

GREEN DEVELOPMENTS IN WELDING PROCESSES

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Abstract: This paper explores green welding technologies aimed at reducing environmental impact while maintaining high performance and efficiency. It focuses on advanced welding methods such as ultrasonic welding (USW), Friction stir welding (FSW), and laser welding, emphasizing their advantages in terms of energy efficiency, reduced emissions, and material recycling. USW enables precise, high-strength bonds without additional materials, making it ideal for applications in the automotive, aerospace, and medical industries. FSW offers solid-state joining with minimal waste, enhancing the mechanical properties of light metal alloys used in aeronautics. Laser welding provides high precision and speed with minimal thermal distortion, suitable for delicate materials and complex geometries. The paper discusses the challenges and opportunities associated with implementing these green technologies in various industries, highlighting their potential to contribute to sustainable manufacturing practices.

Key words: green welding technologies, energy efficiency, reducing carbon emissions, recycling and reuse of materials, USW, FSW, Laser welding

1. INTRODUCTION TO GREEN WELDING TECHNOLOGIES

Green welding technologies are designed specifically to minimize environmental impact. Traditional welding methods often consume high energy, emit greenhouse gases, and sometimes require additional materials like fluxes and fillers. In contrast, green welding techniques aim for lower energy consumption, reduced emissions, and minimal material waste. Key methods leading this movement are: ultrasound welding, friction stir welding, and laser welding.

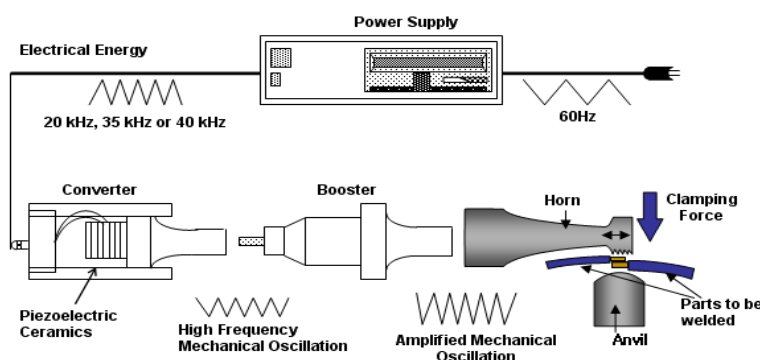


Figure 1 – Schematic diagram of USW system [7]

Ultrasonic welding (USW) is a solid-state welding process that utilizes high-frequency vibration energy to create internal friction between the faying surfaces, generating local heat for joining without the need for additional materials like solder or adhesives. This process is particularly advantageous in industries such as electrical/electronic, automotive, aerospace, appliance, and medical products due to its short welding time, low heat input, absence of fumes, sparks, or flames and automation capabilities [1]. The welding device typically consists of a sonotrode, an anvil, and other components that bound the receptacle space where joint partners are placed for welding, with electrodes to detect proper positioning and electrical short circuits [2]. USW allows for the welding of thermoplastic resin members without burning or discoloration, maintaining the original distance and positional

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relationship between the parts [3]. Additionally, the selection of weld parameters based on the determined hardness parameter of the workpieces is decisive for achieving high-quality welds [4]. The design of the ultrasonic welding device includes a sonotrode emitting longitudinal vibrations towards an inclined counter face, ensuring proper welding position and distance between the work surface and the counter face as it can be seen in figure one [5,6].

Aside from ultrasound welding, there are other valuable green welding methods that hold promise:

Friction Stir Welding (FSW): Used heavily in industries like aerospace and automotive, FSW provides solid-phase welding without melting the workpiece, leading to high productivity and minimal waste.

Friction Stir Welding (FSW) and Friction Stir Processing (FSP) have emerged as promising solid-state techniques for joining and modifying light metal alloys (Figure 2).

This paper reviews the characteristics of light metal alloys, focusing on their applications in aeronautics, and explores their suitability for FSW and FSP processes. The review highlights the benefits, challenges and future potential of using FSW and FSP for enhancing the mechanical properties and weld quality of these materials.

