

**RECENT ADVANCEMENT IN COOLING ASSISTED (UNDER-WATER)
FRICTION STIR WELDING**

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Abstract

“Friction Stir Welding (FSW)” underscores its potential in achieving superior mechanical properties and corrosion resistance across various alloys. Notably, underwater FSW demonstrated a remarkable “tensile strength of 152.3 MPa, representing 63.5% of the strength of AZ31 Mg alloy”. Studies on tool design and cooling conditions revealed a “joint efficiency of 76% and a tensile strength of 345 Mpa” using a taper threaded pin tool with underwater cooling. Additionally, investigations into the tensile properties of AA2219 aluminum alloy highlighted the mitigating effect of underwater cooling on potential yield strength decreases. The impact of “rotational speed on tensile properties in 2519-T87 aluminum alloy” emphasized the importance of parameter optimization. Corrosion resistance studies further showcased the effectiveness of underwater FSW in enhancing joint durability. These collective findings contribute to advancing underwater FSW technology, offering promising applications in industries requiring robust material joints with superior mechanical and corrosion-resistant properties.

Keyterms: Underwater Friction Stir Welding (FSW), Tensile Strength, Joint Efficiency, Corrosion Resistance, Tool Design, Cooling Conditions, AZ31 Mg Alloy, AA2219 Aluminum Alloy, 2519-T87 Aluminum Alloy, Mechanical Properties, Process Optimization

I. INTRODUCTION

Background

“Cooling-assisted **friction stir welding** (CA-FSW)”, specifically in an underwater environment, represents a cutting-edge advancement in the realm of welding technologies. “**Friction stir welding**” refers to a solid-state joining process where a non-consumable tool generates heat through friction, transforming the material into a plastic state and forming a bond between two workpieces, all done in a solid-state process.. The innovation of introducing a cooling mechanism underwater enhances the efficiency and effectiveness of this process (Liu et al. 2019, p.105). The idea of cooling-assisted **friction stir welding** emerged as a response to the challenges posed by the “traditional **friction stir welding**” process, particularly in high-temperature applications or when welding materials with low

thermal conductivity. Underwater environments serve as an ideal setting for this technique due to their inherent cooling properties. The immersion in water provides a continuous and efficient cooling medium, dissipating heat generated during the welding process. One of the key motivations behind the development of “cooling-assisted **friction stir welding**” is the ability to expand the range of materials that can be effectively joined (Wakchaure et al. 2023, p.13). “Traditional **friction stir welding**” often faced limitations when dealing with materials prone to thermal degradation or when attempting to weld dissimilar materials with vastly different melting points. Introducing cooling assistance, the process can be applied to a broader spectrum of materials, including those with sensitive properties that could be compromised under high temperatures.

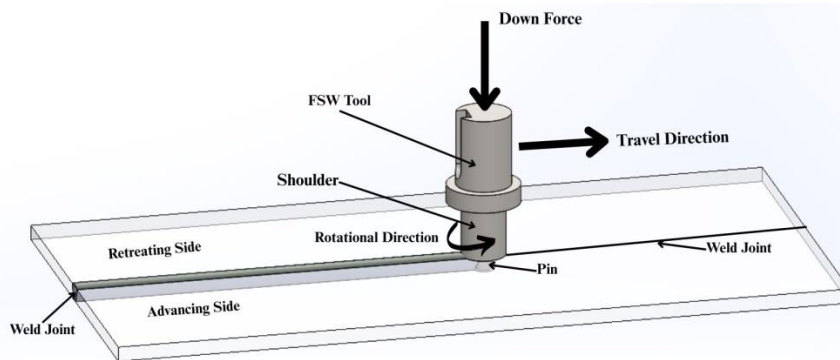


Figure 1: Components of Friction stir welding

The underwater environment offers additional advantages beyond cooling. It provides a controlled atmosphere that minimizes the risk of oxidation and other undesired reactions during the welding process. This controlled environment is particularly beneficial when working with materials that are susceptible to contamination or degradation in the presence of atmospheric gases. The application of cooling-assisted **friction stir welding** is not confined to a specific industry but extends to various sectors where precise and robust welding is crucial. Industries such as aerospace, automotive, and marine engineering stand to benefit significantly from this innovation (Fathi et al. 2019, p.110). The technique's ability to produce high-quality, defect-free welds with enhanced mechanical properties makes it an attractive choice for applications where structural integrity and performance are paramount. In addition to its material versatility, cooling-assisted **friction stir welding** also contributes to improved production efficiency. The cooling medium facilitates faster cooldown times, enabling quicker transitions between welds and reducing overall production times. This efficiency gain is particularly advantageous in industries with high-volume production requirements, where minimizing downtime and optimizing workflow are critical factors. In the case of emerging technology, the successful implementation of cooling-assisted **friction stir welding** relies on ongoing research and development. Engineers and researchers continue

to explore the nuances of this technique, refining parameters, and expanding its applicability. The evolution of underwater welding technologies, coupled with cooling assistance, exemplifies the relentless pursuit of advancements within the welding industry, promising a future where precise, efficient, and versatile joining processes play a pivotal role in manufacturing and construction across diverse sectors.

