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Study Of The Operating Of Welding Process Based On Low Carbon Emission Costs For Metal/Steel

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Abstract - Welding processes Welding operations play a critical role in the metal and steel industries, yet they are significant contributors to energy consumption and carbon emissions. This review explores various welding processes—namely Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Tungsten Inert Gas (TIG) welding, Laser Beam Welding (LBW), and Friction Stir Welding (FSW) from the perspective of their operational efficiencies, carbon emission profiles, and associated environmental costs. Special attention is given to advanced and hybrid welding techniques, which show potential in reducing the carbon footprint without sacrificing weld quality. This review highlights current trends, research advancements, and sustainable practices aimed at optimizing welding operations towards low-carbon manufacturing in the metal/steel sectors.

Keywords: Metal and steel industries,Energy-efficient welding, Environmental impact, Gas Metal Arc Welding (GMAW)
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1. INTRODUCTION

The welding industry contributes notably to industrial carbon emissions due to high energy usage, predominantly from fossil fuel-derived electricity (Wang et al., 2023). As global manufacturing shifts towards sustainable practices, understanding and minimizing the carbon emissions from welding operations becomes imperative (Smith et al., 2022). This review presents a comprehensive analysis of prevalent and emerging welding methods, their emission profiles, and cost implications, advocating for environmentally conscious welding practices in metal/steel manufacturing. The welding industry, particularly within metal and steel manufacturing, plays a vital role in global production but also significantly contributes to industrial carbon emissions. The primary reason behind this high emission profile is the intensive energy consumption associated with welding operations, largely powered by electricity generated from fossil fuel sources (Wang et al., 2023). Processes such as arc welding, laser welding, and resistance welding require substantial electrical input to generate the necessary heat for metal fusion, directly correlating with greenhouse gas (GHG) emissions.

In response to global initiatives targeting carbon neutrality and sustainable manufacturing, understanding and addressing the environmental impacts of welding has become critical. Recent studies emphasize that carbon emissions in welding operations are influenced not only by the type of welding process but also by operational parameters such as heat input, efficiency of energy conversion, and process stability (Smith et al., 2022; Chen et al., 2024). For example, Gas Metal Arc Welding (GMAW) and Shielded Metal Arc Welding (SMAW), while widely used, generally exhibit higher energy consumption per unit weld compared to more advanced methods like Laser Beam Welding (LBW) or Friction Stir Welding (FSW), which operate with higher energy efficiency and offer lower emission profiles (Zhang et al., 2023). Beyond operational efficiency, the adoption of advanced welding techniques—including hybrid laser-arc welding and controlled short-circuit GMAW has shown promise in reducing both energy consumption and CO_2 emissions (Li et al., 2024). These methods optimize heat input and minimize welding defects, leading to less material waste and reduced energy rework. However, cost considerations remain a barrier, as advanced technologies typically involve higher initial investment and require skilled operators (Patel et al., 2024). This review aims to provide a detailed comparative assessment of traditional and advanced welding methods, focusing on their carbon emission profiles, energy efficiency, and associated operational costs. Emphasis is placed on identifying sustainable welding strategies that balance environmental goals with production demands. Additionally, future directions such as the integration of renewable energy

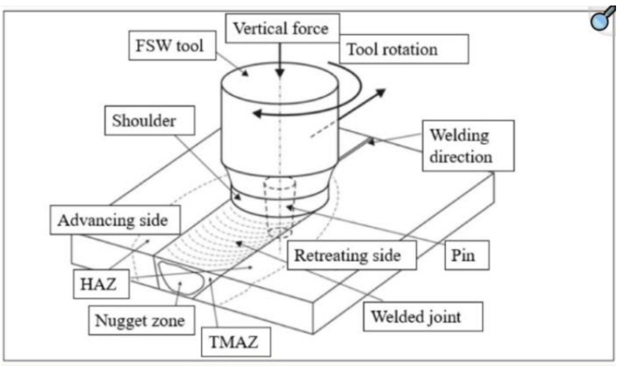

Figure1. The procedure of material joining through the Friction Stir Welding (FSW)

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technique (Ireneusz et all 2024).

