institute of Engineering and Technology, Patiala has the highest total link strength value of 41, indicating excellent networking in collaboration with other authors.

3.2.2 Most Contributing Institutions

This section looks at the top 10 institutes that published MHH related publications in Scopus within the selected period. Table 3 shows the leading research institutes, their geographical locations, and the number of articles published in MHH. *Indian Institute of Technology Roorkee*h as the most active institution with the highest publications of 27. It backs up previous findings on prolific authors. *TIET, Patiala*is the second most publishing institute with 18 documents and 257 citations. It can be observed that the *Indian Institute of Technology Delhi* has fewer publications. Nonetheless, the amount of citations they have got is greater than that of many other higher publishing establishments, suggesting the quality of their research.

3.2.3 Most Cited Documents

Citations are a crucial measure of a published article's real scientific influence. This section examines the citations and citation-based relationships of MHH publications. A minimum number of citations of a document is fixed at ten. Out of the 125 published documents in the field of MHH, 55 meet the threshold. For each record, the number of citation links is calculated. The document with the most significant number of links is selected. A total of 52 papers are discovered to be connected by reciprocal citations. The top ten Scopus publications with the most citation-based linkages to other MHH articles in the specified database is demonstrated in Table 4.

The most cited paper is Rajkumar and Aravindan's '*Microwave sintering of copper-graphite composites'* cited 147 times. The author created a Cu-graphite metal matrix composite using a microwave hybrid heating approach. The work explains the mechanics of joint generation, application, and analysis of joint property[76]. The second most cited paper is *'Development and microstructural characterization of microwave cladding on austenitic stainless steel'* by Gupta et al., cited 111 times. The researchers performed the cladding of nickel-based powder on austenitic stainless steel (SS 316) using the MHH technique. The developed clad was further characterized using EDS, XRD, and SEM[91]. Figure 6 depicts the mutual citation network graphs of MHH articles published in Scopus from 1998 to 2022.

3.2.4 Most Publishing Journals in India

The bibliometric study is performed to determine the citation landscape of published sources. The

Table 2 — Top 10 contributors of microwave hybrid heating

Authors	Institution	Documents	Citations	TLS
Sharma, AK	Indian Institute of TechnologyRoorkee,India	28	904	39
Gupta, D	TIET, Patiala, India	23	429	41
Srinath, MS	Malnad College of Engineering, Hassan, India	18	328	23
Sehgal, S	UIET, Chandigarh, India	14	158	16
Kaushal, S	Gulzar Group of Institutes, Ludhiana, India	13	148	27
Bansal, A	I K Gujral Punjab Technical University, Jalandhar, India	12	227	24
Bhowmick, H	TIET, Patiala, India	10	133	22
Zafar, S	Indian Institute of Technology Mandi,India	9	247	10
Aravindan, S	Indian Institute of Technology Delhi, India	9	272	8
Kumar, P	Indian Institute of TechnologyRoorkee, India	8	273	21

Table 3 — Top contributing organizations

Organization	State	Documents	Citations
Indian Institute of Technology Roorkee	Uttarakhand	27	858
TIET, Patiala	Punjab	18	257
Malnad College of Engineering	Karnataka	17	216
Panjab University	Punjab	14	158
University Institute of Engineering and Technology	Punjab	14	158
National Institute of Technology Surathkal	Karnataka	8	165
Dr. B.R. Ambedkar National Institute of Technology	Punjab	8	69
Indian Institute of Technology Delhi	Delhi	6	184
NMAM Institute of Technology	Karnataka	6	23
Punjab Technical University	Punjab	5	15