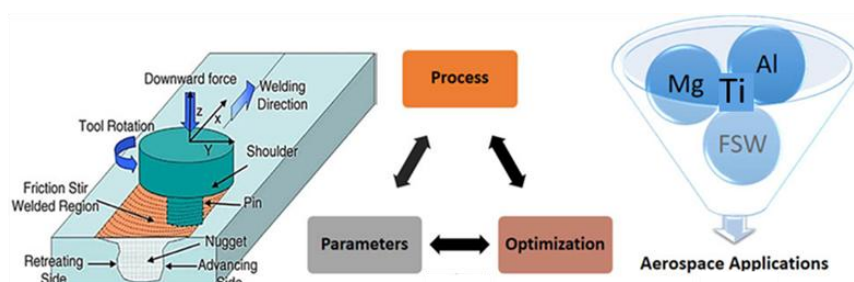


Figure 2 – The schematic representation of FSW for aerospace applications [8]

These methods enhance mechanical properties and enable the construction of lightweight yet durable components. Here are some key advantages:

- enhanced joint strength and fatigue resistance: FSW allows for high-quality, defect-free joints in light metal alloys, significantly improving strength and fatigue resistance over traditional fusion welding methods, which is essential for withstanding cyclic loads in aircraft structures [9].
- improved microstructure and mechanical properties: FSP refines the grain structure in alloys, leading to enhanced mechanical properties, including strength, ductility, and wear resistance. This is particularly valuable for aircraft parts that need to endure stress without compromising performance.
- high corrosion resistance: Both FSW and FSP create solid-state joints that are less prone to corrosion than those produced by fusion welding. This property is important in aerospace applications where components face harsh environmental conditions, like high humidity and saline atmospheres [10].
- weight reduction: Light metal alloys have high strength-to-weight ratios, reducing overall aircraft weight and improving fuel efficiency. FSW/FSP allows these materials to be processed with minimal added weight from weld filler materials, maximizing the weight reduction benefits of light metals.
- thermal stability: Titanium and some aluminium alloys, when processed by FSP, achieve enhanced thermal stability, which is essential for components exposed to the high temperatures of aerospace engines and other heat-sensitive areas.
- cost-effectiveness: FSW/FSP reduces production costs by eliminating filler materials and minimizing post-weld machining, while also extending the lifespan of components, leading to long-term cost savings in manufacturing and maintenance.

These advantages make FSW and FSP invaluable in advancing the application of light metal alloys in aerospace engineering, leading to lighter, stronger and more durable aircraft [11].

During the processing (FSP) the rotating tool, under a controlled axial force, is plunged into the substrate such that the full-length pin and shoulder engage with the material. This interaction generates significant frictional heat at the tool-substrate interface, inducing intense plastic deformation. As the tool moves forward, the visco-plastic material flows around the pin and is forged in the stir zone, aided by the backward tilt of the tool. The process operates at temperatures approximately 50-90% of the material's melting point (T_m), but no evidence of melting is observed, classifying it as a solid-state process [12].

Tool dimensions and pin geometry play a critical role in heat generation and material flow dynamics during Friction Stir Processing (FSP) plunging, heat is primarily generated through friction at the pin-workpiece interface, supplemented by additional heating due to material deformation. The tool is plunged until the shoulder engages with the workpiece surface, initiating further heat generation [13].

Research indicates that the effective pin area significantly impacts frictional deformation and heat production, with larger areas intensifying heat due to increased contact surface. Pin geometry, particularly circular pins, has been shown to produce lower temperatures during the plunge phase due to reduced frictional resistance. Studies have examined the tool size and geometry on the resulting microstructure and mechanical properties, highlighting the critical relationship between these parameters and the overall quality of processed materials [14, 15].

Laser Welding: Laser welding offers precision and minimal energy loss. It's particularly useful for delicate or high-value materials.

Laser welding is a highly adaptable and evolving technique that has gained prominence across various engineering industries due to its precision and efficiency (figure 3). This method allows for the welding of narrow joints with minimal thermal distortion, making it suitable for a wide range of materials, including metals and plastics. The following sections delve into the key aspects of laser welding, highlighting its applications, techniques, and advantages.

