ADVANCES IN MATERIALS SCIENCE, Vol. 25, No. 4 (86), December 2025

DOI: 10.2478/adms-2025-0019

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TUNGSTEN INERT GAS WELDING RESEARCH TRENDS: A 60-YEAR BIBLIOMETRIC ANALYSIS USING VOSVIEWER AND BIBLIOSHINY

ABSTRACT

Tungsten Inert Gas (TIG) welding constitutes a key process in the fabrication of welded structures, with widespread application across various sectors of modern industry. It continues to be the subject of extensive research due to its technical advantages and versatility. However, despite its industrial importance, TIG welding has not yet been the focus of a comprehensive bibliographic review. Therefore, the objective of this study is not only to present the current state of knowledge but also to identify key process directions and emerging research trends through a bibliometric analysis of 8,789 publications indexed in Web of Science. The analyses were performed mainly in VOSviewer 1.6.20 and Biblioshiny tools, determining the networks of connections between bibliometric entities: keywords, journals, authors, countries, and funding agencies. The analysis results were used to illustrate the dynamics of research topics over a 60-year publication history on the TIG process. Current research trends include, among others, the advancement of TIG welding variants to improve process efficiency, the application of artificial intelligence, the application of optimization methods, and deep learning. The most urgent research needs involve determining the weldability of special metals, assessing the environmental degradation of TIG-welded joints, and applying data mining techniques for the optimization of the TIG process. The study may serve as an objective, comprehensive, and author-unbiased complement to traditional systematic review articles on TIG welding and related processes.

Keywords: *Tungsten Inert Gas, Biblioshiny, VOSviewer, Web of Science, bibliometric analyses*

INTRODUCTION

Current demands across various branches of industry necessitate the broader application of welding processes, in particular arc welding, which remains the predominant method for joining components in welded structures throughout many manufacturing sectors [1–4]. The

Received: 26.09.2025; Received in revised form: 16.11.2025; Accepted: 21.11.2025

most commonly used arc welding processes in industrial applications include Shielded Metal Arc Welding (SMAW) [5, 6], Tungsten Inert Gas (TIG) [7–9], Gas Metal Arc Welding (GMAW) [10–13], Flux-Cored Arc Welding (FCAW) [14–16], and Submerged Arc Welding (SAW) [17]. In addition, other advanced joining techniques are extensively applied, such as Laser Beam Welding (LBW) [18–20], Plasma Arc Welding (PAW) [21], Electron Beam Welding (EBW) [22–24], Resistance Welding [25, 26], and Friction Welding [27, 28], including Friction Stir Welding (FSW) [29–32].

The TIG process, designated as process 141 according to EN ISO 4063 and equivalently referred to as Gas Tungsten Arc Welding (GTAW), is an arc welding method that has established a prominent position across numerous industrial sectors [33, 34]. The principle of the process involves the use of a non-consumable tungsten electrode, shielding the welding zone from atmospheric contamination by an inert gas, and the application of a filler material, typically in the form of a rod, and less commonly, as wire [35]. Argon, helium, and mixtures of both are used as shielding gases. Less common and only for specific applications is the use of other welding gases as admixtures: nitrogen, hydrogen and oxygen [36–38]. The use of different gases significantly affects the stability of the process, the effectiveness of the gas shield, distribution of the arc energy and the morphology of the weld. The type of gas is therefore an important welding parameter, often determining the possibility of producing a welded joint of the required quality [39, 40]. When welding metals that are highly prone to oxidation at elevated temperatures (stainless steel, titanium, and aluminium alloys) it is necessary to apply purging gas from the root side [41]. This practice enhances the quality, appearance, and mechanical performance of the welded joints. As purging gases, depending on the material and technological conditions, the most commonly used are: pure argon (I1 according to EN ISO 14175), argon with hydrogen addition (R1: 2–5% H), pure nitrogen (N1), or nitrogen with hydrogen addition (N5: 5–20% H) [42–44]. A welding backing serves a similar function: it is used to support the welding pool, shape the weld root, and protect it from atmospheric contamination, particularly when equipped with a purging gas channel, and may also influence the welding thermal cycle, which helps ensure proper penetration and microstructure and reduces the risk of joint defects [45, 46].

The most significant limitation of the TIG process is its relatively low deposition rate [47]. Nevertheless, this characteristic allows for high-precision welding of extremely thin materials, including components with wall thicknesses below 1 mm. In such cases (up to 5 mm, depending on the base material composition), the process can be conducted autogenously (process 142), without the addition of filler metal [48–50]. Although traditionally performed as a manual process, advancements in automation and robotic integration have enabled TIG welding to be fully incorporated into automated production systems [51–53]. Orbital TIG welding solutions for pipes have also been developed, enabling the consistent production of high-quality, repeatable welds that meet strict acceptance criteria, while mitigating the traditional limitations of the process [54, 55].

The TIG welding process is widely applied across various industrial sectors, including aerospace, automotive, shipbuilding, chemical, petrochemical, energy, food, and pharmaceutical industries, as well as in the fabrication of pressure vessels and piping systems [56–60]. The process is extremely rarely used underwater, where in practice methods based on a consumable electrode are preferred [61–64]. More detailed areas of industrial application of the TIG process include the welding of thin components [65, 66], root passes in combined welding procedures [67, 68], and pipe joints [69]. An important area of application of the process is also the surfacing of metals, particularly when a low dilution of the base material in the weld overlay is required [70–72]. Despite its low productivity and the requirement for extensive operator training, the TIG process remains highly regarded due to its ability to produce welds of superior quality, excellent metallurgical cleanliness, and precise geometry [73]. Importantly, it is highly versatile in terms of metallurgical compatibility, enabling the joining of a wide range of ferrous [74–76] and non-ferrous materials, including nickel, aluminium, magnesium, titanium, copper, and their alloys [77–81]. In the field of steel welding, the process is applied to the fabrication of joints in non-alloyed and alloyed steels, including stainless, heat-resistant, creep-resistant, cryogenic, wear-resistant, and armor steels [82–86]. A major part of the research deals with issues related to the fabrication of dissimilar joints and the associated challenges arising from differences in the physicochemical properties of the welded materials [87–90]. The large number of possible material and technological combinations necessitates the development of processes with carefully selected consumables, preheating parameters, heat treatment, weld bead sequences, the application of buffer layers, and combined procedures [91–95]. Equally important are considerations related to welder safety and the overall costs of manufacturing welded structures, which must not be overlooked [96–98].

Depending on the operating environment in which TIG-welded joints are employed, researchers emphasize the critical role of both static strength and fatigue resistance [99–102]. Abrasion resistance also constitutes an important operational parameter, particularly under conditions involving intensive mechanical interaction [7, 57]. Corrosion resistance, including intergranular corrosion, hot corrosion, high-temperature oxidation, and environmental degradation forms, is equally significant [103–105]. For joints intended for service in power generation systems, particular attention is devoted to the heat resistance of welded joints and their structural stability under elevated temperature conditions [71, 106, 107]. Fundamental research is also being conducted on the thermal processes occurring during welding and the behavior of molten metal in the welding pool [108–110].

In pursuit of increased process efficiency, numerous technological modifications and variants of the TIG process have been introduced, including pulsed TIG [111–113], A-TIG [114, 115], orbital TIG [116], hot-wire TIG [117, 118], keyhole TIG (K-TIG) [119, 120], TopTIG [121], as well as hybrid processes that combine TIG with other energy sources such as laser [122–124]. A specific hybrid configuration consists of processes integrating TIG and MIG (Metal Inert Gas) welding method [125, 126]. Other methods of improving the quality of welded joints involve coupling the process with physical influences, such as magnetic or ultrasonic fields [127–129]. These external factors affect the process either by modifying the electric arc or by influencing the crystallization of the welding pool. Furthermore, TIG welding is increasingly applied in the field of metal additive manufacturing, particularly in Wire Arc Additive Manufacturing (WAAM), where arc stability and precise process control are critical to achieving layer consistency and material integrity [130–133]. A notable advantage, arising from the non-consumable nature of the tungsten electrode, is the capability to remelt base material or existing welds [134]. This approach can be employed to reduce defect rates and to induce beneficial microstructural transformations, ultimately enhancing both the mechanical performance and visual appearance of the weld [135].

Scientometrics, the discipline focused on measuring and analyzing scientific activity, constitutes a key area of contemporary scientific research. It includes bibliometric analysis, which involves a range of analytical and statistical techniques used to quantitatively examine scientific outputs such as publications, citations, authors, institutions, and journals [136]. Science mapping employs various software tools that facilitate the import, transformation, and processing of data extracted from bibliographic databases such as Web of Science, Scopus, Crossref, and Dimensions. These tools support the generation of tabular reports and visualizations, particularly maps and network plots, that depict relationships among the analyzed entities [137–139]. The most widely used bibliometric tools include VOSviewer, Bibliometrix (and its web-based interface Biblioshiny), CitNetExplorer, HistCite, Gephi, and Pajek [140–143].

Web of Science is one of the oldest and most important bibliographic scientific databases, offering access to high-quality peer-reviewed articles and citation indexes [144]. Users value it for its reliable sources and extensive bibliometric tools. The database is often used as a data source for bibliometric analyses, which help assess the scientific significance and impact of bibliometric entities [145].

The WOS database indexes 124 review papers on TIG welding technology. Some of these publications focus specifically on the TIG process, discussing the current state of knowledge and development trends in relation to process parameters and its applications across various industries [146–149]. Other studies address TIG as part of a broader technological and material science context, for example, in comparison with other welding methods, in the processing and application of advanced materials, or in the context of automation and robotization of industrial manufacturing processes [150–154]. Despite the large number of review articles on the TIG welding process, only one study has applied bibliometric analysis, and even then, it was limited to basic citation and publication metrics [155]. For this reason, the aim of the present study was, based on the results of bibliometric analyses of data obtained through an unrestricted temporal and territorial query in the Web of Science database, to determine the current state of knowledge and development of the TIG process, identify prevailing research trends, and highlight knowledge gaps that warrant further investigation.

BIBLIOMETRIC ANALYSES

Methodology

For the bibliometric analyses, popular software tools were employed: VOSviewer 1.6.20 and Biblioshiny, supported by built-in analytical functions of the Web of Science (WOS) and data preparation in Microsoft Excel. The data were retrieved from WOS on December 1, 2025, using the following search terms: “TIG welding” (4,439 publications), “GTAW welding” (2,914 publications), “tungsten inert gas” (3,129 publications), and “gas tungsten arc welding” (4,787 publications). Following the formal preparation and substantive verification of all 15,269 collected publications, 8,789 papers were qualified for further analysis. Formal preparation and substantive verification consisted of removing duplicate (6479) and retracted (1) publications, as well as reviewing the bibliographic information and abstracts to determine the thematic relevance of each work to the scope of this review. This process was conducted manually by carefully reading and assessing each publication, without the use of automated tools. No restrictions were applied to the collected data with regard to publication date, authors’ institutional affiliation (country), or language. VOSviewer 1.6.20 and Biblioshiny tools were used due to their complementary capabilities [156, 157]. The VOSviewer tool enables the visualization of co-occurrence networks of bibliographic entities such as authors, countries, and journals, allowing for an intuitive understanding of the research structure [158]. Co-occurrence networks visualize how frequently bibliographic entities appear together in publications [142, 156, 158]. Biblioshiny, on the other hand, offers advanced statistical tools for bibliometric data analysis, facilitating the exploration of publication trends and collaboration patterns among these bibliographic entities [159, 160]. Figure 1 shows a schematic representation of the methodological framework for analytical and bibliographic research.