Table 4 — Top ten most cited documents

Rank	Title of Article	Authors	Year	Journal	Citation	Links
1.	Microwave sintering of copper-graphite composites	Rajkumar K and Aravindan S	2009	Journal of Materials Processing Technology	147	8
2.	Development and microstructural characterization of microwave cladding on austenitic stainless steel	Gupta D and Sharma AK	2011	Surface and Coatings Technology	111	20
3.	A new approach to joining of bulk copper using microwave energy	Srinath *et al.*	2011	Materials and Design	111	21
4.	Joining of ceramic composites by microwave heating	Aravindan S and Krishnamurthy R	1999	Materials Letters	86	5
5.	Joining of Inconel-625 alloy through microwave hybrid heating and its characterization	Badiger *et al.*	2015	Journal of Manufacturing Processes	71	16
6.	Development and characterizations of WC-12Co microwave clad	Zafar S and Sharma AK	2014	Materials Characterization	65	12
7.	Microwave cladding: A new approach in surface engineering	Gupta D and Sharma AK	2014	Journal of Manufacturing Processes	55	12
8.	On mechanism of in-situ microwave casting of aluminium alloy 7039 and cast microstructure	Mishra RR and Sharma AK	2016	Materials and Design	53	13
9.	Characterization of bulk stainless steel joints developed through microwave hybrid heating	Bansal *et al.*	2014	Materials Characterization	52	9
10.	Microwave processing of sprayed alumina composite for enhanced performance	Sharma AK and Krishnamurthy R	2002	Journal of the European Ceramic Society	52	6

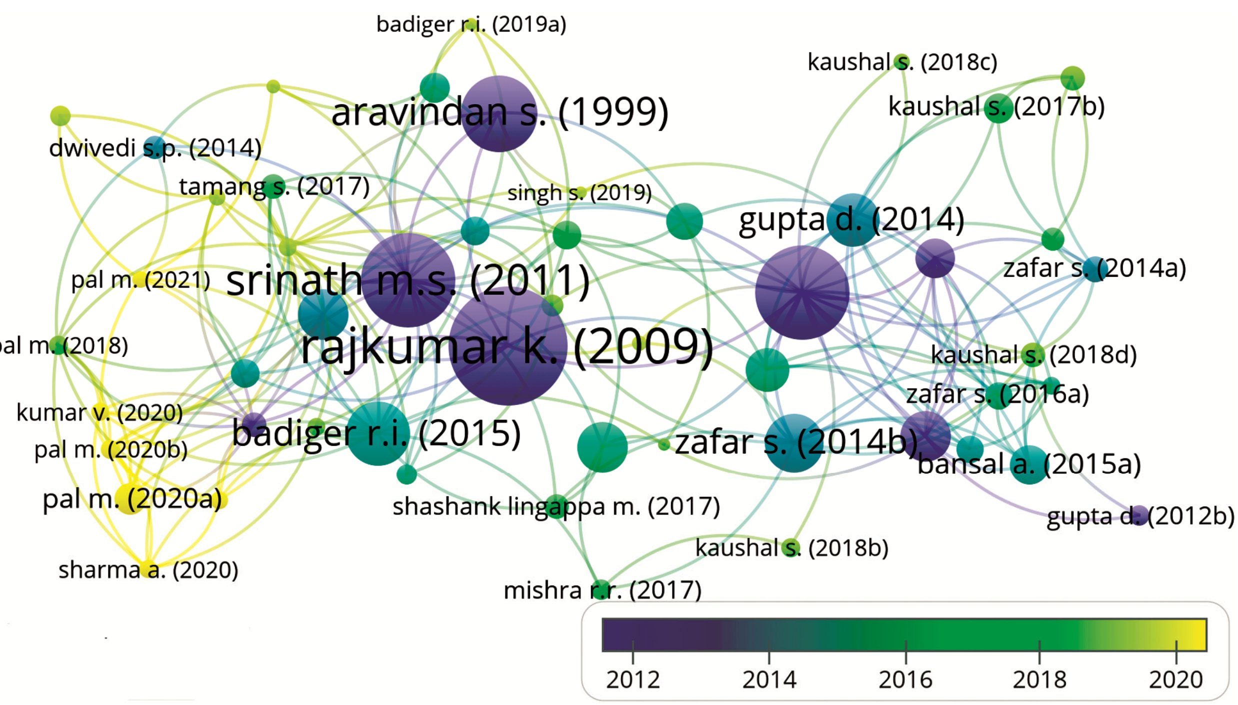

Fig. 6 — Overlay visualization of MHH research publications.

minimum number of documents of a source is kept to two. The bare minimum of citations for a source is kept zero. Out of 59 publishing sources, 22 meet the thresholds. The overall strength of the citation linkages to other sources is determined for each source. The sources with the highest overall link strength are chosen. Table 5 displays the journals with the most significant citations based on TLS values. Table 5 reveals the total number of articles published in Scopus by source, their citations, the number of journals linked by mutual citations, and the overall strength (TLS) of these links. It is noticed that *Materials Today: Proceedings* has the highest number of publications and TLS followed by *Materials Research Express.*

