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Review Article

Robotic welding techniques in marine structures and production processes: A systematic literature review

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ABSTRACT

Robotic welding has garnered significant attention in the maritime industry for its potential to enhance marine structure quality and optimize production processes. This systematic literature review aims to provide a comprehensive overview of the current state of research in robotic welding for marine applications, encompassing marine structures and production processes, following the PRISMA statement and guidelines. The review encompasses various facets, including welding techniques, processed materials, types of robotic welding, technological advancements, potential advantages, and challenges encountered when implementing robotic welding systems in the maritime sector. The results spotlight the pivotal role of gas metal arc welding (GMAW) in propelling robotic welding technology forward, while wire arc additive manufacturing (WAAM) has experienced a notable surge in popularity, signifying its potential to catalyze significant changes in maritime manufacturing processes. Notably, the predominant use of robotic welding centers on carbon steel materials. However, ongoing advancements indicate a growing diversification, with the incorporation of advanced materials like high-strength alloys on the horizon. Additionally, the utilization of 6-axis robot welding in conjunction with fully autonomous systems has emerged as a versatile and potent instrument that has revolutionized welding methodologies across various maritime research domains. Robotic welding provides a number of advantages, such as increased productivity, higher quality, adherence to industry standards, adaptation to confined and dangerous locations, and facilitation of innovative construction techniques. Nevertheless, adoption of this cutting-edge technology is not without challenges. By synthesizing the results from several investigations, this research study offers useful insights into the current knowledge gaps, emerging trends, and future prospects for the growth of robotic welding in maritime applications.

1. Introduction

The shipbuilding and marine industry play a crucial role in global trade and transportation, requiring the construction of robust and reliable vessels and marine structures. The welding process is a critical aspect, as it ensures structural integrity and longevity. However, traditional manual welding methods often suffer from limitations such as inconsistent quality, low productivity, and safety concerns. To overcome these challenges and improve marine structure and production processes, the integration of technological innovation has

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gained significant attention in the maritime industry.

The advent of technological innovation has substantially reshaped many industries, one of which is the maritime sector. This transformation has significantly impacted marine structure construction and production processes, largely driven by the adoption of automation and robotics [1]. Among various automated technologies, robotic welding has emerged as a crucial technique, offering numerous advantages such as improved quality, efficiency, and safety [2].

Robotic welding, a process where automated programmable tools perform welding operations, has been extensively used in different industrial applications [3]. In marine structures and production processes, this technology offers promising potential for enhancing manufacturing efficiency and quality [4]. The effectiveness of robotic welding in this sector, however, is influenced by many factors including process parameters, welding methodologies, material properties, and environmental conditions [5].

The utilization of robotic welding presents numerous benefits in comparison to traditional welding methods, such as enhanced levels of accuracy, consistency, and productivity [6]. The implementation of robotic automation in the welding process enables the attainment of consistently high-quality welds, leading to improved structural integrity and a decrease in the need for rework [7]. Moreover, the incorporation of automated welding systems has the potential to enhance productivity through the reduction of reliance on human labor, the mitigation of overall production duration, and the identification of opportunities for cost reduction [8]. However, there are still challenges and limitations that need to be addressed to fully exploit the potential of robotic welding in the marine industry.

Existing research has focused on various aspects of robotic welding in marine applications. For example, studies have investigated the microstructure, mechanical properties, and corrosion behavior of materials used in robotic welding, such as Incoloy 825 [9], Inconel-625 [10], and Super Duplex Stainless-Steel (SDSS) [11]. These studies provide valuable insights into the suitability of these materials for marine applications and the effects of the welding process on their properties.

Furthermore, research has been conducted on the development of robotic systems for specific tasks in marine welding, such as cooperative mobile robots for fit-out operations inside ship superstructures [6], portable robotic welding platforms for large-scale structures [7], and mobile robotic systems for working in the double-hulled structure of a ship [12]. These studies address the challenges of working in complex and confined spaces in the marine environment and propose innovative solutions for efficient and safe welding operations [13].

Other research has focused on improving the performance and quality of robotic welding through advanced techniques and technologies. For example, studies have investigated the use of vision-assisted robotic finishing [14], laser keyhole weld termination regimes [15], and sensor-enabled multi-robot systems [16] to enhance the accuracy, control, and reliability of welding processes. These studies contribute to the development of intelligent and adaptive robotic welding systems for marine applications.

Additionally, research has explored the optimization of welding parameters and process planning strategies for robotic welding in marine structures. Studies have investigated the optimization of process parameters for steel EN24T [17], the determination of optimum welding parameters for steels used in underwater marine systems [18], and the development of optimal noise filter algorithms for laser vision systems in GMA welding [19]. These studies aim to improve the efficiency, quality, and cost-effectiveness of robotic welding in the marine industry.

To date, numerous studies have investigated the use of robotic welding in marine applications for marine structures and production processes. These studies have explored various aspects, such as different welding techniques, process parameters, quality assessment methods, and productivity enhancement strategies. However, a comprehensive understanding of the existing knowledge, trends, and research gaps in this field is necessary to guide future research efforts and technological advancements.

Considering this context, this study employed a systematic review approach to locate and assess scholarly literature pertaining to the utilization of robotic welding in marine structures and production processes. The subsequent research inquiries served as the guiding framework for the review:

1. Which welding methods are applied using robotic welding technology?
2. Which types of robotic welding were used in the cited research experiments?
3. Which materials were processed in the reported research and experiments?
4. What potential advantages can be derived from the utilization of the indicated robotic welding?
5. What are the current obstacles and deficiencies that hinder its widespread implementation in the industry?

The main objectives of this systematic literature review are threefold: firstly, to identify and classify various robotic welding techniques employed in marine applications, including arc welding, laser welding, hybrid welding, and friction stir welding; secondly, to assess the types and levels of robotic welding mentioned in the literature; and thirdly, to explore the processed materials, including steel, aluminum, nickel-aluminum bronze, and other different metal alloys. Additionally, this review investigates the benefits that could be achieved by using the identified robotic technologies reported in the literature. Moreover, it examines the challenges and limitations faced in implementing robotic welding systems in the maritime sector, including complex marine structures, welding of dissimilar materials, environmental conditions, and combination of building task repeatability and robot control.

The rationale for the review on robotic welding techniques in marine structures and marine production processes is to gather and synthesize existing knowledge in this field. By synthesizing the findings of various studies, this study will provide a comprehensive understanding of the current state-of-the-art, highlight research gaps, and propose recommendations for further research and development. Ultimately, the integration of robotic welding systems in the maritime industry has the potential to significantly improve marine production processes, leading to enhanced efficiency, quality, and competitiveness.

As the maritime industry increasingly embraces advanced materials and intricate designs, the evolution of robotic welding techniques becomes pivotal in addressing the complexities associated with diverse materials, joint configurations, and varying thicknesses. Moreover, the systematic literature review sheds light on the current state of research, showcasing the industry's trajectory and emphasizing the critical need for further advancements. By understanding the intricacies of these techniques, the industry can harness their full potential, ensuring a more efficient, reliable, and sustainable future in marine construction.

2. Methodology

The methodology section outlines the systematic approach employed in conducting the literature review. The outline is structured into two components: an overview of the search strategy and a detailed selection process. The former provides insight into the overarching strategy designed to identify relevant literature, while the latter delves into the specific steps undertaken for the selection of studies.

2.1. Overview of the search strategy

In order to conduct this inquiry, an approach based on systematic review was employed. A systematic literature review (SLR) is a rigorous and comprehensive analysis of the available literature pertaining to a certain subject. The process entails a methodical exploration and evaluation of pertinent scholarly works, adhering to a predetermined approach in order to uphold objectivity and the ability to replicate findings [20–23]. The methodology employed for conducting this systematic literature review on "Robotic Welding Techniques in Marine Structures and Production Processes" was formulated in accordance with the recommendations outlined by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to guarantee a thorough and impartial review [24].

The probability of bias in the selection of publications is a limitation of the systematic review methodology. The application of inclusion and exclusion criteria may also result in the omission of pertinent papers that do not meet these criteria. Many advancements in the field of robotic welding in marine application are driven by practitioners who may not publish in journals or conference proceedings. Consequently, it is possible that pertinent studies published in grey literature or elsewhere were overlooked during the search.

The search strategy was developed to identify all relevant publications related to robotic welding in marine applications. Only publications which are included in ScienceDirect, IEEE Xplore, Scopus, and Web of Science electronic databases were considered [25]. The search terms included combinations and variants of "robotic welding", "marine structures", "shipbuilding", and "production processes".

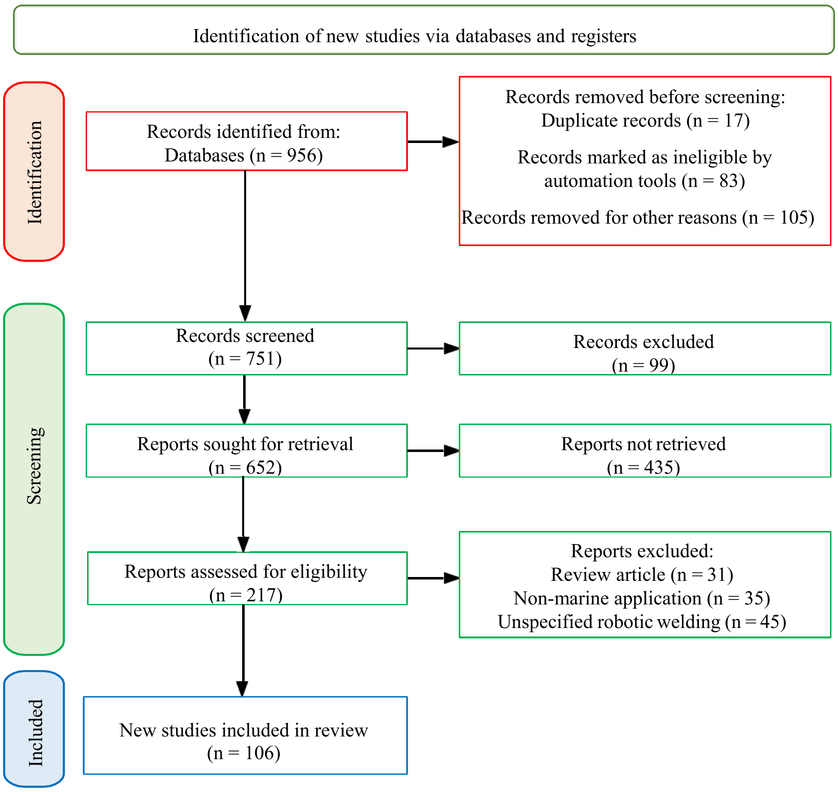

Fig. 1. Process flow diagram for a systematic literature review (PRISMA flowchart).