Fig. 1. Methodological scheme of analytical and bibliometric studies

Exploring Publication and Citation Patterns

The statistical characteristics of the analyzed dataset (8,789 publications from 1965 to 2025) are presented in Tables 1 and 2. Since a single publication may be assigned to multiple categories, the values in Table 1 do not sum to the total number of publications. In addition to standard research papers, scientific achievements in the field of TIG welding are presented at scientific conferences and published in their proceedings. The significant number of review articles (124) indicates the need for a systematic synthesis of knowledge in the field of TIG welding, identification of research gaps, and the definition of directions for future scientific and industrial work. Data papers are relatively rare in this field, with only three identified cases [161–163]. This limitation constrains the development of the research area by hindering result verification and reducing the potential for applying big data analytics, data mining, and machine learning methods [164]. The analyzed dataset comprises 1,549 types of sources, 110,724 references, and 15,681 authors, with an average of 3.78 co-authors per document and 12.58% international collaborations. Among the 8,789 publications, 325 were authored by a single researcher. These indicators suggest a moderate level of collaborative research within the field. English dominates as the primary language of publication (96.37%), while among languages represented by at least ten works, publications appeared in Chinese (1.30%), Portuguese (0.88%), Korean (0.26%), German (0.24%), Spanish (0.23%), Japanese (0.21%), and French (0.17%). In addition, WoS categorizes 22.38% of the publications under different types of Open Access modes.

Table 1. *Types of publications (WOS)*

Document Types	Count
Article	7,031
Proceedings paper	1,762
Review	124
Early access	99
Editorial material	26
Book chapter	22
Note	17
Letter	16
Correction	5
News item	5
Data paper	3
Meeting abstract	4
Book review	2

***Table 2.** Overview of the analyzed bibliometric dataset (Biblioshiny)*

Description	Results
Timespan	1965:2025
Types of sources	1,549
Average citations per document	15.64
References	110,724
Authors	15,681
Single-authored documents	325
Co-authors per doc	3.78
International co-authorships %	12.58

Publication and citation trends from 1965 to 2025 are presented in Figure 2. From 1965 to 1990, both publication output and citation counts were minimal. This was primarily due to the limited number of journals indexed in the only international database available at that time, Web of Science (formerly Science Citation Index), as well as the overall lower publishing activity characteristic of that period [165]. In many countries, particularly outside the Western world, research findings were published mainly in local journals and national languages, which restricted their visibility in the global scientific community. Furthermore, low levels of research funding and a preference for monographs, internal reports, and conference proceedings over peer-reviewed journal articles further contributed to the limited number of publications indexed in Web of Science. A gradual increase in publications began in the early 1990s, accelerating significantly after 2000. The period 2010–2020 witnessed a marked rise in interest in the topic, culminating in peak publication volumes of approximately 500–550 per year between 2018 and 2022. Concurrently, citation counts grew exponentially, exceeding 18,000 by 2024. Notably, a clear correlation is observed between the number of publications and the number of citations within this research area [166]. The small decrease in values for 2025 is due to incomplete data (as of December 1). This pattern of an extended initial phase followed by rapid growth and subsequent stabilization is characteristic of maturing research areas in welding [138, 140, 142]. Overall, the 8,789 publications in the analyzed dataset were cited 135,918 times across 56,934 papers indexed in WoS, resulting in an average of 15.64 citations per article. The h-index for this dataset is 115.

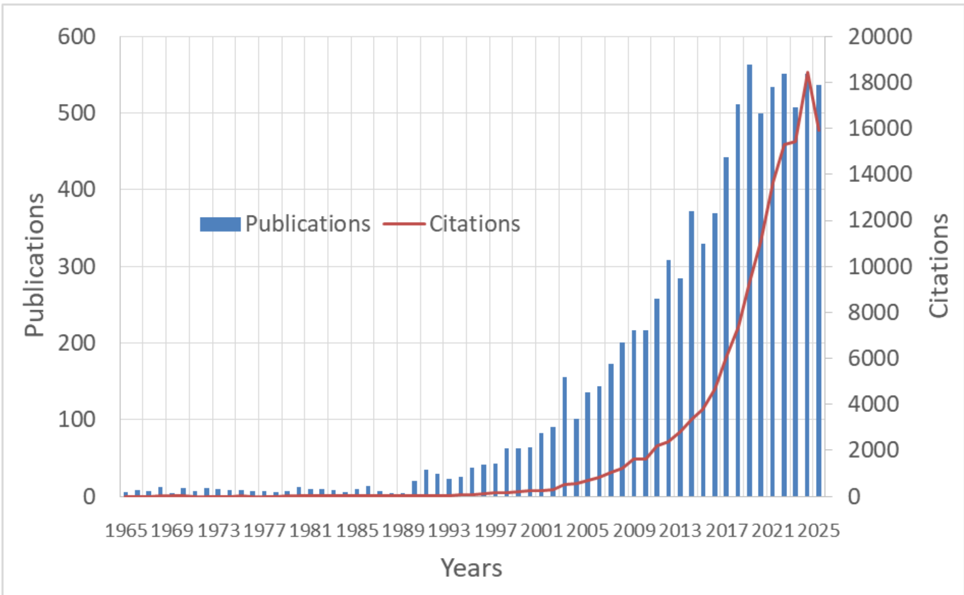
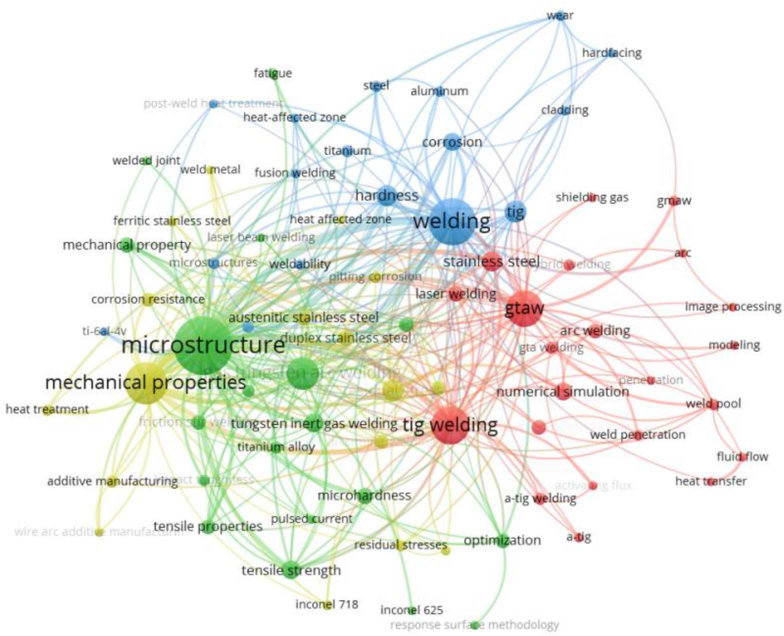


Fig. 2. Trends in TIG welding research publications (WOS). The value for 2025 is current up to December 1.

Evolution of Research Trends

The analysis of research trends in the field of TIG welding and their evolution over time was conducted using four complementary bibliometric methods: word cloud, authors' keywords, text mining network maps, and trend topics (Figures 3-5). Figure 3a presents a word cloud generated in Biblioshiny for the 75 most frequent keywords using a logarithmic scale, whereas Figures 3b–d show author keyword networks for the same 75 keywords, generated in VOSviewer 1.6.20. Fractional counting was applied to obtain a more balanced representation of keyword co-occurrence by preventing keywords from documents with many terms from dominating the analysis [167]. For the analysis of words in publication titles and abstracts, the text mining option available in VOSviewer was used, applying binary counting and initially considering 500 words. After removing terms irrelevant to the research topic analysis (e.g., "sample," "influence," "MPa"), 308 words remained (Figure 4). Trend topics were identified in Biblioshiny, considering a minimum frequency of 15 occurrences and at least two instances per year.

a)



b)

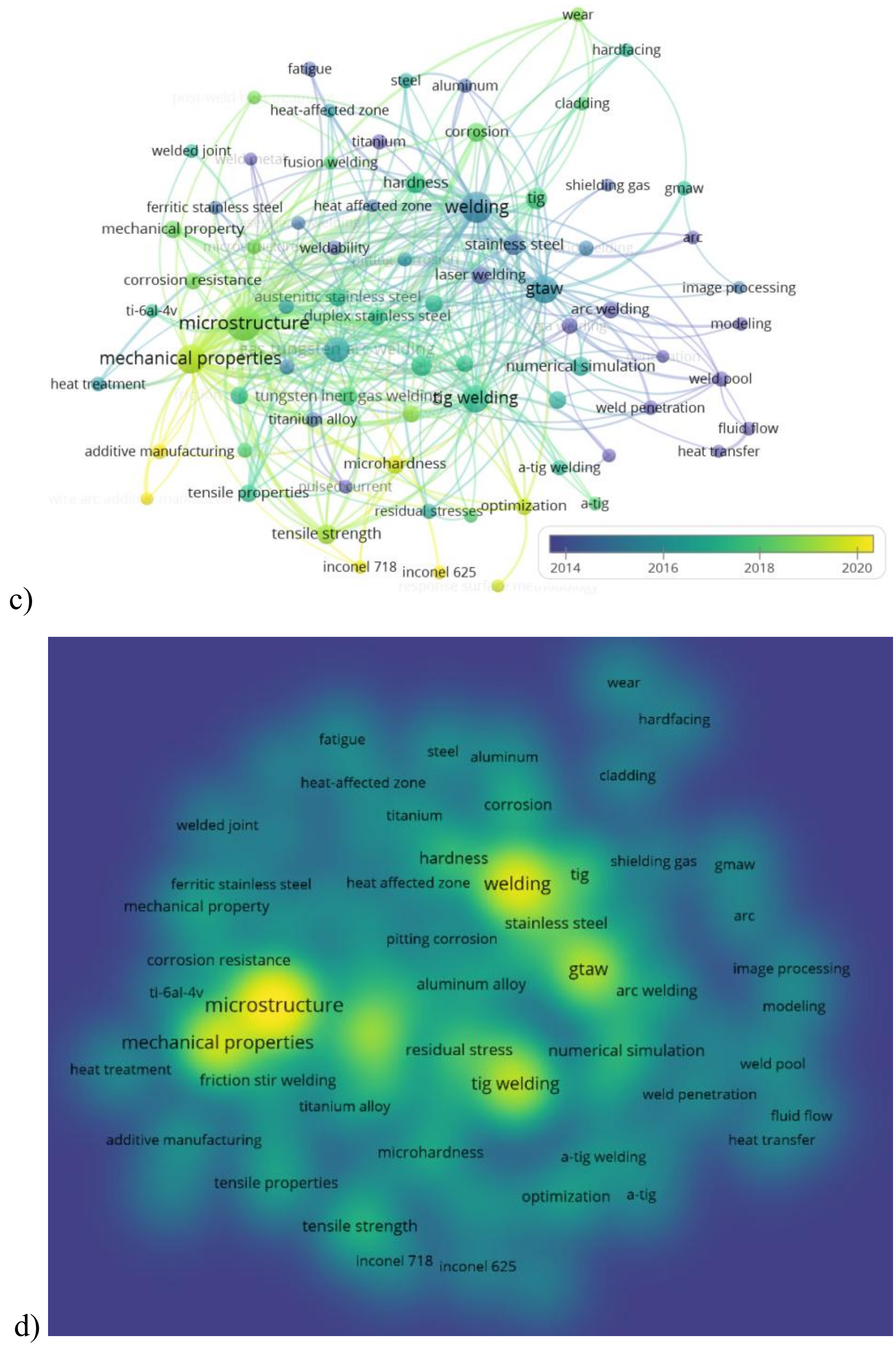
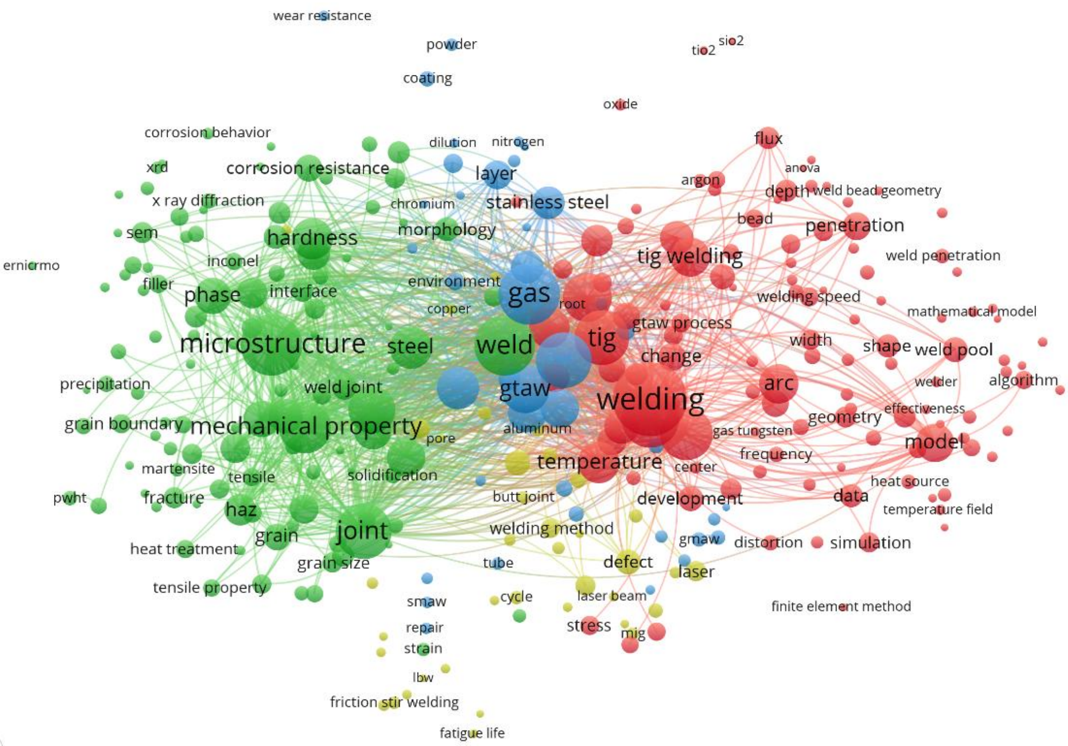