However, *Materials and Design* has the highest number of citations indicating the study standard. With 21 reciprocal citations in Scopus, the *Materials Today: Proceedings* is the most vital citation relationship for the *Journal of Manufacturing Processes*. Similarly, *Materials Today: Proceedings* and the *Journal of Manufacturing Processes* have the strongest link strength (300), with the most mutual citations. Figure 7 depicts the citation-based connections among the numerous sources that publish MHH documents in Scopus.

Table 5 — Top contributing journals

Source	Documents	Citations	TLS
Materials Today: Proceedings	18	141	79
Materials Research Express	8	79	22
Journal of Materials Engineering and Performance	6	104	31
IoP Conference Series: Materials Science and Engineering	5	6	3
Journal of Manufacturing Processes	5	174	69
Journal of Tribology	4	61	13
Materials and Design	4	217	54
Metallography, Microstructure, and Analysis	4	35	21
Proc. of IMechE, Part l: Journal of Materials: Design and Applications	4	54	22
Transactions of Indian Institute of Metals	3	11	12

3.2.5 Keyword Analysis

Keywords are essential variables in characterizing a field of study and reveal scientific trends. This study focuses on the keywords used in articles during the previous decade. The keyword identifies the most important topic of knowledge in the articles. Keyword co-occurrence network measurement reveals the connections between a range of keywords via nodes. A total of 981 keywords are collected from the Scopus database. The keyword count in the articles is utilized in conjunction with the keyword network to analyze the research content. The top keyword correlation matrix is employed to display the relationships between terms. The number of correlations is one when two keywords exist in the same article or record; if not, the value is zero. As a result, the correlations indicate how often these two terms appeared together in the research. If there are a lot of correlations, it establishes that these two keywords come together multiple times in the subject. If the value is low, it indicates the future possibility of those keywords' partnership. The low correlation number in the matrix for the top happening keywords indicates the future likelihood of combining top occurring keywords. The minimum number of occurrences of a keyword is fixed at five. 90 keywords out of 981fulfill the criteria and are plotted for network visualization. '*Microwaves*'is the most often used keyword, with 71 occurrences

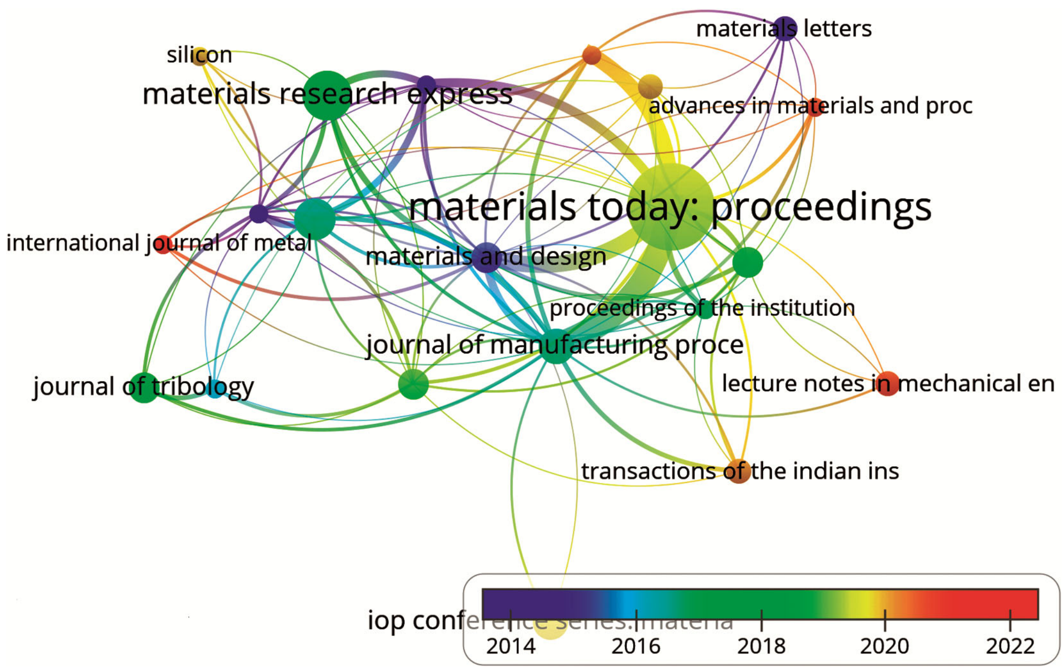

Fig. 7 — Overlay visualization of top contributing sources.