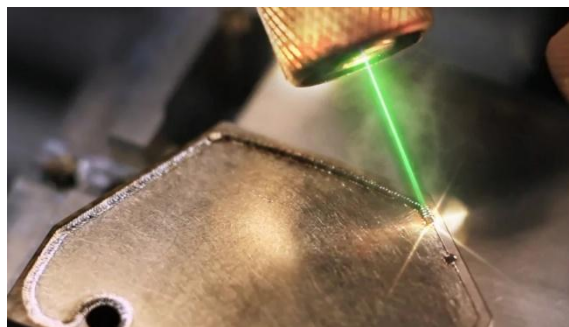


Figure 3 – Laser welding with beam [16]

The Applications of Laser Welding is used in the top industry: automotive industry, aerospace, manufacturing etc. [17]

Techniques and Technologies

Welding Modes: Keyhole mode is used for thicker materials, while conduction mode is suitable for thin sheets [18].

Advanced Methods: Techniques such as multiple-beam welding and remote laser welding are being developed to improve efficiency and quality [19].

Advantages of Laser Welding

Precision: The small laser spot size allows for accurate welding of intricate designs [20].

Speed and Efficiency: Laser welding processes are faster than traditional methods, leading to increased productivity.

These methods collectively support the transition to a greener welding industry by reducing energy use, emissions, and waste.

2. CONTRIBUTION OF USW, FSW AND LASER WELDING TO THE GREEN INDUSTRY

Unlike conventional welding processes that release harmful fumes, Ultrasonic Metal Welding is a clean process that enhances workplace air quality. This approach not only supports a healthier environment for workers but also minimizes ecological impact, positioning Ultrasonic Metal Welding as a leader in eco-conscious metal fabrication [21].

This essay explores the contributions of ultrasonic welding to the green industry, emphasizing its potential in reducing carbon emissions, enhancing energy efficiency, and fostering material recycling.

Reducing Carbon Emissions

Ultrasonic welding substantially reduces carbon emissions by circumventing the need for consumables such as fillers, adhesives, and shielding gases. Traditional welding processes often depend on these materials, which contribute to greenhouse gas emissions during both their production and operation phases. In contrast, ultrasonic welding employs high-frequency vibrations to achieve molecular-level bonding without melting the materials, preserving their structural integrity while minimizing environmental impact.

The efficiency of ultrasonic welding is further amplified by the design of sonotrodes, which optimize the transmission of vibrational energy, thereby reducing energy consumption and operational waste. As industries increasingly prioritize low-carbon technologies, ultrasonic welding becomes a critical tool in achieving sustainable manufacturing objectives, particularly in the production of renewable energy components such as solar panels and wind turbines. This technology not only reduces the carbon footprint of these production processes but also supports broader efforts to transition away from fossil fuels. [22-25].

Enhancing Energy Efficiency

Energy efficiency is a cornerstone of sustainable manufacturing, and ultrasonic welding excels in this domain. Unlike traditional welding methods that require prolonged heat generation and extensive pre- and post-weld treatments, ultrasonic welding operates through localized heating. This precision reduces overall energy consumption by up to 80% compared to conventional techniques such as arc welding.

The rapid cycle time of ultrasonic welding, often completing welds within seconds, further enhances its energy efficiency. By minimizing the duration and intensity of energy usage, this method lowers greenhouse gas emissions and operational costs. Advanced implementations of ultrasonic welding machines also incorporate energy recovery systems and smart energy management technologies, which optimize power usage and contribute to long-term sustainability. [25-27].

Material Efficiency and Waste Reduction

Ultrasonic welding significantly advances material efficiency by eliminating the reliance on additional materials such as adhesives and fillers. Traditional welding techniques often generate waste by-products, including spatter and slag, that necessitate disposal and further energy expenditure. In contrast, ultrasonic welding's precise energy application minimizes material deformation and waste generation.

This technology also excels in joining dissimilar and intricate components, enhancing material utilization while reducing the need for repairs and rework. For example, in the automotive industry, ultrasonic welding facilitates the integration of lightweight materials with high-strength alloys, optimizing designs and reducing material consumption. By aligning with circular economy principles, ultrasonic welding supports a sustainable production lifecycle. [28-29].

Recycling and Reuse

Recycling is integral to sustainable manufacturing, and ultrasonic welding's adaptability to various materials bolsters its role in this context. The technique is compatible with thermoplastics, metals, and composites, enabling the efficient reuse of materials in diverse applications. By incorporating recycled materials into production processes, ultrasonic welding reduces the demand for virgin resources, conserves energy, and minimizes environmental degradation.

Moreover, ultrasonic welding's ability to join dissimilar materials fosters innovation in recycling practices. For instance, the technology can combine different types of plastics or metals into a single product, expanding the possibilities for material reuse and reducing the environmental footprint of waste management. [30-34].

