ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2716-7100 (Online)
CODEN: MCEMC2

Materials & Corrosion Engineering Management (MACEM)

DOI: http://doi.org/10.26480/macem.02.2023.37.43

CrossMark

REVIEW ARTICLE

REVIEW OF ADVANCED WELDING AND TESTING FOR SAFETY IN OFFSHORE OIL AND GAS

Bolaji Ismail Olalere[a], Joachim Osheyor Gidiagba[b*], Akeeb Adepoju Fawole[c], Blessed Afeyokalo Egbokhaebho[d], Nwakamma Ninduwezuor-Ehiobu[e], Jonathan Izuchukwu Okparaeke[f]

[a]Independent Researcher, Lagos.
[b]University of Johannesburg, South Africa.
[c]Eko City College of Management and Technology.
[d]Independent Researcher, UK.
[e]FieldCore Canda, part of GE Vernova.
[f]SAIPEM Lagos.
[*]Corresponding Author Email: joachim.gidiagba@gmail.com

ARTICLE DETAILS

Article History:

Received 04 June 2023
Revised 07 August 2023
Accepted 11 September 2023
Available online 13 September 2023

ABSTRACT

The offshore oil and gas industry plays a crucial role in meeting global energy demands; however, it is fraught with inherent safety risks that necessitate constant welding and testing techniques advancements. This research paper reviews the significance of advanced welding and testing for safety in offshore oil and gas operations. This article explores traditional welding methods and their limitations in ensuring structural integrity and safety. It delves into a comprehensive analysis of advanced welding technologies, including friction stir welding, laser welding, and electron beam welding, highlighting their potential benefits in mitigating safety concerns. Moreover, the study examines the role of non-destructive testing (NDT) methods, such as ultrasonic testing, radiographic testing, and magnetic particle inspection, in evaluating weld quality and structural integrity. An emphasis is placed on integrating advanced welding techniques with NDT, demonstrating how this symbiotic relationship enhances safety and effectively identifies flaws and defects. Real-life case studies exemplify the practical implementation of these technologies in safeguarding offshore structures. The paper also addresses the challenges of adopting advanced welding and testing methods and envisions potential future developments in these technologies. Furthermore, it sheds light on existing regulatory frameworks and standards governing welding and testing in offshore operations, underscoring their role in ensuring safety and compliance.

KEYWORDS

offshore oil and gas, safety, welding techniques, advanced welding, NDT, friction stir welding, laser welding, industry best practices, compliance, regulations, and standards.

1. INTRODUCTION

The offshore oil and gas industry is a pivotal driver in meeting the surging global energy demands, supplying a substantial share of the world's hydrocarbon resources (S. Chen, 2023). However, the exploration and production of oil and gas from remote and challenging offshore environments pose formidable safety risks to both human life and the environment (Guoxin & Rukai, 2020). Ensuring safety in offshore operations is paramount to prevent catastrophic accidents, protect workers, and safeguard delicate marine ecosystems. In this context, the application of advanced welding and testing techniques plays a crucial role in enhancing safety measures and ensuring the structural integrity of offshore installations.

The industry's relentless pursuit of hydrocarbon reserves has pushed exploration and production into increasingly extreme conditions, such as deepwater reservoirs and arctic regions, where the environment and operational complexities intensify safety risks (IFRS, 2022). High-pressure and high-temperature (HPHT) environments, corrosive seawater, and challenging weather conditions demand welding technologies capable of withstanding such stressors (Roseman, Martin, & Morgan, 2016). While widely used historically, conventional welding methods face limitations regarding weld quality, performance, and durability, especially in these demanding environments (H. Chen, Zhang, & Fuhlbrigge, 2020; Cook, 2021). Significant strides have been made in developing advanced welding technologies tailored for offshore applications to address these challenges and improve safety standards. Friction stir welding, laser welding, and electron beam welding have emerged as promising alternatives to conventional techniques, offering benefits such as reduced distortion, higher strength, and improved fatigue resistance in offshore structures (Mishra & Ma, 2005; Mofeed et al., 2021). These advancements enhance weld integrity and reduce the risk of material failure and structural integrity compromise(AWS).

Additionally, the evaluation of weld quality and structural integrity in offshore installations is facilitated by non-destructive testing (NDT) techniques. NDT methods allow for the assessment of welds and materials without causing damage, enabling the detection of internal defects and discontinuities. Ultrasonic testing, radiographic testing, magnetic particle inspection, and other NDT methods are employed to identify flaws and assess the overall condition of critical components in offshore structures (IAEA, 2008).

This research paper presents a comprehensive review of advanced welding and testing techniques in the context of offshore oil and gas safety.

Quick Response Code	Access this article online	
	Website: www.macej.com.my	**DOI:** 10.26480/macem.02.2023.37.43

Cite The Article: Bolaji Ismail Olalere, Joachim Osheyor Gidiagba, Akeeb Adepoju Fawole, Blessed Afeyokalo Egbokhaebho, Nwakamma Ninduwezuor -Ehiobu, Jonathan Izuchukwu Okparaeke (2023). Review of Advanced Welding and Testing for Safety in Offshore Oil and Gas. *Materials & Corrosion Engineering Management, 4(2): 37-43.*

We aim to provide a comprehensive and up-to-date analysis of the latest welding and testing technologies advancements by synthesizing data from reputable scholarly sources, technical reports, and industry publications. Moreover, the paper emphasizes the integration of advanced welding techniques with NDT methods as a holistic approach to enhance safety measures. Case studies will be discussed to illustrate real-life implementations of these technologies, showcasing their practical effectiveness in safeguarding offshore structures and mitigating safety risks. The research also addresses the challenges faced in adopting advanced welding and testing methods, such as regulatory compliance and initial investment costs. To conclude, this research paper seeks to contribute to the continuous efforts to promote safer practices in offshore oil and gas operations.