To select the most relevant publications, inclusion and exclusion criteria were established. The inclusion criteria focused on publications that specifically addressed robotic welding techniques in marine structures and production processes. Additionally, publications had to be written in English and published within the past 15 years (2007–2022) to ensure currency. Exclusion criteria were applied to filter out irrelevant publications that were unrelated to robotic welding, marine applications, or marine structure and marine production processes.

The initial screening process consisted of evaluating the titles and abstracts of the selected publications in order to ascertain their relevance to the research subject. The publications that were chosen were subsequently acquired in their entirety for further evaluation. Every publication underwent a comprehensive evaluation process, wherein the inclusion and exclusion criteria were meticulously applied to determine its suitability for inclusion in the systematic literature review [26].

The quality and relevance of the selected publications were assessed using evaluation criteria such as the rigor of research methodology, the validity of findings, and the reputation of the authors and publishing venues. This assessment helped to ensure that high-quality and reliable publications were included in the systematic literature review [27].

Data were extracted from the selected publications, including information such as authors, title, publication year, research objectives, methodologies, key findings, and the type of robotic welding technique applied. This data extraction process enabled the organization and synthesis of the information obtained from the publications, facilitating the identification of common themes, trends, and research gaps, as well as examining the implications and potential future directions suggested by the reviewed literature. The data were summarized and analyzed descriptively to identify common themes, advancements, and challenges related to robotic welding in marine applications.

The findings of the systematic literature review were organized and presented in a coherent manner, following the structure of the research paper. The methodology, key findings, and insights gained from the reviewed literature were summarized, and any implications and recommendations were discussed.

2.2. Detailed selection process

The flow diagram depicted in Fig. 1 presents a comprehensive outline of the selection procedures conducted for this review, adhering to the guidelines set forth in the PRISMA declaration [24] and utilizing the PRISMA2020 product [28]. The selection process proceeded in the following manner: The three stages of the screening process include: 1) record identification, 2) title and abstract screening, and 3) full-text screening according to predetermined eligibility criteria. Our analysis focused exclusively on peer-reviewed articles, as this approach guarantees that the papers published in academic journals and conferences address pertinent research inquiries and present significant findings [29].

The systematic literature review selection process commenced with the identification of 956 published works from various electronic databases, namely ScienceDirect, IEEE Xplore, Scopus, and Web of Science. Subsequent to this initial retrieval, 17 duplicate records and 83 records deemed ineligible by automation tools were excluded. An additional 105 records were excluded due to a variety of reasons, such as the unavailability of full texts and the absence of relevant URLs, leaving 751 articles to undergo the screening process.

The screening stage employed four stringent inclusion and exclusion criteria. The first criterion was relevance; papers that did not focus on robotic welding in marine applications were immediately excluded. This led to the elimination of works focusing on different types of structures, such as those concerned with robotic applications in the automotive and land-building sectors. The second criterion considered the specificity of the content; papers that failed to clearly specify robotic welding details and those merely providing review articles were also excluded.

After rigorous application of these criteria, the final selection resulted in a substantial collection of 106 articles. This curated group of papers forms the basis for our systematic literature review, providing a comprehensive understanding of robotic welding applications in the marine industry.

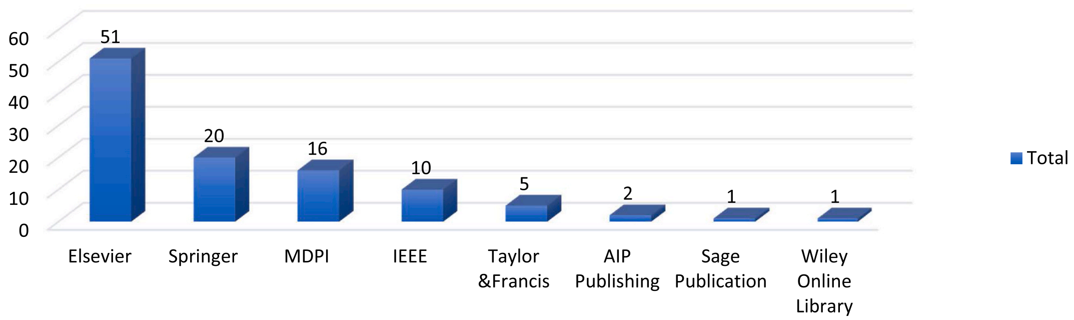

Fig. 2. Distribution of articles according to the publisher.

3. Results

The search and selection procedure yielded a cumulative count of 106 articles that were incorporated into the review. The search process involved identifying relevant articles from various sources, including academic journals and conference proceedings. The selection process involved evaluating the relevance and quality of the articles based on their titles, abstracts, and full texts.

The review's articles address a wide range of subjects relevant to welding in the shipbuilding sector. The utilization of robotic welding systems, additive manufacturing methods, laser welding, arc welding, and the mechanical characteristics of welded connections are a few of the important topics covered. The articles also cover a variety of welding-related topics, including welding flaws, process parameters, and the impact of various variables on the caliber of the welds.

3.1. Summary of selected articles

This systematic literature review report provides a comprehensive summary of the collected articles, as depicted in Fig. 2. The study includes a comprehensive analysis of various sources, with approximately 75% of the data sourced from journal articles and the remaining 25% from conference proceedings, as highlighted in Fig. 3.

The analysis of the sources revealed that the majority of the reviewed articles, accounting for 51 articles, were obtained from Elsevier. Following Elsevier, we found significant contributions from other reputable publishers, such as Springer, MDPI, and IEEE, ranging from 10 to 20 articles each, with 20, 16, and 10 articles, respectively. Taylor & Francis and Wiley Online Library contributed five and one article, respectively, while the literature review yielded two articles from AIP Publishing and one article from Sage Publications. The high representation of articles from Elsevier highlights its prominence as a major publisher in the field, while contributions from other notable publishers underscore the breadth of research in this area.

According to the year of publication, publications referring to robotic welding in marine applications show a fluctuating trend, with one to five articles being published per year from 2007 to 2016. Starting in 2017, there was a considerable increase, with the count moving from 6 papers to 10 in 2018. Despite a slight decline in 2019, the trend continued to rise, reaching a total of 26 articles in 2022. As illustrated in Fig. 4, this pattern indicates an increasing popularity of research related to this topic.

Table 1 presents the number of publications in respect to journals. Overall, there are 81 articles from journal publications or about 76 per cent of the total article. Accordingly, approximately 41 per cent of robotic welding in marine applications studies were published in five journals including Journal of Manufacturing Processes, The International Journal of Advanced Manufacturing Technology, Robotics and Computer-Integrated Manufacturing, Metals, and Marine Structures. In addition, several articles on this topic were obtained from journals related with maritime field including Marine Structures, Journal of Marine Science and Engineering, Ocean Engineering, Journal of Marine Science and Technology, and Ships and Offshore Structures.

The total number of publications that were related to conference proceedings is presented in Table 2. There are a total of 25 articles that were published in the conferences, which accounts for around 24% of the overall number of articles. As a result, approximately fifty percent of the research on robotic welding used in marine applications has been published in the proceedings of five different conferences. These conferences are The International Federation of Automatic Control Proceedings, Materials Today: Proceedings, Procedia Engineering, and Procedia Manufacturing. In addition, the AIP Conference Proceedings has also included some of this research.

The analyzed articles have been systematically categorized into three distinct research areas, each aligned with its primary objectives. These categories encompass production and welding processes, structural and mechanical properties, and the parametric development of robotic welding techniques, as clearly delineated in Table 3. In total, the compilation comprises a comprehensive collection of 43 articles dedicated to the exploration of production and welding processes, an in-depth examination of 40 articles focusing on the intricate realm of structural and mechanical properties, and a dedicated selection of 23 articles delving into the realm of advancements in parametric robotic welding development. This classification allows for a comprehensive and organized overview of the diverse research efforts undertaken within these domains, shedding light on the multifaceted landscape of advancements in this

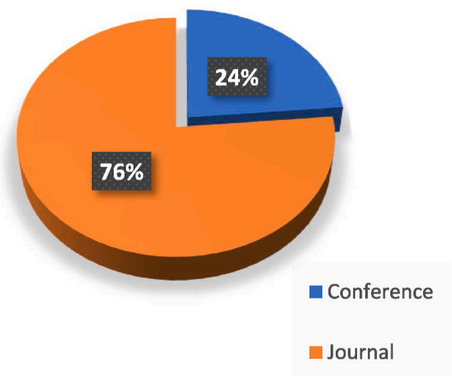

Fig. 3. Proportion of journal articles and conference papers obtained for review.

