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Bibliometric analysis of AZ31 alloy welding: trends in the use of the friction stir welding process

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ABSTRACT: This study presents a bibliometric analysis of research related to lightweight alloys, with a particular focus on the AZ31 magnesium alloy, and the friction stir welding (FSW) process. A structured literature search using the keywords "Weld* AND AZ31*" was conducted in the Web of Science database. From the 1,681 retrieved publications, titles, keywords, and abstracts were analyzed to identify prevailing themes, commonly used terms, and emerging research trends. These trends were subsequently examined in the context of macroeconomic and socio-environmental factors, with particular emphasis on the Environmental, Social, and Governance (ESG) agenda and the role of lightweight alloys in reducing greenhouse gas (GHG) emissions. Magnesium alloys such as AZ31 are employed to produce components with up to 30% less mass than equivalent aluminum parts, thereby contributing to lower fuel consumption and emissions in transportation. The choice of materials must consider the interaction between material, function, process, and form. In this regard, FSW, a solid-state joining process that eliminates the need for filler materials and shielding gases, is particularly effective for joining AZ31 alloys, reducing manufacturing costs and welding defects commonly associated with fusion-based methods. The analysis indicates a growing academic interest in AZ31 alloys, driven by their low density and favorable mechanical properties. However, a notable gap remains regarding multi-pass FSW and the use of machine learning techniques to predict weld behavior. Terms like "double side" or "double pass" appear in only 0.47% of the dataset. By comparison, co-occurrences of "FSW" and "Machine Learning" are limited to 0.3%, encompassing techniques such as deep neural networks, decision trees, XGBoost, and random forests. The most active research groups are located in countries with high production and consumption of magnesium alloys, including China, India, Japan, the United States, and Canada. Brazil, despite being a major magnesite producer, imports metallic magnesium, highlighting the need for national policies to support technological development. Overall, this study contributes by identifying research gaps and proposing future directions in sustainable welding and manufacturing.

Keywords: AZ31 magnesium alloy; bibliometric analysis; double-pass friction stir welding; sustainable manufacturing; welding process optimization.

Análise bibliométrica da soldagem da liga AZ31: tendências no uso do processo de soldagem por fricção e mistura

RESUMO: *Este estudo apresenta uma análise bibliométrica de pesquisas relacionadas a ligas leves, particularmente à liga de magnésio AZ31, e ao processo de soldagem por atrito e mistura (FSW). Uma busca estruturada usando as palavras-chave "Weld* AND AZ31*" foi conduzida no banco de dados da plataforma Web of Science. Dos 1.681 artigos recuperados, foram analisados títulos, palavras-chave e resumos a fim de identificar temas predominantes, termos comumente usados e tendências de pesquisa emergentes. Essas tendências foram examinadas no contexto de fatores macroeconômicos e socioambientais, especialmente a agenda Ambiental, Social e de Governança (ASG) e o papel das ligas leves na redução das emissões de gases de efeito estufa (GEE). Ligas de magnésio como a AZ31 são empregadas para produzir componentes com até 30% menos massa do que peças equivalentes de alumínio, contribuindo para reduzir o consumo de combustíveis e as emissões nos transportes. A escolha dos materiais deve considerar a interação entre material, função, processo e forma. Nesse sentido, a FSW, um processo de união em estado sólido que elimina a necessidade de materiais de adição e gases de proteção, é particularmente eficaz na união de ligas AZ31, reduzindo os custos de fabricação e os defeitos de soldagem comumente associados a métodos baseados em fusão. A análise indica um crescente interesse acadêmico nas ligas AZ31, impulsionado por sua baixa densidade e por propriedades mecânicas favoráveis. No entanto, ainda há uma lacuna notável em relação à FSW multipasse e ao uso de técnicas de aprendizado de máquina para prever o comportamento da solda. Termos como "lado duplo" ou "passe duplo" aparecem em apenas 0,47% do conjunto de dados. Em comparação, as coocorrências de "FSW" e "Aprendizado de Máquina" são limitadas a 0,3%, apresentando técnicas como redes neurais profundas, árvores de decisão, XGBoost e florestas aleatórias. Os grupos de pesquisa mais ativos estão localizados em países com alta produção e consumo de ligas de magnésio, incluindo China, Índia, Japão, Estados Unidos e Canadá. O Brasil, apesar de ser um grande produtor de magnesita, importa magnésio metálico, o que evidencia a necessidade de políticas nacionais de apoio ao desenvolvimento tecnológico. Este estudo contribui identificando lacunas de pesquisa e propondo direcionamentos futuros para soldagem e manufatura sustentáveis.*

Palavras-chave: *análise bibliométrica; fabricação sustentável; liga de magnésio AZ31; otimização de processos de soldagem; soldagem por fricção e mistura de dupla passagem.*

1 Introduction

In response to global challenges related to energy efficiency, magnesium alloys have emerged as strategic materials for reducing fuel consumption. Owing to favorable properties such as good machinability, electromagnetic shielding, biocompatibility, and recyclability, —characteristics exhibited by the AZ31B alloy—magnesium alloys have increasingly replaced aluminum alloys in a range of applications (Brasil, 2024;

Commin *et al.*, 2009). These materials have attracted growing interest from the transportation sector by enabling the production of lighter components, which contribute to overall vehicle weight reduction and, consequently, lower energy demand. Such reductions directly support efforts to decrease greenhouse gas (GHG) emissions and improve energy efficiency, objectives closely aligned with sustainability and carbon neutrality goals (RIMA, [202-?]).

From an Environmental, Social, and Governance (ESG) perspective, the application of magnesium alloys represents a sustainable socio-environmental solution. Environmentally, magnesium alloys offer energy savings during processing and possess a favorable life cycle due to their recyclability, which mitigates the need for primary resource extraction. Socially, these materials support circular economy practices through magnesium recovery from scrap, while also fostering innovation in high-technology sectors, generating employment, encouraging research, and meeting governance expectations aligned with investor and consumer demands (RIMA, [202-?]; USGS, 2020).