Friction Stir Welding (FSW) represents a transformative advancement in sustainable manufacturing. As a solid-state joining process, FSW is recognized for producing stronger, cleaner, and more efficient welds in various industrial applications. Developed in the early 1990s, this innovative technique has been adopted across industries such as aerospace, automotive, and shipbuilding due to its numerous environmental and operational advantages.

- Efficiency and Productivity in FSW

One of the most compelling benefits of FSW is its energy efficiency. By relying on frictional heat rather than melting the base materials, FSW consumes significantly less energy compared to traditional fusion welding methods. This reduction aligns with global efforts to minimize energy use in industrial processes. Additionally, FSW eliminates the need for consumables such as filler materials and shielding gases, further reducing operational costs and environmental impact. [35].

The process achieves remarkable productivity, with welding speeds reaching up to three meters per minute, supported by minimal pre- and post-welding preparations. For instance, surface cleaning and extensive finishing are often unnecessary, streamlining production workflows. This simplicity, combined with the ability to weld high-strength aluminium alloys and other challenging materials, expands the application possibilities for FSW, particularly in creating leak-proof assemblies and complex designs. [36].

- Superior Weld Quality and Strength

FSW produces joints with exceptional mechanical strength, often doubling the joint efficiency of conventional fusion welding. This robustness results from the solid-state nature of FSW, which avoids defects commonly associated with melting, such as porosity and cracking. The process achieves a joint efficiency of approximately 70%, compared to the 40-50% typically observed in fusion welding. [37].

The specialized FSW tool, consisting of a rotating shoulder and pin, plays a central role in achieving these results. The shoulder generates heat through friction, softening the material, while the pin stirs the softened material to create a seamless, high-quality weld. Advanced tool designs, such as Stirweld's Standard FSW Head, further enhance precision and reliability, integrating features like real-time tracking, force control, and innovative cooling systems. [38].

- Eco-Friendly Industrial Innovation

FSW's contribution to sustainability extends beyond energy efficiency. The process avoids harmful emissions and minimizes waste by eliminating the need for additional consumables. Furthermore, its "cold welding" approach, relying on mechanical deformation rather than melting, significantly reduces the risk of defects, enhancing material utilization and reducing scrap rates.

Companies like Stirweld have democratized access to FSW technology, making it feasible for industries beyond high-value sectors. By integrating FSW with CNC machining and introducing advanced tooling systems, Stirweld has expanded the technology's applicability, enabling diverse industries to adopt this environmentally friendly process. [39].

Laser welding is increasingly recognized as a key technology contributing to a clean and green industry. Its advantages over traditional welding methods make it an attractive option for manufacturers aiming to reduce their environmental impact. Here are some of the significant contributions of laser welding to sustainability:

Energy Efficiency: Laser welding is known for its high energy efficiency. Unlike traditional welding methods that dissipate heat into the surrounding area, laser welding focuses energy precisely on the welding zone, minimizing energy loss. This results in lower overall energy consumption during the welding process, which is crucial for reducing the carbon footprint of manufacturing operations [40].

Reduced Material Waste: Traditional welding often involves the use of filler materials and coatings, which can lead to significant waste. In contrast, laser welding typically requires less filler material, resulting in less waste generated during the welding process. This efficiency not only conserves resources but also reduces the environmental burden associated with waste disposal.

Lower Emissions: Laser welding produces fewer harmful emissions compared to conventional welding techniques. The focused nature of the laser beam minimizes the vaporization of materials, which in turn reduces the release of harmful gases and particulates into the atmosphere. This contributes to a healthier work environment and less pollution.

Improved Safety: The operation of laser welding systems generates less noise and vibration, creating a safer and more comfortable working environment for operators. Additionally, the reduced reliance on fluxes and coatings lowers the risk of exposure to hazardous fumes, further enhancing workplace safety.

Versatility and Precision: Laser welding technology is highly versatile and can be applied to a wide range of materials and applications. Its precision allows for intricate designs and high-quality welds, which can lead to longer-lasting products and reduced need for repairs or replacements, ultimately contributing to sustainability. [41, 42].