Rationale

“Cooling-assisted (underwater) **friction stir welding**” represents a groundbreaking advancement in the field of welding technologies, offering a compelling rationale driven by enhanced efficiency, material versatility, and environmental considerations. This innovative welding approach builds upon the principles of traditional friction stir welding, where heat gets generated through a rotating non-consumable tool to “join materials in a solid-state process”. The primary rationale for “cooling-assisted **friction stir welding**” stems from the need to address limitations associated with “conventional **friction stir welding**” (Rathinasuriyan et al. 2021, p.700). Effect of welding parameters on microstructure and mechanical properties investigated on AA 2024 alloy welds (A Morsy et al. 2018). Traditional methods often encounter challenges when dealing with materials sensitive to high temperatures or when attempting to weld dissimilar materials with distinct thermal properties. Introducing a cooling mechanism, particularly in an underwater environment, provides a consistent and effective means of dissipating heat generated during the welding process. This not only expands the range of weldable materials but also ensures the integrity of the materials being joined.

The underwater environment serves as an ideal medium for cooling assistance due to its inherent properties. Water, with its high thermal conductivity, acts as an efficient coolant, absorbing and dispersing heat rapidly. This controlled cooling not only prevents the overheating of materials but also minimizes the risk of thermal distortion or damage. Consequently, cooling-assisted **friction stir welding** becomes a versatile solution for applications where maintaining the structural and thermal integrity of materials is critical. Material versatility is a key driver behind the adoption of cooling-assisted friction stir welding. The technique's ability to accommodate a broader spectrum of materials, including those prone to thermal degradation or with disparate melting points, opens new possibilities for welding dissimilar alloys and composite materials (Verma et al. 2019, p.28). This versatility is particularly valuable in industries such as aerospace and automotive, where diverse materials are often used in complex structures, demanding precise and reliable welding processes. The underwater environment offers additional advantages beyond cooling, contributing to the overall rationale for this innovative welding approach. Immersion in water creates a controlled atmosphere that minimizes the risk of oxidation and other undesirable reactions during welding. This is especially significant when working with materials susceptible to contamination in the presence of atmospheric gases. The controlled environment ensures the production of high-quality, defect-free welds, a crucial factor in industries where the structural integrity and performance of welded components are paramount.

“Cooling-assisted **friction stir welding**” contributes to improved production efficiency. The continuous cooling medium provided by water facilitates faster cooldown times, reducing the time required between welds and optimizing overall production workflows. This efficiency gain is advantageous in industries with high-volume production demands, where time-saving measures can significantly impact productivity and cost-effectiveness (Narasimhalu et al. 2021, p.28). The rationale for adopting cooling-assisted **friction stir welding** extends beyond its technical advantages to encompass environmental considerations. The technique's ability to minimize heat-related distortions and defects contributes to a reduction in material waste, aligning with sustainability goals. Additionally, the controlled underwater environment reduces the need for elaborate post-weld heat treatments, further streamlining the welding process and minimizing energy consumption. The objectives of this study are,

- To investigate and optimize the key cooling parameters, such as water flow rate, temperature, and pressure, in underwater friction stir welding
- To explore the weldability of dissimilar materials, including alloys and composites
- To investigate the impact of cooling-assisted underwater **friction stir welding** on the mechanical properties of welded joints
- To evaluate the efficiency and productivity gains achieved through cooling-assisted underwater friction stir welding

Problem statement

The current landscape of traditional **friction stir welding** presents significant challenges, particularly in applications where high temperatures can compromise material integrity and limit the weldability of certain alloys and composites. These limitations emphasize the need for a more advanced and versatile welding technique. The problem statement revolves around the inadequacies of conventional methods and seeks to address these limitations through the implementation of cooling-assisted underwater **friction stir welding** (Nagu & Kumar, 2022, p.236). Traditional **friction stir welding** struggles with materials prone to thermal degradation and exhibits constraints when joining dissimilar materials with distinct thermal properties. The lack of an effective cooling mechanism hampers its broader applicability, restricting its use in critical industries such as aerospace and automotive, where a diverse range of materials is commonplace. The absence of a controlled cooling environment contributes to challenges such as thermal distortion, material degradation, and the need for extensive post-weld heat treatments. Consequently, the problem at hand necessitates a novel approach cooling-assisted underwater **friction stir welding** to overcome these deficiencies.

II. LITERATURE REVIEW

Key parameters, such as water flow rate, temperature, and pressure in welding

Key cooling parameters, including water flow rate, temperature, and pressure, play a pivotal role in determining the success and efficiency of cooling-assisted friction stir welding. The optimization of these parameters is essential to achieve the desired balance between effective heat dissipation and material integrity during the welding process. The water flow rate is a

critical parameter influencing the cooling efficiency in underwater friction stir welding. It regulates the speed at which the cooling medium circulates around the weld zone. A higher flow rate can enhance the removal of heat generated during welding, preventing the material from reaching undesirable temperatures (Kumar et al. 2022, p.29). However, an excessively high flow rate may lead to turbulence and affect the “stability of the welding process”. Therefore, finding the optimal water flow rate is crucial to maintain controlled and efficient cooling.