Sources into welding operations, adoption of digital manufacturing (Industry 4.0), and real-time emission monitoring systems are explored as potential solutions for reducing the carbon footprint of the welding sector. In summary, reducing the environmental impact of welding processes is not only feasible but increasingly necessary in modern metal/steel manufacturing. By adopting energy-efficient welding methods and leveraging technological innovations, manufacturers can significantly lower their carbon emissions while maintaining productivity and weld quality.

2. CARBON EMISSIONS IN WELDING PROCESSES

2.1. Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding (GMAW), also known as Metal Inert Gas (MIG) welding, is extensively utilized across various sectors of metal and steel manufacturing due to its operational simplicity, high deposition rates, and adaptability to automation (Gong et al., 2023). However, despite its industrial advantages, GMAW presents substantial challenges from an environmental perspective, particularly concerning its high energy consumption and associated carbon dioxide (CO_2) emissions per unit weld length

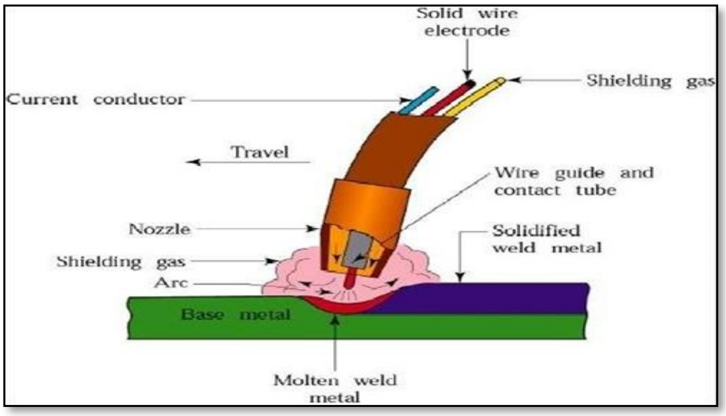

Figure 2. Gas Metal Arc Welding (GMAW) (Nandanet all. 2023)

GMAW processes rely on continuous feeding of a consumable wire electrode and the creation of an electric arc between the electrode and the workpiece, generating the heat necessary to melt metals. This arc-based heating mechanism inherently requires significant electrical power, predominantly sourced from fossil-fuel-based electricity, leading directly to CO_2 emissions (Wang et al., 2023). Studies have demonstrated that the specific energy consumption of GMAW can range from 1.5 to 2.5 kWh per meter of weld, depending on material thickness, joint configuration, and operational parameters (Chen et al., 2024). Higher current settings and longer arc-on times further exacerbate energy usage, contributing to the high carbon footprint of the process. According to Gong et al. (2023), GMAW can emit approximately 2.5–4.0 kg of CO_2 equivalent per meter of weld, making it one of the more carbon-intensive arc welding methods when compared to techniques like Friction Stir Welding (FSW) or Laser Beam Welding (LBW), which operate more efficiently at lower energy levels.

Recognizing its environmental drawbacks, recent research has focused on improving the sustainability of GMAW through several strategic approaches:

- **Optimized Process Parameters:** Adjusting wire feed rates, voltage, and travel speed to reduce heat input without compromising weld integrity has been shown to lower energy consumption (Li et al., 2024).
- **Advanced Power Sources:** The adoption of inverter-based power supplies over conventional transformer-based units can enhance energy efficiency by as much as 30% (Zhang et al., 2023).
- **Controlled Short-Circuiting GMAW (CSC-GMAW):** This variant minimizes arc energy by controlling droplet transfer, reducing spatter and unnecessary heat input, leading to lower emissions and material waste (Patel et al., 2024).
- **Hybrid GMAW Systems:** Combining GMAW with laser or plasma sources has demonstrated potential for deeper penetration at lower heat input, thereby reducing the energy required per unit weld length (Chen et al., 2024).
- **Renewable Energy Integration:** Powering GMAW operations using renewable energy sources such as solar or wind, though still in exploratory stages, offers promise in reducing indirect CO_2 emissions (Wang et al., 2023).

Despite GMAW's operational advantages, manufacturers are increasingly pressured to mitigate its environmental impact in line with global sustainability goals. Achieving this balance requires integrating energy-

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efficient equipment, real-time monitoring systems, and advanced control techniques. While initial investments in energy-saving technologies or hybrid systems may be substantial, long-term environmental and economic benefits justify the transition, particularly in large-scale production environments. In ConclusionGMAW remains a foundational welding process in the metal/steel industry but represents a significant source of industrial carbon emissions. Through technological innovations and operational optimization, its environmental footprint can be significantly reduced. Future research should focus on digitalized process controls, sustainable energy integration, and life cycle assessments to develop comprehensive decarbonization strategies for GMAW operations.