2. Overview of The Offshore Oil and Gas Industry

The offshore oil and gas industry is a critical sector of the global energy landscape, responsible for the exploration, production, and extraction of hydrocarbons from offshore reservoirs. This industry is pivotal in meeting the escalating global energy demands driven by population growth, urbanization, and industrialization (IEA, 2020). The offshore oil and gas industry is a major global oil and natural gas supply component. It could provide an increasingly important source of renewable electricity. The exploration and development of offshore resources have become essential to sustain the energy supply and ensure global energy security. The offshore oil and gas industry holds strategic importance in the context of global energy demands (IEA, 2018).

As onshore reserves become increasingly depleted, offshore reserves present an opportunity to access untapped hydrocarbon resources. Offshore fields often harbor substantial oil and gas reserves, offering a sustained source of energy production over extended periods. The ability to access these reserves is vital in meeting the growing global energy consumption as the demand for energy continues to rise. According to the International Energy Agency (2018), the offshore sector is expected to contribute significantly to future oil and gas production. Offshore fields, particularly those located in deepwater and ultra-deepwater regions, are estimated to account for a substantial portion of the world's hydrocarbon production in the coming decades. Therefore, offshore oil and gas production is a key element in the global energy mix and is expected to play a crucial role in economic growth and development.

The offshore oil and gas industry involves diverse stakeholders, including major international oil companies (IOCs), national oil companies (NOCs), independent operators, and service providers. IOCs are prominent players with a global presence, significant financial resources, and access to advanced technologies. These companies include industry giants such as ExxonMobil, Royal Dutch Shell, Chevron, BP, and Total (IRENA, 2021). NOCs represent their respective countries oil and gas sector interests and often control significant offshore reserves. Examples of major NOCs include Saudi Aramco, Petrobras, Petronas, and Gazprom (Ayala H, 2009). These state-owned companies play a crucial role in developing and managing offshore resources to meet domestic and international energy needs. Independent operators are smaller companies that specialize in exploration and production activities. They often focus on specific regions or niche markets and contribute to the industry's diversity and innovation. On the other hand, service providers offer a range of specialized services, including drilling, engineering, construction, and maintenance, supporting the operations of both IOCs and NOCs.

The offshore oil and gas industry operates in some of the planet's most challenging and hostile environments. Offshore installations are subject to various safety risks, which can severely affect human life, the environment, and infrastructure. Some of the inherent safety risks associated with offshore operations include (Akpan, Wansah, & Udom, 2022):

a) Extreme Weather Conditions: Offshore installations are exposed to extreme weather events, including hurricanes, storms, and high winds. These conditions can cause structural damage, equipment failures, and potential accidents during installation, production, and maintenance activities.

b) Blowouts and Oil Spills: Drilling and production operations pose the risk of well blowouts, leading to uncontrolled oil and gas releases. Major oil spills, such as the Deepwater Horizon incident 2010 have demonstrated the devastating environmental and economic consequences of such accidents (Safford, Ulrich, & Hamilton, 2012).

c) Fire and Explosions: Flammable hydrocarbons and ignition sources on offshore platforms create the potential for fire and explosions. Accidents involving fire and explosions can result in injuries, fatalities, and significant damage to infrastructure.

d) Transportation Risks: Offshore workers typically commute to installations by helicopter or marine vessels (Sommers & Cullen, 1981). Transportation accidents pose a risk to personnel, especially during adverse weather conditions and challenging sea states.

e) Structural Integrity and Corrosion: Offshore structures are exposed to corrosive seawater, which can compromise their structural integrity over time. Regular inspections, maintenance, and the use of corrosion-resistant materials are vital to ensure the long-term safety of these installations.

f) Health and Safety of Workers: Offshore operations involve physically demanding tasks in isolated and remote environments. Occupational hazards, fatigue, and the handling of heavy equipment pose risks to the health and safety of offshore workers.

Although API (2021b) did note that the oil and natural gas industry and the federal government are working together to continuously improve the safety of offshore operations, the industry has placed a particular focus on increasing its ability to prevent spills from occurring, intervene to halt any spill that does occur, and respond to spills with the most effective mitigation measures possible. Addressing these safety risks requires the implementation of robust safety management systems, adherence to industry best practices, and continuous innovation in technologies and operational procedures. Industry standards and regulations play a crucial role in setting safety guidelines and ensuring compliance to safeguard both the workforce and the marine environment.

In summary, the offshore oil and gas industry holds significant importance in meeting global energy demands, offering substantial hydrocarbon reserves that contribute to the world's energy supply. Major international oil companies, national oil companies, independent operators, and service providers form the core players in this industry, each with unique roles and contributions. However, offshore operations face inherent safety risks associated with operating in harsh and challenging environments. The mitigation of these safety risks requires a steadfast commitment to safety, the application of advanced technologies, and continuous improvement in safety practices. The industry's efforts to implement rigorous safety management systems and adhere to industry standards are essential to ensure offshore hydrocarbons' sustainable and safe production while minimizing the potential for safety incidents.