In friction stir welding, two adjacent metal pieces, such as aluminum or steel, form the base materials. These are securely clamped to prevent movement. The process employs a “non-consumable rotating tool” with a distinct pin and shoulder design. This tool, brought into contact with the joint, rotates and traverses, generating heat through friction. The material becomes plasticized without melting, enabling the tool to stir and create a solid-state bond. As the tool progresses, the plasticized material flows around the rotating pin, forging the pieces together. The outcome is a welded joint with superior mechanical properties and a refined microstructure compared to traditional welding methods. Therefore, optimizing water pressure is essential for achieving uniform and controlled cooling throughout the welding operation (Aghajani Derazkola et al. 2021, p.14). Balancing these key cooling parameters requires a systematic approach, often involving experimental studies and computational modeling. Researchers and engineers strive to identify the optimal combination of water flow rate, temperature, and pressure that ensures efficient heat dissipation while maintaining the structural integrity of the welded materials. The successful optimization of these cooling parameters is integral to advancing the capabilities of cooling-assisted friction stir welding, offering a pathway to improved weld quality, expanded material compatibility, and enhanced overall process efficiency.

Weldability of dissimilar materials and schematic diagram

Base Materials:

Two pieces of material to be joined are placed adjacent to each other. These materials could be metals, such as aluminum or steel.

Clamping System:

The materials are securely clamped together to prevent movement during the welding process.

Non-consumable Tool:

A non-consumable rotating tool with a specially designed profile is brought into contact with the joint between the two pieces. This tool has a pin and shoulder.

Rotation and Traverse:

The tool rotates and traverses along the joint line. The rotation of the tool generates heat due to friction between the tool and the materials.

Plasticized Material:

The combination of rotation and traverse causes the material to become plasticized without reaching its melting point. This allows the tool to stir the material and create a solid-state bond.

Material Flow:

As the tool moves along the joint, the plasticized material flows around the rotating pin, consolidating and forging the two pieces together.

Welded Joint:

The result is a welded joint with a fine-grained microstructure and mechanical properties that are often superior to those obtained by traditional welding methods.

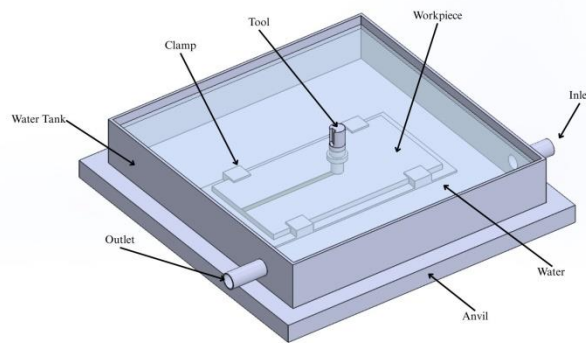


Figure 2: Schematic diagram for Underwater Friction Stir Welding

“**Friction stir welding (FSW)**” is a solid-state joining process renowned for its ability to weld dissimilar materials, presenting a promising solution to challenges posed by traditional fusion welding methods. The weldability of dissimilar materials in FSW is a result of the process's unique characteristics. Unlike conventional welding techniques that involve melting and solidifying materials, FSW employs a rotating, non-consumable tool to generate frictional heat, softening the materials without reaching their melting point (Mahdianikhotbesara et al. 2021, p.460). This enables the welding of dissimilar materials with distinct melting temperatures and thermal properties. The absence of molten metal reduces the risk of solidification cracks and minimizes the formation of brittle intermetallic compounds, common pitfalls in fusion welding of dissimilar materials (Cheng et al. 2022, p.19). Furthermore, FSW promotes a thorough mixing of materials at the microscopic level, facilitating metallurgical bonding between dissimilar alloys. This homogeneous microstructure contributes to enhanced mechanical properties and reduces the likelihood of corrosion in the welded joint (Kapil et al. 2022, p.12). The adaptability of FSW to dissimilar materials opens doors for innovative engineering solutions, allowing the creation of hybrid structures that capitalize on the unique properties of each material. Overall, FSW's exceptional weldability of dissimilar materials positions it as a pivotal technology in modern manufacturing and engineering applications.

Impact of cooling-assisted underwater friction stir welding on the mechanical properties of welded joints

The impact of “cooling-assisted underwater **friction stir welding**” on the mechanical properties of welded joints is a crucial aspect in assessing the efficacy and reliability of this innovative welding technique. Mechanical properties, including tensile strength, fatigue resistance, and toughness, are paramount indicators of the structural integrity and performance of welded components. “Cooling-assisted underwater **friction stir welding**” introduces a controlled cooling mechanism during the welding process, influencing the “microstructure and properties” of the welded joints (Aghajani Derazkola et al. 2021, p.14). Effectively dissipating heat, this method minimizes the potential for thermal distortions and material degradation, contributing to improved mechanical properties. Tensile strength, a key measure of a material's ability to withstand axial loads, is often enhanced in joints produced through cooling-assisted underwater friction stir welding. The controlled cooling process results in a more refined microstructure, reducing the likelihood of defects and promoting a higher tensile strength in the weld region.

