Innovative techniques for joining and processing of some aluminum alloys used in the aircraft industry

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Abstract: *The continuous development of various cutting-edge fields of science and technology, including the aerospace industry, is advancing at an accelerated pace. To meet current technical, economic, and environmental demands, new ecological and efficient material joining and processing techniques have been developed, aiming to replace some of the commonly used industrial procedures. For aluminum alloys, friction-based joining and processing methods with a rotating tool element are presented in this paper, with potential applications in the aerospace industry. Data is provided on Friction Stir Welding (FSW), known for its ability to produce high-quality joints without compromising the structural integrity of materials, highlighting its advantages over traditional welding methods. The diversity of metallic materials, their characteristics and properties, as well as the technical requirements of different applications, have led to the development of variants of the friction stir welding process, one of which is Submerged (underwater) Friction Stir Welding (SFSW). Data on FSW and SFSW welding as well as several aluminum alloys that can be used in the aerospace industry are included in the paper. The paper also discusses ISIM's approaches in the FSW/SFSW domain for aluminum alloys EN AW 6082 and EN AW 7075 that are applicable to the aerospace industry because of their relevance and interest. The positive outcomes show that FSW and SFSW welding can be developed for a variety of metallic materials. The goal of ISIM's current and future research is to apply the principles of the FSW/SFSW process to the FSP/SFSP processing of non-ferrous alloys, which can be used in a variety of industries.*

Key Words: *friction stir welding (FSW), aluminum alloy 6082, aluminum alloy 7075, aerospace, liquid working environment, friction stir processing (FSP), submerged (underwater) friction stir welding (SFSW)*

1. INTRODUCTION

In modern industry, particularly in aeronautics, there is a growing need to reduce weight and improve material performance. Aluminum alloys are preferred because of their excellent weight-to-strength ratio. In this context, joining and machining techniques have evolved significantly. Innovative solutions aim to reduce carbon emissions, optimize energy consumption and minimize environmental impact.

Friction Stir Welding (FSW) and Submerged Friction Stir Welding (SFSW) are joining techniques that have revolutionized the way metallic materials, especially aluminum alloys, are processed. FSW uses a rotating tool to generate heat by friction, creating a solid joint without melting the material. This reduces stresses and structural defects. SFSW is a variant of FSW in an underwater working environment [1]. The advantages of FSW and SFSW techniques are numerous, offering superior solutions compared to traditional joining methods. One of the main benefits is that these processes do not involve the use of an additive material, which eliminates the risk of contamination and reduces costs. Deformation and residual stresses are also minimized due to the fact that the material does not melt during joining, thus maintaining the integrity of the structure. The mechanical strength of the joints is outstanding, with excellent performance under load. In addition, the process is considered environmentally friendly as energy consumption is low and environmental impact is minimal [2, 3, 4].

In terms of applicability, the FSW and SFSW techniques are widely used in the aerospace industry, where the joining of critical components requires high reliability and durability. These technologies are also ideal for the manufacture of lightweight structures in the automotive and space industries, where light weight and structural performance are essential for efficiency and safety [5, 6, 7].

2. MATERIALS

Friction Stir Welding (FSW) is an improved solid-state welding process in which materials are joined without being melted. In FSW, there is a rotating tool that is inserted into the joint between two workpieces with a designed pin. The friction that comes from the rotation of the tool serves to heat up the material and soften it. The softened material stirs and mixes together as the tool traverses along the joint line, and a solid bond is created. Because the material is below its melting point, the process avoids those problems usually associated with solidification defects and shrinkage [2]. FSW offers several advantages, including the ability to produce high-quality, stronger joints than traditional fusion welding techniques while minimizing defects. FSW is also an energy-efficient technique, as it consumes less energy compared to conventional methods and does not involve melting the material [8]. Another major advantage is that the process is environmentally friendly, producing no fumes, splashes or radiation, making it a clean and environmentally friendly solution. Due to its low heat input, FSW minimizes thermal distortion and residual stresses in the material [9]. In addition, this technique has the ability to join materials that are traditionally difficult to weld or impossible to join, such as aluminum alloys like EN AW 6082 and 7075 [10].