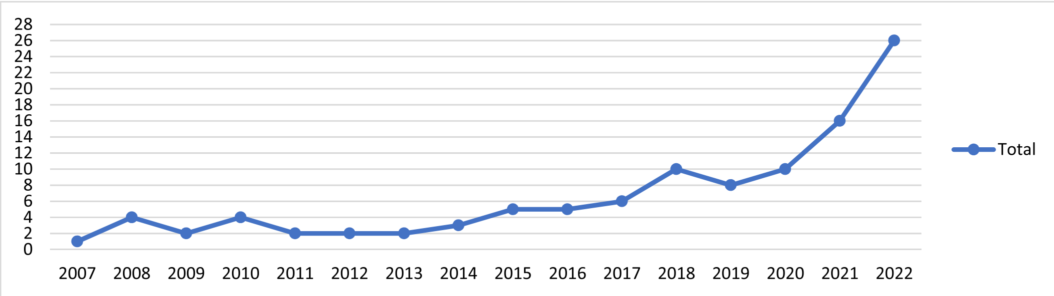

Fig. 4. Number of publications per year after selection.

Table 1
Number of publications by journal.

Journal	Publisher	References	Article
Journal of Manufacturing Processes	Elsevier	[4,15,30–36]	9
The International Journal of Advanced Manufacturing Technology	Springer	[37–44]	8
Robotics and computer-Integrated Manufacturing	Elsevier	[12,45–50]	7
Metals	MDPI	[11,51–54]	5
Marine Structures	Elsevier	[55–58]	4
Journal of Marine Science and Engineering	MDPI	[59–61]	3
Sensors	MDPI	[16,62,63]	3
Journal of Marine Science and Technology	Springer	[64,65]	2
Welding International	Taylor & Francis	[66,67]	2
Welding in the World	Springer	[68,69]	2
Additive Manufacturing	Elsevier	[70,71]	2
Materials	MDPI	[72,73]	2
Ocean Engineering	Elsevier	[74]	1
Ships and Offshore Structures	Taylor & Francis	[75]	1
Neural Computing and Applications	Springer	[76]	1
Robotics and Autonomous systems	Elsevier	[77]	1
Journal of Cleaner Production	Elsevier	[78]	1
Vacuum	Elsevier	[9]	1
Advanced Engineering Materials	Wiley Online Library	[79]	1
Optics &Laser Technology	Elsevier	[80]	1
Buildings	MDPI	[81]	1
Science and Technology of Welding and Joining	Taylor & Francis	[82]	1
CIRP Journal of Manufacturing Science and Technology	Elsevier	[83]	1
Infrared Physics &Technology	Elsevier	[84]	1
Journal of Materials Engineering and Performance	Springer	[85]	1
International Journal of Mechanical Sciences	Elsevier	[86]	1
Journal of Materials Processing Tech.	Elsevier	[87]	1
Computer-Aided Design	Elsevier	[88]	1
Proc. IMechE, Part E: Journal of Process Mechanical Engineering	Sage Publication	[89]	1
Processes	MDPI	[90]	1
Defence Technology	Elsevier	[91]	1
European Journal of Mechanics/A Solids	Elsevier	[92]	1
Journal of Iron and Steel Research International	Springer	[93]	1
Fusion Engineering and Design	Elsevier	[94]	1
Materials Letters	Elsevier	[95]	1
Sustainability	MDPI	[96]	1
Materials Science and Technology	Taylor & Francis	[10]	1
The Journal of The Minerals, Metals & Materials Society (TMS)	Springer	[97]	1
Mechatronics	Elsevier	[98]	1
Wear	Elsevier	[99]	1
Metallurgical and Materials Transactions B	Springer	[100]	1
International Journal of Precision Engineering and Manufacturing	Springer	[101]	1
Engineering Failure Analysis	Elsevier	[102]	1
Materials &Design	Elsevier	[103]	1
Grand Total			81

field.

Fig. 5 depicts the distribution of publications based on the geographic location of the primary author's affiliated institute. The majority of scholarly publications pertaining to the subject were authored by scholars based in China, with a total of 31 papers, followed by Korea, India, United Kingdom, Singapore, and Australia which has 17, 12, 8,6, and 4 articles, respectively. When

Table 2
Number of publications by conference proceeding.

Conference	Publisher	References	Article
The International Federation of Automatic Control Proceedings	Elsevier	[104–107]	4
Materials Today: Proceedings	Elsevier	[18,108,109]	3
Procedia Engineering	Elsevier	[19,110]	2
Procedia Manufacturing	Elsevier	[14,111]	2
AIP Conference Proceedings	AIP Publishing	[112,113]	2
Mexican International Conference on Artificial Intelligence	IEEE	[114]	1
Sixth International Conference on Natural Computation (ICNC)	IEEE	[115]	1
International Conference on Control Automation Robotics & Vision (ICARCV)	IEEE	[7]	1
International Conference on Industrial Technology (ICIT)	IEEE	[116]	1
Iberian Robotics Conference	Springer	[117]	1
International Conference on Intelligent Robots and Systems (IROS)	IEEE	[118]	1
International Conference on Control and Automation	IEEE	[119]	1
Conference on Emerging Technologies & Factory Automation (ETFA)	IEEE	[120]	1
International Workshop on Advanced Motion Control (AMC)	IEEE	[121]	1
International Conference on Control, Automation and Information Sciences (ICCAIS)	IEEE	[122]	1
Light Metals	Springer	[123]	1
International Symposium on Robot and Human Interactive Communication (RO-MAN)	IEEE	[6]	1
Grand Total			25

Table 3
Research areas and their included topics.

Research areas	Included Topics	References
Production and Welding Processes (43 articles)	Production and assembly process, weld bead geometry, workspace analysis, life cycle assessment, welding process, space posture of arc welding guns, post-production analysis, decision-making, welding sequence optimization, CAD integrated weld paths, vision-assisted for corner joints, welding in intersecting joint, filling shape-varying geometry, wireless teaching pendant, weld formation, path planning and forming, welding position.	[6,7,12,14,30,31,33,35,36,38,39,41,44,45,47,54,58,60,64,66,67,69,70,75,77–79,81,88,90,91,96,98,104–107,110–112,114,117,120]
Structural and mechanical properties (40 articles)	Microstructure and mechanical properties, structural analysis, fatigue resistance, corrosion-fatigue crack growth, wear and corrosion resistance, dynamic behavior, micro and macro examination, forming appearance, thermomechanical analysis, electrochemical evaluation, material composition, fracture mechanism.	[9–11,15,32,37,40,42,43,51–53,55–57,59,61,68,71–74,80,83–87,89,92–95,97,99,100,102,103,108,123]
Parametric development (23 articles)	Welding seam tracking, corner-finding algorithm, feedforward filling control, optimum welding parameter, hybrid machine learning, hybrid offline programming, seam-tracking algorithm, intuitive task programming, structured-light vision system, cost-function driven adaptive welding, laser vision sensing, noise filter algorithm, sensor-enabled robot system, parametric evaluation, object detection and motion planning, deposition ratio, active heat management, end-effector measurement system.	[4,16,18,19,34,46,48–50,62,63,65,76,82,101,109,113,115,116,118,119,121,122]

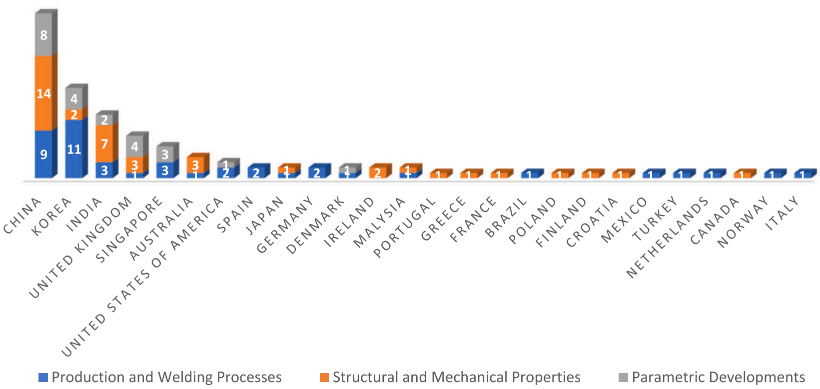

Fig. 5. Number of publications by geographical distribution across their research areas.

examining the geographic distribution of scholarly papers pertaining to research areas, it becomes apparent that academics in Korea are at the forefront of investigating marine production processes through the utilization of robotic welding techniques, as evidenced by the publication of 11 articles on this subject, followed by China with 9 articles. Meanwhile, researchers from China, who led the research in this field, focused on 14 papers observing the structural and mechanical properties of materials processed using robot welding technology, followed by India with 7 articles. Research that focuses on parametric developments for the robot technology used is also dominated by China with 8 papers followed by Korea, India, United Kingdom and Singapore (2–4 papers each).

3.2. The network, overlay and density visualization of keywords co-occurrence

To visualize and examine the relationship between research keywords and published documents based on occurrences and total link strength we have performed a network analysis. Mainly, there are three types of visualization which were developed by using VOS viewer including density visualization, network visualization, and overlay visualization. Co-occurrence analysis was done based on a criterion of author-provided keywords. All the keywords (331), out of these selected keywords (30) are threshold based on a minimum of three co-occurrences. As a result, the top 30 keywords used by the authors' in robotic welding in marine applications articles are shown in Table 4.

Fig. 6 depicts the density map of co-occurrence keywords, where the color of the nodes indicates the frequency of the terms. Each point in the visualization of item density is colored according to the item density at that location. The closer the color of a point to yellow, the greater the number of items in its vicinity and the greater the weights of those items. On the other hand, the closer a point's color to blue, the fewer neighboring items there are and the lighter their weights, the smaller the number of items in its vicinity. According to the occurrences, "wire arc additive manufacturing" is the most used keyword with a total of 20 occurrences. Other keywords which have more than 10 occurrences are "welding", "microstructure", "robotic welding", "mechanical properties", and "laser welding" with total occurrences of 17, 15, 15, 14, and 11, respectively. However, based on the total link strength (TLS), "microstructure" has the highest TLS with 37 links, followed by "mechanical properties," "wire arc additive manufacturing," and "welding" with total link strengths of 33, 28, and 28, respectively.