3. Traditional Welding Techniques in Offshore Applications and Their Limitations

Traditional welding techniques have been widely used in the offshore oil and gas industry for fabricating and joining various components of offshore structures. Some of the commonly used traditional welding techniques include:

a) Shielded Metal Arc Welding (SMAW)

Shielded Metal Arc Welding, also known as stick welding, is a manual welding process that uses a consumable electrode covered with a flux to create the weld (Juers, 1993). SMAW is versatile and can be used in various positions and environments, making it suitable for offshore applications. However, SMAW has some limitations concerning safety and performance. It produces relatively slower weld deposition rates, which can be a concern for large-scale offshore projects, leading to increased construction time and costs. The process also generates significant welding fumes and spatters, posing health hazards to welders and requiring proper ventilation and personal protective equipment (Alkahla & Pervaiz, 2017; Sanchez et al., 1995).

b) Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding, or MIG/MAG welding, is an automatic or semi-automatic welding process that uses a continuous wire electrode and a shielding gas to protect the weld (Ngo, Duy, Phuong, Kim, & Kim, 2007). GMAW is known for its high welding speed and ease of operation, making it suitable for offshore construction projects (Kah, Suoranta, & Martikainen, 2013). However, the use of shielding gases, such as carbon dioxide or argon, can present safety challenges, particularly in confined spaces, where gas accumulation can be hazardous. Moreover, GMAW may result in weld spatter and require post-weld cleaning, which can be time-consuming and add to project costs (Henderson, 2006).

c) Flux-Cored Arc Welding (FCAW)

Flux-Cored Arc Welding is a variation of GMAW that uses a tubular wire filled with flux to shield the weld (Phillips et al., 2022). FCAW offers higher deposition rates and deeper penetration compared to other traditional techniques. However, the use of flux-cored wires may release harmful fumes and require proper ventilation and respiratory protection (TWI, 2023b). Additionally, the presence of flux can lead to slag inclusion and require thorough cleaning after welding, which may be challenging in offshore environments.

4. Advanced Welding Techniques and Their Potential Benefits in Mitigating Safety Concerns

Friction Stir Welding is one of the advanced solid-state welding processes. It uses a non-consumable tool to join materials (Akinlabi et al., 2020). FSW generates frictional heat, softening the materials without reaching the melting point, resulting in a joint that is free from solidification defects and porosity. FSW offers significant benefits in terms of safety and performance. As a solid-state process, it eliminates the risk of hot cracking. It reduces the emission of harmful fumes, improving the working environment for welders. Additionally, FSW produces high-quality, high-strength welds with low distortion, enhancing offshore structures' structural integrity and longevity (Shah & Tosunoglu, 2012; Sidhu & Chatha, 2012).

Laser Welding is another advanced welding technique. It is a precise and focused welding process that uses a laser beam to join materials (Chludzinski, Dos Santos, Churiaque, Ortega-Iguña, & Sánchez-Amaya, 2021). Laser welding offers numerous safety advantages, including minimal heat input, reduced risk of distortion, and precise control over the weld parameters. The use of lasers minimizes the need for shielding gases, reducing potential hazards associated with gas handling. Moreover, laser welding allows for remote or robotic operations, enabling the welding of hard-to-reach areas, further enhancing worker safety in offshore environments (MachineMFG, 2023; Xometry, 2023).

Electron Beam Welding is a high-energy welding process that uses a focused beam of electrons to join materials (Patterson, Hochanadel, Sutton, Panton, & Lippold, 2021). EBW provides deep penetration and narrow welds with minimal heat-affected zones. The process operates in a vacuum, eliminating the need for shielding gases and reducing the risk of gas-related hazards. The high precision and minimal heat input of EBW result in welds with high strength and minimal distortion, ensuring the safety and integrity of offshore structures (Chowdhury et al., 2018; Nahmany et al., 2019).

Traditional welding techniques have been widely used in the offshore oil and gas industry. However, they come with certain limitations concerning safety and performance. Advanced welding techniques, such as Friction Stir Welding, Laser Welding, and Electron Beam Welding, offer promising solutions to mitigate safety concerns associated with traditional methods. These advanced techniques provide benefits such as improved weld quality, reduced emissions, minimal distortion, and precise control over the welding process, making them well-suited for enhancing safety and structural integrity in offshore applications.

5. Non-Destructive Testing (NDT) Methods for Evaluating Weld Integrity in Offshore Structures

Non-destructive testing (NDT) plays a critical role in the offshore oil and gas industry to assess the integrity of welds and materials without causing damage to the structures. These NDT techniques allow for the detection of internal defects, discontinuities, and material degradations, ensuring the safety and reliability of offshore installations. Below are several frequently utilized NDT methods for assessing weld integrity in offshore structures.

a) Ultrasonic Testing (UT)

Ultrasonic testing is a widely used NDT method that relies on high-frequency sound waves to evaluate the internal structure of welds and materials (Gholizadeh, 2016). UT involves using a transducer that emits ultrasonic waves into the material, and the reflected waves are analyzed to detect flaws and discontinuities. This technique can identify various defects, including cracks, porosity, and lack of fusion in welds, providing valuable information about the weld quality and integrity of offshore components (Mirmahdi, Afshari, & Karimi Ivanaki, 2023; Zhang et al., 2022).

b) Radiographic Testing (RT)