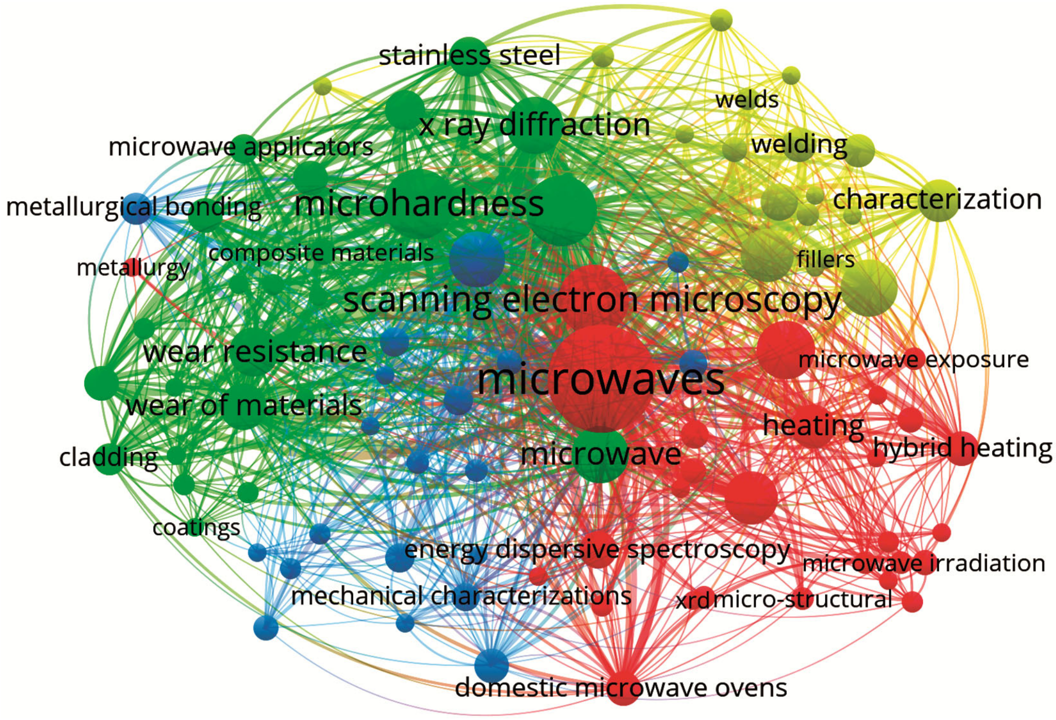

Fig. 8 — Keyword analysis.

Table 6 — Keyword analysis

Keyword	Occurrences	TLS
Microwaves	71	716
Microhardness	38	441
Microstructure	37	415
Scanning Electron Microscopy	37	399
Microwave	27	360
X Ray Diffraction	27	333
Carbides	26	248
Tensile Strength	24	245
Wear Resistance	22	242
Wear of Materials	20	242

(TLS of 716). It is followed by '*Microhardness*'with 38 occurrences (TLS of 441) and '*microstructure'*with 37 occurrences (TLS of 415). Keyword *'Microwaves'* has co-occurred with 89 other keywords. Table 6 displays the most commonly used terms in MHH research publications. Figure 8 depicts the graphical correlations between the terms used in the studies. It reveals that the researcher has primarily examined the microhardness and microstructure characteristics of microwave-processed materials. Some studies are also executed to characterize materials using SEM and XRD. Primarily, mechanical characteristics of microwave processed materials are being studied in which microhardness determination of the specimen is most prevalent. It is trailed by the study of tensile strength and wear resistance properties.