Fig. 3. Keyword-based bibliometric analysis of TIG publications: a) word cloud (Biblioshiny), b) authors' keywords network c) authors' keywords overlay, d) authors' keywords density (VOSviewer)

The keyword network analysis reveals four main research areas (Figure 3b): structural materials (stainless steel, Inconel, aluminium, titanium alloys), process parameters and TIG variants (A-TIG, welding current, shielding gas, electrode), mechanical properties and weld microstructure (heat-affected zone, penetration, hardness, residual stresses), and new technologies and specialized applications (additive manufacturing, hybrid welding, dissimilar metal joining). As can be seen from Figure 3c, earlier studies focused on traditional topics, namely the identification of the fundamental mechanisms governing the welding process and its impact on materials, whereas more recent research concentrates on advanced materials (Ni-based alloys) and additive manufacturing technologies


wear resistance
powder
coating
tio2
sio2
oxide
corrosion behavior
xrd
corrosion resistance
dilution
nitrogen
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weld bead geometry
x ray diffraction
chromium
stainless steel
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morphology
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inconel
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gtaw process
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mechanical property
aluminum
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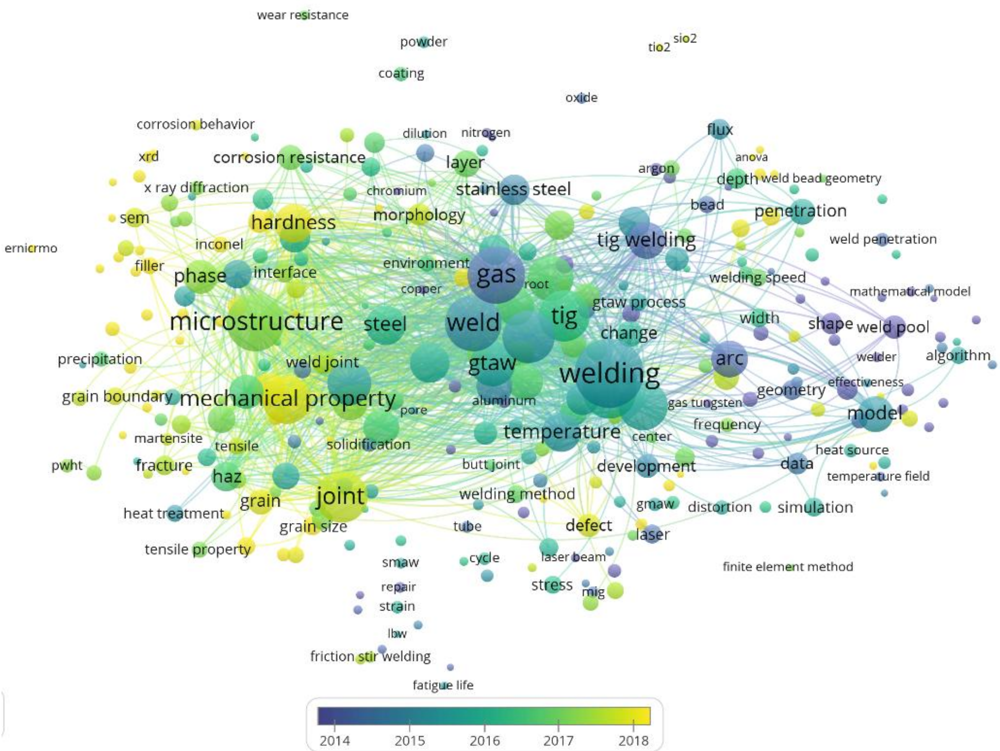
a)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temperature
center
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butt joint
development
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temperature field
haz
grain
joint
welding method
gmaw
distortion
simulation
heat treatment
grain size
defect
tube
laser
tensile property
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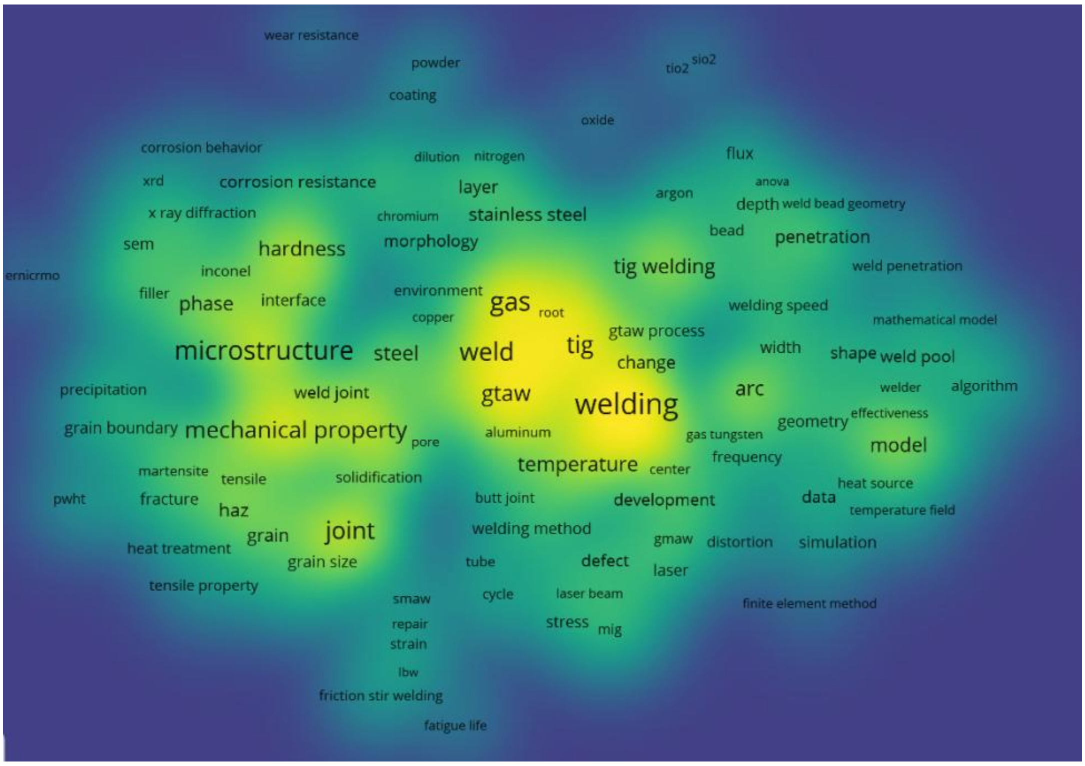
b)



c)

Fig. 4. Bibliometric analysis of titles and abstracts using text mining: a) network b) overlay, c) density (VOSviewer)

Similar conclusions can be drawn from the results of text mining analyses (Figure 4). Research in this field has evolved from the classical optimization of process parameters and material selection toward advanced methods such as pulsed TIG, A-TIG, and hybrid welding processes. Increasing importance is being placed on numerical simulations, automation, and applications in high-tech industries, particularly aerospace. The latest trends connect TIG with additive manufacturing technologies, highlighting emerging interdisciplinary research directions. Four clusters can be distinguished in the map: process parameters and weld quality, materials and applications, advanced TIG variants, and simulations with microstructural analysis. The largest and oldest clusters are those related to process parameters and materials, whereas the more recent clusters, advanced TIG variants and simulations, are smaller but rapidly developing.

The plot in Figure 5 presents temporal trends in the occurrence of authors' keywords. As shown, some keywords are currently rarely used (e.g., penetration control, weld shape), some have been consistently used since the beginning of the analyzed period (e.g., surface tension), and others have emerged in recent years (e.g., deep learning, WAAM).

Summarizing the temporal evolution of research trends resulting from the multifaceted keyword analysis, it was found that the three research areas were intensively developed earlier (structural materials, process parameters and TIG variants, as well as mechanical properties and weld microstructure), whereas the most recent publications focus on integrating TIG with additive manufacturing technologies and innovative industrial applications. It is characteristic that analyses of the process and material behavior in TIG welding are often performed in comparison with other welding methods, such as SMAW, LBW, PAW, GMAW, and FSW, as documented in studies [168–177].

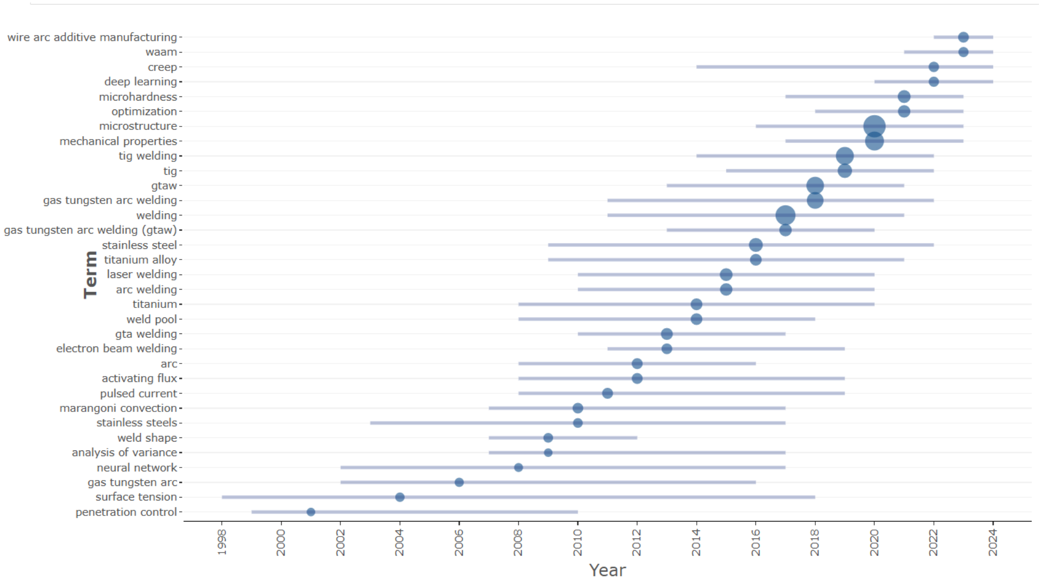


Fig. 5. Trends in TIG welding research topics derived from authors' keywords (Biblioshiny)

Journals

Figure 6 shows the 20 journals most frequently selected by authors for publications on the TIG process, with the first 14 belonging to Zone 1 as described by Bradford's law [178]. According to Bradford's law, a small number of journals publish the majority of significant articles in a given field, while the remaining journals contain progressively fewer articles on the topic. Three groups of journals can be distinguished: the core, the middle zone, and the peripheral zone [179]. For core journals, a cumulative publication plot on the topic under consideration is presented in Figure 7. Figure 8 presents VOSviewer maps illustrating the network of relationships among the journals shown in Figure 6, based on mutual citations.