Radiographic testing, commonly known as X-ray or gamma-ray testing, uses penetrating radiation to create images of the internal structure of welds and materials (Sowerby & Tickner, 2007). This technique detects volumetric flaws, such as internal cracks, inclusions, and porosity. RT is capable of providing detailed images of the welds, enabling inspectors to assess the quality and integrity of the welds in offshore structures (Naddaf-Sh et al., 2021).

c) Magnetic Particle Inspection (MPI)

Magnetic Particle Inspection is a surface-based NDT method used to detect surface and near-surface defects in ferromagnetic materials (Bozóki, 2014). The process involves applying magnetic particles to the surface of the weld, and the presence of defects creates magnetic fields that attract the particles, making the defects visible. MPI is suitable for detecting surface cracks and other superficial flaws that may compromise weld integrity (Rosli, 2013; Sharma, Bhatia, & Ucharia, 2015).

d) Liquid Penetrant Testing (PT)

Liquid Penetrant Testing is another surface-based NDT technique used to detect surface defects in welds and materials (Roshan, Raghul, Ram, Suraj, & Solomon, 2019). PT involves applying a liquid penetrant to the surface, which seeps into any surface-breaking defects (Sathishkumar, Udayakumar, Vincent, & Kumar, 2020). After a specific time, the excess penetrant is removed, and a developer is applied to draw out the penetrant, making the defects visible. PT is effective in identifying small surface cracks and discontinuities that might be missed by visual inspection.

e) Eddy Current Testing (ECT)

Eddy Current Testing is employed to detect surface and near-surface defects in conductive materials. ECT utilizes electromagnetic induction to generate eddy currents in the material, and any changes in conductivity due to defects result in detectable signals. ECT is commonly used for detecting cracks, corrosion, and other surface flaws in offshore structures, particularly those made of non-ferromagnetic materials (Dogaru & Smith, 2001; Sophian et al., 2001).

f) Acoustic Emission Testing (AE)

Acoustic Emission Testing is a passive NDT method that detects and analyzes acoustic signals emitted by materials when subjected to stress or deformation (Gholizadeh et al., 2015). AE can be employed to monitor the structural integrity of offshore components during service, allowing for the early detection of defects or anomalies that might require attention (TWI, 2023a).

In conclusion, NDT methods are indispensable tools in the offshore oil and gas industry for evaluating weld integrity and ensuring the structural integrity of offshore structures. Ultrasonic testing, radiographic testing, magnetic particle inspection, liquid penetrant testing, eddy current testing, and acoustic emission testing are among the commonly used NDT techniques. Each method offers distinct capabilities in detecting different types of flaws and discontinuities, contributing to enhanced offshore installations' safety, reliability, and performance.

6. Integration of Advanced Welding and Ndt

Integrating advanced welding techniques with non-destructive testing (NDT) is paramount in ensuring weld quality, structural integrity, and safety in offshore structures. This collaborative approach combines the benefits of advanced welding methods, such as Friction Stir Welding, Laser Welding, and Electron Beam Welding, with the capabilities of NDT methods like Ultrasonic Testing, Radiographic Testing, Magnetic Particle Inspection, and others (Juengert et al., 2022; Raj, Subramanian, & Jayakumar, 2000).

This integration results in a holistic approach to identifying and mitigating defects and flaws, offering several key advantages. For instance, advanced welding techniques are designed to produce high-quality welds with improved mechanical properties and reduced distortion. Integrating these techniques with NDT allows welders and inspectors to confirm weld integrity without compromising the structure. Combined with NDT, advanced welding ensures that the welds meet strict quality standards and performance criteria for offshore applications. NDT methods, such as Ultrasonic Testing and Radiographic Testing, are highly effective in detecting internal and surface defects, such as porosity, cracks, and lack of fusion. Conducting NDT inspections immediately after welding enables early identification of defects in the fabrication process. This timely detection allows for necessary corrective measures to be taken and prevents the spread of defects that might compromise structural integrity and safety (Juengert et al., 2022; Lasserre et al., 2017; Rosado et al., 2010).

Despite their numerous advantages, advanced welding techniques may not entirely eliminate the possibility of defects. Through the integration of NDT methods, accurate detection of potential defects that might have occurred during the welding process, like incomplete fusion or weld discontinuities, becomes possible (Dai et al., 2020). This combined strategy thoroughly identifies defects and minimizes the chance of unnoticed flaws in offshore structures. Some NDT techniques, such as Acoustic Emission Testing, offer real-time monitoring capabilities during welding. This real-time monitoring allows inspectors to detect any anomalies or deviations from expected weld quality as they occur, providing an opportunity for immediate adjustments and interventions to maintain weld integrity and safety (TWI, 2012). The integration of NDT methods with advanced welding techniques extends beyond initial fabrication. Periodic NDT inspections can be conducted throughout the service life of offshore structures to monitor structural health and detect any signs of deterioration, corrosion, or fatigue. This proactive approach enables timely maintenance and repair, ensuring the continued safety and reliability of the offshore installations. Integrating advanced welding techniques with NDT is essential for compliance with industry standards and regulatory requirements. Offshore structures are subject to stringent safety and quality standards, and the combination of these approaches helps meet the rigorous inspection and certification criteria set by regulatory bodies (TWI, 2012).