4 Conclusion

This study is the first in its type to execute an analytical bibliometric examination of the available MHH documents published by Indian scholars. Such analysis allows for a more in-depth comprehension of MHH's growth and inception. This bibliometric study produces a tentative *'reading list'* on MHH. It also reveals India's publishing trend and the most significant papers, sources, and authors in MHH technology. The present body of knowledge on MHH is organized around numerous categories such as welding, sintering, cladding, surface modification, heat treatment, casting, etc. The findings indicate that, while the literature on MHH is presently limited, the publication trend suggests that this subject of study is quickly expanding. Finally, the outcomes of this inquiry might aid new academics in the field in acquiring a better grasp of trends and major writers internationally. However, MHH has considerable scope for future research. Future researchers may concentrate on following to mature the process.

- Minimal study on numerical modeling and FEM simulation of microwave processing is reported owing to the confined availability of experimental data. It leads to low reproducibility of empirical data, limiting its applicability in industries.

- The processing of larger specimens is a limitation of microwave processing by the domestic oven. Researchers should develop a low-cost in-house microwave setup to process more extensive materials.
- Limited work has been done in the micro-processing of materials using microwaves like micro-drilling, micro joining, etc.
- The application of MHH to join dissimilar materials is not significantly explored. Moreover, very limited materials have been joined using the microwave hybrid heating technique.
- Most of the researchers have used nickel-based interface powder to join the specimen. Different metallic powders may be investigated.
- Pre-heating the interfacial powder aids in the production of high-quality joints. However, the quantity of pre-heating and its influence on joint characteristics have not been thoroughly explored.
- Many studies utilized various weight percentages of interfacial powder and epoxy resin to make a slurry. However, interfacial powder and epoxy resin weight proportion is not yet standardized for industrial purposes.