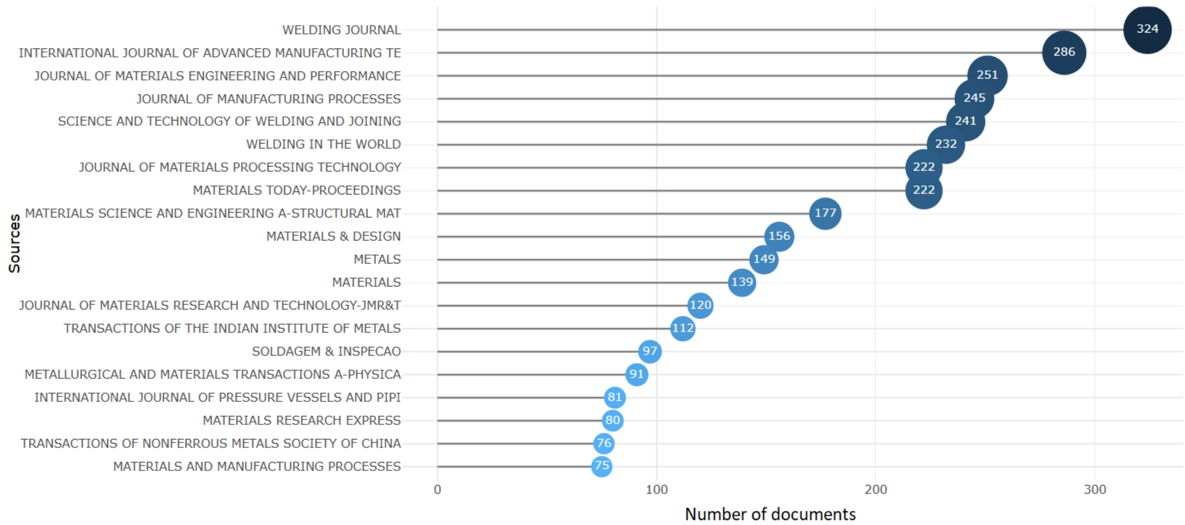


Fig. 6. Number of publications on TIG processes per journal (Biblioshiny)

Although Welding Journal is the most frequently chosen source by authors (Figures 6 and 7), it is the oldest journal in the analyzed set. To account for differences in the time of activity of journals, the year of the first publication on the TIG process was taken as the starting point and the average annual publication growth was calculated. The highest values were recorded in Journal of Manufacturing Processes, Metals, and Materials Today: Proceedings, while the lowest were observed in Transactions of the Indian Institute of Metals, Welding in the World, and Journal of Materials Research and Technology (JMR&T).

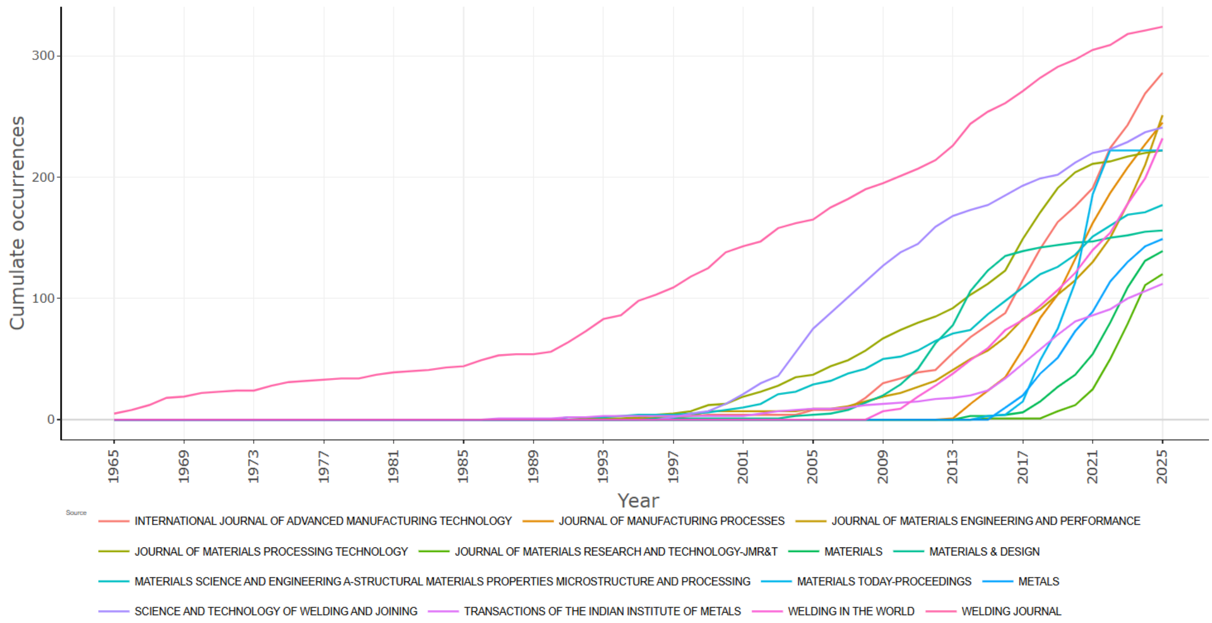
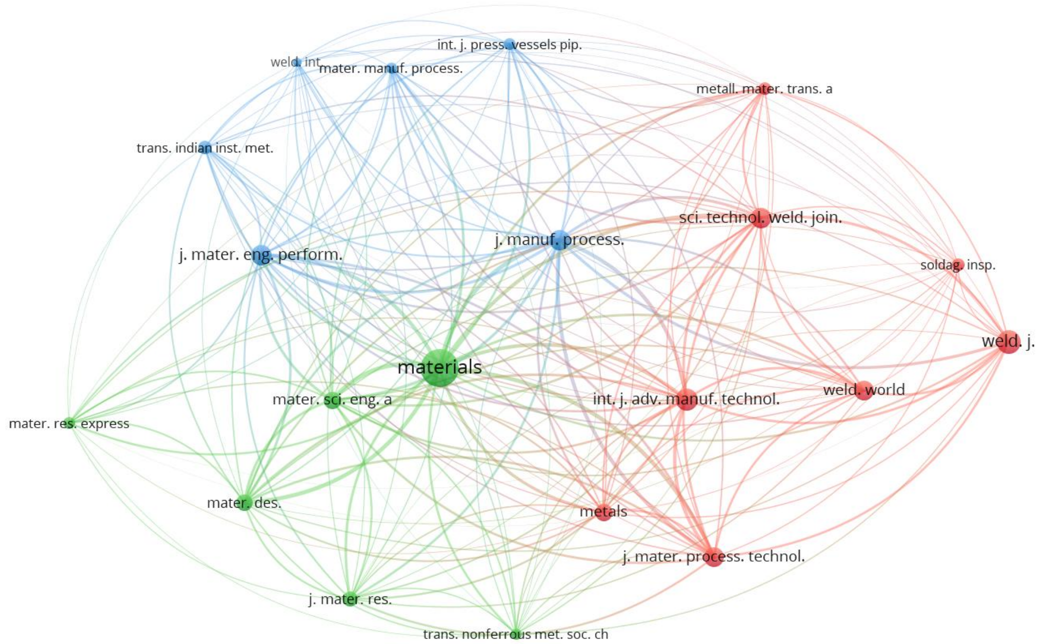
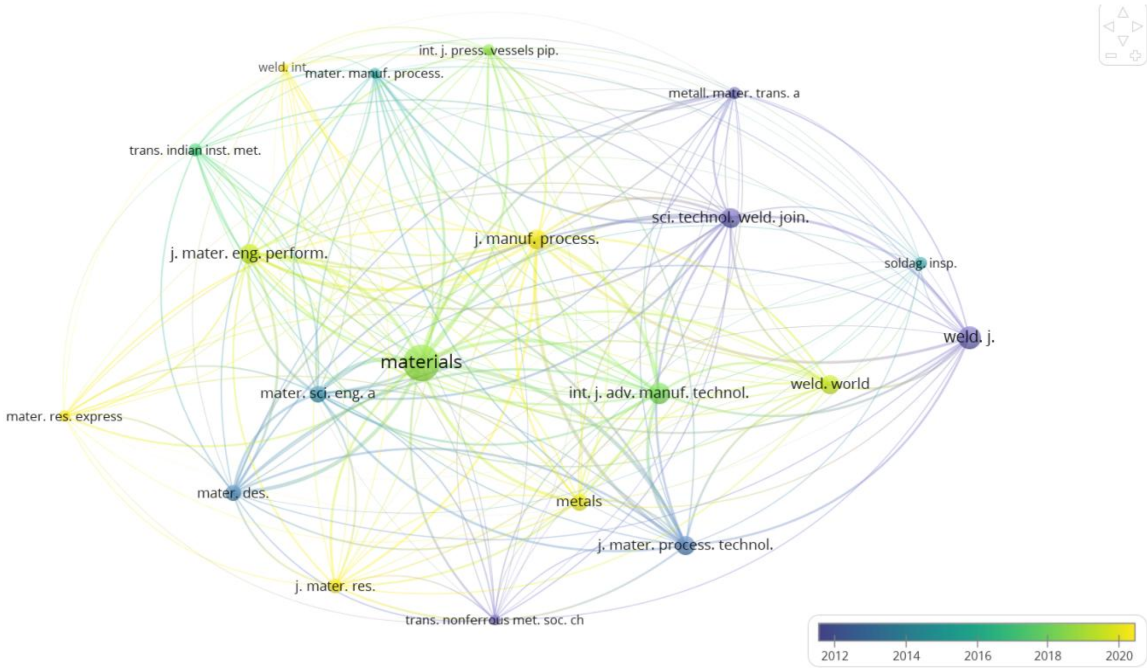


Fig. 7. Cumulative number of publications on TIG process over time for the 14 journals in Zone 1 (Bradford's law) (Biblioshiny)



a)



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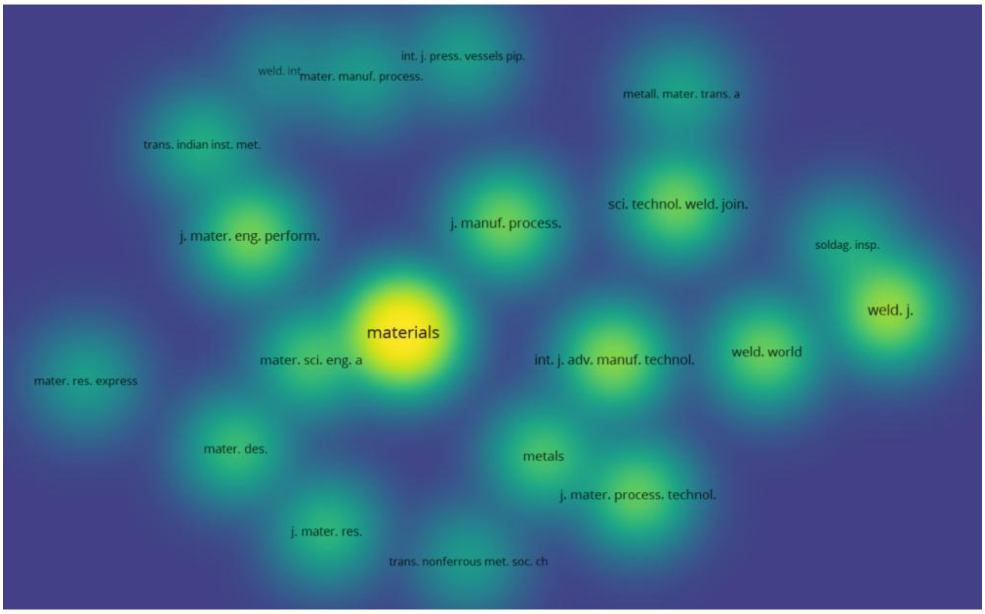

c)

Fig. 8. Bibliometric visualization of TIG process literature sources: a) sources network, b) sources network overlay c) sources density (VOSviewer)

The majority of publications on TIG welding are concentrated in a limited number of leading journals, which serve as the primary sources of literature for researchers in this field. Nonetheless, shifts in the prominence of individual journals are evident, potentially influenced by factors such as open access publishing models, variations in the number of articles published, and requirements from research funding institutions to publish in reputable journals with a high impact factor. An example is the decreasing average number of publications in Materials and Design, Welding Journal, and Science and Technology of Welding and Joining accompanied by a simultaneous increase in Materials Today: Proceedings, Metals, and Journal of Manufacturing Processes. Citation network analysis (Figure 8a) revealed three distinct clusters of journals: one focused specifically on welding (highlighted in red), and two encompassing sources related to broader topics in materials science as well as materials manufacturing and processing techniques (green and blue). The citation network exhibits a relatively uniform structure, suggesting frequent and evenly distributed cross-citation among journals within the research domain.