According to the Brazilian National Mining Agency (ANM), Brazil holds approximately 2.5% of the world's magnesite reserves. However, the country has limited production of metallic magnesium and depends largely on imports, primarily from China, which holds about 12.8% of global reserves. Russia accounts for the largest share, with 29.5%. In Brazil, magnesite is primarily used in the production of refractory coatings, fertilizers, feed additives, and as an alloying element in aluminum processing (ANM, 2024; Brasil, 2024; RIMA, [202-?]).

Recognized as an eco-friendly material, magnesium alloys exhibit the highest strength-to-weight ratio among metals, with a density approximately 35% lower than that of aluminum. They also demonstrate favorable weldability, strength, ductility, and toughness, making them particularly suitable for the automotive industry, which accounts for roughly 90% of global magnesium alloy consumption (Brasil, 2024; RIMA, [202-?]). Their usage has grown at an average annual rate of approximately 20%, outperforming aluminum and steel by 40% and 75%, respectively (USGS, 2020). Accordingly, these alloys are regarded as a strategic choice for a cleaner, more efficient, and socially responsible industry, with applications extending to the naval, aerospace, and automotive sectors. However, several processability requirements must be satisfied to ensure successful applications, including the capacity to be welded using various techniques (Klenam *et al.*, 2021).

Among fusion-based welding processes used with magnesium alloys are gas tungsten arc welding (GTAW or TIG), laser beam welding (LBW), electron beam welding (EBW), and hybrid techniques (Huang *et al.*, 2018; Mehdi; Mishra, 2020). Regarding solid-state welding methods, friction stir welding (FSW) is notable for its effectiveness in joining aluminum, magnesium, and copper alloys. FSW has also been applied to materials with high melting points, such as titanium alloys, nickel-based superalloys, and metal matrix composites (Aditya; Majumdar; De, 2016).

Conventional fusion welding methods are prone to producing defects such as porosity, large heat-affected zones (HAZ), element vaporization, and brittle phase precipitation due to rapid solidification (Klenam *et al.*, 2021). In this context, friction stir welding has emerged as an efficient alternative. FSW involves a rotating, non-consumable tool that traverses the interface of two juxtaposed surfaces made of similar or dissimilar materials (Verma; Gupta; Misra, 2016). As a solid-state process, it operates at temperatures between 70% and 95% of the material's melting point (Colaço *et al.*, 2020; Yang *et al.*, 2011) thereby mitigating fusion-related drawbacks and recrystallization effects. This characteristic makes FSW advantageous for joining aluminum, magnesium,

ISSN 2447-9187

and titanium alloys (Colaço *et al*., 2020; Matitopanum *et al*., 2023). Moreover, FSW does not require filler materials or shielding gases.

Table 1 presents the main magnesium alloys and their typical applications (Klenam *et al*., 2021). This study focuses specifically on AZ31B, a magnesium alloy classified by the American Society for Testing and Materials (ASTM). The alphanumeric designation indicates approximately 3% aluminum and 1% zinc as the primary alloying elements. The suffix "B" denotes a second-generation variant containing 0.2% manganese, which enhances structural stability and corrosion resistance (AZO Materials, 2012). AZ31B is widely adopted due to its balanced properties, including weldability, machinability, mechanical strength, and plasticity, rendering it suitable for general-purpose engineering applications.

Table 1 ▼ Characteristics and application areas of magnesium alloys. *Source: adapted from Klenam et al. (2021)*

Alloy	Characteristics and areas of application
AM20	Good impact resistance and appreciable ductility
AM50	Suitable for high-pressure die casting
AS21, AE42	High creep resistance at operating temperatures up to 150 °C
AZ31	Easy to weld, with intermediate strength and excellent plasticity
AZ61	High strength combined with good weldability
AZ63	Excellent ductility at room temperature, along with good toughness and strength
AZ81	Suitable for pressure-tight die-cast components
AZ91	Well-suited for sand and die casting
EZ33	Good castability, easy to weld, and creep resistance up to 250 °C
HK31	Suitable for sand casting; easy to weld, with good creep resistance up to 350 °C
QE22	Easy to weld, with high yield strength at temperatures up to 250 °C
QH21	Easy to weld, with good yield strength up to 300 °C and enhanced creep resistance
WE43	Easy to weld, with excellent corrosion resistance
WE54	High strength at both elevated and room temperatures
ZC63	Suitable for pressure-tight castings; good thermal resistance and weldability
ZK51, Z61	Ideal for sand casting, with good strength at room temperature and high ductility

Accordingly, this study aims to conduct a bibliometric analysis to identify research trends, collaborative networks, and research gaps related to friction stir welding (FSW) of AZ31 magnesium alloys. The remainder of this article is organized as follows: Section 2 details the research design and tools employed, including search terms and data processing techniques. Section 3 presents the overall number of relevant publications, key research topics, temporal trends, frequently used keywords, motivating factors for lightweight alloy adoption, and global research and collaboration networks. Section 4 summarizes the main findings and highlights opportunities for further research in this field.

2 Method

To identify research trends, gaps, and thematic relevance, a bibliometric approach was employed to systematically examine the body of work published in major technical and scientific databases. In this study, the bibliometric analysis was limited to the Web of Science database. Other platforms, such as Scopus, Springer, and Google Scholar, structure their data differently, which can complicate metadata extraction and limit the clarity and consistency of results. In addition, automated data collection (web scraping) from Google Scholar violates the platform's terms of use and may result in access restrictions. These limitations may be addressed in future research through alternative data integration strategies.

A structured search was conducted between February 10 and 21, 2025, using the Web of Science database, recognized as one of the most comprehensive indexing platforms for journals and conferences in welding metallurgy. The query string applied was: *"WELD* AND AZ31*"*, searched across all fields. No additional filters were applied, as the goal was to map the entire historical record involving the two search terms and their related expressions.