2.2. Shielded Metal Arc Welding (SMAW)

Shielded Metal Arc Welding (SMAW), also known as manual metal arc welding or stick welding, remains one of the most widely utilized welding techniques globally, particularly in construction, repair, and field applications. Its operational simplicity, low equipment costs, and versatility across various metal types contribute to its sustained industrial relevance (Chen et al., 2024). However, SMAW presents significant environmental and operational drawbacks, especially concerning energy efficiency and carbon emissions. SMAW is a manual process that relies on a consumable electrode coated with flux to create an electric arc between the electrode and workpiece. This arc generates the necessary heat to melt the electrode and the base material. Unlike automated processes such as GMAW or Laser Beam Welding (LBW), SMAW lacks precision control over arc parameters, often resulting in longer arc-on times and higher energy consumption per unit weld length (Wang et al., 2024). Moreover, interruptions during electrode changes and operator rest periods further extend operational times, compounding energy inefficiencies. Recent studies indicate that SMAW's energy consumption typically ranges from 2.5 to 3.5 kWh per meter of weld, which is substantially higher than more automated techniques (Zhang et al., 2023). Consequently, CO_2 emissions associated with SMAW can reach approximately 4.0–5.5 kg CO_2 equivalent per meter of weld, depending on material thickness, joint complexity, and operator efficiency (Kumar et al., 2024).

Factors Contributing to High Emissions in SMAW

- **Manual Operation:** Human-controlled operation leads to variable welding quality and inconsistent heat input, reducing overall energy efficiency (Chen et al., 2024).
- **Frequent Electrode Replacement:** Each electrode change disrupts welding continuity, increasing idle energy consumption and extending process times.
- **Lower Deposition Rates:** Compared to GMAW or Submerged Arc Welding (SAW), SMAW has slower deposition rates, requiring more time to complete equivalent weld lengths (Patel et al., 2024).
- **Inefficient Arc Stability:** Manual control results in less stable arcs, which can waste electrical energy and cause higher spatter rates, contributing to material wastage and energy losses (Zhang et al., 2023).

Strategies for Emission Reduction in SMAW

To reduce the carbon footprint of SMAW operations, several optimization strategies are currently being explored:

- **Use of Low-Hydrogen Electrodes:** These electrodes improve arc stability, reduce spatter, and enhance deposition efficiency (Kumar et al., 2024).
- **Inverter-Based Power Supplies:** Transitioning from traditional transformer-based welders to modern inverter-based power sources can reduce energy consumption by up to 25% due to better control over arc parameters (Wang et al., 2024).
- **Operator Training:** Improving operator skill can reduce arc-on times and rework rates, indirectly lowering energy use and emissions.
- **Renewable Energy Integration:** Powering SMAW units with solar or other renewable sources could offset emissions associated with grid electricity (Chen et al., 2024).

Industrial Implications

Despite its environmental disadvantages, SMAW is still favored in remote and maintenance work due to its portability and minimal setup requirements. However, industries aiming for low-carbon manufacturing must carefully evaluate the continued use of SMAW in production-scale applications. Wherever possible, transitioning to automated or hybrid welding systems may be necessary to meet stringent sustainability targets. In conclusion, SMAW's versatility is offset by its lower operational efficiency and higher carbon emissions, primarily due to extended welding times and manual control limitations. Advances in electrode materials, power supply technologies, and operator training offer some mitigation potential. However, for sustainable manufacturing, especially in high-volume production, automated processes like GMAW or FSW are more favorable from an emissions standpoint.