Authors

Table 3 presents a summary of the ten leading authors who have published more than 65 articles on TIG welding. Four researchers have published more than 100 papers on this topic: S.B. Chen, Y.M. Zhang, L.M. Liu, and M. Vasudevan. Figure 9 illustrates the temporal distribution of publication activity for these ten authors.

***Table 3.** Leading authors of TIG processes literature (WOS)*

Authors	Affiliation	Number of publications	% of n=8,789	Citations	Citations per publication
Chen SB	Shanghai Jiao Tong University, School of Materials Science and Engineering, Shanghai, China	125	1.439	3277	26.2
Zhang YM	Department of Electrical and Computer Engineering and Institute for Sustainable Manufacturing, University of Kentucky, Lexington, USA	119	1.370	3164	26.6
Liu LM	School of Materials Science and Engineering, Dalian University of Technology, Dalian, China	108	1.243	2437	22.6
Vasudevan M	Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, India	108	1.243	2796	25.9
Balasubramanian V	Faculty of Engineering and Technology, Annamalai University, Annamalainagar, Tamilnadu	99	1.140	2780	28.1
Arivazhagan N	School of Mechanical Engineering, Vellore Institute of Technology, Vellore, TN, India	90	1.036	2177	24.2
Pandey C	Department of Mechanical Engineering, Indian Institute of Technology, Jodhpur, India	81	0.932	2162	26.7
Tanaka M	Joining and Welding Research Institute (JWRI), Osaka University, Osaka, Japan	80	0.921	2156	27.0
Ramkumar KD	School of Mechanical Engineering, VIT University, Vellore, India	75	0.863	1992	26.6
Lin SB	State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology,China	65	0.748	1906	26.2

A clear difference in the duration of publication activity can be observed: some researchers (e.g., SB Chen, YM Zhang, M Tanaka) have been active since the 1990s, whereas others (e.g., C Pandey, KD Ramkumar, SB Lin) began publishing intensively only after 2010. It is worth noting that the past ten years have witnessed a substantial increase in publication output, highlighting the expanding focus on TIG welding. Furthermore, despite the varying lengths of research careers, the more recent authors have achieved a publication intensity comparable to that of the earlier leaders, indicating both the expansion of the active research community and the intensification of developments in this field. Interestingly, regardless of the publication period and the total number of articles produced, the average number of citations per paper remains both relatively high and consistent, ranging from 22.6 to 28.1. This indicates that, independent of publication intensity, their works exert a comparable impact within the scientific community.

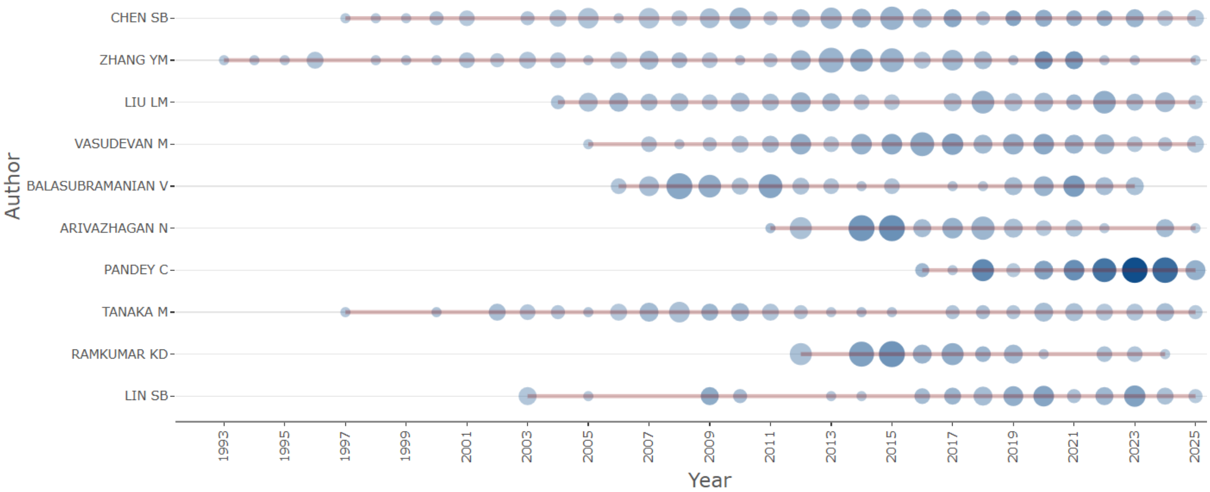

Fig. 9. Publication output of the ten most prolific authors in the field of TIG welding (Biblioshiny)

The visualization networks shown in Figure 10 illustrate co-authorship relationships among 219 researchers in TIG process research, developed based on a minimum publication threshold of 15 and using the fractional counting procedure. The network is extensive, with multiple connections between nodes representing authors. The main findings are consistent with previous analyses: several leading research groups are centered around SB Chen, YM Zhang, M Tanaka, and Balasubramanian, who published earlier works, while the most recent publications appear in teams led by C Pandey, KD Ramkumar, and N Arivazhagan.

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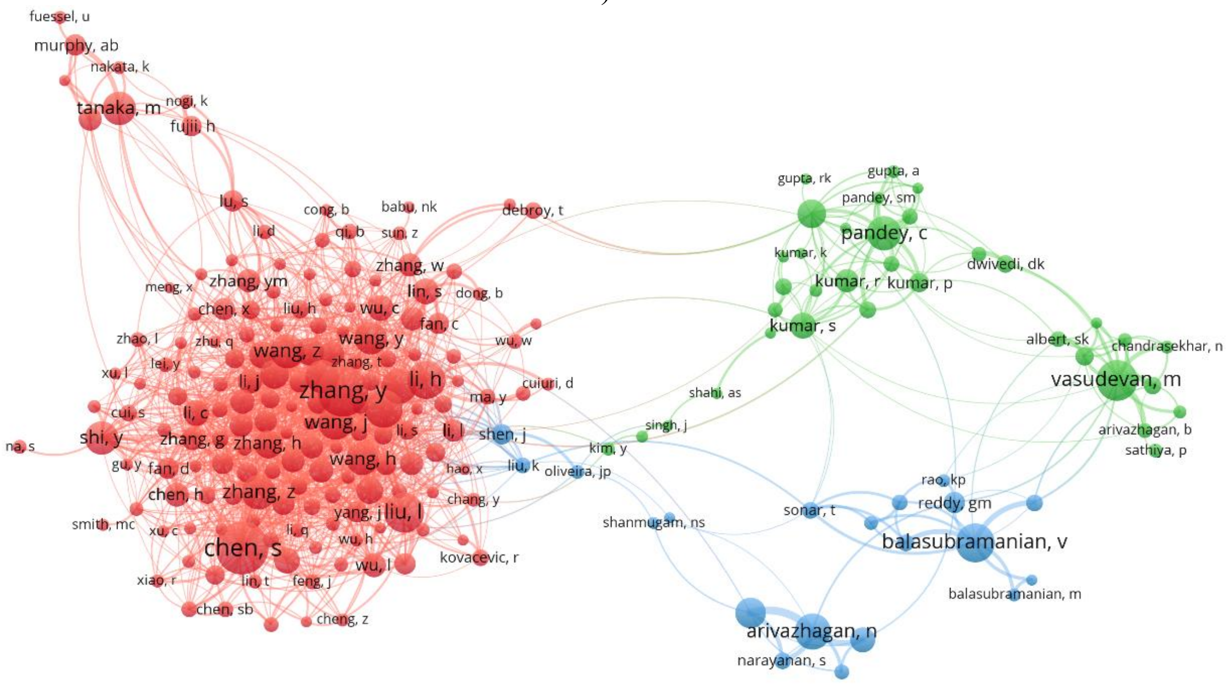
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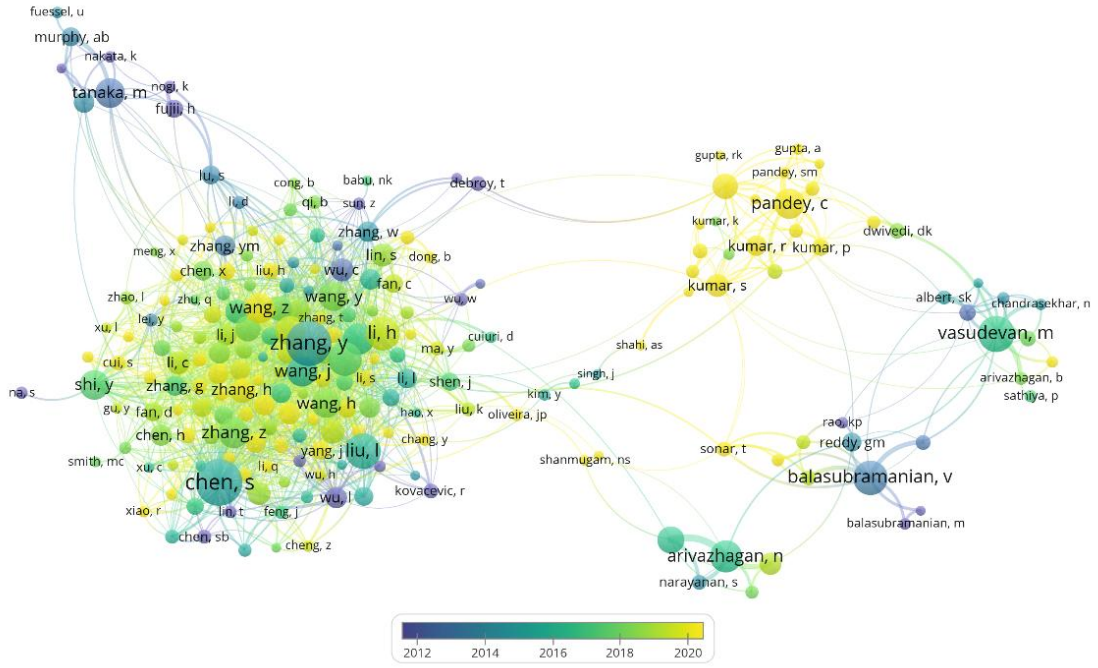
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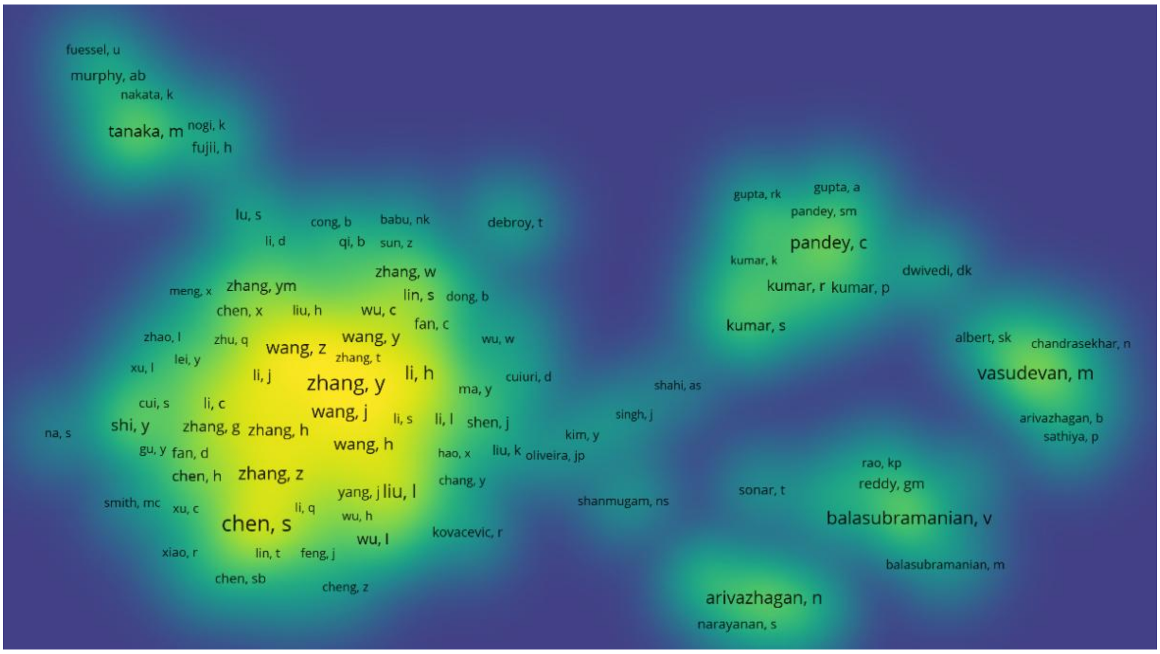
c) 