7. Case Studies

a) Case Study 1: Friction Stir Welding in Subsea Pipelines

In this case study, Toguyeni, Pfeiffer, Caliskanoglu, and Oppeneiger (2020) investigated the implementation of friction stir welding (FSW) in the construction of subsea pipelines for a deepwater oil and gas project. FSW was chosen due to its ability to produce high-quality welds with reduced distortion and improved fatigue resistance (Toguyeni et al., 2020). The study found that FSW not only enhanced the structural integrity of the pipelines but also significantly reduced the installation time and costs. The implementation of FSW contributed to enhanced safety by eliminating the need for traditional welding, which involved higher risks of defects and weld failures.

b) Case Study 2: Laser Welding for Repairing Offshore Structures

In a study by Sun et al. (2022), laser welding was employed for the repair of corroded and damaged offshore structures. The laser welding technique allowed for precision welding with minimal heat-affected zones, reducing the distortion and material degradation risk. The case study demonstrated that laser welding offered a fast and efficient method for repairing offshore components, minimizing downtime, and enhancing the safety and integrity of the structures (Sun et al., 2022).

8. Challenges and Future Perspectives

While advanced welding and testing technologies offer significant advantages in improving safety and weld quality in the offshore industry, their implementation comes with specific challenges and barriers.

Firstly, the initial investment required for adopting advanced welding and testing technologies can be substantial. Offshore projects already entail high capital expenditures, and the additional costs of procuring and training personnel to use advanced equipment and techniques can be a significant barrier for some companies. Advanced welding and testing methods often require specialized equipment and skilled personnel to operate them effectively. Ensuring that the workforce is adequately trained and certified to handle these technologies can pose a challenge, especially in remote offshore locations. Additionally, integrating advanced welding and testing technologies into existing offshore infrastructure and operations may require modifications and adaptations to accommodate the new equipment and techniques. Compatibility issues and the need for retrofitting can add complexities and costs to the implementation process.

Safety concerns may arise as the offshore industry transitions to new welding and testing technologies. Operators must ensure that safety protocols and procedures are established and followed during the adoption phase to minimize any potential risks to personnel and assets. The offshore industry is subject to stringent safety and quality regulations. Implementing new technologies must be done in compliance with these regulations, which may necessitate additional validation and certification processes. Lastly, the adoption of advanced welding and testing technologies often requires a cultural shift within the industry. Convincing stakeholders of the benefits of these innovations and overcoming resistance to change can be a significant barrier.

8.1 Potential Future Developments in Welding and Testing Technologies

Advancements in welding and testing technologies are continually being explored to further enhance safety in the offshore industry. Automation and robotics are expected to play a more significant role in offshore welding and testing. Robots can perform precise and repetitive welding tasks, reducing human involvement in hazardous environments and ensuring consistent weld quality. Additionally, robotic inspection systems can conduct NDT inspections more efficiently and with greater accuracy.

Future developments may focus on integrating real-time monitoring and control systems during welding. These systems can detect deviations and anomalies, allowing for immediate adjustments to maintain weld quality and reduce the risk of defects. In addition, NDT methods are continuously evolving to become more sensitive, reliable, and faster. Techniques like phased array ultrasonic testing and digital radiography are already showing promise in providing detailed and accurate defect detection in a shorter timeframe.

The development of advanced materials, such as high-strength alloys and composite materials, will drive the need for welding technologies that can accommodate these materials while maintaining their integrity. Welding methods may evolve to address the specific challenges posed by these new materials. More importantly, Artificial intelligence (AI) and data analytics can play a crucial role in analyzing vast amounts of welding and inspection data. AI algorithms can assist in predictive maintenance, detecting patterns of degradation, and optimizing welding parameters for enhanced weld quality and safety.

9. Regulations and Standards

The offshore oil and gas industry operates within a highly regulated environment to ensure safety, environmental protection, and compliance with industry standards. Various international organizations, national regulatory bodies, and industry associations have established specific regulations and standards related to welding and non-destructive testing (NDT) in offshore operations. These regulatory frameworks play a crucial role in maintaining safety, quality, and environmental standards throughout the lifecycle of offshore structures. Some key regulatory frameworks and standards include:

- American Petroleum Institute (API): The API develops and publishes widely recognized and adopted standards in the offshore industry. The API's standards cover a broad range of topics, including welding procedures, materials, and inspection requirements. For example, API RP 2X "Recommended Practice for Ultrasonic and Magnetic Particle Examination of Welds" provides guidelines for ultrasonic and magnetic particle inspection of welds in offshore structures. Compliance with API standards is often a requirement for operators, contractors, and service providers working in the offshore sector (API, 2021a).

- International Organization for Standardization (ISO): The ISO sets global standards for various industries, including offshore oil and gas. ISO standards related to welding and NDT ensure consistency in testing procedures and equipment calibration. ISO 17635:2016 "Non-destructive testing of welds - General rules for metallic materials" provides general guidelines for NDT in welding, while ISO 3834 series focuses on quality requirements for fusion welding of metallic materials (ISO, 2023).

- International Maritime Organization (IMO): The IMO is responsible for the safety and environmental performance of international shipping and offshore operations. IMO conventions, such as the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL), include provisions related to welding and NDT requirements on offshore platforms and vessels (IMO, 2019).

- Offshore Industry Regulations (e.g., UK HSE, BSEE): Many countries have specific regulatory bodies that oversee offshore operations and have established their own set of regulations and standards. For instance, the UK Health and Safety Executive (HSE) and the US Bureau of Safety and Environmental Enforcement (BSEE) have comprehensive regulations that cover welding procedures, inspection, and safety requirements for offshore installations within their respective jurisdictions (BSEE, 2021; ICLG, 2023).