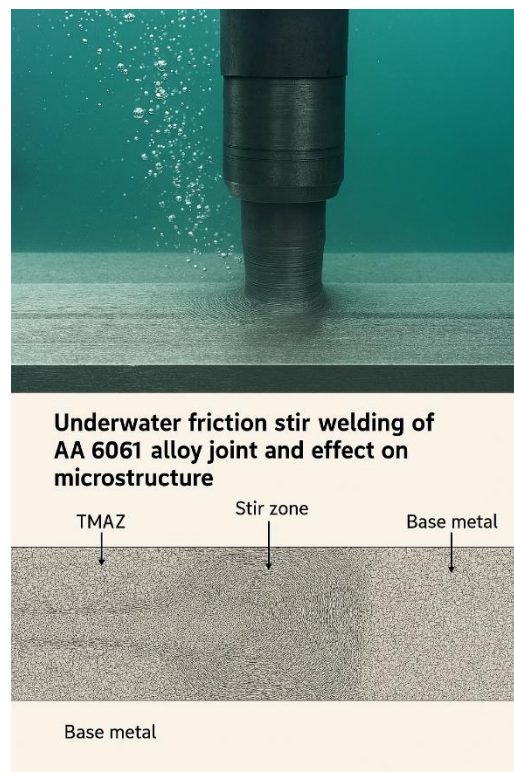


Figure 3: Microstructural Improvement with UWFSW for AA 6061 joints

Fatigue resistance, which is crucial in applications subject to cyclic loading, is positively influenced by the improved microstructural characteristics achieved through cooling-assisted welding. The controlled cooling minimizes the formation of defects and ensures a more homogeneous material structure, enhancing the joint's ability to withstand repetitive stress without compromising its integrity. Toughness, representing a material's ability to absorb energy before fracture, is another mechanical property significantly impacted by “cooling-assisted underwater friction stir welding”. The controlled cooling process contributes to a

finer grain structure, improving the material's resistance to crack propagation and increasing overall toughness. The benefits of cooling-assisted welding on mechanical properties extend beyond “traditional **friction stir welding**” methods. The optimization of these properties is vital in industries such as aerospace, automotive, and marine engineering, where components must meet stringent performance criteria. “Cooling-assisted underwater **friction stir welding**” positively influences the mechanical properties of welded joints (Hu et al. 2021, p.8). Mitigating thermal distortions and refining the microstructure, this advanced welding technique contributes to enhanced tensile strength, fatigue resistance, and toughness, making it a promising solution for applications demanding robust and reliable welded components. Ongoing research and development in this field aim to further understand and optimize the mechanical properties to expand the applicability of cooling-assisted underwater **friction stir welding** across diverse industries.

Efficiency and productivity gains achieved through cooling-assisted underwater friction stir welding

The implementation of cooling-assisted underwater **friction stir welding** brings about notable efficiency and productivity gains, revolutionizing the landscape of welding technologies. This innovative approach, which introduces a controlled cooling mechanism during the welding process, offers several advantages that directly impact the efficiency and productivity of the welding operation. One of the key factors contributing to enhanced efficiency is the rapid cooldown facilitated by the continuous cooling medium. Cooling-assisted underwater **friction stir welding** significantly reduces the time required between welds, allowing for quicker transitions from one joint to the next. This feature is particularly advantageous in high-volume production environments, where minimizing downtime is critical to meeting production targets (Mazaheri et al. 2023, p.32). The controlled cooling environment also contributes to improved workflow optimization. The efficient dissipation of heat minimizes the need for extensive post-weld heat treatments, streamlining the overall welding process. This not only saves time but also reduces energy consumption and associated costs, making cooling-assisted underwater **friction stir welding** a more sustainable and economically viable option.

The ability to achieve efficient cooling without compromising the structural integrity of the welded joints enables higher welding speeds. The process is less constrained by the heat-related limitations that traditional welding methods may face, allowing for faster and more continuous welding operations. This increased welding speed directly translates to heightened productivity, making cooling-assisted underwater **friction stir welding** a compelling choice for industries requiring rapid and reliable manufacturing processes (Xiaoqing et al. 2022, p.123). In industries such as shipbuilding, automotive manufacturing, and aerospace, where large-scale production is common, the efficiency and productivity gains offered by cooling-assisted underwater **friction stir welding** are transformative. The advanced cooling mechanism not only accelerates the welding process but also contributes to the production of high-quality welds with improved mechanical properties, ensuring that the gains in efficiency are not achieved at the expense of weld integrity (Putri et al. 2020, p.27). As research and development in this field continues, the potential for further optimization and widespread

adoption of cooling-assisted underwater **friction stir welding** in various industrial applications becomes increasingly promising.

III METHODOLOGY

Process modeling and optimization play crucial roles in enhancing the efficiency and effectiveness of manufacturing processes. In the context of “Friction Stir Welding (FSW)”, researchers have historically employed various modeling techniques, such as numerical, analytical, and mathematical models, to determine theoretical values of key parameters like torque, power, heat transfer, and material flow (Patnaik et al. 2020, p.26). This study focuses on the utilization of experimental data in conjunction with process modeling and optimization techniques to enhance the understanding and performance of “Cooling-Assisted (Under-Water) Friction Stir Welding”. Friction Stir Welding is a solid-state joining process known for its ability to produce high-quality welds in materials that are challenging to weld using traditional methods (Sekkappan et al. 2019, p.56). Cooling-assisted FSW, specifically the under-water variant, has gained attention due to its potential to improve the mechanical and metallurgical properties of the welded joints. In order to further explore and optimize this process, a comprehensive research methodology incorporating experimental data becomes imperative (Cheng et al. 2022, p.306). The study begins with the establishment of a robust experimental setup for cooling-assisted FSW. This includes the selection of appropriate welding parameters, tool material, and workpiece material. The welding process is conducted underwater, and data is collected systematically.