VOS viewer generates two separate maps for network and overlay visualization. Both visualizations employ a two-dimensional distance-based map that illustrates the degree of object relationships based on their distance [124]. Greater distance indicates a stronger association, and vice versa. Conversely, a closer distance indicates a deeper bond. A label and a circle, the size of which denotes the significance of the keyword, are used to identify it. The network visualization depicts information about keyword cluster groupings, whereas the overlay visualization illustrates the average annual publication of each keyword.

The network visualization of keywords can be seen in Fig. 7 in which various clusters are formed. The item's color is dictated by the cluster to which it belongs. The weight of an object determines the size of the label and the circle of the item. The greater the item's

Tabel 4
Keywords occurrences and link strength in the cited articles.

No	Keywords	Occurrences	Total link strength
1	Wire arc additive manufacturing	20	28
2	Welding	17	28
3	Microstructure	15	37
4	Robotic welding	15	14
5	Mechanical properties	14	33
6	Laser welding	11	16
7	Additive manufacturing	8	14
8	Mobile welding robotic	8	12
9	Shipbuilding	8	13
10	Corrosion	6	12
11	Hybrid laser arc welding	6	9
12	Residual stress	6	9
13	Double hull structure	5	10
14	Gas metal arc welding	5	4
15	Multi-pass welding	5	7
16	Robot vision systems	5	6
17	seam tracking	5	6
18	Finite element analysis	4	4
19	Mechanism design	4	9
20	Nickel aluminum bronze	4	9
21	Optimization	4	7
22	Path planning	4	5
23	Flux-cored arc welding	3	2
24	Genetic algorithm	3	2
25	High-strength steel	3	9
26	Offline programming	3	5
27	Robot	3	3
28	Robotics	3	3
29	Shipyard	3	7
30	Tensile	3	3

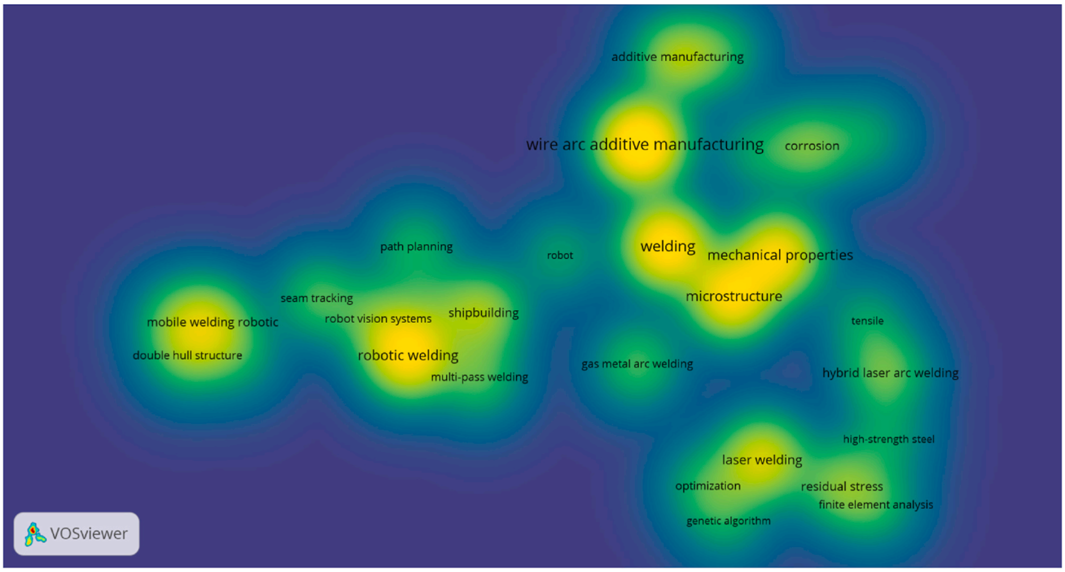

Fig. 6. Density visualization of keywords co-occurrence with minimum three occurrences.

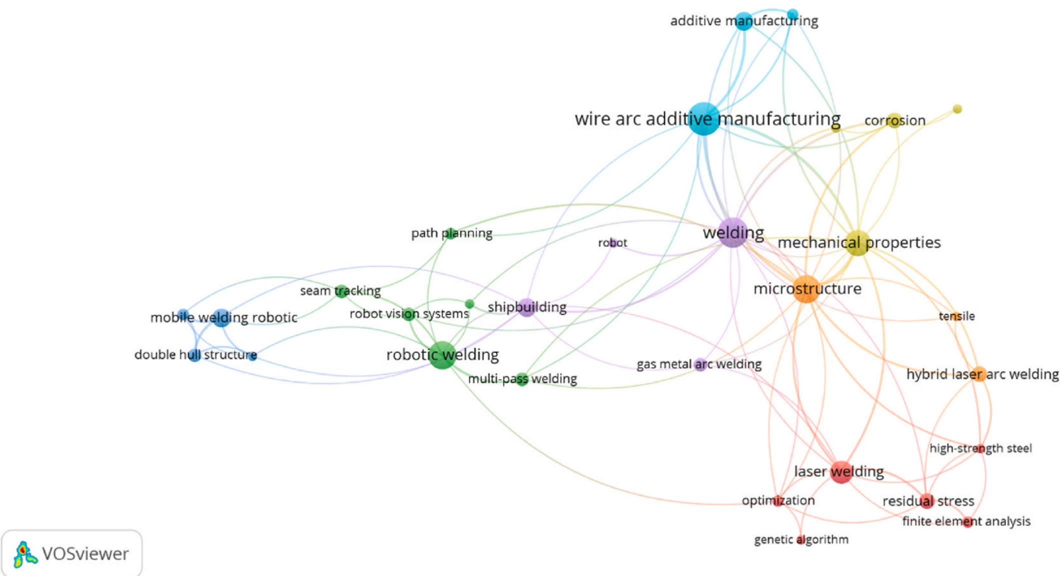

Fig. 7. Network visualization of keywords co-occurrence for robotic welding in marine applications.

weight, the larger the item's label and circle. The inter-linked nodes show that keywords are used together in the study, while the lines weight illustrate the link strength between the keywords. It can be observed that wire arc additive manufacturing keyword is strongly linked with microstructure and mechanical properties. On the other hand, robotic welding itself is strongly linked with robot vision systems, multi-pass welding and seam tracking.

Fig. 8 depicts the keywords relationship through overlay visualization across the year. Links between nodes denote a cooperative or co-occurrence relationship. The colored node indicates the publication year of the article carrying the keyword. It was discovered that the nodes of "corrosion", "wire arc additive manufacturing", "microstructure", "mechanical properties", "hybrid laser arc welding", "path planning", "finite element analysis" and "tensile" represented recent average publication time in past few years. Collectively, these keywords have been highly active and constitute prospective research opportunities.

3.3. Types of robotic welding technologies and the processed materials

Fig. 9 presents the evolution of the welding methods employed using robots from 2007 to 2022. Predominantly, gas metal arc

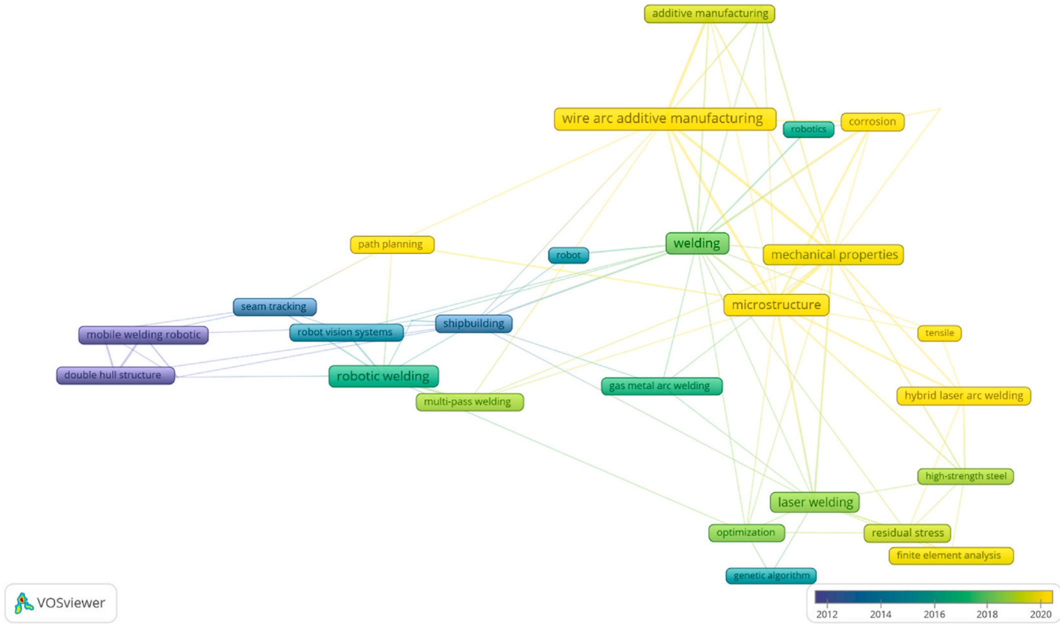

Fig. 8. Keyword's overlay visualization of co-occurrence for robotic welding in marine applications.