References

1 Mehta K, *Adv Manuf Technol*, edited by Gupta K (Springer International Publishing), 2017, 101.

2 Samyal, R, Bagha, A K, & Bedi R, *Mater Today Proc*, 26 (2020) 423.

3 Sahota DS, Bansal A & Kumar V, *Mater Today Proc*, 43 (2021) 466.

4 Naik SR, Gadad GM & Hebbale AM, *Mater Today Proc*, 46 (2021) 2635.

5 Srinath M S, Sharma AK, & Kumar P, *Mater Des*, 32 (2011) 2685.

6 Somani N, Singh N, & Gupta N K, *J Eng Des Technol*, 19 (2021) 1344.

7 Tamang S & Aravindan S, *Int J Therm Sci*, 172 (2022) 107281.

8 Handa V, Goyal P & Sehgal S, *Mater Today Proc*, 28 (2020) 1355.

9 Tamang S & Aravindan S, *J Mater Eng Perform*, 31 (2022) 1130.

10 Pal M, Sehgal S, Kumar H & Singh A P, *Mater Today Proc*, 5 (2018) 28149.

11 Gupta P, Kumar V, Chaudhary S, Kumar S, Singh J K & Chauhan PK. *Mater Today Proc*, 47 (2021)3877.

12 Handa V, Goyal P & Goyal S, *Indian J Eng Mater Sci*, 29 (2022) 378.

13 Badiger R I, Hebbale A M, Manjaiah M & Naik G M, *Trans Indian Inst Met*, 74 (2021) 531.

14 D N Gamit & M K Chudasama, *IOP Conf Se Mater Sci Eng,* 1004 (2020) 012007.

15 Samyal R, Bagha A K & Bedi R, *Mater Today Proc*, 26 (2020) 1279.

16 Singh S, Gupta D & Jain V, *Mater Des*, 111 (2016) 51.

17 Gupta D & Sharma A K, *J Manuf Process*, 16 (2014) 176.

18 Arora R, Kapoor J & Sharma R C, *Int J Veh Struct Syst*, 13 (2021).

19 Bansal A, Sharma A K, Kumar P & Das S, *Mater Charact*, 91 (2014) 34.

20 Kumar V & Sehgal S, *Adv Mater Process Technol*, 8 (2022), 456.

21 Gautam U, *Trans Indian Inst Met*, 75 (2022) 653.

22 Singh J, Kataria M, Kumar V, Jawalkar C & Belokar R M, *World J. Eng* (2021).

23 Samyal R, Bagha A K & Bedi R, *J Manuf Process*, 68 (2021) 1.

24 Pal M, Kumar V, Sehgal S, Kumar H, Saxena K K & Bagha A K, *Mater Manuf Process*, 36 (2021) 1554.

25 Kumar S, Sehgal S, Singh S & Bagha A K, *Mater Today Proc*, 28 (2020) 1319.

26 Sharma A, Sehgal S & Goyal D, *Mater Today Proc*, 28 (2020) 1323.

27 Pal M, Sehgal S, Kumar H & Goyal D*, Met Powder Rep*, 76 (2021) S18.

28 Pal M, Sehgal S & Kumar H, *J Adv Manuf Syst*, 19 (2020) 543.

29 Bansal A, Vasudev H, Sharma A K & Kumar P, *Mater Res Express*, 6 (2019) 086554.

30 Badiger R I, Narendranath S, Srinath M S & Hebbale A M, *Trans Indian Inst Met*, 72 (2019) 811.

31 Kumar A, Sehgal S, Singh S & Bagha A K, *Mater Today Proc*, 26 (2020) 2502.

32 Bagha L, Sehgal S, Thakur A, Kumar H & Goyal D, *Eng Res Express*, 1 (2019) 025035.

33 Badiger R I, Narendranath S & Srinath M S, *Proc Inst Mech Eng B J Eng Manuf*, 232, (2018) 2462.

34 Bansal A, Sharma A K & Kumar P, *J Mater Eng Perform*, 26 (2017) 2322.

35 Singh, S, Singh R, Gupta D, & Jain V, *J Manuf Sci Eng*, 139 (2017) 064503.

36 Tamang S & Aravindan S, *J Manuf Process*, 28 (2017) 94.

37 Gamit D, Mishra R R & Sharma A K, *J Manuf Process*, 27(2017) 158.

38 Bansal A, Sharma A K, Kumar P & Das S, *Proc Inst Mech Eng B J Eng Manuf*, 230 (2016) 439.

39 Bansal A, Sharma A K, Das S & Kumar P, *Proc Inst Mech Eng L J Mater Des Appl*, 230 (2016) 939.

40 Singh S, Suri N M & Belokar R M, *Mater Today Proc*, 2(2015) 1340.

41 Badiger R I, Narendranath S & Srinath M S, *J Manuf Process*, 18 (2015) 117.

42 Aravindan S & Krishnamurthy R, *Mater Lett*, 38 (1999) 245.

43 Aravindan S & Krishnamurthy R,*Ind Ceram (Italy)*, 18 (1998) 173.

44 Zafar S & Sharm A K, *Mater Charact*, 96 (2014) 241.

45 Kaushal S, Gupta D & Bhowmick H, *Proc Inst Mech Eng L J Mater Des Appl*, 235 (2021) 1036.

46 Mago J, Bansal S, Gupta D & Jain V,*Proc Inst Mech Eng C J Mech Eng Sci*, 235 (2021) 1258.