Fig. 10. Bibliometric visualization of co-authorship in TIG process literature: a) sources network, b) sources network overlay c) sources density (VOSviewer)

Table 4 presents the five publications with the highest citation counts according to the Web of Science (WOS). These studies address topics extending beyond conventional TIG welding, encompassing aspects of additive manufacturing using TIG [180, 181] as well as articles on the weldability of ferritic–austenitic duplex steels and nickel alloys [182–184]. This clearly indicates that among current research trends, additive manufacturing holds a significant position, particularly WAAM (Wire Arc Additive Manufacturing), which is a process that uses an electric arc as a heat source to build metal components layer by layer from wire feedstock.

Table 4. *The top five publications with the highest number of global citations (WOS)*

Article	Citations	Citations per year
Baufeld, B., Van der Biest, O., & Gault, R. (2010). Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: microstructure and mechanical properties. *Materials and Design*, *31*, S106-S111.	477	27.8
Muthupandi, V., Srinivasan, P. B., Seshadri, S. K., & Sundaresan, S. (2003). Effect of weld metal chemistry and heat input on the structure and properties of duplex stainless steel welds. *Materials Science and Engineering: A*, *358*(1-2), 9-16.	419	19.0
Henderson, M. B., Arrell, D., Larsson, R., Heobel, M., & Marchant, G. (2004). Nickel based superalloy welding practices for industrial gas turbine applications. *Science and Technology of Welding and Joining*, *9*(1), 13-21.	388	18.4
Dinovitzer, M., Chen, X., Laliberte, J., Huang, X., & Frei, H. (2019). Effect of wire and arc additive manufacturing (WAAM) process parameters on bead geometry and microstructure. *Additive Manufacturing*, *26*, 138-146.	330	55
Verma, J., & Taiwade, R. V. (2017). Effect of welding processes and conditions on the microstructure, mechanical properties and corrosion resistance of duplex stainless steel weldments—A review. *Journal of Manufacturing Processes*, *25*, 134-152.	320	40

Countries

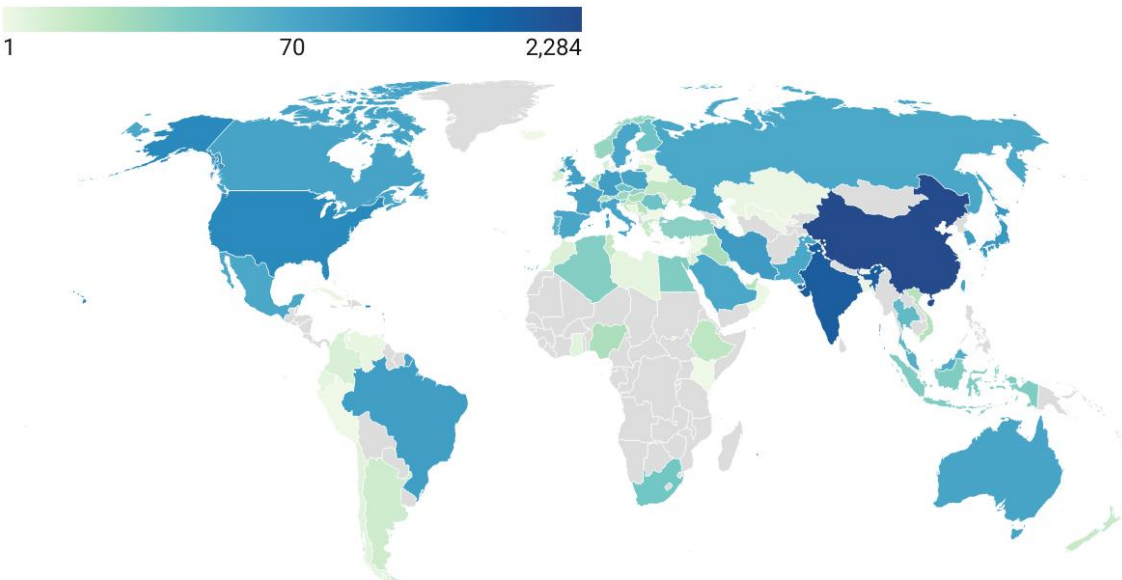
Based on the statistical distribution of countries in which the authors of publications on the TIG process are affiliated (Table 5 presents regions that account for at least 1% of the 8,789 publications), a strong concentration is observed in a few countries, while the contribution of many others remains relatively minor. The largest share is represented by China (26.3%) and India (21.4%), which together account for nearly half of all records. The United States ranks third but with a significantly smaller share (9.1%). The high share of publications authored by researchers affiliated with institutions in these three countries results from multiple factors. First, the data are presented in absolute terms, and these countries have a substantial number of researchers. Moreover, industry plays a significant role in their economies, which drives interest in manufacturing technologies. The high publication output is also supported by extensive higher education systems and numerous research institutions, strong engagement of funding agencies, significant investments in research and development enabling advanced scientific projects, and a well-established publication culture in which scholarly articles constitute a key metric for assessing academic careers and research institutions. Asian countries: China, India, Japan, Iran, South Korea, and Taiwan dominate the top ten, highlighting the region's significance in this field, whereas the contribution of European countries is considerably lower, with none exceeding 3.5%.

Table 5. *Leading countries of TIG processes literature (WOS)*

Country	Record Count	Share of total, n=8,789 (%)
Peoples Republic of China	2284	26.3
India	1863	21.4
United States	789	9.1
Japan	447	5.1
Iran	368	4.2
Brazil	316	3.6
South Korea	310	3.5
Germany	300	3.4
England	281	3.2
France	201	2.3
Taiwan	190	2.1
Poland	173	1.9
Canada	162	1.8
Australia	146	1.6
Turkey	138	1.5
Italy	121	1.3
Spain	101	1.1
Sweden	91	1.0

Figure 11 presents the global mapping of TIG welding research and inter-country collaboration links. Analysis of the co-authorship network of scientific publications on TIG welding indicates a progressive globalization of research and a clear shift of activity from Western countries toward Asia and developing nations (Figure 11b). China plays a leading role in this process, whereas India focuses primarily on regional collaboration and partnerships with countries in the Global South. The largest nodes in the network, corresponding to the highest number of publications and co-authorship links, are represented by China, India, the United States, Japan, Germany, Iran, Brazil, and South Korea. Additionally, medium-sized centers, such as France, Poland, Saudi Arabia, and Malaysia, serve as bridges between major players and smaller countries. The network structure allows the identification of six main research clusters. The first, the Asian cluster (blue), includes China, Japan, South Korea, and Taiwan, maintaining strong connections with the United States and Germany. The second cluster (yellow-green) is centered around India, which collaborates intensively with the Gulf countries, Sub-Saharan African nations (Nigeria, South Africa), and countries in Southeast Asia. The third, European cluster (green), includes Germany, Poland, the Czech Republic, Romania, Austria, and Ukraine. Another, Middle Eastern cluster (red) comprises Saudi Arabia, Egypt, Jordan, and Turkey, which maintain strong links with India and Europe. A separate Latin American cluster (turquoise) is formed by Brazil, Colombia, and Ecuador, primarily connected with Germany, the United States, and Spain. The final group consists of smaller peripheral clusters, represented by countries such as Lithuania and Ethiopia (light green).

Temporal analysis of publication activity reveals heterogeneous growth rates across countries (Figure 11c and d). Established research centers include Japan, the United States, and Germany. In the more recent period (2018–2022), dynamic growth in publication activity was observed in India, Saudi Arabia, Egypt, Malaysia, and Nigeria. China, on the other hand, has demonstrated a consistently sustained research output over an extended period. Analysis of international collaborations confirms particularly strong cooperation among China, the United States, Germany, and Japan, while highlighting the role of Central European countries, such as Poland, the Czech Republic, and Romania, as connectors between East and West. The activity of Middle Eastern and African countries is steadily increasing, as they integrate into the global research network. India plays a particularly significant role as a regional hub, facilitating mainly South–South cooperation that integrates countries across Asia, Africa, and the Middle East.