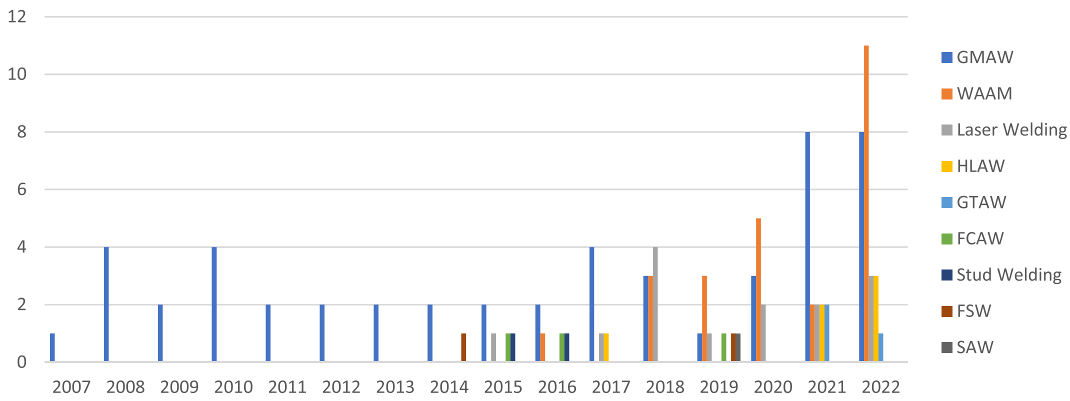

Fig. 9. Robotic welding method in year distribution.

welding (GMAW) played a pivotal role in the progression of robotic welding technology, as depicted in the blue chart. Between 2007 and 2013, only the GMAW method was featured in the documented studies, with a frequency of 1–4 papers annually. However, from 2014 to 2017, research began to diversify. In the field of marine structure and production, various welding techniques emerged, including friction stir welding, laser welding, stud welding, wire arc additive manufacturing, flux-cored arc welding, and hybrid laser arc welding, each being the subject of at least one paper. Notably, from 2019 onwards, robotic welding studies focused on wire arc additive manufacturing surged in popularity, with the number of papers on this topic surpassing those on GMAW, culminating in a peak of 11 articles by 2022.

In the studies, carbon steel was the predominant processed material, as depicted in Fig. 10. From 2007 to 2013, carbon steel was the sole material used in the reviewed studies, with the number of articles each year ranging from one to four. In the subsequent four years, materials such as aluminum, stainless steel, nickel-aluminum bronze, and high-strength steel began to be processed using robotic welding, each material being the subject of one paper. Starting in 2018, a broader range of materials were introduced to the realm of robotic welding. The studies started to feature advanced materials and alloys such as nickel-copper alloys, stainless steel, copper-aluminum alloy, super duplex stainless steel, high-Mn steel, nickel-chromium, duplex stainless steel, and even titanium. These materials typically featured in one to two papers each year.

Regarding the application of robotic welding to various types of materials, Table 5 defines the welding methods employed in robotic welding technologies and showcases their utilization across different materials. In general, the cited papers discuss nine robotic welding methods in marine applications, with gas metal arc welding, wire arc additive manufacturing, laser welding, and hybrid laser arc welding being the most frequently referenced. In comparison, flux-cored arc welding, gas tungsten arc welding, stud welding,

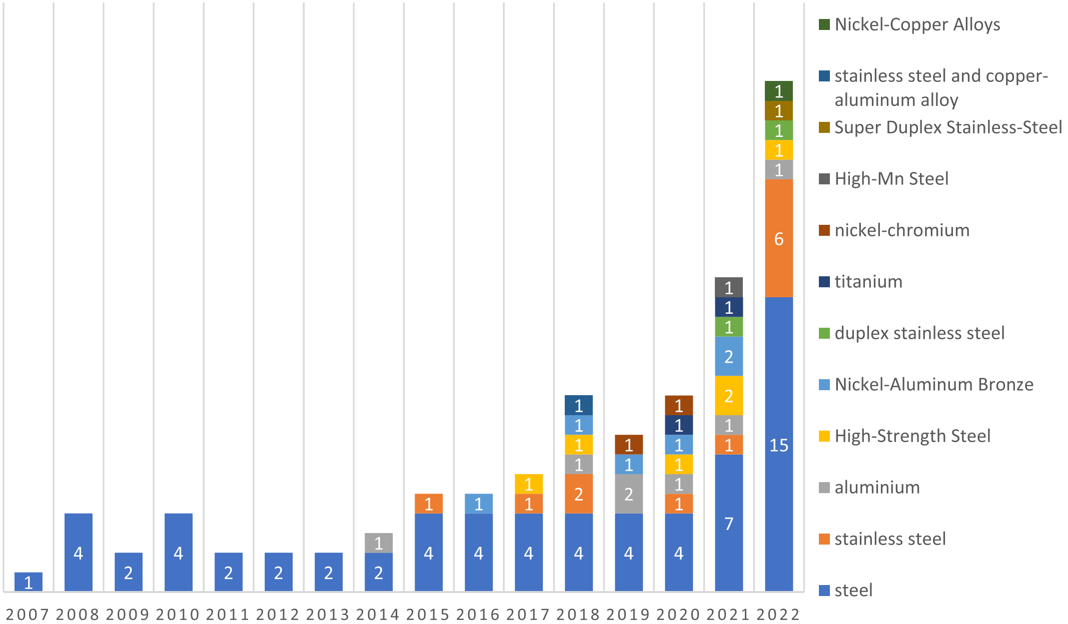

Fig. 10. Yearly distribution of processed materials.

friction stir welding, and submerged arc welding received less attention.

In terms of the distribution of robotic technologies across processed materials, as indicated in Table 5, gas metal arc welding primarily focused on steel, accounting for 39 articles, followed by stainless steel, high-strength steel, aluminum, nickel-aluminum bronze, and duplex stainless steel, totaling 11 articles. Steel, nickel-aluminum bronze, stainless steel, aluminum, nickel-chromium, super duplex stainless steel, duplex stainless steel, stainless steel-copper-aluminum alloy, and nickel-copper alloys were widely used in the context of wire arc additive manufacturing. However, steel remained the most frequently processed material for the other welding methods, followed by stainless steel, high-strength steel, high-MN steel, aluminum, and titanium.

3.4. Robotic welding types from the cited research experiments

The cited articles cover a wide range of robotic welding processes used in various applications, including shipbuilding. These processes include TIG welding, ultrasonic-frequency pulse underwater wet welding, laser welding, wire arc additive manufacturing, gas metal arc welding, friction stir welding, and laser-MIG hybrid welding. These processes are used for joining different materials and have applications in marine structures, shipbuilding, and underwater environments. As shown in Table 6, some specific robotic welding systems used in the research experiments such as ABB, KUKA, Fanuc, Motorman, OTC Daihen, Panasonic, Rail Runner, Universal Robot, and Yaskawa are mentioned in 73 articles. These robot types are well-known in the field of industrial robotics and are likely to have developed 6-axis robotic welding systems that utilize the mentioned welding processes.

The term “6-axis robotic welding” pertains to a welding technique that employs a robotic arm possessing six degrees of freedom for the execution of welding tasks, as depicted in Fig. 11. The robotic arm is outfitted with a welding flame and possesses the capability to maneuver in various orientations, hence enabling the execution of intricate and accurate welding operations. The utilization of this technology has garnered considerable interest across several industries, such as shipbuilding, owing to its capacity to enhance productivity, quality, and safety within welding procedures.

One of the primary benefits of 6-axis robotic welding is its capacity to execute welding tasks in hard-to-reach or tight regions. In shipbuilding, for example, where double-hulled constructions must be welded, a mobile robotic system with 6-axis capabilities has been created [12]. This technique enables efficient and accurate welding in the confined gaps between a ship’s inner and outer hulls.

In addition to its versatility, 6-axis robotic welding offers improved seam-tracking capabilities. Seam-tracking algorithms have been developed to detect characteristic points and track the welding path, ensuring accurate and consistent welds [46]. These algorithms use sensors and vision systems to monitor the welding process and make adjustments in real-time, compensating for any deviations from the desired welding path.

Furthermore, 6-axis robotic welding can be integrated with other advanced technologies to enhance the welding process. For example, the use of digital twin-driven systems and offline programming methods can optimize the production line and improve the efficiency of the welding process [50,60]. Additionally, the integration of sensors and in-process ultrasonic non-destructive evaluation (NDE) systems enables real-time monitoring of the weld quality, ensuring that defects are detected and corrected during the welding process [16].

The choice of welding method and parameters is crucial in 6-axis robotic welding. Different welding methods, such as gas metal arc

Table 5
Types of robotic welding method and the processed materials.

References	Robotic Welding Technology	Description	Processed Material	Article
[4,7,12,19,36–41,43–50,52,57–60, 62–67,76,77,88,89,96,98,99,101, 104–107,110–112,114,115, 117–119,122]	Gas Metal Arc Welding GMAW (50)	Referred to as MIG (Metal Inert Gas) welding or MAG (Metal Active Gas), is an arc welding process that uses a continuous solid wire electrode fed through a welding gun and into the weld pool. This process involves the use of an externally supplied shielding gas (commonly argon, carbon dioxide, or a mixture) that protects the molten weld pool from atmospheric contamination.	steel stainless steel high-strength steel aluminum nickel-aluminum bronze duplex stainless steel	39 4 3 2 1 1
[9–11,32,33,35,51,68,70–73,75,78, 81–83,85,90,92,95,97,102,109, 123]	Wire Arc Additive Manufacturing WAAM (25)	Additive manufacturing technique that employs an arc welding process to create metal parts. Using electric arcs as the heat source and wire as feedstock, layers of material are deposited successively to build up a three-dimensional object.	steel nickel-aluminum bronze stainless steel aluminum nickel-chromium super duplex stainless-steel duplex stainless steel stainless steel & copper-aluminum alloy nickel-copper alloys	8 5 4 2 2 1 1 1 1
[15,31,42,53,55,56,79,80,84,86,87,94, 100,108]	Laser Welding (14)	A fusion welding technique that employs a laser as the heat source to melt and join materials together.	steel stainless steel titanium high-strength steel	8 3 2 1
[54,61,69,74,93,103]	Hybrid Laser Arc Welding HLAW (6)	A method of fusion welding that combines the principles of arc and laser welding.	steel high-strength steel high-MN steel	3 2 1
[18,120,121]	Flux-Cored Arc Welding FCAW (3)	An arc welding process that employs a continuously fed tubular electrode containing a flux to produce the weld. This flux provides the necessary shielding from atmospheric contamination, which can sometimes be enhanced with additional external shielding gas.	steel	3
[16,34,113]	Gas Tungsten Arc Welding GTAW (3)	Commonly known as Tungsten Inert Gas (TIG) welding, this particular arc welding technique employs a non-consumable tungsten electrode to generate the weld. In order to prevent atmospheric contamination, the weld region is protected through the use of an inert shielding gas, often argon or helium.	aluminum steel stainless steel	1 1 1
[6,116]	Stud Welding (2)	A technique where a metal stud is joined to a metal workpiece without the use of a filler material. This process involves placing the stud in contact with the workpiece and igniting an arc. The heat from the arc melts the base of the stud and a portion of the workpiece, allowing them to fuse together. Upon solidification, a solid bond is created. Stud welding is often used for attaching fasteners, such as bolts or pins, to metal sheets in industries.	steel	2
[14,30]	Friction Stir Welding FSW (2)	A solid-state joining process in which two workpieces are fused without melting the base materials. A rotating tool with a pin and shoulder is plunged into the interface of the workpieces and traversed along the joint. The frictional heat generated softens the material, allowing it to be stirred and bonded together.	aluminum	2
[91]	Submerged Arc Welding SAW (1)	An arc welding process that utilizes a continuously fed consumable electrode to produce a weld. The arc and molten weld zone are submerged beneath a blanket of granular fusible flux, which protects the weld from atmospheric contamination and refines its properties. As the arc moves along the joint, the flux gets melted, and upon solidification, it forms a protective slag on the weld bead. SAW is known for its deep weld penetration, high deposition rates, and ability to produce sound welds, making it ideal for welding thick plates.	steel	1
	Grand Total			106