- American Welding Society (AWS): The AWS publishes codes and standards related to welding practices, qualifications, and inspections. AWS D1.1 "Structural Welding Code - Steel" and AWS D1.2 "Structural Welding Code - Aluminum" are widely used in the offshore industry for structural welding applications (AWS, 2015, 2020).

9.1 Role in Ensuring Safety and Compliance

The existing regulatory frameworks and standards concerning welding and testing in offshore operations play a critical role in ensuring safety and compliance. These frameworks serve several purposes.

They establish minimum safety standards for welding procedures, equipment, and NDT inspections. Compliance with these standards is crucial to prevent accidents, injuries, and structural failures. They include industry best practices for welding and testing, encouraging operators and service providers to voluntarily adopt these practices to ensure quality and reliability in offshore structures. Compliance with established standards helps maintain consistent quality assurance in welding and NDT practices, reducing the risk of defects and enhancing the safety and longevity of offshore installations.

Many regulations also have provisions for environmental protection, aiming to prevent leaks or spills caused by welding defects. These measures contribute to safeguarding the marine environment and minimizing the environmental impact of offshore operations. Regulatory frameworks offer certainty and clarity for all stakeholders involved in offshore projects. Compliance with recognized standards fosters transparency and confidence among operators, regulators, contractors, and investors. International standards and conventions promote global cooperation and harmonization of safety practices in the offshore industry. This cooperation helps ensure that the highest safety and quality standards are adhered to worldwide.

10. Conclusion

This paper review on welding and testing in offshore oil and gas operations has highlighted these processes' crucial role in ensuring safety, structural integrity, and environmental protection. Advanced welding techniques and non-destructive testing (NDT) methods have emerged as key components in safeguarding offshore structures against potential defects and failures. The existing regulatory frameworks and standards related to welding and testing in offshore operations are instrumental in establishing minimum safety requirements. Compliance with these standards is vital to prevent accidents, injuries, and structural failures.

Advanced welding and NDT methods facilitate quality assurance by identifying and rectifying defects during the construction and maintenance of offshore structures. This ensures the longevity and reliability of these installations. Welding defects can lead to leaks and spills that harm marine ecosystems. Offshore operators can minimize the environmental impact and protect marine life by employing advanced techniques and stringent testing. Regulatory frameworks often include industry best practices for welding and testing. Encouraging operators and service providers to voluntarily adopt these practices further enhances offshore structures' safety and quality. International standards and conventions promote global cooperation and harmonization of safety practices in the offshore industry. This collaboration ensures that the highest safety and quality standards are followed worldwide.

This study has highlighted the importance of continuously improving welding and testing technologies. Advancements in automation, robotics, and data analytics can enhance efficiency and accuracy, reducing the likelihood of defects and failures. The research emphasizes that advanced welding and testing are integral to ensuring offshore oil and gas structures' safety, integrity, and environmental sustainability. However, there are potential areas for further research and improvements:

- Exploring and refining advanced NDT methods can enhance defect detection accuracy and improve overall inspection efficiency.
- Investigating new welding materials and techniques can lead to stronger and more corrosion-resistant structures, contributing to improved safety and longevity.
- Developing real-time monitoring systems for offshore structures during their operational lifespan can help identify potential issues early, allowing for timely interventions and maintenance.
- Conducting comprehensive risk assessments for specific offshore projects can provide valuable insights for optimizing welding and testing strategies.
- Enhancing the training and certification programs for welding and NDT personnel can ensure a skilled workforce capable of executing advanced techniques effectively.

In conclusion, the research underscores the significance of advanced welding and testing in offshore oil and gas operations. These processes are vital for maintaining safety, structural integrity, and environmental protection. Continual research and improvements in welding and testing methodologies can further enhance safety measures and ensure the sustainability of offshore structures for years to come.

References

Akinlabi, E. T., Mahamood, R. M., Akinlabi, E. T., & Mahamood, R. M. 2020. Introduction to friction welding, friction stir welding and friction stir processing. Solid-state welding: friction and friction stir welding processes, 1-12.

Akpan, J. J., Wansah, J. F., & Udom, P. O. 2022. Offshore oil and gas risks and hazards management. Global Scientific, 10(10). Retrieved from https://www.globalscientificjournal.com/researchpaper/OFFSHORE_OIL_AND_GAS_RISKS_AND_HAZARDS_MANAGEMENT.pdf

Alkahla, I., & Pervaiz, S. 2017. Sustainability assessment of shielded metal arc welding (SMAW) process. Paper presented at the IOP conference series: materials science and engineering.

API. 2021a. API Standards for Safe Offshore Operations. Retrieved from https://www.api.org/oil-and-natural-gas/wells-to-consumer/exploration-and-production/offshore/api-standards-for-safe-offshore-operatio

API. 2021b. Offshore Safety. Retrieved from https://www.api.org/oil-and-natural-gas/health-and-safety/exploration-and-production-safety/offshore-safety

AWS. WELDING HANDBOOK- Welding Processes (Vol. 3).

AWS. 2015. Structural Welding Code—Steel. Retrieved from https://pubs.aws.org/Download_PDFS/D1.1-D1.1M-2015-PV.pdf

AWS. 2020. Structural Welding Code —Steel. Retrieved from https://pubs.aws.org/Download_PDFS/D1_1_2020SecondP_PV.pdf

Ayala H, L. F. 2009. IOCs and NOCs: The Fourteen (and plus) Sisters. The Way Ahead, 5(03), 2-3.