Following the search process, three datasets were generated and exported as Excel files, made available as supplementary documents through the link provided in this article. These datasets contain bibliographic information, including titles, authors, keywords, publication years, countries of origin, citation counts, abstracts, and other relevant metadata. The initial query returned 1,681 records, encompassing journal articles, review articles, conference papers, and early access publications. Duplicates and entries without the term "weld*" in the title were removed. Data processing was performed using a Python-based algorithm implemented in the Google Colab® environment.

Several Python libraries were employed for data processing and analysis. The primary bibliometric indicators considered were the number of published works, total citation counts, and international collaboration networks. In the co-authorship network constructed, the 30 most cited authors are represented using three encoded dimensions: connections (edges), edge thickness (collaboration count), and node color (citation magnitude). The network topology reveals collaborative patterns, in which nodes positioned in close proximity represent actively cooperating research teams.

The *pandas* library was utilized for data structuring and manipulation, while matplotlib and pyplot were used for graphical visualization. Natural language processing tasks were performed using the *Natural Language Toolkit (NLTK)*, and *NetworkX* was used to generate visual representations of international cooperation networks. This methodological approach was based on procedures described by Donthu *et al*. (2021), Bagal *et al*. (2023), Ary *et al*. (2023), Ribeiro *et al*. (2024), and Silva *et al*. (2025).

3 Results and discussion

Aiming to identify the main welding processes used for joining lightweight alloys, the statistical and computational approaches applied, and the key mechanical properties analyzed, this bibliometric research confirmed the predominance of Friction Stir Welding (FSW) in the joining of magnesium alloys. This predominance is justified by FSW's ability to produce welds with fewer than 10% of the defects typically found in joints made by traditional fusion welding methods (Chadha *et al*., 2022). As shown in Table 2, approximately 45% of the identified studies focus on FSW. However, the integration of artificial intelligence techniques with FSW remains incipient, appearing in only 0.2% of the analyzed publications. Additionally, no significant occurrences were found that associate FSW with double-pass methods and AI-based approaches.

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The search yielded a total of 1,681 articles related to the application of welding processes to AZ31 magnesium alloys. Since most techniques are explicitly mentioned in the article titles, Table 2 presents the most frequently referenced welding methods. Less common alternatives, accounting for 514 articles, were excluded from the analysis due to their limited relevance to the scope of this study.

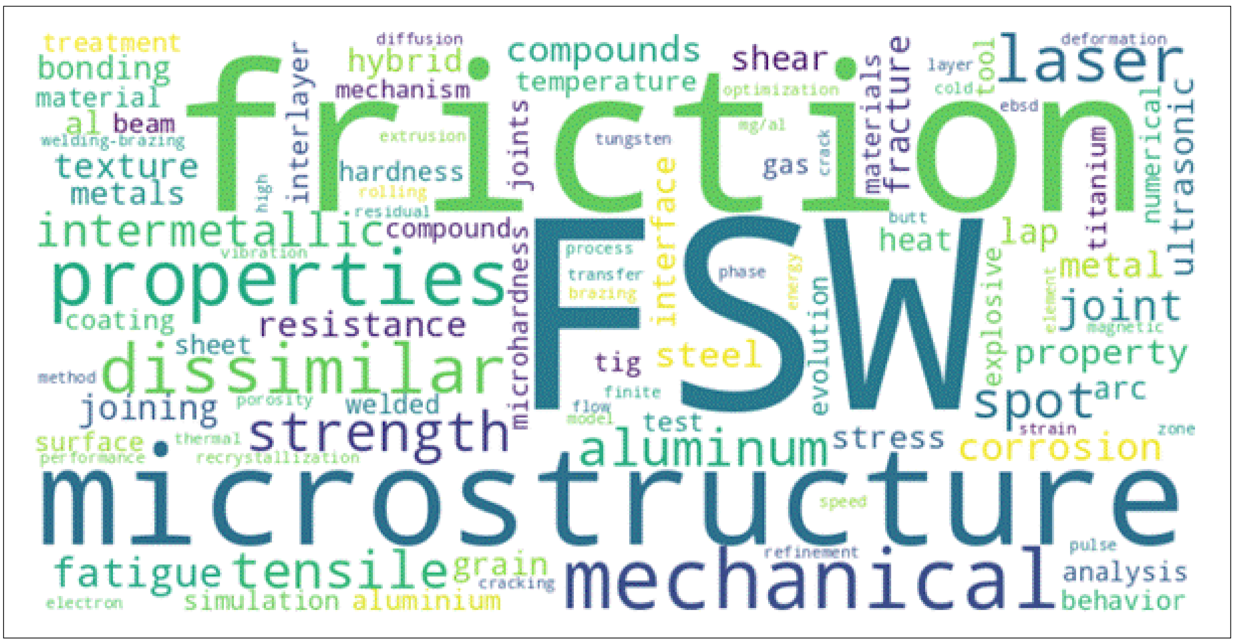
Table 2 ▶ Main welding processes used for joining AZ31 alloys. *Source: research data*

Welding process	Number of occurrences
Friction stir welding (FSW)	756
Laser Beam Welding (LBW)	273
Gas Tungsten Arc Welding (GTAW) or Tungsten Inert Gas (TIG)	70
Brazing	41
Gas Metal Arc Welding (GMAW) or Metal Inert Gas (MIG)	13
Electron Beam Welding (EBW)	12
Resistance Welding (RW)	2

The predominance of the friction stir welding (FSW) process in joining AZ31 alloys is evident. Of the 756 articles addressing FSW, 199 focused on dissimilar joints involving AZ31 and other materials, such as aluminum, stainless steel, or titanium alloys. The remaining 557 publications addressed similar joints using AZ31 alloy alone.

Figure 1 presents a word cloud generated from the most frequent keywords. Notably recurring welding techniques include FSW, laser (LBW), MIG (GMAW), TIG (GTAW), explosion welding, and resistance spot welding. Additionally, the frequent appearance of terms such as corrosion, treatment, microstructure, and properties suggests a significant research focus on mechanical behavior, fatigue life, corrosion resistance, heat treatment strategies, and the influence of microstructural characteristics on macroscopic properties of welded joints.