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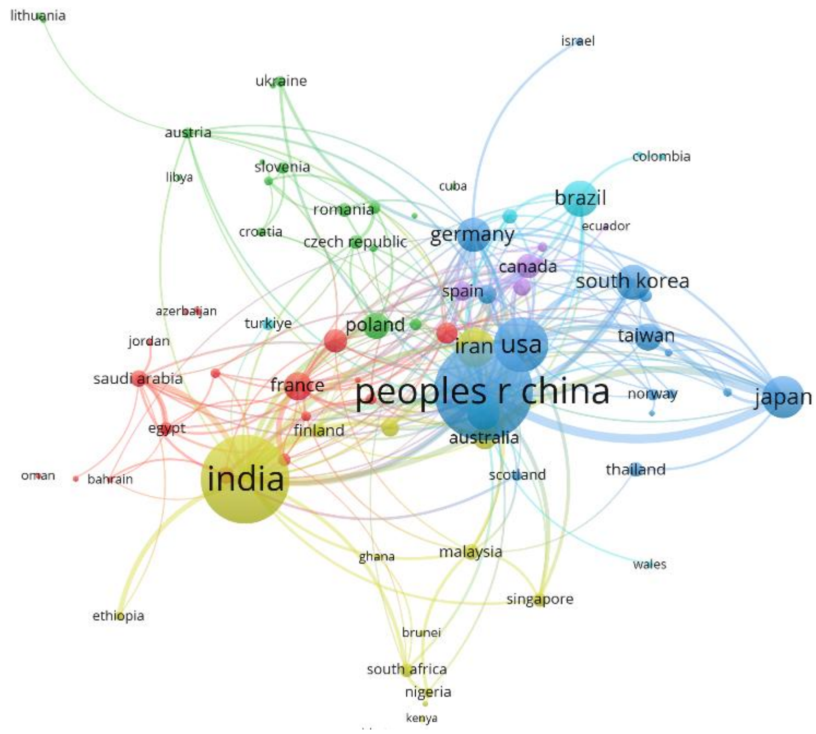
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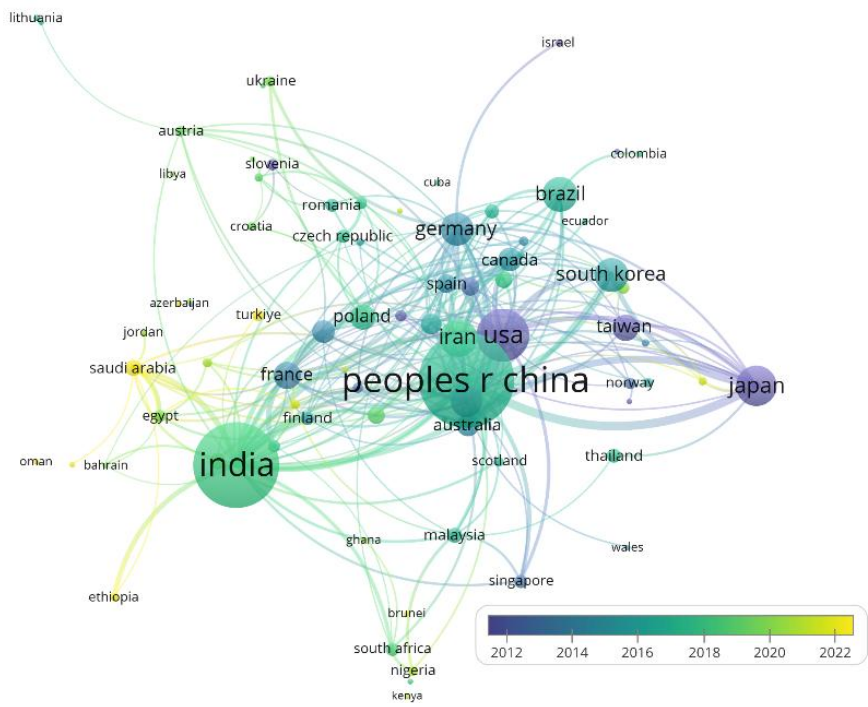
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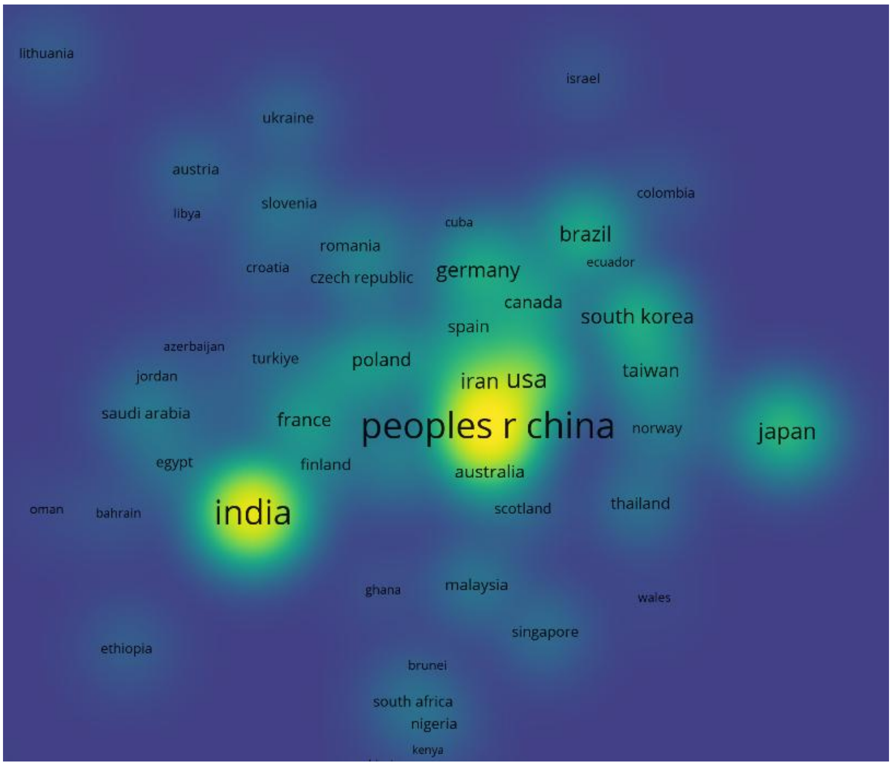
d) 

Fig. 11. Global research landscape of TIG welding: a) world map (https://www.datawrapper.de/maps/choropleth-map), b) countries network, c) countries network overlay, d) countries density (VOSviewer)

Funding

Analysis of data from the WOS allows for the identification of previous sources of research funding, thereby revealing potential opportunities for applying for research grants. In the case of data concerning TIG welding, assuming a minimum numerical share of 1% per funding institution, China emerges as the leading contributor, accounting for nearly 20% of all projects, with the largest share (12.2%) provided by the National Natural Science Foundation of China (NSFC). Brazil occupies the second position, primarily due to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), supported by state foundations and industry. The United States and Europe together finance approximately 5–6% of research, with dominance by the National Science Foundation (NSF) in the United States (0.92%) and the United Kingdom Research and Innovation (UKRI) in the UK (0.69%). India and Japan have a similar share, around 1.2% each, with the main sponsors being the Department of Science and Technology (DST) in India and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan (0.46%). Poland and other Central European countries do not exceed a 1% share in funding TIG research. Table 6 lists ten funding agencies that supported the highest number of publications within the dataset of 8,789 articles. Many other institutions are also funding these studies, but each contributes only to a minor extent. It should be emphasized that these analyses consider only the number of projects, not the funding amounts. Nevertheless, the results are consistent with the patterns observed in analyses of the countries and institutions with which the authors are affiliated (Tables 3 and 5, Figures 9-11).

***Table 6.** Top 10 funding agencies supporting the largest number of publications from the set of 8,789 articles*

Funding Agencies	Record Count	Share of total, n=8,789 (%)
National Natural Science Foundation Of China NSFC	1057	12.166
Fundamental Research Funds For The Central Universities	105	1.209
National Key Research Development Program Of China	99	1.140
Conselho Nacional De Desenvolvimento Cientifico E Tecnologico CNPQ	93	1.070
National Science Foundation NSF	80	0.921
China Postdoctoral Science Foundation	73	0.840
Coordenacao De Aperfeicoamento De Pessoal De Nivel Superior Capes	69	0.794
Ministry Of Science And Technology Taiwan	65	0.748
UK Research Innovation UKRI	60	0.691
Engineering Physical Sciences Research Council EPSRC	56	0.645

SUMMARY

The subject of this study is the analysis of records from the Web of Science database, comprising bibliographic descriptions of 8,789 publications on TIG welding. The inclusion criteria for the dataset were strictly limited to relevance, without imposing any additional restrictions. The application of bibliometric tools, mainly VOSviewer 1.6.20 and Biblioshiny, and the subsequent analysis of the results made it possible to determine the current state of knowledge and its evolution over the past 60 years, beginning with the publication of the first Web of Science-indexed paper on the TIG method. This approach provided insight into the dynamic development of research in this field, covering a wide thematic spectrum, and served as a basis for identifying research gaps and potential future directions.

The majority of publications are written in English (96.37%) and consist primarily of standard research articles, with a relatively substantial number of review papers (124). Data papers are rare exceptions, indicating limited availability of raw data, which may hinder the replication of studies and the verification of results. The dominance of standard research articles suggests that the main focus is on the interpretation of results rather than on sharing underlying datasets [185]. The publication trend in TIG welding reflects patterns typical of materials engineering and welding research [138, 140, 142]. The development of research, as analyzed using bibliometric methods, can be divided into an initial low-activity phase (1965–1990), a growth phase beginning in the early 1990s, and a phase of intensive expansion after 2000.

While single-authored publications are relatively rare, the degree of international collaboration in this field is still limited. The international collaboration rate of 12.58% should be regarded as a significant limitation to the development of research in the field of TIG welding [186]. Compared with global trends, this value is relatively low, which may negatively affect the quality, innovation potential, and international visibility of research outcomes [187]. International partnerships play a crucial role in facilitating knowledge exchange, jointly addressing scientific challenges, and advancing modern technological solutions. Moreover, they significantly support the acquisition of research funding, particularly from supranational sources [188, 189]. Therefore, strengthening international cooperation between research institutions should be considered a key priority for the further development of this field. Such an approach may substantially accelerate scientific progress and enhance the global impact of research on TIG welding processes.

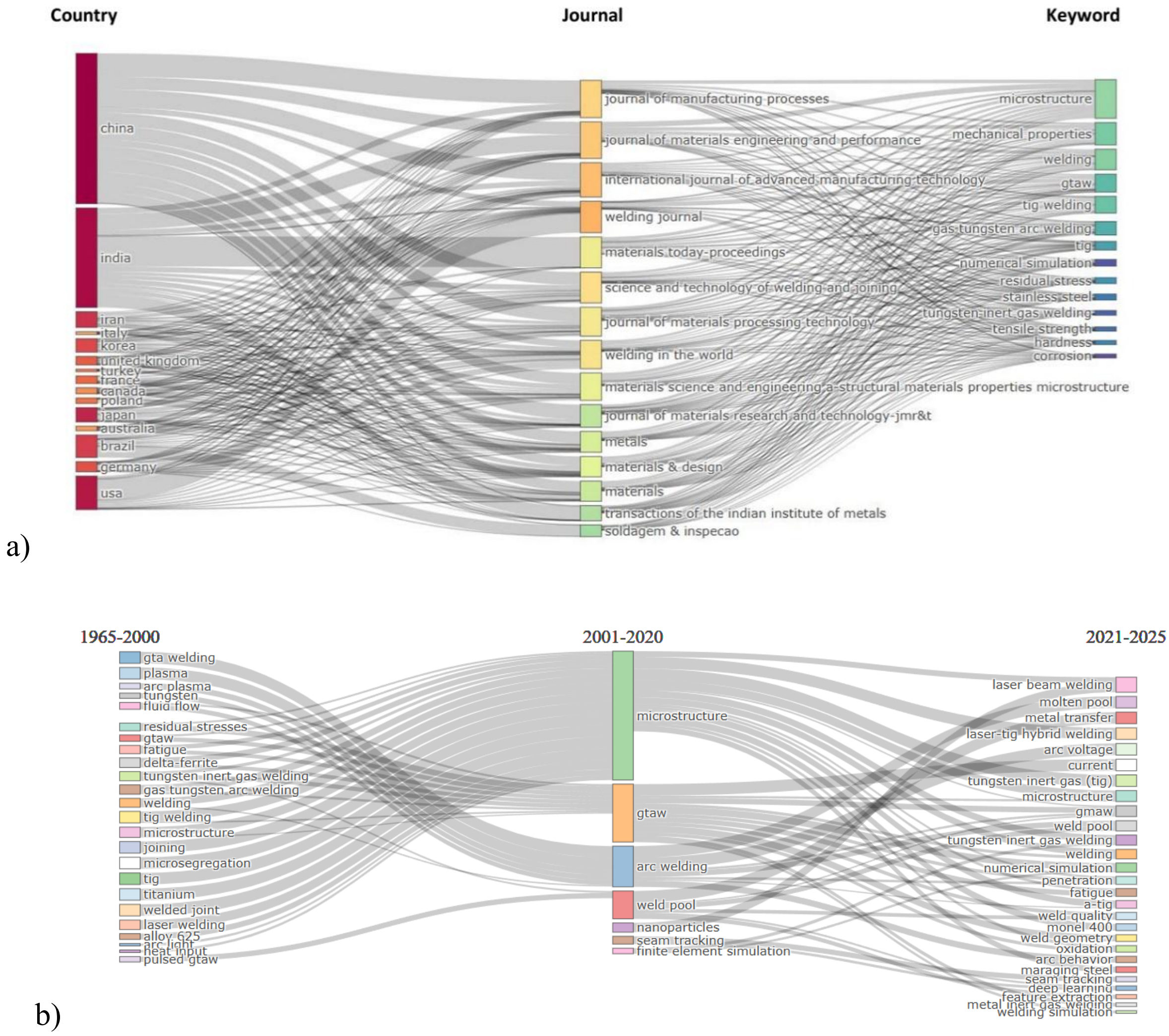


Fig. 12. Thematic development of the TIG welding: a) three-field plot of countries, journals, and keywords, b) authors' keywords time trend (Biblioshiny)