Bozóki, J. 2014. Non–Destructive Material Testing (Ndt) Techniques Applied for the Life Extension Program of the Aircraft in the Hungarian Defence Forces. Academic And Applied Research In Military And Public Management Science, 13(2), 361-377.

BSEE. 2021. Office of Offshore Regulatory Programs. Retrieved from https://www.bsee.gov/what-we-do/offshore-regulatory-programs

Chen, H., Zhang, B., & Fuhlbrigge, T. 2020. Welding process optimization methods: a review. Transactions on Intelligent Welding Manufacturing: Volume III No. 1 2019, 3-21.

Chen, S. 2023. SMMA and China's Foreign Quest for Oil and Gas. In China's Approach to Energy Security: An International Comparative Perspective (pp. 193-216): Springer.

Chludzinski, M., Dos Santos, R. E., Churiaque, C., Ortega-Iguña, M., & Sánchez-Amaya, J. M. 2021. Pulsed laser welding applied to metallic materials—A material approach. Metals, 11(4), 640.

Chowdhury, S., Yadaiah, N., Khan, S. M., Ozah, R., Das, B., & Muralidhar, M. 2018. A perspective review on experimental investigation and numerical modeling of electron beam welding process. Materials Today: Proceedings, 5(2), 4811-4817.

Cook, M. 2021. Trends in global energy supply and demand. In Developments in Petroleum Science (Vol. 71, pp. 15-42): Elsevier.

Dai, W., Mujeeb, A., Erdt, M., & Sourin, A. 2020. Soldering defect detection in automatic optical inspection. Advanced Engineering Informatics, 43, 101004.

Dogaru, T., & Smith, S. T. 2001. Giant magnetoresistance-based eddy-current sensor. IEEE Transactions on magnetics, 37(5), 3831-3838.

Gholizadeh, S. 2016. A review of non-destructive testing methods of composite materials. Procedia structural integrity, 1, 50-57.

Gholizadeh, S., Leman, Z., & Baharudin, B. 2015. A review of the application of acoustic emission technique in engineering. Struct. Eng. Mech, 54(6), 1075-1095.

Guoxin, L., & Rukai, Z. 2020. Progress, challenges and key issues in the unconventional oil and gas development of CNPC. China Petroleum Exploration, 25(2), 1.

Henderson, M. R. 2006. An Overview of GMAW Including Applications, Common Problems and Solutions. Paper presented at the ASME Pressure Vessels and Piping Conference.

IAEA. 2008. Training Guidelines in Non-destructive Testing Techniques. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/TE_628_Rev_2_web.pdf

ICLG. 2023. Oil & Gas Laws and Regulations South Africa 2023. Retrieved from https://iclg.com/practice-areas/oil-and-gas-laws-and-regulations/south-africa

IEA. 2018. Offshore Energy Outlook 2018. Retrieved from https://www.iea.org/reports/offshore-energy-outlook-2018

IEA. 2020. The Oil and Gas Industry in Energy Transitions. Retrieved from https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions

IFRS. 2022. [Draft] IFRS S2 Climate-related Disclosures Appendix B Industry-based disclosure requirements. Retrieved from UK: https://www.ifrs.org/content/dam/ifrs/project/climate-related-disclosures/industry/issb-exposure-draft-2022-2-b11-oil-and-gas-exploration-and-production.pdf

IMO. 2019. Conventions. Retrieved from https://www.imo.org/en/About/Conventions/Pages/ListOfConventions.aspx

IRENA. 2021. International Oil Companies and The Energy Transition. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Feb/IRENA_Oil_Companies_Energy_Transition_2021.pdf

ISO. 2023. ISO/TC 44/SC 5 Testing and inspection of welds. Retrieved from https://www.iso.org/committee/48620.html

Juengert, A., Werz, M., Maev, R. G., Brauns, M., & Labud, P. 2022. Non-destructive Testing of Welds. In Handbook of Non-destructive Evaluation 4.0 (pp. 819-858): Springer.

Juers, R. H. 1993. Shielded metal arc welding. Small, 100(50), 200.

Kah, P., Suoranta, R., & Martikainen, J. 2013. Advanced gas metal arc welding processes. The International Journal of Advanced Manufacturing Technology, 67, 655-674.

Lasserre, F., Roue, D., Laube, J., Dumas, P., Kingler, B., Cartier, F., & Roy, O. 2017. Industrialization of a large advanced ultrasonic flexible probe for non-destructive testing of austenitic steel pieces with irregular surface. Journal of Civil Engineering and Architecture, 11(10).

MachineMFG. 2023. Pros and Cons of Laser Welding: Advantages and Disadvantages. Retrieved from https://www.machinemfg.com/advantages-and-disadvantages-of-laser-welding/

Mirmahdi, E., Afshari, D., & Karimi Ivanaki, M. 2023. A review of ultrasonic testing applications in spot welding: defect evaluation in experimental and simulation results. Transactions of the Indian Institute of Metals, 76(6), 1381-1392.

Mishra, R. S., & Ma, Z. 2005. Friction stir welding and processing. Materials science and engineering: R: reports, 50(1-2), 1-78.

Mofeed Alam, M., Jha, A. K., Mukherjee, S., Panda, S., & Chakraborty, S. S. 2021. A review on friction stir welding—a green manufacturing technology. Recent Trends in Manufacturing and Materials Towards Industry 4.0: Selected Articles from iM3F 2020, Malaysia, 869-880.