47 Babu A, Arora H S, Singh R P & Grewal H S, *Silicon*,14 (2022) 1069.
48 Palanisamy C, Sivakkraman V & Muthu K, *J Eng Appl Sci (Asian Res PublNetw)*, 15 (2020) 792.
49 Hebbale A M, Badiger R I, Srinath M S & Naik G M, *Metallogr Microstruct Anal*, 9 (2020) 293.
50 Bansal S, Gupta D & Jain V, *Proc Inst Mech Eng L J Mater Des Appl*, 234 (2020) 881.
51 Minhaj M, Singh B & Zafar S, *J Tribol,* 142 (2020) 051702.
52 Mishra T K, Kumar A & Sinha S K, *Mater Today Proc*, 26 (2020) 1418.
53 Singh K & Sharma S, *Prot Met Phys Chem Surf*, 55 (2019) 352.
54 Hebbale A M, Bekal A & Srinath M S, *SN Appl Sci*, 1 (2019) 1.
55 Prasad C D, Joladarashi S, Ramesh M R, Srinath M S & Channabasappa B H, *Silicon*, 11 (2019) 2975.
56 Akshata M K, Hebbale A M & Srinath M S, *MATEC Web of Conf* (EDP Sciences) 144 (2018) 02010.
57 Kaushal S, Singh D, Gupta D, Bhowmick H & Jain V, *Mater Res Express,* 5 (2018) 036401.
58 Kaushal S, Gupta D & Bhowmick H, *Mater Res Express*, 5 (2018) 066405.
59 Zafar S & Sharma A K,*Surf Coat Technol*, 291(2016) 413.
60 Bansal A, Zafar S & Sharma A K,*J Mater Eng Perform*, 24 (2015) 3708.
61 Gupta D & Sharma A K, *J Mater Eng Perform*, 21 (2012) 2165.
62 Singh S, Gupta D & Jain V, *Int J Met Cast*, 15 (2021) 969.
63 Lingappa S M, Srinath M S & Amarendra H J, *J Braz Soc Mech Sci Eng*, 40 (2018) 1.
64 Mishra R R & Sharma A K, *J Mater Sci,* 53 (2018) 16567.
65 Lingappa M S, Srinath M S & Amarendra H J, *Mater Today Proc*, 4 (2017) 471.
66 Lingappa, M S, Srinath M S, & Amarendra H J, *Mater. Res. Express*, 4 (2017) 076504.
67 Kaushal S, *Int J Met Cast*, 16 (2022) 2150.
68 Bhatt S, Suthar S, Mistry D & Ghetiya N, *Mater Today Proc*, 44 (2021) 1312.
69 Gangwar V, Kumar S, Singh V & Singh H, *IOP Conf Se Mater Sci Eng*,804(2020) 012019.
70 Mishra R R & Sharma A K, *Mater Des*, 131 (2017) 428.
71 Mishra R R & Sharma A K,*Mater Des*, 112(2016) 97.
72 Veera Venkata Nagaraju K, Kumaran S & Srinivasa Rao T, *Powder Metall*, 65 (2022) 200.
73 Venkata Nagaraju K V, Kumaran S & Rao T S, *Mater. Manuf. Process*, 37 (2022) 1132.
74 Nagaraju K V V, Kumaran S & Rao T S*, Mater Lett*, 302(2021) 130394.
75 Tamang S, Potaliya P & Aravindan S,*Mater Res Innov*, 22 (2018) 422.
76 Rajkumar K & Aravindan S, *J Mater Process Technol*, 209 (2009) 5601.
77 Prashar G, Vasudev H & Thakur L,*Surf Topogr Metrol Prop*, 9 (2021) 043002.
78 Venkateswaran C, Sharma S C, Chauhan V S &Vaish R, *J Am Ceram Soc*, 101 (2018) 140.
79 Sharma A K & Krishnamurthy R, *Pro Inst Mech Eng Part J J Eng Tribol*, 224 (2010) 497.
80 Sharma A K & Krishnamurthy R, *J Eur Ceram Soc*, 22 (2002) 2849.
81 Singh P, Bansal A, Vasudev H & Singh P, *Surf Topogr Metrol Prop*, 9 (2021) 035053.
82 Kaushal S, Gupta D & Bhowmick H, *Surf Eng,* 34 (2018) 809.
83 Prasad C D, Joladarashi S, Ramesh M R, Srinath M S & Channabasappa B H, *Mater. Res. Express*, 6 (2018) 026512.
84 Singh K & Sharma S, *Mater Manuf Process*, 33 (2018) 50.
85 Zafar S & Sharma A K, *J Mater Eng Perform*, 26 (2017) 1382.
86 Gupta D & Sharma A K, *Proc Inst Mech Eng E J Process Mech Eng*, 226 (2012) 132.
87 Tamang S & Aravindan S, *Mater Lett*, 254(2019) 145.
88 Rudradawong C, Sukwisute P, Limsuwan P, Harnwunggmoung A, Horprathum M, Sakdanuphab R & Sakulkalavek A, *J Alloys Compd*, 879 (2021) 160513.
89 Yadav L K, Misra J P, Kumar V, Saxena K K & Buddhi D, *Proc Inst Mech Eng E J Process Mech Eng*, (2022) 09544089221132737.
90 Mongeon P & Paul-Hus A, *Scientometrics*, 106 (2016) 213.
91 Donthu N, Kumar S, Mukherjee D, Pandey N & Lim W M, *J Bus Res*, 133 (2021) 285.
92 Gupta D & Sharma A K*, Surf Coat Technol,* 205 (2011) 5147.