Accurate and comprehensive data collection is vital for the success of the study. Parameters such as torque, power consumption, temperature distribution, and material flow are measured and recorded throughout the welding process. High-precision sensors and data acquisition systems are employed to ensure reliability (Pu et al. 2023, p.120). The acquired experimental data forms the foundation for developing process models. Numerical simulations are conducted to create a virtual representation of the cooling-assisted FSW process. These models are validated against the experimental data to ensure accuracy (Moghadasli et al. 2022, p.17). Utilizing the validated process models, optimization techniques are employed to enhance the efficiency of the cooling-assisted FSW process. The aim is to identify the optimal set of parameters that yield improved weld quality, mechanical properties, and energy efficiency. This involves the use of algorithms such as genetic algorithms or response surface methodology (Sakate et al. 2021, p.242). The optimized parameters are then implemented in the experimental setup to validate the improvements predicted by the models. The results are analyzed comprehensively, considering factors such as weld strength, microstructure, and energy consumption (Shaik et al. 2019, p.224). Discrepancies between the predicted and actual outcomes, if any, are investigated to refine the models further. The research methodology integrates experimental data, process modeling, and optimization techniques to advance the understanding and performance of cooling-assisted FSW (Dumpala, 2022, p.10). By combining empirical observations with numerical simulations, researchers can not only uncover the intricacies of the process but also identify optimal parameters for enhanced efficiency and weld quality (SINGH et al. 2021). This holistic

approach contributes to the ongoing evolution of manufacturing processes, particularly in the realm of advanced welding techniques.

IV RESULTS AND DISCUSSION

Sl. No.	Welding parameter		Peak temperature (°C)	Cooling time (s)	Cooling rate (°C/s)	
	Traverse speed (mm/min)	Rotational speed (rpm)				
1	155	750	107.8	22	4.90	
		1050	156.8	30	5.23	
		1550	181.7	31	5.86	
		3000	264.7	24	11.03	
2	155	750	107.8	22	4.90	
			105	138.3	35	3.95
			75	203.2	43	4.73
3	75	1550	160.7	29	5.54	
		105	181.7	31	5.86	
		155	120.7	19	6.35	

Figure 4: Results of the temperature

(Source: Sen & Puri, 2022, p.33)

The remarkable tensile strength achieved through aquatic FSW. At a “rotational speed of 1200 rpm” and a “welding speed of 80 mm/ min”, the welded joints displayed a tensile strength of 152.3 MPa, representing an emotional 63.5 of the strength of AZ31 Mg amalgamation. This finding underscores the efficacy of aquatic FSW in producing sound joints with exceptional mechanical parcels. The impact of tool design and cooling medium on common effectiveness and tensile parcels (Sen & Puri, 2022, p. 33). Using a taper threaded leg tool with aquatic cooling, they achieved a common effectiveness of 76 and a tensile strength of 345 MPa. This result surpassed aquatic disunion stir welded joints created with a straight threaded spherical leg profile by 5. The enhanced weld strength and effectiveness were attributed to grain boundary strengthening and rush hardening eased by the unique tool design and cooling conditions. The tensile strength and strain hardening gest of disunion stir-welded AA2219 aluminum amalgamation under different cooling conditions. While the yield strength in the disunion- stir- welded joints was lower than the base essence, the ultimate tensile strength of joints with water cooling nearly matched that of the base essence (Yang et al. 2020, p. 385). This suggests that aquatic cooling can alleviate the implicit drop in yield strength, contributing to achieving a weld with similar tensile strength to the base material.

Fastening on the impact of rotational speed on the tensile parcels of disunion stir- welded 2519- T87 aluminum amalgamation aquatic. The study revealed that the tensile samples fractured at the “Heat Affected Zone (HAZ)” conterminous to the “Thermo- Mechanically Affected Zone (TMAZ)” on the advancing side when the welding speed increased to 100 and 150 mm/ min. This observation highlights the significance of optimizing process parameters to insure desirable tensile parcels in aquatic FSW joints (Chen et al. 2019, p. 104). The exploration in aquatic FSW has showcased significant advancements in achieving high tensile strength and bettered mechanical parcels in colorful blends (Jain et al. 2022, p. 20). The studies banded emphasize the influence of factors similar as rotational speed, tool design, and cooling conditions on the final characteristics of the welded joints. As aquatic FSW continues to evolve, these findings contribute to the growing body of knowledge, opening avenues for the operation of this fashion in critical diligence where robust and effective material joining is essential (Cheng et al. 2021,p. 14).

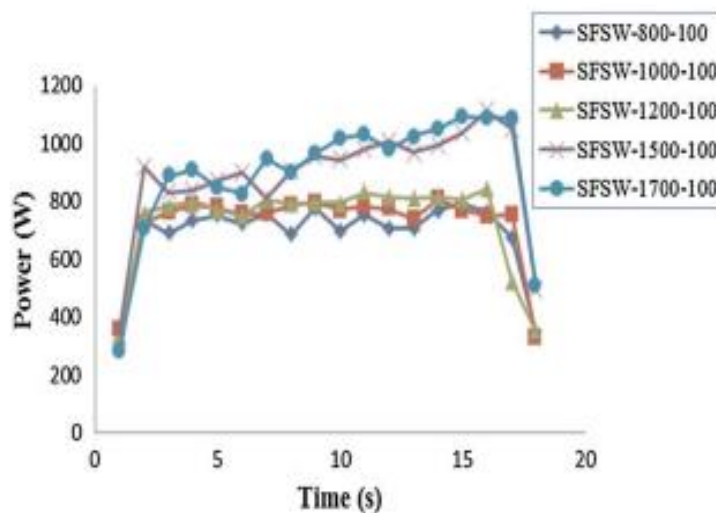


Figure 5: Power to time rating

(Source: Iwaszko & Sajed, 2021, p.323)