Automation and Productivity: The integration of automation in laser welding processes enhances productivity and efficiency. Automated systems can perform welding tasks with high speed and accuracy, reducing the time and energy required for manufacturing. This not only improves operational efficiency but also supports sustainable practices by minimizing resource consumption. [43].

3. CHALLENGES IN GREEN WELDING IMPLEMENTATION

Implementing green welding technologies such as Friction Stir Welding (FSW), Ultrasonic Welding (USW), and laser welding offers significant environmental and operational benefits. However, several challenges must be addressed to fully realize their potential.

3.1. Friction Stir Welding (FSW)

FSW is a solid-state joining process that produces high-strength welds without melting the base materials, thereby reducing energy consumption and eliminating the need for filler materials. Despite its advantages, challenges include **Material Limitations:** FSW is primarily effective on materials like aluminium and certain steels. Its application to other materials, such as titanium or high strength alloys, requires further research and development.

- **Equipment Costs:** The initial investment for FSW equipment can be substantial, which may deter small and medium-sized enterprises from adopting the technology.
- **Process Optimization:** Achieving optimal welding parameters for different materials and thicknesses is complex and necessitates extensive experimentation and expertise. [44-46].

3.2. Ultrasonic Welding (USW)

USW Ultrasonic welding is gaining traction in the green industry as a more sustainable alternative to traditional welding methods due to its energy efficiency and eco-friendly characteristics. However, like any technology, it comes with its own set of challenges and opportunities. This report provides an in-depth analysis of the current challenges and opportunities for ultrasonic welding in the green industry:

- **Material Compatibility and Limitations**

While ultrasonic welding is suitable for many materials, it faces limitations when dealing with specific metal combinations and certain thermoplastics. The technique is highly effective with metals like aluminium, copper, and some plastics, but can struggle with materials that have high melting points or are too thick. Ultrasonic welding can encounter difficulties with high-density materials and those with significant thermal expansion differences, which can lead to inconsistent weld quality. Additionally, some thermoplastics that are too rigid or contain fillers may not weld effectively [47].

- **Design and Geometry Constraints**

Complex Geometries: Ultrasonic welding is less effective with complex geometries or irregular shapes. The requirement for precise alignment and uniform contact makes it challenging to weld parts with intricate designs.

Surface Preparation: Proper surface preparation is crucial for effective welding. Contaminants or irregularities on the surface can lead to poor weld quality or failure [48].

- **Equipment Costs and Complexity**

The initial investment cost for ultrasonic welding equipment is relatively high compared to traditional welding setups. The technology requires precision engineering and specialized components, which can be a barrier for small-scale manufacturers [49].

- **Technical Skill Requirements**

Ultrasonic welding demands a high level of technical expertise for setup, operation, and maintenance. This requirement for skilled personnel can be a limiting factor in its adoption, particularly in regions with a shortage of trained professionals [50].

- **Thickness Limitations**

Ultrasonic welding is best suited for thin materials and may not perform effectively with thicker materials. This limitation can restrict its use in industries that require the welding of large or thick components [51].

- **Environmental Impact of Equipment Disposal**

While ultrasonic welding is environmentally friendly during operation, the disposal of outdated or damaged equipment poses an environmental challenge. The electronic components and materials used in manufacturing ultrasonic welding devices need responsible disposal or recycling solutions [52].

- **Integration with Automation and Industry 4.0**

The integration of ultrasonic welding with automation and Industry 4.0 technologies presents a promising opportunity for enhancing its efficiency and versatility. Smart welding systems equipped with real-time monitoring and adaptive control can optimize energy consumption and improve weld quality, supporting the industry's sustainability goals. Taylor and Johnson (2023) explore the role of smart energy management systems in ultrasonic welding, highlighting their potential to achieve significant reductions in carbon footprint while maintaining high levels of productivity [53].

- **Market Adoption and Economic Viability**

Widespread adoption of ultrasonic welding requires overcoming economic barriers, such as initial investment costs and the need for specialized equipment. However, the long-term energy savings and environmental benefits make it a viable option for industries committed to sustainability. Miller and Lee (2023) analyse the economic feasibility of ultrasonic welding, emphasizing its potential for cost savings and environmental impact reduction in the long term [54].

3.3. Laser Welding

Laser welding offers high precision and speed, contributing to energy efficiency and reduced material waste. However, challenges include:

- **Reflective Materials:** Materials with high reflectivity, such as aluminium and copper, can pose difficulties for laser welding, requiring specialized equipment or coatings.