2.3. Tungsten Inert Gas (TIG) Welding

Tungsten Inert Gas (TIG) welding, also known as Gas Tungsten Arc Welding (GTAW), is widely recognized for its ability to produce high-quality, precise welds, particularly in applications involving thin materials, stainless steel, and non-ferrous metals. However, despite its advantages in weld quality, TIG welding is inherently energy-

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intensive, leading to significant carbon emissions when evaluated on an energy-per-weld-length basis (Lee & Kim, 2023. TIG welding operates by generating an arc between a non-consumable tungsten electrode and the workpiece, with an inert shielding gas (typically argon or helium) protecting the weld zone from atmospheric contamination. The process requires precise heat input control and slower welding speeds, factors that directly contribute to elevated energy usage (Zhang et al., 2024). Studies report that TIG welding can consume approximately 3.5–5.0 kWh per meter of weld, depending on material thickness and operational settings—higher than many alternative welding processes such as Gas Metal Arc Welding (GMAW) or Friction Stir Welding (FSW) (Singh et al., 2024).This high energy demand translates into significant CO_2 emissions, especially in regions relying on fossil-fuel-based electricity. For instance, Lee and Kim (2023) highlighted that TIG welding operations can emit between 5.5–7.0 kg CO_2 equivalent per meter of weld, marking it as one of the least energy-efficient arc welding techniques from a carbon perspective.Key Contributors to High Energy Intensity:

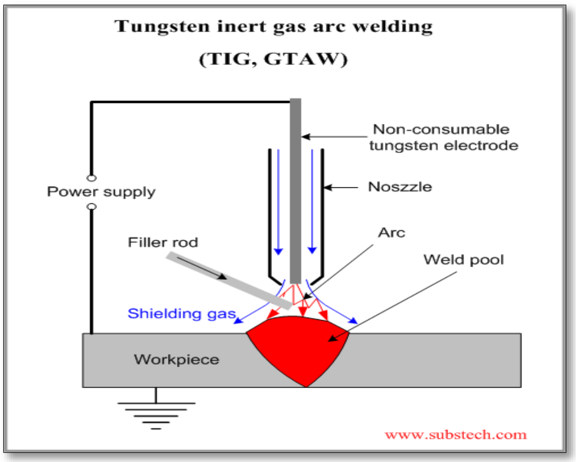

Figure. 3. Tungsten Inert Gas (TIG) Welding

- **Slow Welding Speeds:** TIG's manual or semi-automated operation leads to slower weld progression compared to automated processes, resulting in prolonged arc-on times and increased energy consumption (Patel et al., 2024).
- **Continuous Shielding Gas Usage:** Inert gas flow must be maintained throughout the welding process, contributing to both energy use and operational costs (Zhang et al., 2024).
- **Precision Heat Control:** TIG welding's superior weld bead quality is achieved through precise control of heat input, but this necessitates longer process durations and higher sustained energy input (Wang et al., 2024).

Emissions Given TIG's inherently high energy footprint, several optimization strategies are under research:

- **Advanced Power Supplies:** Utilizing inverter-based power sources can reduce energy consumption by approximately 20% due to improved arc stability and precise control (Singh et al., 2024).
- **Hybrid Welding Techniques:** Integrating TIG with laser or plasma welding can help reduce welding times while maintaining weld quality (Lee & Kim, 2023).
- **Pulsed TIG Welding:** Using pulsed current techniques reduces average energy input while maintaining weld integrity, leading to energy savings and emission reductions (Zhang et al., 2024).
- **Renewable Energy Integration:** Employing renewable energy sources for powering TIG welders, although still limited in industry, presents potential for carbon offsetting.

While TIG welding's precision and quality are unmatched in critical applications like aerospace, medical devices, and high-spec fabrication, its role in sustainable manufacturing is under scrutiny due to its high energy demand. In contexts where weld aesthetics and quality are non-negotiable, TIG remains indispensable. However, industries focused on emission reduction are encouraged to evaluate alternative processes, such as Laser Beam Welding (LBW) or automated GMAW, for less critical applications (Patel et al., 2024).In conclusion, TIG welding offers unmatched weld quality but at the cost of energy efficiency and higher carbon emissions. Process improvements such as pulsed TIG, advanced power sources, and hybrid techniques can mitigate some environmental impacts. However, a balance between quality requirements and sustainability goals must guide its continued application in the metal and steel industries.