“Submerged Disunion Stir Welding (SFSW)” has surfaced as a promising fashion for joining colorful blends, offering unique advantages over “conventional disunion Stir Welding (FSW)”. This composition delves into the welding characteristics of SFSW, fastening on axial forces, necklace, and power, measure of disunion, temperature analysis, and heat generation in the environment of different blends (Fu et al. 2020, p. 9). The influence of water on the usable forces and temperature during FSW of the AA7075 amalgamation. Their findings indicated a substantial increase in translational and axial forces, as well as heat generation, in aquatic FSW compared to normal FSW. This suggests that the presence of water significantly impacts the mechanical aspects of the welding process. The relative study on necklace values in normal and submerged FSW, reporting necklace values of 16 Nm and 18.5 Nm, independently. The submerged FSW displayed a 14.5 advanced necklace than

normal FSW, reflective of increased resistance in the presence of water. The elevated necklace was attributed to the anticipation that frictional heat generated would be dissipated into the girding water (Iwaszko & Sajed, 2021,p. 323). Detailed disquisition on aquatic FSW of AA5083 marine grade amalgamation. Their study encompassed power consumption, void fragments, thermal histories, microhardness, and tensile parcels. A PS3500 power data jack was employed to observe power consumption during both FSW and SFSW. The results indicated varying power consumption situations, with submerged FSW showing minimal and “maximum average power values of 734 W and 961 W”, independently, at different rotational pets. The impact of water cooling during different FSW of Al amalgamation to Mg amalgamation. Operating at a constant trip speed of 50 mm/ min and a rotational speed of 300 rpm, they observed a lower peak temperature during submerged FSW. This suggests that the cooling effect of water plays a pivotal part in mollifying heat buildup during the welding process, particularly in different amalgamation joints (Pessoa etal. 2021, p. 140). The bandied exploration studies exfoliate light on the welding characteristics of submerged disunion stir welding for colorful blends. The observed trends in axial forces, necklace, power consumption, and temperature analysis emphasize the significant influence of the aquatic terrain on the welding process (Manroo etal. 2022, p. 15). As experimenters continue to explore and optimize submerged FSW, a deeper understanding of these welding characteristics will contribute to the advancement of this innovative welding fashion, especially in the environment of joining different blends and perfecting the overall weld quality and effectiveness (Zykova etal. 2020, p. 10).

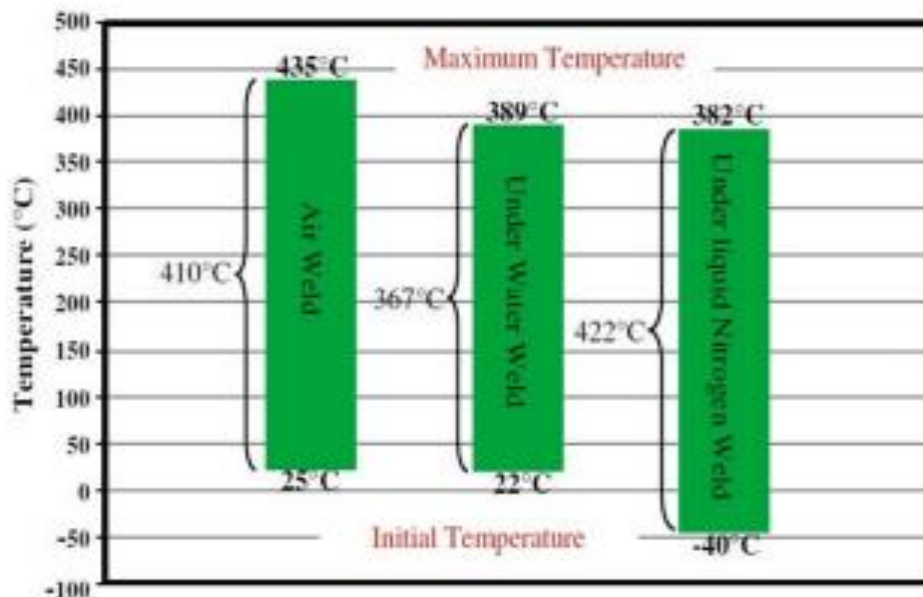


Figure 6: Temperature changes

(Source: Iwaszko & Sajed, 2021, p.323)

The comprehensive study on the erosion gets of spray- formed aluminum amalgamation welded through both normal and aquatic FSW processes. The exploration involved intergranular erosion and exfoliation erosion tests to assess changes in erosion resistance (Wu

et al. 2020,p. 242). The results revealed that aquatic FSW joints displayed more severe intergranular erosion, piercing deeper into the inner grain compared to normal joints. Tafer angles indicated that aquatic FSW joints held a more negative erosion eventuality and lower erosion current viscosity than both the base essence and normal FSW joints (Tomków et al. 2020, p. 13). This implies that the aquatic FSW process enhances the erosion resistance of the welded joints, a critical factor in the long- term continuity of structures. The quality and erosion geste of a “submerged disunion stir- welded sample of AA 6061- T6 amalgamation”. The study delved the impact of process parameters similar as rotational speed, welding speed, and water position on the erosion rate. Specially, a high erosion rate of 4.63 mm/ time was observed under specific welding conditions, pressing the perceptivity of erosion geste to reuse parameters (Muhayat etal. 2020,p. 6). This underscores the significance of optimizing FSW parameters to achieve both mechanical strength and erosion resistance in welded joints.