FSW finds application in industries that require strong and precise joints. These areas include the aerospace industry, where FSW is used for joining structural elements, the automotive industry for lightweight vehicle components, shipbuilding for marine vessels, and the rail sector, particularly for high-speed trains. FSW is also used in the electronics industry for components such as heat sinks and other critical elements. Submerged Friction Stir Welding (SFSW) is a variant of the FSW process in which the welding operation is carried out in a liquid medium, usually water [8]. The submerged environment makes it easier to manage heat generation during the welding process, providing more effective temperature control [11]. One of the main advantages of SFSW is the increased cooling efficiency. Water cools quickly and efficiently, providing better control of the welding temperature, which reduces thermal distortion and residual stresses. Weld quality is also improved, as water shielding can lead to a finer microstructure, which improves the mechanical properties of the weld. Another major benefit of this process is the inhibition of oxidation; underwater welding minimizes oxidation of the weld surface, which significantly improves the corrosion resistance of the material [8, 11]. SFSW is particularly effective for heat-sensitive materials such as aluminum alloys such as EN AW 6082, which are widely used in the marine and aerospace industries due to their excellent corrosion resistance and low weight [10]. Heat sensitive materials are used where the thermal profile needs to be carefully controlled so as not to affect the integrity of the material during the working process [8].

In the aerospace industry, light weight is essential to improve efficiency and reduce costs. Aluminum alloys are preferred because of their low weight, but their traditional welding can create problems. FSW is used for joining aluminum panels in aircraft fuselages and in the construction of spacecraft, providing strong and flawless joints. SFSW is also ideal for cryogenic missile cryogenic tanks, providing tight and strong joints. FSW is also effective in welding dissimilar metals, such as aluminum and titanium, used in hybrid structures such as engine mounts. Titanium and magnesium alloys, although corrosion resistant, can be weakened by conventional welding, but FSW minimizes defects and is used in highly stressed components such as landing gear and engines [10]. Also, because FSW operates at cooler temperatures, it does not deform heat-sensitive parts such as aircraft casings and fuel lines. Welds are the vulnerable points of a structure, and traditional welding can leave cracks or air voids, dangerous in extreme conditions. FSW provides stronger and safer welds, essential in components such as rocket casings and nozzles. In addition, FSW reduces the number of fasteners needed, helping to reduce weight and cost, critical in aerospace [12].

3. ISIM APPROACHES IN FSW/SFSW FOR SOME ALUMINUM ALLOYS USABLE IN THE AIRCRAFT INDUSTRY

3.1 Equipment for friction stir welding and processing in various working environments

For the experimental welding program, the FSW processes will be carried out using the FSW 4-10 welding machine from ISIM (Fig. 1 - a). For SFSW welding, a specialized enclosure system will be integrated into the FSW machine (Fig. 1 - b) to create the necessary liquid working environment for underwater welding. This system will allow for either continuous or intermittent water flow, ensuring the materials to be joined are fully submerged during the welding process.

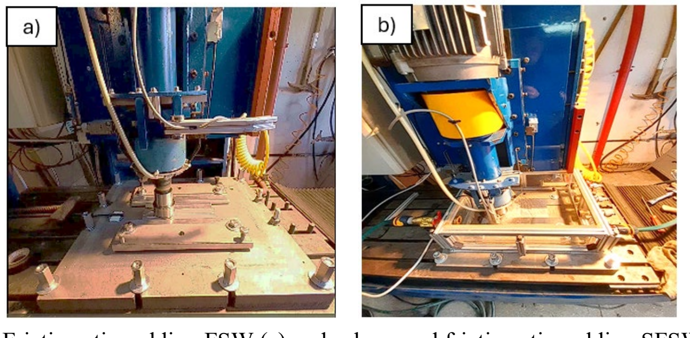


Fig. 1 Friction stir welding FSW (a) and submerged friction stir welding SFSW (b)

To monitor the welding process, an endoscopic camera will be positioned inside the water enclosure, at the material's thickness level along the weld line.