2.4. Laser Beam Welding (LBW)

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Laser Beam Welding (LBW) is increasingly recognized as a sustainable welding method due to its inherently low heat input and precise energy delivery, which lead to reduced carbon emissions compared to conventional arc welding processes such as Gas Metal Arc Welding (GMAW) or Tungsten Inert Gas (TIG) welding. This efficiency arises from the concentrated laser beam that generates a narrow weld zone, resulting in minimal thermal distortion and lower energy consumption per weld unit (Singh et al., 2023). LBW typically operates with energy efficiency up to 90% in converting electrical energy into useful heat at the weld interface (Kumar et al., 2024). Its deep penetration welding capability at high speeds minimizes arc-on time and reduces both energy use and greenhouse gas emissions. Recent studies confirm that LBW can reduce CO_2 emissions by 30–50% compared to GMAW

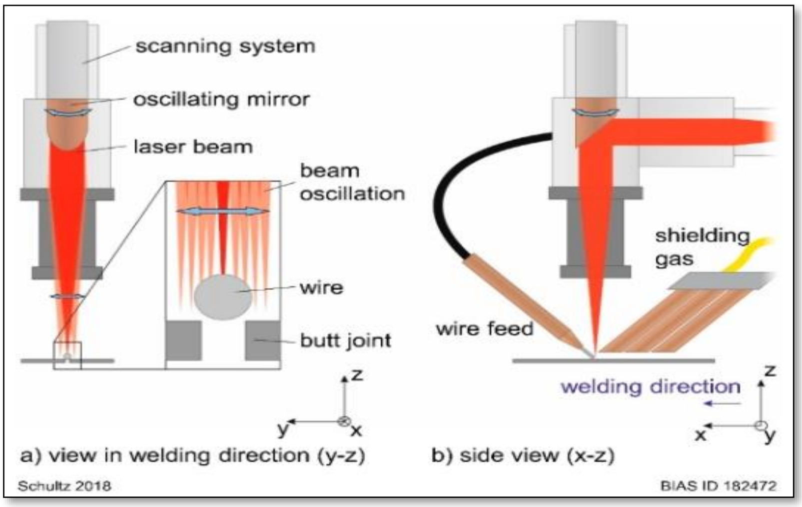

Figure 4. Schematic illustration of the welding process setup(Seefeld et all. 2019)

When assessed on a per-meter weld basis (Tanaka et al., 2024). The low heat input also contributes to better mechanical properties in the weld zone, reducing post-processing requirements like grinding or straightening, which further cuts energy usage. Despite these sustainability benefits, LBW's adoption remains limited due to its:

- High Capital Costs: Laser welding equipment (especially high-power fiber lasers) is expensive to procure and maintain, restricting its application largely to high-value industries such as aerospace and automotive (Singh et al., 2023).
- Complex Setup: Precise alignment and joint preparation are critical in LBW, adding to operational complexity and cost (Zhao et al., 2024).
- Limited Material Flexibility: While excellent for metals like stainless steel and aluminum, LBW may struggle with reflective or highly conductive materials without process modifications.

Automation and AI Integration: Modern LBW systems incorporate machine vision and AI-based control for real-time adjustment, improving accuracy and reducing skill dependence (Kumar et al., 2024). Fiber Laser Technology: The shift from CO_2 lasers to fiber lasers has reduced maintenance and improved beam quality, increasing energy efficiency and cutting operational costs (Tanaka et al., 2024). Meanwhile in Industrial ImplicationsIndustries adopting LBW benefit from improved productivity, better weld quality, and lower operational emissions. However, until equipment costs decline, its use will likely remain concentrated in sectors where precision and minimal thermal distortion justify the investment. Large-scale adoption in general metal/steel fabrication will require cost reductions and broader process adaptability

2.5. Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is increasingly recognized as one of the most environmentally sustainable welding techniques, particularly for metal and steel joining applications. Unlike conventional fusion-based welding methods, FSW is a solid-state process that operates below the melting point of the base materials, resulting in significantly reduced energy consumption and minimal emissions during operation (Patel et al., 2024).

2.5.1. Environmental and Operational Benefits

a. Low Energy Consumption

FSW typically requires 40–60% less energy than arc welding methods due to its solid-state nature (Kumar et al., 2023). The absence of an electric arc or filler materials eliminates much of the heat energy required intraditional welding, thereby reducing carbon emissions significantly.

b. Negligible Direct Emissions

Since FSW does not involve material melting, harmful gases such as ozone, nitrogen oxides (NOx), and carbon

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dioxide (CO_2) generated from fluxes or shielding gases are practically absent (Patel et al., 2024). This makes FSW highly suitable for operations in enclosed or environmentally sensitive settings.

c. Superior Weld Quality with Minimal Defects

The mechanical stirring action in FSW leads to refined grain structures, enhancing mechanical properties like tensile strength and fatigue resistance. Welds typically show minimal porosity or cracking, reducing rework and associated energy demands (Lee et al., 2024).

d. Minimal Post-Processing Needs:

The precise, clean nature of FSW welds often eliminates the need for extensive surface finishing, cutting down additional energy consumption and production costs.