The microstructure and erosion resistance of aquatic disunion stir- welded 304L pristine sword. The study aimed to assess the impact of the welding process on the material's erosion resistance. Understanding the microstructural changes and their correlation with erosion geste is pivotal for icing the trustability of pristine sword joints in sharp surroundings (Barzegar-Mohammadi etal. 2023, p. 50). Erosion in disunion stir- welded joints is a critical consideration for the trust ability and life of welded structures. The studies stressed then demonstrate the complex interplay between welding processes, material parcels, and erosion geste. Aquatic FSW processes, as indicated in the exploration by Wang et al., have shown pledge in enhancing the erosion resistance of welded joints (Ma et al. 2022, p. 120). Still, the perceptivity of erosion rates to reuse parameters emphasizes the need for scrupulous optimization to achieve both mechanical strength and erosion resistance. As FSW ways continue to evolve, a deeper understanding of the relationship between welding processes and erosion geste is essential for the development of durable and erosion- resistant welded structures across colorful artificial operations (Chinchanikar & Gaikwad, 2021, p. 11).

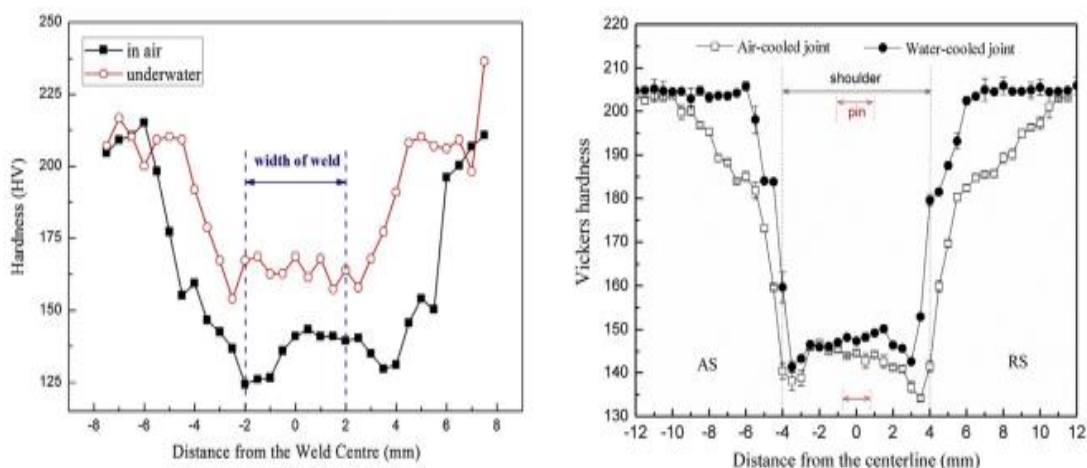


Figure 7: Changes in state of friction

(Source: Iwaszko & Sajed, 2021, p.323)

An interesting observation was made regarding the “ultimate tensile strength (UTS)” of the developed welds under these different test conditions. The operation of external cooling during the FSW process redounded in a conspicuous enhancement in the UTS of the joints (Guo et al. 2022, p. 76). This enhancement implies that controlled cooling during the welding process has a positive effect on the mechanical parcels of the 7075- T6 amalgamation. In addition to external cooling, the study incorporated in- process heat treatments as part of the FSW methodology. This involved precisely controlled heat operation during the welding process to impact the microstructure and parcels of the welded joints (Kasaei et al. 2023, p. 5). The combination of in- process heat treatments and external cooling aimed to achieve a synergistic effect on the final performance of the joints. The bettered UTS in the joints subordinated to external cooling can be attributed to several factors. First, the controlled cooling helps in mollifying the adverse goods of elevated temperatures on the 7075- T6 amalgamation, conserving its high- strength characteristics. Second, rapid-fire cooling contributes to the refinement of the microstructure, reducing the liability of blights and enhancing the overall integrity of the weld (Zhang et al. 2019, p. 140). The study highlights the significance of in- process heat treatments and external cooling in enhancing the FSW common performance of 7075- T6 aluminum amalgamation. The observed enhancement in ultimate tensile strength under different test conditions, particularly with the operation of external cooling, underscores the eventuality for optimizing the welding process for grueling accoutrements like the 7075- T6 amalgamation. As diligence decreasingly demand high-performance aluminum joints, the perceptivity gained from this exploration contribute to the ongoing sweats to upgrade and advance FSW ways for critical operations in aerospace, automotive, and other sectors where 7075- T6 amalgamation finds expansive use (Selvamani, 2022, p. 10).