Table 6
Robotic welding types across the method used in the cited articles.

Type of Robot	FCAW	FSW	GMAW	GTAW	HLAW	Laser Weld	Stud Weld	WAAM	Grand Total
ABB (other type)			1			2		6	9
ABB IRB 140			1						1
ABB IRB 1410	1		1			1			3
ABB IRB 1520ID								1	1
ABB IRB 2400			1					1	2
ABB IRB 4400						1			1
ABB IRB 6660			1						1
Adaptive robotic control				1					1
Almega OTC AX V6								1	1
FANUC ARC M-100iC/12			1						1
FANUC M-10iA			1					1	2
FANUC M700i B45						1			1
Kawasaki (other type)			1						1
Kawasaki FA 06E			2						2
KUKA (other type)			1		2	3			6
KUKA KR 120						1			1
KUKA KR 16 arc HW								1	1
KUKA KR 16-2			3						3
KUKA KR 30 HA								2	2
KUKA KR 60 HA						2			2
KUKA KR3 R540			1						1
KUKA KR5 Arc HW				1					1
KUKA LWR 4+							2		2
Motorman HP20D								2	2
OTC Daihen (Other type)								1	1
OTC Daihen FD-B6			1					1	2
Other 6-axis industrial robot						1			1
Panasonic TA-1400								1	1
Prototype 6 axis robot			2						2
Prototype Robot			4						4
Rail Runner (RRX)			4						4
Rail Runner (RRX3)			3						3
Rail Runner (RRX4)			1						1
Rail Runner (RRXC)			1						1
Semi automatic robot			1						1
SP-MAG Panasonic			1						1
Stäubli TX200 robot		1							1
Universal Robot (UR16e)								1	1
YASKAWA HP20						1			1
Grand Total	1	1	33	2	2	13	2	19	73

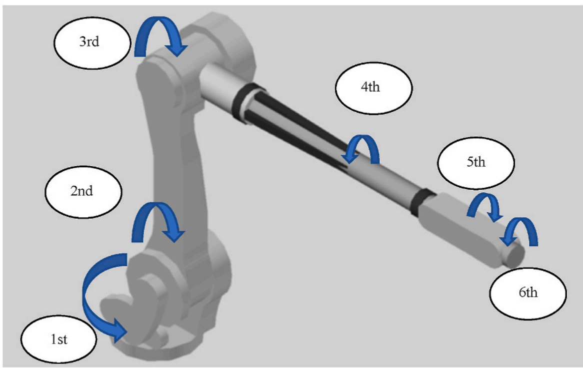

Fig. 11. Six axes' movements of the robotic welding.

welding (GMAW), tungsten inert gas (TIG) welding, laser welding, and friction stir welding, have been applied in various applications [30,52,61,91]. The selection of the appropriate welding method depends on factors such as the material being welded, the desired weld quality, and the specific requirements of the application.

Moreover, the optimization of welding parameters, such as welding speed, current, and shielding gas composition, plays a significant role in achieving high-quality welds [18,97,113]. Advanced techniques, such as machine learning and genetic algorithms, have been employed to optimize welding speed and control parameters, ensuring optimal weld quality and reducing defects [34,48, 74].

3.5. Robotic welding categorization and technological evolution

As presented in Fig. 12, the classification of referenced robotic welding can be categorized into three main groups, which are determined by the mechanism used to manage the robotic systems. These categories include fully autonomous robots, remotely controlled robots, and robots operated by an onboard person. The category of fully autonomous robots operates without any human interference, while the category of remotely controlled robots includes systems that are controlled from a distance. Lastly, the category of onboard operator robots refers to those that are controlled by a human operator present on the robot itself [125]. The category of fully autonomous robots received the highest number of citations, with 68 articles accounting for around 64 percent of the total. In contrast, the categories of remote controlled and onboard operator robots were referred less frequently, with a total of 19 papers, or 18 percent of the citations.

The depiction of robotic welding categories across different time periods is elucidated in Fig. 13. The visual trend portrays the evolution in the utilization of distinct robot categories as observed in the analyzed research papers. Initially, during the initial eight years, remote-controlled and onboard-controlled robots emerged as the prevailing choices. However, a noteworthy shift occurred in the subsequent eight years, as the fully autonomous robot category gained ascendency.

Delving into the specifics, the application of remote-controlled and onboard-controlled robotic welding methods exhibited consistency throughout the entire timeline, with an annual publication rate of one to three papers. In contrast, the ascendancy of the fully autonomous category within the research sphere became evident starting from the year 2015. This category displayed an initially fluctuating pattern, marked by three to six annual publications until 2019. The subsequent years saw a remarkable surge in the use of fully autonomous robotic welding, asserting its dominance with 9, 14, and 25 papers in the final three years, respectively.

Fully autonomous robots have the capability to operate independently, devoid of any human intervention or assistance. The robots possess sensory capabilities and employ algorithms to comprehend their environment, make autonomous judgements, and perform tasks without human intervention. For example, Ahmed et al. [118] made an automated welding system for tubular joints that uses object detection and motion planning algorithms to do welding chores on its own.

In contrast, remotely controlled robots are under the command of human operators who manipulate their motions and behaviors from a distant site. These robots are commonly outfitted with a variety of sensors and cameras that facilitate the acquisition of data, enabling the operator to make well-informed decisions and successfully manipulate the robot. In their study, Oh et al. [88] developed a teaching pendant software specifically tailored for a mobile shipbuilding welding robot. This program allows for remote control and monitoring of the robot's movements and welding process through the utilization of a Personal Digital Assistant (PDA).

The control of onboard operator robots is facilitated by an operator who is either physically situated on the robot itself or in close proximity to it. These robotic systems are frequently employed in scenarios that necessitate human involvement for jobs that cannot be entirely mechanized. For instance, a mathematical model was developed to describe the spatial configuration of the arc welding gun equipped with rotational arc sensors in a gas metal arc welding robot [38]. The technology allows for an aboard operator to effectively manage the robot's movements and carry out welding duties.

The robotic welding technologies mentioned can be classified into three distinct groups based on their state of development: implementing, developing, and prototyping (see Fig. 14). The term "implementing category" pertains to technologies that have reached a state of full maturity and have been successfully employed in real-world construction projects. The developing category pertains to emerging technologies that, upon reaching a state of maturity, have the potential to significantly expand their applications within industrial projects. The prototyping group pertains to the ongoing development of robotic technologies, which are currently faced with various technological obstacles.

In general, the papers reviewed in this study predominantly utilized well-developed robotic welding techniques to conduct their research. Specifically, researchers in this field were engaged in prototyping and developing robotic welding technologies between 2007 and 2013, resulting in an annual output of one to three papers. In contrast, post-2014 witnessed a substantial growth in the

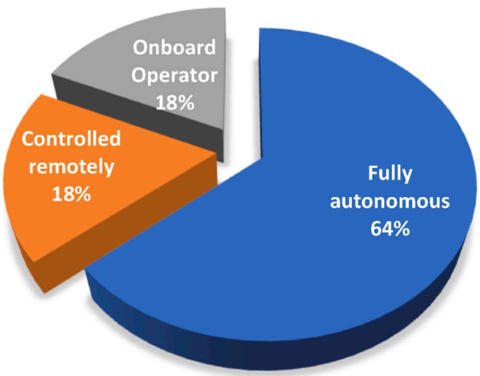

Fig. 12. Classification of referenced robotic welding based on robotic system control mechanism.

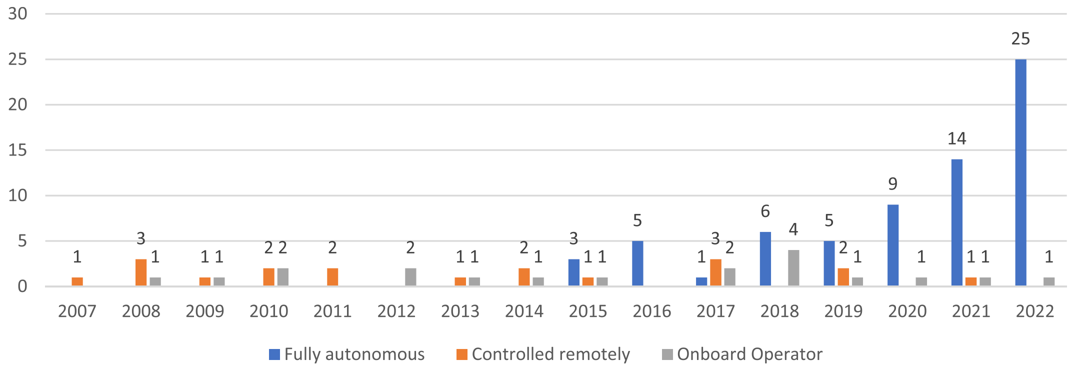

Fig. 13. The categorization of robotic welding across the years.