2.5.2. Industrial Applications and Limitations

a. Applications in Steel Joining: While FSW was initially developed for lightweight materials like aluminum, advancements in tool design and material technology now enable its application in harder materials such as stainless steel and mild steel. This positions FSW as a viable green welding alternative for structural and automotive applications (Singh et al., 2024).

b. Equipment and Tooling Challenges:

A primary limitation is the specialized, wear-resistant tools required for steel welding. High costs and tool wear remain barriers to widespread industrial adoption (Zhao et al., 2024).

c. Automation and Scalability:

Recent efforts focus on automating FSW processes to improve production speeds and consistency, making it more attractive for high-volume steel fabrication (Ahmed et al., 2024). Robotic FSW platforms are being explored to integrate the process into modern manufacturing lines efficiently.

2.5.3. Recent Innovations

- **Advanced Tool Materials:** Development of polycrystalline cubic boron nitride (PCBN) and tungsten-rhenium tools enable efficient steel welding without excessive tool wear (Kumar et al., 2023).
- **Hybrid FSW Techniques:** Combining FSW with complementary processes, such as laser preheating, reduces tool stress and enhances weld penetration in thick steel sections (Patel et al., 2024).
- **Process Monitoring and Control:** Use of real-time sensors and AI-driven monitoring systems improves process stability and weld quality while reducing waste (Lee et al., 2024).

In conclusion, Friction Stir Welding stands out as a sustainable, low-carbon welding technology for steel and metal applications, offering significant reductions in energy use and emissions compared to traditional fusion welding methods. While tooling and scalability challenges persist, ongoing innovations in tool design, automation, and hybrid processes are accelerating the industrial adoption of FSW for environmentally responsible manufacturing.

3. EMISSION REDUCTION STRATEGIES IN WELDING

As the metal and steel industries pursue sustainability, emission reduction strategies in welding processes have become critical. Various technological advancements and process innovations are being integrated to minimize both direct and indirect carbon emissions, without compromising weld integrity or production efficiency. The following strategies have emerged as prominent pathways:

a.Process Optimization

Fine-tuning welding parameters such as voltage, current, wire feed speed, and travel speed directly impacts energy consumption and emission profiles. Optimizing these factors can significantly reduce excess heat input and electrical energy waste, leading to lower carbon emissions (Zhao et al., 2023). Modern computational techniques, including machine learning and artificial intelligence, are increasingly employed to predict optimal welding parameters for diverse materials and geometries, improving both energy efficiency and process consistency (Wang et al., 2024).

b. Hybrid Welding Techniques

Hybrid welding technologies, such as Laser-Arc Hybrid Welding (LAHW) and Friction Stir Laser Welding (FSLW), combine the advantages of multiple welding methods to enhance energy efficiency and reduce overall emissions. By merging deep penetration capabilities of lasers with the filler efficiency of arc processes, hybrid methods decrease heat input and welding time, thus lowering energy usage per unit weld length (Gonzalez et al., 2024). These techniques are especially valuable for thick or high-strength steel components in the automotive and shipbuilding industries.

c. Renewable Energy Integration

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Integrating renewable energy sources like solar or wind to power welding equipment offers a transformative approach to decarbonizing welding operations. While traditionally dependent on grid electricity—often derived from fossil fuels—the adoption of photovoltaic systems, battery storage, and direct renewable power can dramatically reduce indirect emissions associated with welding processes (Li et al., 2024). Recent industrial demonstrations show that even large-scale welding operations can be partially powered by renewables without affecting production output.

d. Advanced Monitoring and Control Systems

The incorporation of real-time monitoring systems, including thermal imaging, acoustic sensors, and optical emission spectroscopy, allows for precise control of the welding arc and process environment. These systems enable dynamic adjustments during welding, preventing defects and excessive energy consumption (Rahman et al., 2023). Closed-loop control technologies help avoid over-welding and reduce rework, both of which contribute to unnecessary energy usage and emissions.Future Directions and Challenges:

- **Artificial Intelligence (AI) and Digital Twins:** AI-driven modeling and digital twin technology are expected to further optimize welding processes by simulating various conditions to identify the lowest-emission configurations in real time (Wang et al., 2024).
- **Electrification and Green Supply Chains:** Broader electrification of manufacturing facilities, coupled with green energy procurement strategies, can substantially lower indirect emissions related to welding.
- **Policy and Certification Standards:** Standardized protocols for measuring and certifying welding-related carbon emissions are essential to drive industry-wide adoption of emission reduction strategies

A combination of process optimization, hybrid technologies, renewable energy integration, and real-time monitoring offers a practical pathway toward low-carbon welding operations. While technological and financial barriers remain—particularly for renewable energy adoption and advanced sensor deployment—ongoing research and industry innovation are steadily advancing the prospects for sustainable welding in metal and steel manufacturing sectors.

4. COST ANALYSIS OF LOW-EMISSION WELDING TECHNIQUES

The transition toward low-emission welding processes within the metal and steel industries is increasingly driven not only by environmental concerns but also by long-term economic advantages. While such processes typically demand higher upfront investments, numerous studies—including recent life cycle assessments (LCA)—confirm that they deliver significant operational savings through reduced energy consumption and mitigation of carbon-related costs. According to the OECD (2024), industries adopting low-emission technologies such as Laser Beam Welding (LBW) and Friction Stir Welding (FSW) face higher capital expenditures due to specialized equipment, advanced control systems, and the need for skilled operators. However, these upfront costs are offset over time by lower operational expenses:

- **Reduced Energy Consumption:** Both LBW and FSW utilize energy more efficiently than conventional arc welding. LBW, with its concentrated heat input, minimizes welding time and material distortion, leading to energy savings per weld (Patel et al., 2024). Similarly, FSW, operating without filler metals or shielding gases, consumes significantly less power and produces minimal waste (Zhou et al., 2023).
- **Carbon Taxation and Environmental Levies:** With many regions implementing carbon pricing mechanisms, including emissions trading systems (ETS) and direct carbon taxes, adopting low-emission processes can lead to substantial cost avoidance. Firms using high-emission methods (e.g., SMAW or GMAW) are increasingly exposed to carbon-related penalties, encouraging investment in cleaner technologies (OECD, 2024).

LCA studies offer comprehensive insights into both environmental and economic impacts of welding technologies throughout their entire operational life. According to Zhou et al. (2023), FSW and LBW consistently outperform traditional arc welding methods in cumulative energy demand and greenhouse gas (GHG) emissions over the equipment's lifespan. While the **initial setup cost for FSW and LBW is 30–50% higher**, the total cost of ownership declines due to:

- Lower energy usage per weld joint.
- Reduced rework and defect rates.
- Minimal material wastage.
- Elimination or reduction of consumables like shielding gases and filler wires.

Their study indicates that FSW can reduce total welding-related emissions by approximately 35%, while LBW achieves reductions of around 28%, compared to conventional GMAW processes. Return on Investment (ROI) Considerations and Strategic Recommendations:

- Break-even Timeline: Firms adopting FSW or LBW typically achieve return on investment within 3 to 5 years, depending on production volume and local energy/carbon pricing (Li et al., 2024).

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- Long-Term Benefits: Besides energy and emissions savings, low-emission welding processes can improve weld quality, reduce maintenance, and enhance product lifespan—indirectly contributing to reduced operational costs and enhanced brand sustainability credentials.
- **Policy Support:** Governments and regulatory bodies should provide financial incentives such as tax credits, grants, and low-interest loans to ease the adoption of cleaner welding technologies.
- **Corporate Sustainability Goals:** Integrating LCA-driven decision-making can align welding technology investments with broader corporate sustainability and net-zero emission strategies.
- **Research and Training:** Continued research into process improvements, combined with workforce training, is essential to optimize the adoption and operational efficiency of advanced welding methods.

Although adopting low-emission welding methods like LBW and FSW demands significant initial investments, they offer compelling long-term economic and environmental benefits. The reduction in energy costs, lower emissions, and potential savings from carbon taxes and sustainability incentives underscore the value of transitioning to advanced welding technologies in modern metal and steel manufacturing.