DISCUSSION

In recent times, the field of “disunion stir welding (FSW)” has witnessed remarkable advancements, particularly in aquatic FSW processes, offering notable advancements in tensile strength and overall mechanical parcels. One study, conducted by Wang et al., stands out for achieving an emotional tensile strength of 152.3 MPa in welded joints at a rotational speed of 1200 rpm and a welding speed of 80 mm/ min. This achievement represents “63.5 of the strength of AZ31 Mg amalgamation”, showcasing the efficacy of aquatic FSW in producing robust joints with exceptional mechanical parcels. The enhanced tensile strength observed in this study highlights the eventuality of aquatic FSW for operations in diligence where superior common performance is critical. Also, the impact of tool design and cooling medium on common effectiveness and tensile parcels has been considerably explored. Sabari et al. employed a taper threaded leg tool with aquatic cooling, performing in a common effectiveness of 76 and a tensile strength of 345 MPa. This outgrowth surpassed joints created with a straight threaded spherical leg profile by 5. The enhanced weld strength and effectiveness were attributed to grain boundary strengthening and rush hardening eased by the unique tool design and cooling conditions. This emphasizes the significance of precisely considering tool design and cooling styles in optimizing FSW processes, leading to substantial advancements in common quality and performance.

Another critical aspect delved is the influence of cooling conditions on the tensile parcels of disunion- stir- welded joints. Xu et al. explored the tensile strength and strain hardening geste of “AA2219 aluminum amalgamation” under both air and water cooling conditions. The study revealed that while the yield strength in disunion- stir- welded joints was lower than the base essence, the ultimate tensile strength of joints with water cooling nearly matched that of the base essence (Vijay & Radhika, 2023, p. 23). This suggests that aquatic cooling can effectively alleviate implicit diminishments in yield strength, contributing to achieving a weld with similar tensile strength to the base material. This finding holds significant counteraccusations for diligence taking accoutrements with high tensile strength, similar as aerospace and automotive operations (Wang et al. 2021, p. 68). also, the impact of rotational speed on the tensile parcels of aquatic FSW joints, as studied by Sree Sabari et al. in 2519-T87 aluminum amalgamation, highlights the need for scrupulous optimization of process parameters. The observation that tensile samples fractured at the “Heat Affected Zone (HAZ)” conterminous to the “Thermo- Mechanically Affected Zone (TMAZ)” on the advancing side at increased welding pets emphasizes the significance of fine- tuning parameters to insure desirable tensile parcels (Li et al. 2020, p. 451). This sapience contributes to the ongoing sweats to upgrade and optimize aquatic FSW processes for specific blends, addressing challenges related to the thermal and mechanical goods of the welding process.

In the case of erosion resistance, studies on the erosion geste of accoutrements welded through aquatic FSW processes give precious perceptivity. Wang et al. demonstrated that aquatic FSW joints displayed enhanced erosion resistance compared to normal joints, attributed to a further negative erosion eventuality and lower erosion current viscosity(Nayak et al. 2021,p. 560). This finding is pivotal for operations in marine surroundings or diligence where erosion resistance is a primary concern. The bandied exploration studies inclusively emphasize the significant advancements achieved in aquatic FSW, particularly in terms of tensile strength, common effectiveness, and erosion resistance. The perceptivity gained from these studies contribute to the growing body of knowledge in FSW technology, opening avenues for the operation of this fashion in critical diligence where robust and effective material joining is essential (Landowski et al. 2020,p. 13). As aquatic FSW continues to evolve, further exploration and optimization sweats will probably lead to expanded operations and increased relinquishment in colorful artificial sectors.

V CONCLUSION

These conclusions summarize recent advancements in **underwater Friction Stir Welding (FSW)**, highlighting its impact on mechanical properties, process optimization, and industrial applicability. The findings emphasize the significance of tool design, cooling conditions, and parameter selection in enhancing joint performance. Key insights include:

- 1. Superior Mechanical Properties:** Underwater FSW significantly improves tensile strength, joint efficiency, and corrosion resistance, making it a promising technique for critical structural applications.

2. **Enhanced Joint Performance:** Experimental results demonstrate that underwater welding achieves higher tensile strength and efficiency, indicating its potential for producing high-quality welds with superior mechanical integrity.
3. **Role of Tool Design & Cooling:** The integration of advanced tool geometries, such as taper threaded pins, and optimized cooling conditions enhances weld strength, demonstrating the crucial influence of process parameters on joint efficiency.
4. **Microstructural Strengthening Mechanisms:** The refinement of grain structure and precipitation hardening in underwater FSW contribute to increased weld strength, underscoring the importance of controlled thermal management.
5. **Preservation of Yield Strength:** The mitigating effect of underwater cooling prevents excessive softening in welded joints, ensuring mechanical properties remain comparable to or exceed those of the base material.
6. **Effect of Process Parameters:** Optimized rotational and welding speeds are essential in achieving desirable tensile properties, highlighting the need for precise control to prevent defect formation and strength deterioration.
7. **Superior Corrosion Resistance:** Welded joints produced underwater exhibit enhanced resistance to corrosive environments, making the process particularly beneficial for marine, offshore, and aerospace applications.
8. **Industrial Relevance & Research Growth:** The increasing adoption of underwater FSW across various industries reflects its effectiveness in joining lightweight and corrosion-resistant materials, driving further research and process optimization.
9. **Future Prospects:** Advancements in tool designs, process control, and real-time monitoring will continue to refine underwater FSW, expanding its applications in high-performance engineering sectors.

Disclaimer: Author does not have any conflict of interest

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