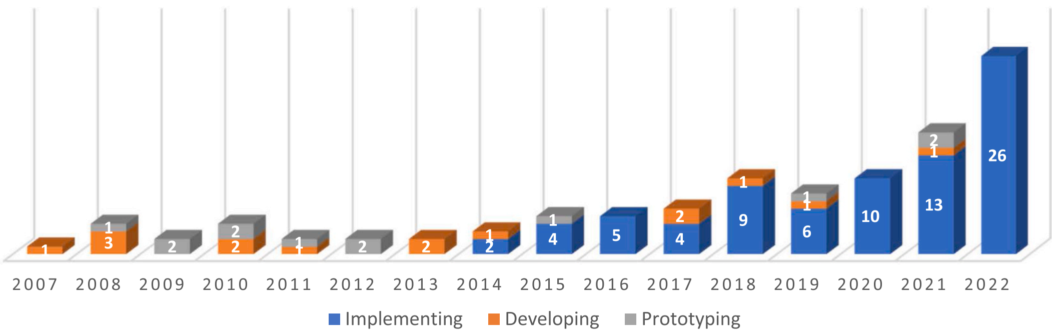

Fig. 14. Level of development of robotic welding technology across the years.

development of industrial robot welding, leading many researchers to gravitate towards this technology as a solution for a myriad of research challenges. From 2014 to 2017, a range of two to five articles were identified, all of which applied well-developed robotic welding methodologies within the research domain. Notably, within the last five years, this trend experienced a significant uptick, culminating in the publication of 26 papers in 2022. This surge unequivocally underscores the pervasive adoption of industrial robots, as all recorded papers exclusively employed these advanced robotic systems.

3.6. Benefits and challenges in the robotic welding application

The utilization of robotic welding has numerous advantages in terms of increased efficiency, improved quality, meeting industrial criteria, suitability for confined and hazardous environments, and enabling new construction techniques. As depicted in Fig. 15, a significant proportion of the publications place emphasis on the advantages associated with the utilization of robotic welding in order to boost efficiency, accounting for 39 percent of the total. A notable proportion of the publications, specifically 26 percent, emphasize the potential of robotic welding in enhancing product quality. Subsequently, 20 percent of the papers focus on the subject of meeting industrial criteria. The papers highlight two additional advantages, namely the capacity to operate in confined and dangerous settings (9 percent) and the facilitation of new construction techniques (6 percent).

Robotic welding offers significant advantages in terms of greater efficiency in marine applications. The use of robotic welding systems in shipbuilding and other marine industries allows for faster and more efficient welding processes [104]. Robotic systems can work continuously without the need for breaks, resulting in increased productivity and reduced cycle times [78]. Additionally, they can be programmed to optimize welding parameters, such as travel speed and wire feed rate, to achieve the desired weld quality and efficiency [91].

In terms of quality improvement, robotic welding offers several advantages. The use of robotic systems eliminates human errors and inconsistencies, resulting in more consistent and reliable welds [100]. Additionally, robotic welding enables the use of advanced welding techniques, such as laser welding and wire arc additive manufacturing (WAAM), which offer improved weld quality and performance [68,80]. Laser welding provides precise control and high-quality welds [80]. WAAM allows for the fabrication of complex geometries and customized components, reducing the need for manual welding and assembly [68].

Robotic welding is well-suited for enclosed and hazardous environments. The use of automation technology reduces the need for human operators to perform activities in hazardous situations such as tight spaces, hot environments, and poisonous substance locations [12,45,46,64,88,105,107]. This method enhances safety and reduces the likelihood of incidents and injuries [106]. Robotic welding systems can also be designed to withstand extreme temperatures and corrosive atmospheres, ensuring their dependability and

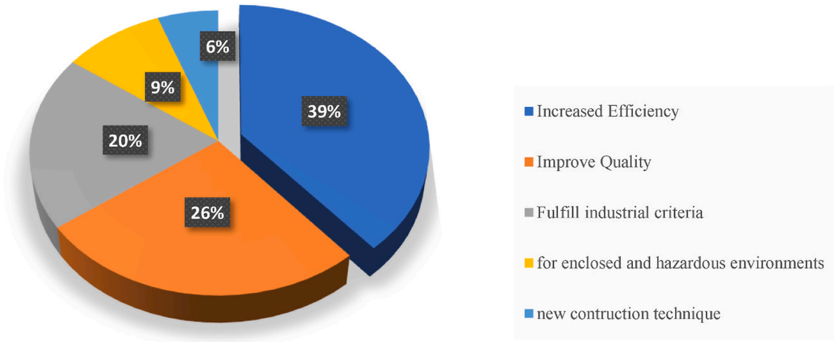

Fig. 15. Advantages of robotic welding in marine applications.

endurance [46,47].

The use of robotic welding in marine applications offers significant advantages in terms of fulfilling industrial criteria. Robotic welding systems can be designed and optimized to meet the specific requirements and standards of the marine industry [65]. They can be integrated into shipbuilding processes, providing precise and efficient welding solutions that adhere to industry regulations and specifications [66]. Welding joints manufactured under acceptable conditions meet Non-Destructive Testing (NDT) and mechanical test requirements as defined in standards [69]. Robotic welding systems can also be programmed, allowing for the generation of welding programs that meet the desired criteria and quality standards [116]. These techniques can meet the stringent requirements of marine applications, ensuring the durability and reliability of welded structures [6].

Robotic welding enables the adoption of new construction techniques, such as arc welding and additive manufacturing, in certain marine structure components [32,33,35,57,109]. Robotic welding systems can be used for wire arc additive manufacturing (WAAM), which involves depositing metal layers to build up a part [32,33]. Robotic welding systems can also be used for other advanced welding techniques, such as welding execution in underwater marine systems, which offer improved weld quality and performance [18].

Despite the benefits, robotic welding in marine applications faces several challenges related to practical data, integrity of structure, also consistency and controllability reported in 49 articles, as shown in Fig. 16. These challenges can impact the efficiency and effectiveness of the welding process, as well as the quality and reliability of the welded structures. The most cited challenge is the availability and accuracy of practical data for robotic welding (35 articles). Robotic welding systems require accurate information about the geometry and position of the workpiece to perform precise and consistent welds. The integrity of the welded structure is another critical challenge in robotic welding for marine applications (7 articles). The structural integrity and safety of marine vessels depend heavily on the strength and quality of the welds. The strength and quality of the welds can be influenced by elements including welding parameters, welding technique, and material qualities. To produce welds of sufficient strength and excellent quality, it is crucial to optimize the welding settings and procedures. Consistency and controllability are also significant challenges in robotic welding for marine applications (7 articles). Consistent welding quality and performance are essential for ensuring the reliability and durability of welded structures. Robotic welding systems should be capable of maintaining consistent welding parameters, such as arc voltage, current, and travel speed, throughout the welding process. Advanced control algorithms and sensing techniques can be employed to achieve consistent and controllable welds.

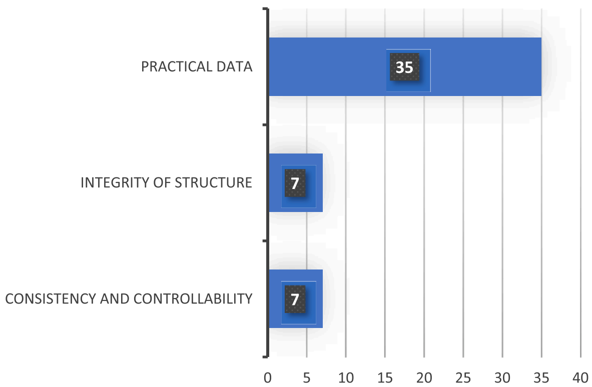

Fig. 16. The challenges associated with the use of robotic welding in marine applications.

4. Discussion

Robotic welding has gained significant attention in the marine industry for the production and construction of marine structures. The review includes a wide range of studies that cover various aspects of robotic welding, including different welding techniques, materials, categorizations, technological advancements, and the benefits and challenges in their application.

4.1. Robotic welding techniques and treated material types

Extensive investigations have explored the application of arc welding integrated with robotic systems to enhance marine structures and production processes such as GMAW, FCAW, GTAW, and SAW [16,38,43,91,121]. Additionally, numerous studies have investigated the utilization of laser welding [31,55,56,80], with certain investigations using the integration of arc welding to form the Hybrid Laser-Arc Welding (HLAW) technique [54,61,69,74,93,103]. However, the integration of wire arc additive manufacturing (WAAM) techniques with welding processes offers new possibilities for marine structures and production process. Additive manufacturing can be used to create complex and customized components, while welding is employed for joining and fabricating larger structures. The combination of these technologies enables efficient production and enhances design flexibility. Research by Taşdemir [75] demonstrated the integration of AM and welding for shipbuilding industry, showcasing the benefits of combining these processes. The integration of AM and welding facilitates rapid prototyping, reduces material waste, and opens up new design opportunities in marine applications.

The variability of materials and joint configurations in marine applications poses a challenge for robotic welding. The cited articles involve welding of various materials, such as steel [56], aluminum [123], nickel-aluminum bronze [71], stainless steel [78], duplex stainless steel [85], titanium [84], and nickel-cooper alloys [95] with different properties and thermal conductivities. Joint designs and configurations may vary significantly, including butt joints [31], fillet joints [115], tubular x-joints [57], and the welding position (e.g. horizontal and vertical-up) [69]. These variations require adaptability and flexibility in robotic welding systems to adjust welding parameters and techniques accordingly. Proper process development, parameter optimization, and sensor-based control systems are necessary to address material and joint variability challenges.