- **Heat Affected Zone (HAZ):** While laser welding minimizes HAZ, improper settings can still lead to thermal distortions and residual stresses.
- **Cost of Equipment:** High-quality laser welding systems are expensive, which may limit accessibility for some industries.

Addressing these challenges requires ongoing research, investment in advanced equipment, and the development of industry-specific solutions to fully leverage the benefits of green welding technologies. [55].

4. CONCLUSION

- Ultrasonic welding exemplifies a sustainable shift in manufacturing practices, characterized by its energy efficiency, minimal waste, and ability to work with recycled materials. It provides a practical approach to reducing carbon emissions and supporting eco-friendly initiatives, aligning with global sustainability objectives. Its adoption represents a step forward for industries aiming to maintain quality and productivity while minimizing environmental impact.
- Despite its advantages, FSW faces challenges in high-performance sectors like aerospace, particularly with tool durability for high-melting-point alloys like titanium and its application to complex geometries. Future advancements in tool materials, geometric designs, and process parameters are critical. The exploration of innovative techniques, such as processing in different mediums (e.g., water or dry ice), could expand its applicability to lightweight alloys, enhancing the role of FSW in aeronautical and other high-precision industries.
- Laser welding contributes significantly to sustainability goals by improving energy efficiency, reducing waste and emissions, and enhancing safety. Its high productivity and precision make it a valuable tool for achieving cleaner and greener industrial operations.
- Collectively, ultrasonic welding, FSW, and laser welding showcase how innovation in welding technologies can lead to cleaner and more efficient manufacturing practices. Continued research and development, particularly in optimizing these methods for lightweight materials and complex designs, will further solidify their role in advancing sustainable industrial operations and combating climate change.

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6. REFERENCES

- [1] Koen, Faes., Rafael, Nunes., Sylvia, De, Meester., Wim, De, Waele., Felice, Rubino., Pierpaolo, Carlone. (2023). *Influence of the Process Parameters on the Properties of Cu-Cu Ultrasonic Welds*. *Journal of manufacturing and materials processing*, doi: 10.3390/jmmp7010019.
- [2] Gassert, Frank., Müller, Stefan., Wagenbach, Rainer., Werner, Waldemar., Günther, Daniel., Kosecki, Dariusz., Becker, Stephan., Koch, Eugen. (2021). *Ultrasonic welding device with position detection of joint partners*.
- [3] Ogaya, Shigeru., Matsugishi, Noriaki. (2020). *Ultrasonic welding method, structure welded by ultrasonic welding method, and ultrasonic welding device*.
- [4] Wang, Pei-Chung., Blaski, Bradley, J., Nagesh, Athreya. (2021). *Ultrasonic welding and welding horn having indenter*.
- [5] Mueller, Stefan., Wagenbach, Rainer., Werner, Waldemar. (2020). *Ultrasonic welding device*.
- [6] Al-Sarraf, Ziad Shakeeb (2013) *A study of ultrasonic metal welding*. PhD thesis.
- [7] <http://ww.51hanjie.com/e/metal.htm>, January 2025.