This setup will provide real-time images of the contact between the welding tool and materials, which will be viewed on a connected PC.

A water temperature control system will be used during SFSW, consisting of a thermoregulator, electro valve, and thermoresistance. If the water temperature exceeds a set limit, the system will adjust the water flow to maintain stability throughout the process.

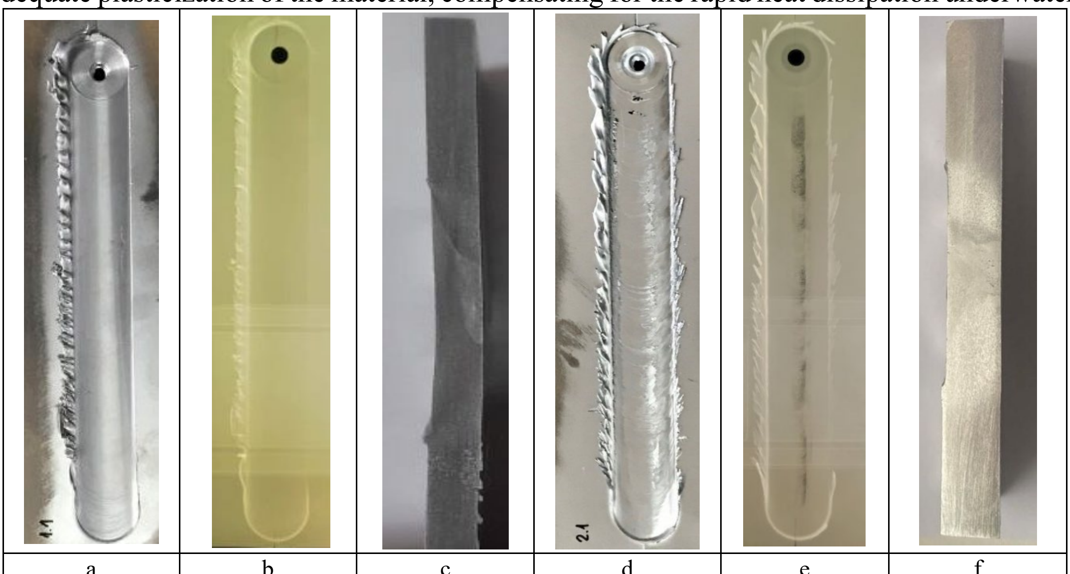
3.2 Materials covered in the paper

The comparative study focuses on two aluminum alloys: EN AW 6082 and EN AW 7075. These alloys were selected due to their diverse mechanical properties and industrial applications. EN AW 7075 is a high-strength alloy, primarily alloyed with zinc, magnesium, and copper, making it ideal for high-stress applications such as aerospace. It exhibits excellent mechanical properties, including high hardness and tensile strength, which are critical in demanding environments. However, these properties also make it more sensitive to welding process parameters, as the high strength of the material requires careful control of heat input to avoid defects during welding.

On the other hand, EN AW 6082 is a medium-strength alloy known for its good weldability and excellent corrosion resistance. It is primarily alloyed with silicon and magnesium, making it suitable for heat treatment and strengthening processes like tempering. This alloy is widely used in industries such as construction, transportation, and marine applications, where its strength-to-weight ratio and corrosion resistance are essential. Additionally, EN AW 6082 is favoured for extrusion profiles due to its good machinability and ease of working, making it versatile for a range of fabrication methods, including welding and machining. These differences in alloy composition and properties made them ideal candidates for evaluating the effects of Friction Stir Welding (FSW) and Submerged Friction Stir Welding (SFSW).