Figure 1 ▼ Word cloud of main keywords. *Source: research data*



Of the 1,681 articles, only 18 mention "design of experiments" (DOE), representing approximately 1% of the total. Among these, 13 studies (72%) are associated with FSW, indicating a frequent pairing of traditional statistical approaches and this solid-state welding method. Another commonly applied statistical approach is the Taguchi method, which appears in 29 articles (1.7% of the total). Mentions of machine learning, such as reinforcement learning or deep learning, are rare, with only four occurrences overall, two of which are linked to FSW. These findings indicate that the application of machine learning to property prediction and process optimization in this context remains underexplored.

A structured query was also performed to identify studies on the "characterization of corrosion resistance in FSW joints," which returned 86 articles. In contrast, searches using terms such as "double-sided" or "multi-pass" in combination with FSW yielded only 11 studies (Behmand *et al*., 2016; Chen *et al*., 2013; Chowdhury *et al*., 2010; Ke *et al*., 2022; Nukathoti *et al*., 2025; Thakur; Sharma; Bhadauria, 2021; Thakur; Sharma; Bhadauria, 2023; Wang; Morisada; Fujii, 2021; Weng *et al*., 2020; Zhang *et al*., 2023). These studies suggest that double-sided or multi-pass techniques can offer advantages in terms of grain orientation, grain refinement, and improved ultimate tensile strength (UTS).

Therefore, both the use of machine learning techniques and the investigation of double-sided FSW represent underexplored research domains. Notably, no publications were identified combining the three elements: FSW, machine learning, and double-sided techniques, indicating a clear research gap and the potential for novel contributions. See Table 3.

Table 3 ▶
Terms of interest and number of occurrences in abstracts.
Source: research data

Terms	Number of occurrences
Corrosion and FSW	86
Design of Experiments or DOE	18
FSW and DOE	13
Machine Learning or Deep Learning	4
FSW and Machine Learning or Deep learning	2
Double (multiple) sided welding	9
FSW and Double-sided and Machine Learning	0

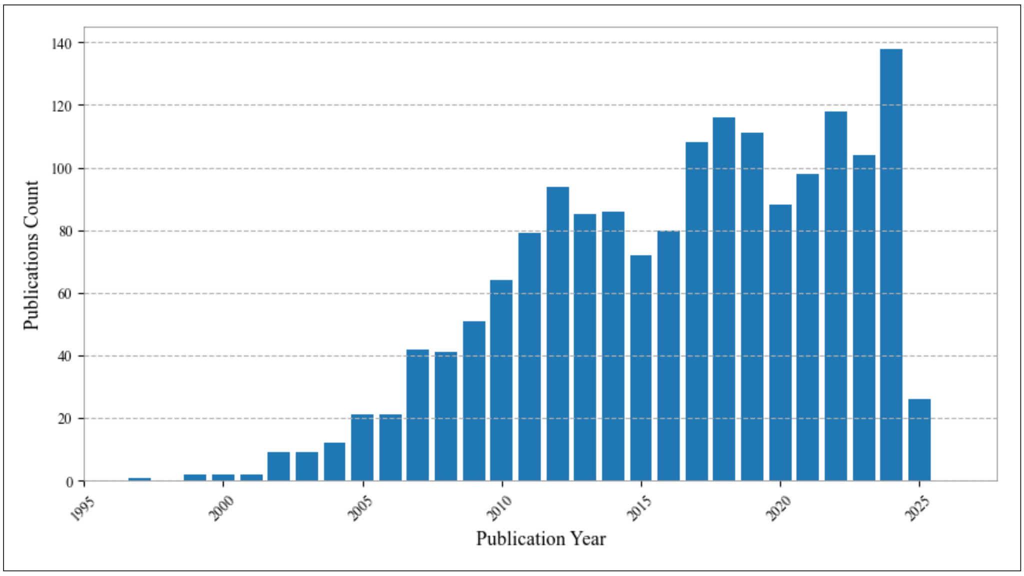
Publications addressing "double-sided" or "double-pass" FSW represent approximately 0.47% of all articles retrieved. Table 4 summarizes these studies, including the title, journal, year of publication, total citations, and authors. Notably, 70% of these works were published between 2021 and 2024, suggesting a growing academic interest. For instance, Nukathoti *et al*. (2025) applied a combined experimental and computational approach and reported that the double-pass technique promotes dynamic recrystallization, refined grain structures, and phase dissolution—resulting in a 19.4% increase in UTS. Similarly, Weng *et al*. (2020) observed superior elongation and tensile strength in double-pass joints, outperforming single-pass welds by 7.27% under comparable conditions.

Table 4 ▼
Articles investigating the theme "double-side".
Source: research data

Title	Journal	Publication year	Total citations	Author
Improving tensile properties by varying the welding conditions of the passes of the double-sided friction stir welding of AZ31B magnesium alloy	Materials Today Communications	2023	8	Thakur; Sharma; Bhadauria (2023)
Tensile properties and strain-hardening behavior of double-sided arc welded and friction stir welded AZ31B magnesium alloy	Materials Science and Engineering: A	2010	116	Chowdhury *et al.* (2010)
Interface strengthening in dissimilar double-sided friction stir spot welding of AZ31/ZK60 magnesium alloys by adjustable probes	Journal of Materials Science & Technology	2021	12	Wang; Morisada; Fujii (2021)
Thermal process and material flow during dissimilar double-sided friction stir spot welding of AZ31/ ZK60 magnesium alloys	Journal of Materials Research and Technology	2022	55	Ke *et al.* (2022)
Effect of tool tilt angle on weld joint strength and microstructural characterization of double-sided friction stir welding of AZ31B magnesium alloy	CIRP Journal of Manufacturing Science and Technology	2021	21	Thakur; Sharma; Bhadauria (2021)
The Influence of the Mechanism of Double-Sided FSW on Microstructure and Mechanical Performance of AZ31 Alloy	Metals	2021	0	Cha; Hou; Zhang (2021)
Fine grained Mg-3Al-1Zn alloy with randomized texture in the double-sided friction stir welded joints	Materials Science and Engineering: A	2013	72	Chen *et al.* (2013)
Improving joint performance of friction stir welded AZ31/ AM60 dissimilar Mg alloys by double-sided welding	Materials Science and Engineering: A	2023	10	Zhang *et al.* (2023)
Double-sided friction-stir welding of magnesium alloy with concave–convex tools for texture control	Materials & Design	2015	51	Chen; Ueji; Fujii (2015)
Influence of double-pass friction stir welding and blank position on formability of aluminum tailor welded alloy blanks	International Journal on Interactive Design and Manufacturing (IJIDeM)	2024	0	Nukathoti *et al.* (2025)