The TIG welding process follows a natural path of development, evolving from classical studies that focused on identifying the fundamental mechanisms governing the welding process and its effects on materials, to contemporary research centered on advanced materials, such as nickel-based alloys, and additive manufacturing technologies. This trend is evident across all the presented bibliometric analyses, based on keyword evaluations and the publications with the highest citation counts. Numerical simulations and automation are gaining increasing importance, particularly in applications within high-tech industries, such as the aerospace sector. The summary of the thematic evolution of the investigated process is presented in Figure 12 through three-field plots of countries, journals, and keywords and the changes in major authors' keywords over the period before and after 2000. The connection analysis presented in Figure 12a confirms observations regarding the main publication areas related to the TIG process. Research on TIG technology is primarily concentrated in Asian countries, such as India, China, and Iran, with findings mainly published in journals focusing on manufacturing technologies and materials science. In both analyses, summarizing the studies reported in this work, a clear shift in research trends can be observed: from early investigations of fundamental process properties (arc plasma) and welded joints (microsegregation, residual stress) to more advanced research techniques, such as numerical simulations using the finite element method (FEM) and hybrid methods.

TIG welding research is largely concentrated in a small number of core journals, which serve as primary references for the field. Citation network analysis revealed three clusters of journals: one focused directly on welding and two encompassing broader areas of materials science as well as materials manufacturing and processing technologies. Changes in the prominence of individual journals (i.e., the number of papers published over a given period) are also evident, indicating shifts in the publication preferences of authors. Recently, most articles have appeared in Materials Today: Proceedings, Metals, and the Journal of Manufacturing Processes.

Ten leading authors have published more than 65 articles on TIG welding, and the past decade has seen a substantial increase in publication output. The average number of citations per paper remains stable (22.6–28.1), indicating that, regardless of publication intensity, these works exert a comparable impact within the scientific community. The co-authorship network is extensive, with numerous interconnections between authors. Leading research groups are centered around SB Chen, YM Zhang, M Tanaka, and Balasubramanian, who contributed earlier works, whereas the most recent publications originate from teams led by C Pandey, KD Ramkumar, and N Arivazhagan. The analysis of co-authorship further highlights the progressive globalization of research and a clear shift in activity from Western countries toward Asia and developing regions.

China is the leading contributor to TIG research funding, accounting for nearly 20% of all projects, primarily through NSFC, followed by Brazil with significant support from CNPq, state foundations, and industry. Other countries, including the United States, Europe, India, Japan, and Central Europe, provide smaller shares (generally below 6%), with funding dominated by NSF, UKRI, DST, and MEXT, while Poland and its neighbors remain below 1%.

TIG welding is a mature process with a well-established industrial position, intensively developed scientifically, featuring numerous technological variants that mitigate its drawbacks. It is versatile in many aspects while simultaneously addressing specific material and structural niches, with a promising outlook for further development. Despite the field being well-developed, there is still a need for systematic knowledge consolidation, improved availability of research data, and strengthened international and inter-institutional collaboration. Based on the results of the conducted analyses, a summary of current trends in knowledge development was presented, and future research needs were identified (Table 7).

Current research trends identified through bibliometric analyses cover both technological and material-related issues, which are often interlinked. This group of development activities includes the establishment of welding procedures and the investigation of technological and service-related properties for new grades of steels and non-ferrous metals, including dissimilar joints [190]. In particular, this concerns steels intended for operation in harsh environments: stainless steel grades and those designed for service at low and elevated temperatures as well as nickel-based alloys [191, 192]. The research focuses on the application of technological measures such as preheating, heat treatment, welding sequence optimization, as well as joint preparation methods, including variations in beveling and the use of butter layers [193]. The TIG process holds a special position as a method used for performing the root pass in welded joints within combined welding techniques involving other welding processes [194, 195]. Progress is also being made in process development: more efficient and productive TIG welding methods are being developed, including those using activating fluxes, various hybrid process variants, hot wire and dual wire solutions, three tungsten electrodes method and external assistance such as ultrasonic vibrations or magnetic fields [196–199]. The demands of the rapidly evolving industry drive the increasingly widespread implementation of automation and robotic systems in welding, incorporating, among others, adaptive control, seam-tracking, and integrated sensor technologies [200, 201]. Furthermore, the increase in productivity and welded joints quality drives interest in arc control capabilities through the development of advanced welding power sources and process parameter regulation systems [202, 203]. Current research trends in welding increasingly involve the use of numerical simulations, particularly for the analysis and optimization of TIG processes [204]. Artificial intelligence is gaining importance by supporting process control, quality prediction, and defect detection in welded joints. The application of optimization methods, deep learning, and expert systems is also rapidly advancing, enabling greater automation and improved precision in welding operations [205, 206]. The application areas of various TIG process modifications increasingly extend into high-tech industries, including aerospace, nuclear engineering, medical device manufacturing, electronics and microelectronics, advanced automotive technologies, energy systems, and space engineering. It results from the fact that modified TIG processes provide exceptional precision, cleanliness, controlled heat input, and the capability to transition from manual operation to fully automated and robotic modes, making them ideally suited to the demanding requirements of modern high-technology industries [207–209].

Among the primary gaps in the current knowledge of TIG welding, which require intensified research efforts, are studies on the weldability of special metal alloys such as tungsten, molybdenum, tantalum, niobium, and zirconium [210–212]. In practice, the TIG process yields the best results when welding these difficult-to-weld materials, making its further development particularly necessary.

Despite the increasing number of publications on TIG welding, further systematic studies on the service performance of welded joints are still required [213]. This applies to mechanical degradation phenomena (inter alia, fatigue, creep, brittle fracture), chemical degradation phenomena (among others, uniform corrosion, pitting corrosion, intergranular corrosion), as well as coupled mechanisms, including hydrogen embrittlement [214, 215].

The reluctance of authors working on welding-related topics to publish studies in the form of data papers, as previously observed by the authors during bibliometric analyses of the FCAW welding process, is noteworthy [140]. The publication of data papers requires a significant effort, including the verification, cleaning, and detailed documentation of data, as well as ensuring their proper accessibility. Authors often express concerns regarding the loss of control over their data, the risk of misinterpretation by third parties, and the possibility of other researchers using the data for their own publications. Moreover, within the current academic evaluation system, the benefits associated with publishing data sets are limited [216–218]. Consequently, many researchers refrain from sharing their data, despite the potential advantages for scientific advancement. It is therefore essential to raise awareness among authors regarding the value of data papers and to promote open data sharing as a critical component of scientific progress.

Similarly, it should be noted that there is a lack of published results from systematic studies on the harmful effects of welding conditions on welders' health and on environmental contamination. It appears that a barrier to broader research in this area may be the difficulty in establishing collaboration between welding engineering researchers and industrial/occupational hygienists specializing in welding fumes and chemical exposure. A review of the literature indicates that such publications are produced mainly by teams that do not include welding engineers [219, 220].

A further significant limitation is the difficulty in accessing literature and tools for reliable welding cost estimation, which applies to all welding methods. Welding costs are sensitive to process conditions and parameters, making accurate estimation dependent on precise data [221].

Table 7. *Current trends and key knowledge gaps in TIG welding*

Trends	Knowledge gaps
• Research on various types of steel and non-ferrous metals • Development of alternative TIG welding variants to increase efficiency • Weldability improvement strategies for dissimilar materials, including buttering • Development of hybrid and combined welding procedures • Numerical simulations of the TIG welding process • Application of artificial intelligence • Application of optimization methods, deep learning and expert systems • Additive manufacturing using TIG welding • Applications in high-tech industries	• Properties and weldability of special metals (tungsten, molybdenum, tantalum, niobium, zirconium) and their alloys • Evaluation of fatigue performance of welded joints • Environmental degradation of TIG-welded joints (corrosion, hydrogen embrittlement, microbiologically influenced corrosion, erosion, cavitation, thermal damage and high-temperature oxidation) • Limitations of applying data mining techniques to the optimization of the TIG process due to insufficient data reports • Health and safety in the TIG process • Methods for assessing welding costs

The authors have made every effort to ensure that the presented analyses and their interpretations accurately reflect the current state of knowledge, research trends, and existing knowledge gaps. However, due to methodological limitations inherent in bibliometric analyses, some inconsistencies or omissions may occur [222, 223]. The primary source of uncertainty in the presented results is the use of a single database (WOS). In addition, bibliometric analyses are quantitative in nature and do not assess the quality or reliability of publications, which is a standard feature of traditional review articles. They may also omit recent or locally published studies, do not consider methodological context, and inconsistencies in author names or affiliations can lead to errors in data aggregation. Finally, although bibliometrics allows for the identification of trends and interconnections, it only enables scientific interpretation and critical assessment of the impact of results on the development of the field to a limited extent. Nevertheless, based on systematic reviews and their own expertise, the authors consider this work to be of significant value and believe it provides an accurate representation of the historical and contemporary development of the TIG welding process, with respect to the main bibliographic dimensions of scientific output: publications, research topics, journals, authorship, countries, funding and scientific collaborations.

CONCLUSIONS

Based on the results of bibliometric analyses of 8,789 publications on TIG welding conducted using the VOSviewer 1.6.20 and Biblioshiny tools, the following basic conclusions were formulated

- The evolution of the research landscape over the 60-year publication history can be divided into three stages: an initial period of low activity, a growth phase beginning in the 1990s, and an intensive expansion after 2000. During this time, a clear shift in research focus occurred from fundamental issues (plasma arc behavior, residual stresses) toward advanced materials, additive and hybrid technologies, automation, and numerical simulations.
- A noticeable shift in research activity from Western countries to Asia can be observed, reflecting broader global trends in the welding industry. Research efforts are now concentrated primarily in Asia (China, India, Iran). Funding is dominated by China and Brazil, while the contributions of Europe, the United States, and Japan remain relatively limited.
- Publications are concentrated in a few key journals in the fields of welding, materials science, and manufacturing technology (Journal of Manufacturing Processes, Metals, and Materials Today: Proceedings). The most active authors produce consistently cited works, and co-authorship networks are increasingly extensive, although international collaboration remains limited.
- Current research directions include the application of advanced TIG variants (A-TIG, hot-wire, dual-wire, ultrasonic or magnetic field-assisted), automation and robotic welding processes, integration of sensors and adaptive control, as well as the use of artificial intelligence for joint quality optimization and diagnostics. The significant adoption of TIG welding in high-technology sectors such as aerospace, nuclear power, medical engineering, and space technology is emphasized.
- Areas still requiring in-depth study include the weldability of special metals, long-term joint durability (creep, fatigue, corrosion, hydrogen embrittlement), and the impact of TIG processes on welder health and the environment. Strengthening interdisciplinary collaboration and improving the accessibility of research data remain important challenges.
- Although TIG is a mature, industrially established process, it continues to undergo intensive development, therefore, consolidation of knowledge, better data availability, and stronger international collaboration are necessary.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Dariusz Fydrych holds the position of Deputy Editor-in-Chief of Advances in Materials Science, while Aleksandra Świerczyńska serves as Associate Editor of the same journal. Both have been excluded from the publication process.

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