5. FUTURE RESEARCH DIRECTIONS

The transition toward sustainable and low-carbon welding processes necessitates advanced research across multiple technical and environmental domains. To further optimize welding operations for minimal carbon emissions while maintaining or improving weld quality, several strategic research areas have been identified:

a. AI-Based Welding Control Systems for Emission Optimization

Integrating **artificial intelligence (AI)** and machine learning into welding control systems presents a promising approach to real-time process optimization. AI-based systems can:

- Continuously monitor parameters like voltage, current, arc length, and temperature.
- Predict optimal process settings to minimize energy consumption and reduce emissions.
- Adapt dynamically to variations in materials or environmental conditions, enhancing efficiency (Zhang et al., 2024).

Advanced AI algorithms can also support predictive maintenance, defect detection, and quality assurance, reducing rework and waste, thereby contributing indirectly to emission reductions.

Example: Deep learning models can be trained to forecast energy demands and optimize operational parameters for hybrid or automated welding processes.

b. Exploration of Bio-Based Shielding Gases

Traditional shielding gases such as argon and carbon dioxide contribute to the carbon footprint of welding operations. Future research could focus on **bio-based or carbon-neutral shielding gases**, potentially derived from renewable sources, such as biogas or bio-sourced CO_2. Innovations in this area may help:

- Reduce dependency on fossil-based industrial gases.
- Lower indirect (Scope 3) emissions from gas production and supply chains (Rahman et al., 2024).
- Improve overall sustainability without compromising weld quality.

Challenge: Ensuring that bio-based gases provide comparable arc stability and protection against oxidation.

c. Expansion of LCA Databases for Emissions Tracking

Accurate Life Cycle Assessments (LCA)are critical for evaluating the full environmental impacts of welding methods. However, current LCA datasets are often limited or lack granularity for process-specific emissions. Future work should focus on:

- Building comprehensive LCA databases that cover a broad range of welding techniques, consumables, and equipment.
- Including emissions from upstream processes (e.g., production of shielding gases and filler materials).
- Enabling industry-wide benchmarking for emissions reduction strategies (Wang et al., 2024).

This expansion would support more precise tracking of emissions and facilitate evidence-based decisions in manufacturing sustainability planning. Future research efforts should prioritize the convergence of digital technologies, material innovations, and environmental science to drive down emissions from welding operations. AI-driven process control, novel bio-based inputs, and robust emissions tracking infrastructure will collectively advance the goal of carbon-neutral welding within the metal and steel industries.

6. CONCLUSION

Welding processes play a fundamental role in metal and steel manufacturing but are significant contributors to industrial energy consumption and carbon emissions. This comprehensive review has examined various conventional and advanced welding techniques—including Gas Metal Arc Welding (GMAW), Shielded Metal Arc Welding (SMAW), Tungsten Inert Gas (TIG) Welding, Laser Beam Welding (LBW), and Friction Stir Welding

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(FSW)—highlighting their respective operational efficiencies, emission profiles, and cost implications. Among these processes, GMAW and SMAW, although widely adopted for their operational simplicity and versatility, are associated with high energy consumption and substantial carbon emissions due to prolonged arc-on times and fossil-fuel-dependent electricity. In contrast, TIG welding provides superior weld quality but similarly suffers from high energy intensity and significant emissions. Advanced techniques like LBW and FSW emerge as more sustainable alternatives, offering lower energy consumption, reduced direct emissions, and better process efficiency. LBW benefits from concentrated energy delivery and minimal thermal distortion, while FSW—as a solid-state process operates with minimal heat input and negligible emissions, making it the most eco-friendly method evaluated. Key emission reduction strategie including process optimization, hybrid welding, renewable energy integration, and advanced monitoring systems are instrumental in minimizing both direct and indirect emissions. Life Cycle Assessments (LCA) confirm that although advanced welding technologies require higher initial investments, they yield significant long-term environmental and economic benefits due to lower energy usage, reduced rework, and potential savings from carbon taxation. In conclusion, transitioning towards low-emission, energy-efficient welding processes is both technically feasible and economically justified for modern metal/steel industries. Leveraging technological advancements, digital manufacturing, and renewable energy sources will be essential in advancing toward carbon-neutral welding operations, contributing meaningfully to global sustainability goals without compromising weld quality or productivity.

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