Furthermore, the choice of materials and welding techniques can also influence the sustainability of robotic welding. The application of robotic welding in terms of energy efficiency and sustainability can be analyzed through a life cycle assessment (LCA) approach. LCA is a systematic method used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal [78,79]. In the context of robotic welding, LCA can provide insights into the energy consumption, greenhouse gas emissions, and other environmental impacts associated with the manufacturing and operation of robotic welding systems.

4.2. Categorization of robotic welding and technological advancements

According to robotic welding categorization, each category of robotic control mechanism has its advantages and limitations. Fully autonomous robots offer the potential for increased efficiency and productivity as they can operate continuously without human fatigue or limitations [50]. However, they require sophisticated sensing and decision-making capabilities, as well as robust algorithms to ensure safe and accurate operation [46]. Remotely controlled robots provide the flexibility of human decision-making and intervention, allowing for adaptability to changing conditions and complex tasks [47]. Onboard operator robots offer the advantage of direct human control and physical presence, which can be beneficial for tasks that require dexterity and fine motor skills [115]. The choice of control mechanism depends on the specific requirements of the task and the desired level of human intervention. Further research and development in these areas can lead to advancements in robotic systems and their applications in various industries, including shipbuilding, welding, and manufacturing.

Regarding technological evolution, robotic welding plays a crucial role in research, encompassing various stages from prototyping to technology development and industrial implementation. In the prototyping stage, researchers focus on designing the automatic robotic welding process and introducing advanced algorithms and sensors. Sanders et al. [65] introduced a corner-finding algorithm to help recognize shipbuilding parts, improving the automatic robotic welding process in shipbuilding. Park et al. [62] developed a precise 3D lug pose detection sensor using a structured-light vision system for automatic robot welding, contributing to the accuracy and efficiency of robotic welding systems. Kang et al. [104] developed a multi-welding robot system for sub-assembly in shipbuilding, demonstrating the practical implementation of robotic welding in the shipbuilding industry.

Developing the technology involves improving and optimizing the platform for portable robotic welding in large-scale structures. Dharmawan et al. [7] conducted a survey of platform designs for portable robotic welding in large-scale structures, exploring different design considerations and proposing solutions to improve the portability and flexibility of robotic welding systems. Lee et al. [77] optimized a mobile welding robot by through examination of its workspace utilizing a 3P3R serial manipulator.

Implementing robotic welding in industrial settings requires addressing specific challenges and optimizing the welding process. For example, Kumar et al. [80] conducted a comparative study of pulsed Nd: YAG laser welding of AISI 304 and AISI 316 stainless steels, providing insights into the welding parameters and material composition for optimal weld quality. Furthermore, the use of advanced technologies such as laser penetration welding and wire arc additive manufacturing (WAAM) has been explored in shipbuilding. Rong et al. [56] investigated laser penetration welding of ship steel EH36 and its application in predicting residual stress. Bekker & Verlinden [78] conducted a life cycle assessment of wire + arc additive manufacturing compared to other manufacturing processes in stainless steel, highlighting the environmental benefits of this technology.

4.3. Applications of robotic welding: advantages and challenges

Robotic welding offers several benefits in terms of efficiency, improved quality, meeting industrial criteria, suitability for confined and hazardous environments, and enabling new construction techniques. These advantages make robotic welding a valuable tool in various industries, including shipbuilding, manufacturing, and construction. However, robotic welding in marine applications faces challenges related to practical data, integrity of structure, consistency, and controllability. These challenges can be addressed through the use of advanced technologies, such as object detection and motion planning, laser vision sensing, optimization of welding parameters, and adaptive control algorithms. Yet, high initial investment and maintenance costs are significant barriers to the adoption of these technologies, especially for small and medium enterprises [96]. Therefore, cost-effective solutions and governmental support could be vital in facilitating the widespread use of robotic welding in the marine industry. Future research should focus on developing cost-effective, reliable, and durable robotic welding systems, especially for marine structures and production processes.

The use of 6-axis robotic welding in shipbuilding and other industries offers numerous benefits, including increased productivity, improved welding quality, and enhanced worker safety. However, challenges such as the need for accurate path planning, control of heat input, and mitigation of residual stresses and deformations still need to be addressed [72,86,114]. In addition, its ability to perform complex welding tasks, reach difficult-to-access areas, and integrate with advanced technologies makes it a valuable tool for improving productivity and weld quality. Future research and development efforts can be addressing these challenges and further improving the capabilities and performance of 6-axis robotic welding systems.

Addressing these challenges and limitations in implementing robotic welding in marine applications requires a comprehensive approach that includes technological advancements, careful cost analysis, skill development, and effective process planning. Overcoming these hurdles will enable shipbuilders to harness the full potential of robotic welding and optimize marine structures and production processes.

5. Conclusion

The systematic literature review conducted in this study has comprehensively explored the realm of robotic welding techniques within the context of marine structures and production processes. Through a rigorous analysis of 106 studies that demonstrate rigor, credibility, and relevance, this review has shed light on the significant potential and evolving role that robotic welding holds in the marine industry. This conclusion delineates contributions in recognizing research trends and outlines potential avenues for future research.

5.1. Contribution

This review significantly contributes to the existing literature by offering a comprehensive overview and mapping the expanding body of research on robotic welding in the maritime context. The dominance of peer-reviewed journal publications among the cited research articles underscores the scholarly authority of this study. This contribution not only clarifies existing findings but also identifies trends and gaps, providing valuable insights for researchers and industry professionals.

The global landscape of research in this field is elucidated by the prominent contributions from key countries such as China, Korea, India, the United Kingdom, and Singapore. In this context, Korea stands out as a pioneer, devoting efforts to the investigation of robotic welding techniques for marine production processes. Conversely, China assumes a leading role in observing the structural and mechanical properties, as well as parametric advancements facilitated by robotic welding. The yearly distribution of research reveals a noticeable upward trend in the popularity of studies pertaining to this topic. This trend mirrors the increasing interest and recognition of the manifold benefits that robotic welding imparts to marine structures and production processes. Notable among the keyword occurrences in the cited articles is the rising popularity of wire arc additive manufacturing. This highlights the growing interest in this emerging technology, which has the potential to transform marine manufacturing processes. Additionally, the microstructure and mechanical properties of materials subject to robotic welding have garnered considerable attention, followed closely by the optimization of the welding process parameters.

5.2. Potential areas for future research

Welding techniques have demonstrated their instrumental role in shaping the trajectory of robotic welding technology. Notably, Gas Metal Arc Welding (GMAW) has been pivotal in advancing the domain of robotic welding. Wire arc additive manufacturing (WAAM) has had a significant increase in popularity, highlighting its potential to bring about dramatic changes in maritime manufacturing processes. The selection of welding techniques assumes significance beyond technical considerations, influencing the sustainability of robotic welding applications. Insightful studies employing a life cycle assessment approach underscore the energy consumption, greenhouse gas emissions, and broader environmental impacts linked to the operation and manufacturing of robotic welding systems. Moving forward, future research should focus on developing energy-efficient welding processes, such as the integration of renewable energy sources and waste heat recovery systems. Additionally, the environmental impact of robotic welding, including emissions and waste management, should be addressed to promote sustainable marine industry practices.

A notable observation made in the evaluation relates to the materials processed by robotic welding. Conventional materials, such as steel, continue to dominate the landscape, while sophisticated materials remain underrepresented. Given the increasing adoption of high-strength alloys and other advanced materials within the maritime sector, future research must investigate welding challenges and optimization strategies to ensure compatibility with robotic welding techniques.

In the sphere of technology, 6-axis robotic welding is a versatile and potent instrument that has revolutionized the welding processes in a variety of marine industries. Recent implementations of fully autonomous systems underscore the growing utility of this technology. The tangible advantages of robotic welding – heightened efficiency, superior weld quality, alignment with industrial standards, enhanced safety, and reduced production time – resonate deeply in the marine construction domain. Nevertheless, the adoption of these advanced technologies is not without challenges.

Foremost among these challenges is consistency and controllability in achieving uniform weld quality and performance. Amplifying sensor technologies to enable real-time monitoring of welding parameters, joint tracking, and adaptive control holds the potential to enhance the reliability and durability of welded marine structures. To this end, the integration of advanced sensors, artificial intelligence, and machine learning is poised to enable real-time process optimization and defect detection.

The integrity of marine structures introduces another layer of complexity. Given their diverse geometries, intricate joint configurations, and varying thicknesses, robotic welding confronts challenges. In this vein, future research should concentrate on engineering designs that synergize seamlessly with robotic welding technology to tackle these intricate configurations effectively.

As robotic welding technology evolves, the interaction between humans and robots in welding operations assumes a pivotal role. Facilitating human-robot collaboration is an emerging frontier, pivotal in driving productivity while ensuring worker safety. This research underscores the imperative of developing collaborative systems that are not only safe but also enhance productivity, offering potential avenues for further exploration.

The analysis of challenges notably highlights the need for more practical data. The reliance on laboratory-scale experiments underscores the lack of real-world validation. The formidable initial investment and ongoing maintenance costs stand as substantial barriers to technology adoption. Consequently, future research must investigate cost-effectiveness and the long-term return on investment associated with integrating robotic welding systems within marine construction. Cost-benefit analyses and economic models specific to the marine industry would provide valuable insights for decision-makers. By addressing the challenges posed by several of these research gaps, it is expected that the utilization of robotic welding can be widely implemented and become a reliable and feasible technology for the advancement of the global maritime industry.

CRediT authorship contribution statement

Sufian Imam Wahidi: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft. **Selda Oterkus:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Erkan Oterkus:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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