Figure 2 illustrates the steady increase in publications focusing on the welding of AZ31 alloys over time. The earliest record of welding AZ31 alloys using various processes dates back to 1978. A significant growth in publications is observed starting in 2007, when the annual number of articles surpassed 40. This growth can be attributed to technological maturation and widespread adoption of industrial processes for producing these alloys during the 1990s. Prior to this period, the application of AZ31 alloys was limited, in part due to their relatively poor corrosion resistance.

Figure 2 ►
Publications count versus year of publication.
Source: research data



Two additional factors contributed to this upward trend. First, although FSW technology was introduced in the early 1990s (Vijayaraghavan *et al*., 2024), it only began to achieve broad adoption in the 2000s. Second, during the same period, rising environmental concerns related to energy efficiency and weight reduction prompted scientific and industrial interest in alternatives to steel. Magnesium alloys, due to their favorable physical and mechanical properties, emerged as promising candidates to replace conventional engineering materials (Singh *et al*., 2024). The bar corresponding to the year 2025 in Figure 2 represents preliminary data, as the current study considered only the first quarter of the year, which explains the lower publication count for this period.

Figure 3 displays the distribution of publication types, including original research articles indexed in scientific databases, conference proceedings, review articles, and early access papers.

Figure 3 ▼
Publications count versus manuscript type.
Source: research data

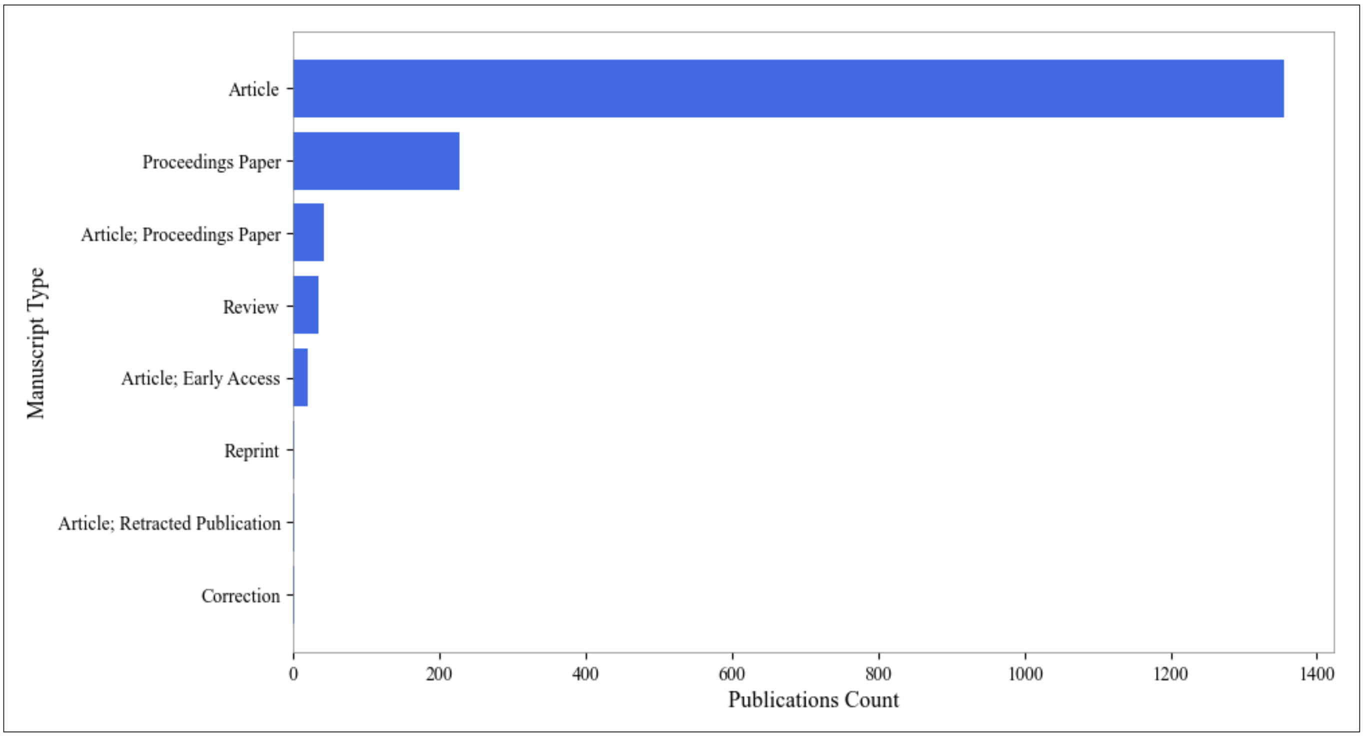


Table 5 ▼
Ten most cited articles by title, journal, year, and total citations.
Source: research data

Table 5 presents the ten most-cited articles on the topic. The most cited paper is a review article published in 2020.