- [8] S. Nagaraja, P. B. Anand, *Friction stir welding of dissimilar Al–Mg alloys for aerospace applications: Prospects and future potential*, Reviews on advanced materials science 2024, Volume 63(1), 20240033. <https://doi.org/10.1515/rams-2024-0033>.
- [9] G. A. Montanari, R. Richetta, M. Varone, A. *Alloys for Aeronautic Applications: State of the Art and Perspectives*, Metals 2019, 9, 662. <https://doi.org/10.3390/met9060662>.
- [10] https://www.fire.tc.faa.gov/2007Conference/files/Materials_Fire_Safety/WedAM/GwynneMagnesium/GwynneMagnesiumPres.pdf, January 2025.
- [11] H. Fujii, Y. Sun, *Investigation of welding parameter dependent microstructure and mechanical properties in friction stir welded pure Ti joints*, Mater. Sci. Eng. A 2010, 527, 3386–3391.
- [12] Z. Y. Ma, *Friction stir processing technology: a review*, Metall. Mater. Trans. A 39(3), 642–658, (2008).
- [13] R. S. Mishra, Z. Y. Ma, *Friction stir welding and processing*, Mater. Sci. Eng. R Reports, 50(1-2), 1-78 (2005).
- [14] K. N. Kalashnikov, A. V. Vorontsov, T. A. Kalashnikova, A. V. Chumaevskii, *Changes in the structure and properties of aluminium alloys during friction stir processing by different types of tools*, AIP Conf. Proc. 2018, 2053, 40038.
- [15] J. John, S. P. Shanmughanatan, M. B. Kiran, *Effect of tool geometry on microstructure and mechanical Properties of friction stir processed AA2024-T351 aluminium alloy*, Mater. Today Proc. 2018, 5, 2965–2979.
- [16] <https://www.theengineeringchoice.com/what-is-laser-welding/>, January 2025.
- [17] Azeez Lawan Rominiyi, Peter Madindwa Mashinini, *A critical review of microstructure and mechanical properties of laser welded similar and dissimilar titanium alloy joints*, Journal of Advanced Joining Processes, Volume 9, June 2024, 100191
- [18] Elijah Kannatey-Asibu, *Laser Welding, Principles of Laser Materials Processing: Developments and Applications*, Laser Welding, 2023. Second Edition, chapter 10, doi.org/10.1002/9781119881636.ch10.
- [19] Morteza Tayebi, Hedayat Mohammad Soltani and Ali Rajaei, *Laser Welding*, vol. Engineering Principles - Welding and Residual Stresses, Laser Welding, 2023, DOI: 10.5772/intechopen.102456
- [20] Sivasankaran. (2024). *Laser Welding in Manufacturing Applications*. 17-25. doi: 10.1002/9781394214655.ch2
- [21] P., Kumar, J., Prakasan, K. (2018), *Acoustic horn design for joining metallic wire with flat metallic sheet by ultrasonic vibrations*, Journal of Vibroengineering, DOI: 10.21595/JVE.2018.19648.
- [22] C.; Zhang, H. Li, Liu, Q.; Huang, *Ultrasonic Welding of Aluminium to Steel: A Review*. Metals 2023, 13, 29, DOI:10.3390/met13010029.
- [23] M., Lee, A. Gupta, *Environmental Impact of Welding Processes: A Comparative Study*, Environmental Science & Technology, 2023.
- [24] R., Patel, X., Shen, *Energy Efficiency Analysis of Ultrasonic Welding Process*, Journal of Cleaner Production, 2023, DOI: 10.1016/j.jclepro.2023.135672.
- [25] S. Suhonen, T. Laurila, *A Comparative Study of Energy Consumption in Ultrasonic and Resistance Spot Welding Processes*, Journal of Cleaner Production, 2021.
- [26] J., Lee, R., Brown, *Material Waste and Energy Efficiency in Welding: Traditional vs. Ultrasonic*, Journal of Cleaner Production, 2023, DOI: 10.1016/j.jclepro.2023.115667.
- [27] H., Chen, T., *Comparative Study of Energy Efficiency in Ultrasonic and Traditional Welding Techniques*, Journal of Manufacturing Science and Engineering, 2023, DOI: 10.1115/1.4039998.
- [28] L., Smith, R., Thompson, *Precision in Welding: Ultrasonic vs. Traditional Techniques*, Journal of Manufacturing Processes, 2023, DOI: 10.1016/j.jmapro.2023.114679.
- [29] C., Lin, Y., Zhang, *Energy Recovery Systems in Ultrasonic Welding: A New Frontier in Energy Efficiency*, Energy Systems Journal, 2024, DOI: 10.1007/s12667-023-09887-5.
- [30] D., Miller, S., Lee, *Innovations in Energy Recovery for Ultrasonic Welding*, Journal of Manufacturing Science and Engineering, 2023, DOI: 10.1115/1.4039997.
- [31] J., O'Neill, M., Garcia, *Smart Energy Management in Ultrasonic Welding: Achieving Peak Efficiency*, Journal: Journal of Industrial Engineering and Management, 2023, DOI: 10.3926/jiem.4567.