Naddaf-Sh, M.-M., Naddaf-Sh, S., Zargarzadeh, H., Zahiri, S. M., Dalton, M., Elpers, G., & Kashani, A. R. 2021. Defect detection and classification in welding using deep learning and digital radiography. In Fault diagnosis and prognosis techniques for complex engineering systems (pp. 327-352): Elsevier.

Nahmany, M., Hadad, Y., Aghion, E., Stern, A., & Frage, N. 2019. Microstructural assessment and mechanical properties of electron beam welding of AlSi10Mg specimens fabricated by selective laser melting. Journal of Materials Processing Technology, 270, 228-240.

Ngo, M. D., Duy, V. H., Phuong, N. T., Kim, H. K., & Kim, S. B. 2007. Development of digital gas metal arc welding system. Journal of Materials Processing Technology, 189(1-3), 384-391.

Patterson, T., Hochanadel, J., Sutton, S., Panton, B., & Lippold, J. 2021. A review of high energy density beam processes for welding and additive manufacturing applications. Welding in the World, 65(7), 1235-1306.

Phillips, S., Quintana, M., Jia, D., Wang, J., & Wang, Y.-Y. 2022. Self-Shielded Flux-Cored Arc Welding-Practical Approaches for Improved Performance of Girth Welds in High-Strength Steel Pipelines. Paper presented at the International Pipeline Conference.

Raj, B., Subramanian, C., & Jayakumar, T. 2000. Non-destructive testing of welds.

Rosado, L. S., Santos, T. G., Piedade, M., Ramos, P. M., & Vilaça, P. 2010. Advanced technique for non-destructive testing of friction stir welding of metals. Measurement, 43(8), 1021-1030.

Roseman, M., Martin, R., & Morgan, G. 2016. Composites in offshore oil and gas applications. In Marine Applications of Advanced Fibre-Reinforced Composites. 233-257: Elsevier.

Roshan, C. C., Raghul, C., Ram, H. V., Suraj, K., & Solomon, J. 2019. Non-destructive testing by liquid penetrant testing and ultrasonic testing—A review. Int. J. Adv. Res. Ideas Innov. Technol, 5, 694-697.

Rosli, M. 2013. Surface defect characterisation using non-contact ultrasound. University of Warwick,

Safford, T. G., Ulrich, J. D., & Hamilton, L. C. 2012. Public perceptions of the response to the Deepwater Horizon oil spill: Personal experiences, information sources, and social context. Journal of environmental management, 113, 31-39.

Sanchez-Osio, A., Liu, S., Olson, D., & Ibarra, S. 1995. Designing shielded metal arc consumables for underwater wet welding in offshore applications.

Sathishkumar, N., Udayakumar, A., Vincent, B., & Kumar, V. A. 2020. Study and analysis of 3D printed FDM components by non-destructive testing techniques. International Journal of Researchand Review, 7(5), 217-222.

Shah, S., & Tosunoglu, S. 2012. Friction stir welding: current state of the art and future prospects. Paper presented at the 16th World multi-conference on systemics, cybernetics and informatics, Orlando, Florida.

Sharma, C., Bhatia, O. S., & Ucharia, V. 2015. A framework towards achieving quality in casting: A review. Int. J. Adv. Sci. Eng. Inf. Technol, 3(6).

Sidhu, M. S., & Chatha, S. S. 2012. Friction stir welding–process and its variables: A review. International Journal of Emerging Technology and Advanced Engineering, 2(12), 275-279.

Sommers, L. M., & Cullen, B. T. 1981. Offshore living accommodations for North Sea oil exploitation. Geographical Review, 71(1), 91-97.

Sophian, A., Tian, G., Taylor, D., & Rudlin, J. 2001. Electromagnetic and eddy current NDT: a review. Insight, 43(5), 302-306.

Sowerby, B., & Tickner, J. 2007. Recent advances in fast neutron radiography for cargo inspection. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 580(1), 799-802.

Sun, G., Wang, Z., Lu, Y., Chen, M., Yang, K., & Ni, Z. 2022. Underwater laser welding/cladding for high-performance repair of marine metal materials: a review. Chinese Journal of Mechanical Engineering, 35(1), 5.

Toguyeni, G., Pfeiffer, C., Caliskanoglu, O., & Oppeneiger, L. 2020. Friction Stir Welding of Steel for Pipeline Fabrication.

TWI. 2012. A novel NDT Technique For Inspecting Offshore Structures. Retrieved from https://www.twi-global.com/media-and-events/insights/subctest-development-of-a-novel-ndt-technique-for-inspecting-offshore-structures-488

TWI. 2023a. What is acoustic emission testing? A definitive guide. Retrieved from https://www.twi-global.com/technical-knowledge/faqs/acoustic-emission-testing

TWI. 2023b. What Is Flux-Cored Arc Welding (Fcaw Aka Dual Shield Welding)? Retrieved from https://www.twi-global.com/technical-knowledge/faqs/flux-cored-arc-welding-fcaw

Xometry. 2023. Laser Welding: Definition, How it Works, Process, Types, and Advantages. Retrieved from https://www.xometry.com/resources/sheet/laser-welding/

Zhang, Z., Li, Q., Cao, A., Yeoh, W., Liu, M., & Yang, W. 2022. Defect identification in thick porous and wavy composites with hybrid use of ultrasound non-reciprocity and scattering. Composites Science and Technology, 225, 109514.