Title	Journal	Publication year	Total citations	Citation
Latest research advances on magnesium and magnesium alloys worldwide	Journal of Magnesium and Alloys	2020	975	Song *et al*. (2020)
Friction stir welding/ processing of metals and alloys: A comprehensive review on microstructural evolution	Progress in Materials Science	2021	621	Heidarzadeh *et al*. (2021)
Friction stir welding of AZ31 magnesium alloy rolled sheets: Influence of processing parameters	Acta Materialia	2009	395	Commin *et al*. (2009)
Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys	Scripta Materialia	2004	547	Sato *et al*. (2004)
Microstructure and tensile properties of friction stir welded AZ31B magnesium alloy	Materials Science and Engineering: A	2008	310	Afrin *et al*. (2008)
MWCNTs/AZ31 surface composites fabricated by friction stir processing	Materials Science and Engineering: A	2006	306	Morisada *et al*. (2006b)
Prospects of laser welding technology in the automotive industry: A review	Journal of Materials Processing Technology	2017	245	Hong; Shin (2017)
Texture variation and its influence on the tensile behavior of a friction-stir processed magnesium alloy	Scripta Materialia	2006	245	Woo *et al*. (2006)
Effect of friction stir processing with SiC particles on microstructure and hardness of AZ31	Materials Science and Engineering: A	2006	234	Morisada *et al*. (2006a)
Grain structure evolution during friction-stir welding of AZ31 magnesium alloy	Acta Materialia	2009	211	Suhuddin *et al*. (2009)

Among the ten most cited articles, eight focus on friction stir welding (FSW), reaffirming its relevance in the field. One review article, published in 2017, addresses laser welding. A recurring and particularly noteworthy theme in these highly cited works is the correlation between the number of welding passes and grain refinement. This relationship is associated with improved mechanical performance, including a 13% increase in tensile strength and up to a 26% enhancement in elongation compared to single-pass welds. These results were consistently obtained in tests conducted in accordance with ASTM E8/E8M standards (Cha; Hou; Zhang, 2021; Chen *et al*., 2013; Thakur; Sharma; Bhadauria, 2023; Zhang *et al*., 2023).

Furthermore, double-pass welding increases the volume of processed material, promoting enhanced material mixing, improved bead symmetry, and more homogeneous and robust joint structures (Zhang *et al*., 2023). The referenced studies indicate that mechanical and metallurgical properties tend to improve linearly with the implementation of second or multiple passes, particularly regarding tensile and fatigue resistance (Nukathoti *et al*., 2025). However, the effects of multi-pass techniques on corrosion behavior and production time remain largely unexplored.

Figure 4 presents the ten most productive authors in the field, with Hong Tao Liu (Liu *et al*., 2017) ranking first with 60 publications. These researchers are predominantly based in Asia, particularly in the People's Republic of China. This geographical concentration is consistent with the data shown in Figure 5, which reinforces China's leadership in scientific and technological output, as also reported by the *Nature Index*[1].

[1] Nature Index. Available at: https://www.nature.com/nature-index/country-outputs/China. Accessed on: 23 may. 2025.

Figure 4 ▶ Authors versus publications count. *Source: research data*

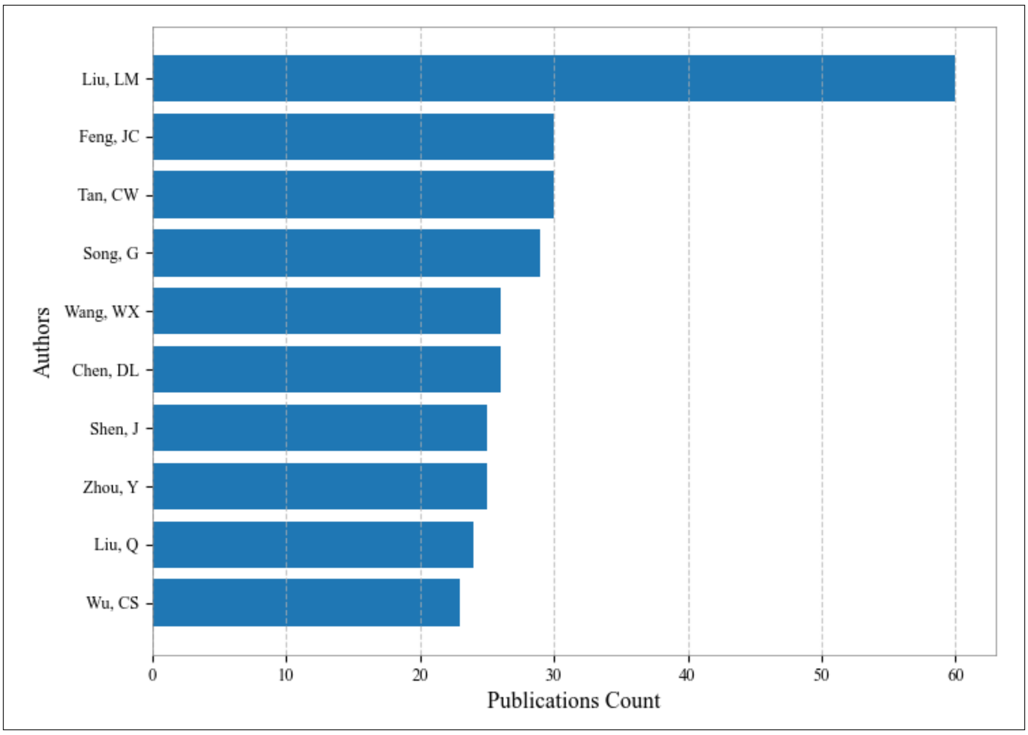
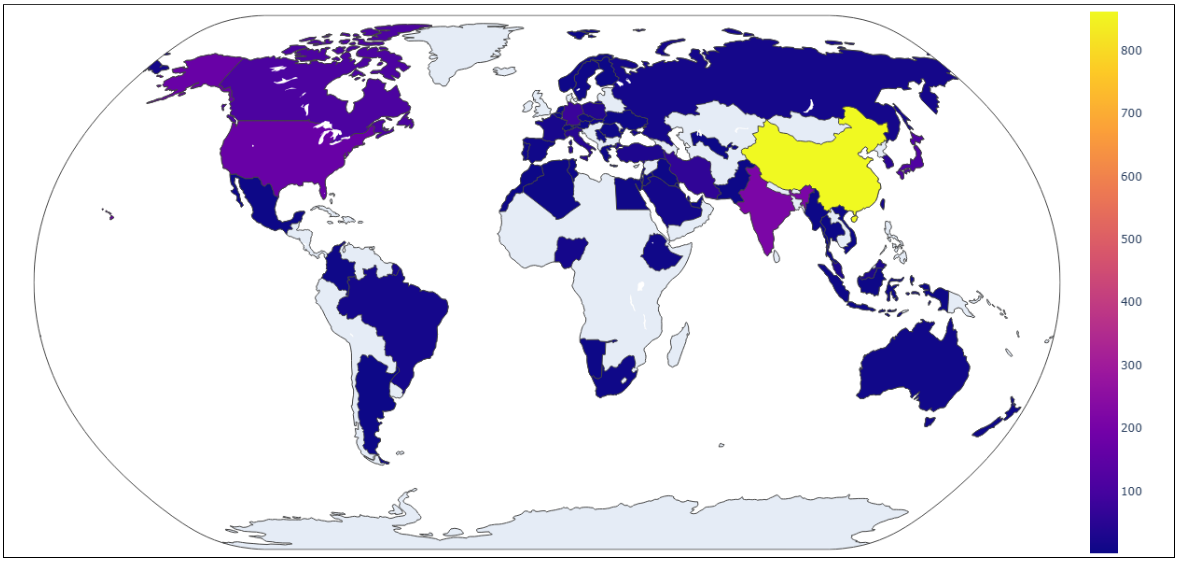