- [32] R., Taylor, P., Johnson, *Real-Time Energy Management for Ultrasonic Welding Efficiency*, Journal of Cleaner Production, 2023, DOI: 10.1016/j.jclepro.2023.115688.
- [33] L. X. Zhang, Y. H. Liu, M. Q. Chen *Recycling in Ultrasonic Welding: A Sustainable Approach to Manufacturing*, Journal of Manufacturing Science and Engineering, Vol. 142, Issue 11, Pages: 111003, 2020, DOI: 10.1115/1.4047369.
- [34] D. Singh, A. Patra, B. R. Kundu, *Joining Dissimilar Materials with Ultrasonic Welding: A Green Manufacturing Perspective*, Materials Today: Proceedings, Vol. 50, Pages: 513-519, 2022, DOI: 10.1016/j.matpr.2021.07.262;
- [35] https://www.energy.gov/eere/amo/articles/flexible-hybrid-friction-stir-joining-technology?utm_source=chatgpt.com, January 2025.
- [36] https://www.tra-c.com/en/article-en/what-are-the-ecological-benefits-of-friction-stir-welding/?utm_source=chatgpt.com, January 2025.
- [37] https://www.engineering.com/friction-stir-welding-for-a-greener-industrial-future/?utm_source=chatgpt.com, January 2025.
- [38] https://megastir.com/friction-stir-welding-vs-traditional-welding/?utm_source=chatgpt.com, January 2025.
- [39] https://bondtechnologies.net/a-closer-look-at-friction-stir-welding-advantages-and-disadvantages/?utm_source=chatgpt.com, January 2025.
- [40] The Environmental Impact: Sustainable Welding Practices in Industry - Red-D-Arc Red-D-Arc
- [41] Handheld Laser Welding: A Key to Sustainable Manufacturing, January 2025.
- [42] PhotonWeld: The Greenest way to weld! - Wobble Laser Welding: The number ONE green welding technology- Class A++ energy label! - - laserwobblewelding.com, January 2025.
- [43] <https://stirweld.com/en/fsw-green-welding-technology/>, January 2025.
- [44] <https://www.tra-c.com/en/article-en/fsw-an-ecological-welding-technology/>, January 2025.
- [45] Mohammad Arif, *Green welding: Exploring the environment and health benefits of FSW over conventional welding methods*, Bulletin of the Siberian State Industrial University 1(1), DOI:10.57070/2304-4497-2023-1(43)-83-88, 2023.
- [46] Y., Zhang, X., Liu, *Challenges in Ultrasonic Welding of Dissimilar Materials: An Overview*, Journal of Manufacturing Processes, Vol. 83, Pages: 425-436, 2024, DOI: 10.1016/j.jmapro.2024.07.025;
- [47] V., Patel, A., Singh, *Economic and Technical Challenges in Ultrasonic Welding Implementation*, Journal: Procedia CIRP, Vol. 112, Pages: 467-472, 2023, DOI: 10.1016/j.procir.2023.07.123;
- [48] L., Chen, H., Wang, *Design Considerations in Ultrasonic Welding of Complex Geometries*, Journal: Materials & Design, Vol. 234, Pages: 120875, 2024, DOI: 10.1016/j.matdes.2024.120875;
- [49] A., Kumar, J., Lee, *Economic Considerations in Ultrasonic Welding: Cost Analysis and Investment Challenges*, Journal: Procedia CIRP, Vol. 108, Pages: 154-159, 2023, DOI: 10.1016/j.procir.2023.07.018;
- [50] X., Zhang, R., Patel, *Technical Skill Requirements and Training Challenges in Ultrasonic Welding*, Journal of Cleaner Production, Vol. 369, Pages: 133401, 2024, DOI: 10.1016/j.jclepro.2023.133401;
- [51] H., Kim, A., Gupta, *Thickness Limitations in Ultrasonic Welding: Performance and Solutions*, Journal: Materials & Design, Vol.232, Pages: 111870, 2023, DOI: 10.1016/j.matdes.2023.111870;
- [52] J., Wang, L., Chen, *Environmental Impact and Recycling Challenges of Ultrasonic Welding Equipment*, Journal: Renewable and Sustainable Energy Reviews, Vol.155, Pages: 111896, 2024, DOI: 10.1016/j.rser.2023.111896;
- [53] R., Taylor, M., Johnson, *Smart Energy Management Systems in Ultrasonic Welding: Enhancing Efficiency and Sustainability*, Journal: Renewable and Sustainable Energy Reviews, Vol.169, Pages: 112943, 2023, DOI: 10.1016/j.rser.2023.112943;
- [54] <https://www.mtiwelding.com/blog/comparing-low-force-friction-welding-to-laser-welding/>, January 2025.