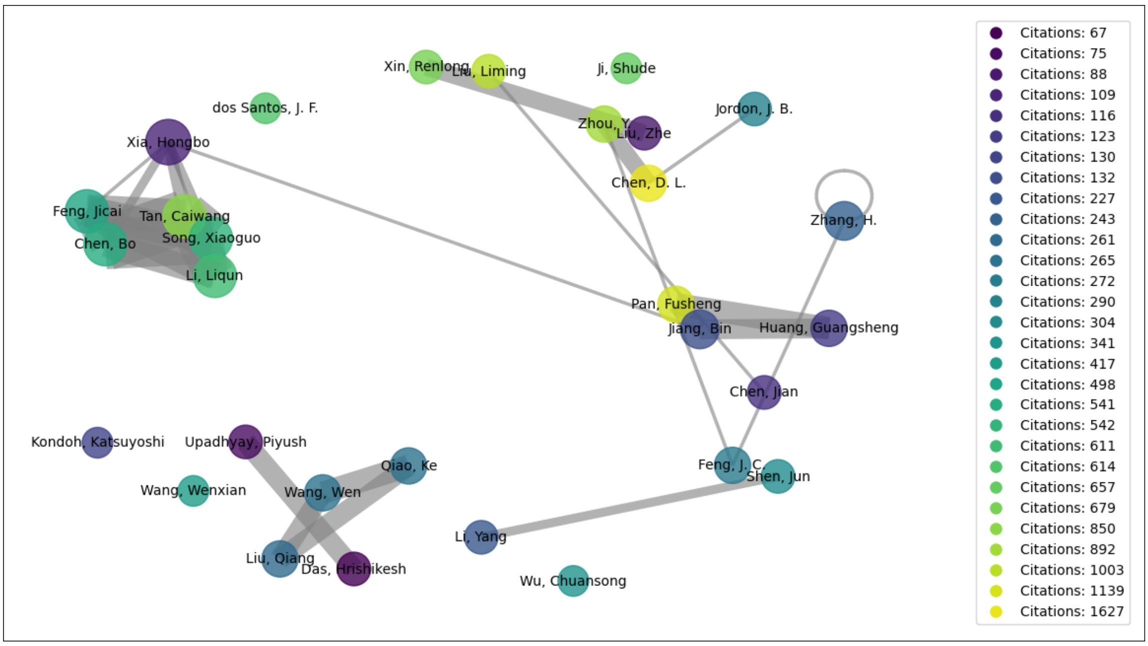
Figure 5 ▼
Country versus publications count.
Source: research data



China leads with over 800 publications in the field, followed by India, the United States, Japan, and Canada. Asia is projected to become the largest producer and consumer of magnesium alloys by 2029, driven by their applications in the automotive and aerospace industries (Mordor Intelligence, 2025). As major consumers of these materials, these countries are also the focus of significant research efforts aimed at improving their application efficiency and operational safety.

Lastly, Figure 6 shows the collaboration network of the 30 most cited authors, revealing three major research groups. The thickness of the connecting lines reflects the relative influence of individual researchers within these networks. Notably, some renowned researchers, like Santos from the Pacific Northwest National Laboratory (USA), are not part of the main clusters but still rank among the top 30 most cited authors.

Figure 6 ▼
Collaboration network of the 30 most cited and collaborative authors.
Source: research data



Jorge Fernandez dos Santos is currently the Chief Materials Scientist in the Applied Materials and Manufacturing Group of the Energy and Environment Division (EED) at the Pacific Northwest National Laboratory. He is the only Brazilian researcher on this list, with over 700 citations and more than 50 co-authors. His research covers solid-phase joining, materials processing, and development technologies, mainly focusing on optimizing processes, microstructural evolution, and mechanical performance. His studies include welding lightweight alloys, multi-pass techniques, and improving mechanical properties.

In a publication by Bergmann *et al*. (2025), the Friction Stir Welding (FSW) process was examined for joining dissimilar materials like aluminum alloy (AA6082) and stainless steel (AISI 316), especially for naval uses. Although explosion welding is still common in this sector, it has limitations like low efficiency, high CO_2 emissions, and safety hazards. Therefore, alternative methods like FSW are being actively explored. In their study, tensile strength values exceeding 200 MPa were achieved, representing an increase of approximately 33% relative to the tensile strength limit of the lower-strength base alloy (AALCO, 2005).

Another study by Chen *et al*. (2025) analyzed microstructural refinement in a magnesium alloy (Mg-0.5Zn-0.3Ca, wt.%). Results showed significant improvements in compressive yield strength (CYS), ultimate compressive strength, and failure plastic strain, by 11%, 28%, and 66%, respectively.

In the co-authorship network, the top 30 cited authors are shown with three encoded features: connections (edges), edge thickness (number of collaborations), and node color (citation count). The network structure reflects collaborative patterns, where nodes close together indicate active research groups.

4 Conclusions

The results of the bibliometric analysis reveal a growing research interest in welding AZ31 magnesium alloys, as evidenced by the substantial increase in publications in recent years, with a peak observed in 2024. This trend underscores the increasing importance of AZ31 alloys in modern manufacturing, as well as sustained efforts within the scientific community to develop efficient and reliable joining techniques.

Among the most common welding methods, Friction Stir Welding (FSW), Laser Beam Welding (LBW), and Gas Tungsten Arc Welding (GTAW) emerge as the dominant techniques. However, despite the expanding literature, the use of advanced statistical tools for optimizing welding parameters remains limited. Only 18 publications were identified that used robust statistical approaches like Design of Experiments (DOE); an additional 29 studies employed Taguchi methods, and just four studies incorporated Machine Learning techniques to analyze multivariate responses, including ultimate tensile strength (UTS), corrosion resistance, and fatigue life. This highlights a notable methodological gap in the field.

The application of robust statistical methods could reduce the number of experiments needed and help focus on the most influential variables affecting welding quality. It would also allow researchers to explore parameters often overlooked, beyond welding speed, rotational speed, and tilt angle, such as the effects of double-pass welding, post-weld aging heat treatment, and adding alloying elements, as well as their influence on mechanical properties. The implementation of these strategies could improve the predictability of material characteristics and in-service performance. Additionally, statistical methods like

Box-Behnken, Definitive Screening, and Plackett-Burman are particularly effective in multivariate processes, aiding in identifying higher-order interactions, model curvature, trends, and behaviors through response surface methodology.

In Brazil, RIMA is the only company operating in Latin America that produces metallic magnesium and its alloys, primarily in the form of ingots, magnesium powder, desulfurizers, and cast components. This production accounts for less than 3% of global magnesium production. Nevertheless, according to the International Magnesium Association (IMA, 2014), the silicothermic process used by RIMA has the lowest CO_2eq/kg Mg emission rate among the main global production methods, at about 10.1 kg CO_2eq/kg Mg, which is 56.7% and 39.1% of the emissions from Pidgeon and Electrolysis processes, respectively. These figures place the Brazilian company at the forefront of producing the world's lightest structural metal, which is also environmentally friendly and crucial for the recyclability of metal alloys.

Due to its high biocompatibility, chemical stability, magnetic impermeability, corrosion resistance, and mechanical strength, magnesium is used in biomedicine, electronics manufacturing, and transportation, especially in structural components and accessories. Within this context, integrated policies connecting producers and consumers are both strategic and vital for national industrial integration. Fiscal incentives and investments in R&D through measures like the Lei do Bem, Lei de Informática, and public-private partnerships (PPPs) can create a development ecosystem that integrates geographically isolated yet economically linked productive sectors.

Proposing alternatives to address the limitations imposed by Brazil's vast size and its predominantly road-based transportation network is crucial for enabling more efficient asset integration and material flow. In this context, policymakers need to engage in strategic planning to ensure that auctions, concessions, and other political-administrative tools promote the development of a diversified, logistically and economically efficient transportation system, including railways and waterways. Such infrastructure would accelerate the movement of raw materials, inputs, and processed goods, decrease import dependence, and strengthen sustainable national value chains, such as RIMA's capacity to produce metallic magnesium and alloys, and EMBRAER's need to use these materials as a leading Brazilian aircraft manufacturer. According to institutional reports, EMBRAER is expected to produce around 11,000 new aircraft over the next 20 years, corresponding to an estimated market value of approximately USD 650 billion (Embraer, 2025), and creating employment and income across various regions.

In the naval industry, the use of light alloys greatly enhances vessel efficiency by increasing cargo capacity, boosting displacement speed, and lowering energy consumption (Bhattacharjee *et al*., 2023). Given Brazil's extensive coastline, one of the 20 longest in the world, spanning approximately 7,300 km, and the strategic potential of its navigable waterways, continued investment in research, development, and innovation is crucial. These efforts are vital for boosting sector competitiveness and reestablishing the domestic and export flow of goods, both critical for the recovery and sustained growth of the national economy (Pompermayer; Campos Neto; Morais, 2014).

The analysis further indicates that double or multi-pass welding using FSW remains underexplored, with only eight studies identified to date. Notably, no research was found combining FSW, double-sided welding, and Machine Learning techniques for joining AZ31 alloys. This scarcity highlights the originality of this study and points to promising future research directions aimed at improving weld quality and performance through integrated technological approaches.

Furthermore, the most productive research groups are based in countries like China, India, Japan, the United States, and Canada, regions known for their leadership in magnesium alloy production and application. Despite being one of the world's largest magnesite producers, Brazil lacks sufficient domestic infrastructure to convert this resource into semi-finished metallic products. As a result, Brazil mainly relies on imports of refined magnesium from China for its industries. This situation reveals a strategic gap in the country's industrial policy and emphasizes the urgent need to strengthen domestic technological capabilities. Addressing this gap could contribute to alignment with global ESG (Environmental, Social, and Governance) objectives, reductions in greenhouse gas emissions, and the growing demand for magnesium from international automotive manufacturers operating in Brazil.

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Conflict of interest

The authors declare no conflict of interest.

Contributions to the article

FIGUEIRÊDO, A. F.: conceptualization of the study; analytical processing and interpretation of data. **MELO, R. H. F.:** Critical revision of the manuscript for important intellectual content. All authors participated in writing, discussion, reading, and approval of the final article version.

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