3.3 ISIM results for FSW and SFSW welding of EN AW 6082 and EN AW 7075 alloys

The welding experiments, conducted at ISIM, compared the performance of FSW and SFSW processes on EN AW 6082 [13] and EN AW 7075 [14] alloys. Both processes used a tool made of X38CrMoV5 steel with a threaded cylindrical pin. For FSW, standard tool rotation and welding speeds were applied in an air environment. However, during SFSW, adjustments were necessary due to the cooling effect of the submerged environment. For both alloys, the SFSW process required a higher tool rotation speed and a lower welding speed to ensure adequate plasticization of the material, compensating for the rapid heat dissipation underwater.



a	b	c	d	e	f
Exp. 1.1 FSW joint - EN AW 6082 (3mm), n= 800 rpm, v= 100 mm/min			Exp. 2.1 FSW joint EN AW 7075 (5 mm), n= 1100 rpm, v= 110 mm/min		

Fig. 2 Surface appearance of FSW/SFSW: welded joints of EN AW 6082 (a), X-ray control (b) and macroscopic analysis (c); welded joints of EN AW 7075 (d), X-ray control (e) and macroscopic appearance (f)

The surface quality of the welded joints varied between the two processes. In FSW, both alloys produced uniform joints with consistent weld width, though EN AW 7075 exhibited some excessive plasticization on the retreating side, leading to the formation of burrs. In contrast, SFSW joints showed fewer surface defects for both materials. EN AW 7075, displayed better plasticization control during SFSW, with no visible burrs, indicating that the submerged environment helped regulate the welding process more effectively for this high-strength alloy [13-14]. Structural and mechanical testing highlighted key differences in performance. Macrostructural analysis revealed grain refinement in both FSW and SFSW joints, with more pronounced refinement in SFSW due to the cooling effect. Hardness and tensile tests for EN AW 7075 indicated slightly lower values for SFSW compared to FSW, likely due to the reduced heat input in the submerged process. However, both methods maintained high strength, suitable for aerospace applications. For EN AW 6082, the results of hardness and tensile tests were comparable between FSW and SFSW, reflecting the alloy's inherent good weldability.

Visual and X-ray inspections confirmed the internal soundness of both FSW and SFSW joints. In FSW, minor surface imperfections, such as burr formation in EN AW 7075, were observed due to higher plasticization. SFSW, however, resulted in smoother surfaces and more stable plasticization, particularly for EN AW 7075, where the cooling environment played a significant role in preventing defects. The X-ray images aligned with visual assessments, showing no significant internal defects in either alloy for both welding methods. In conclusion, SFSW proved to be particularly beneficial for the high-strength EN AW 7075 alloy, while both welding methods provided reliable results for EN AW 6082 [13-14].

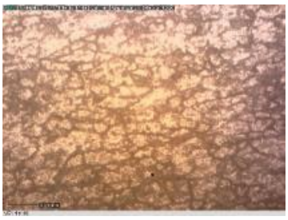
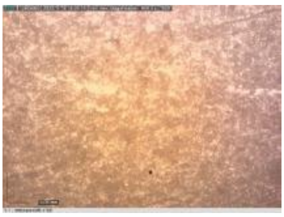
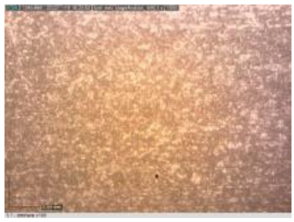
			Exp. 1.1
BM (100x)	1.1. BM+welded joint (100x)	1.1. welded joint (100x)	

Fig. 3 Microscopic appearance: base materials BM, FSW and SFSW welded joints (Exp.1.1)

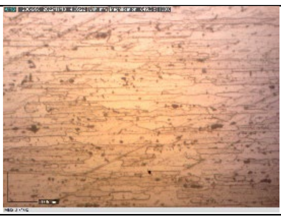
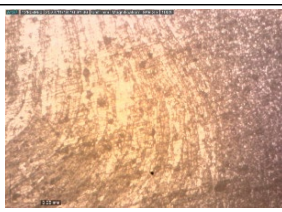
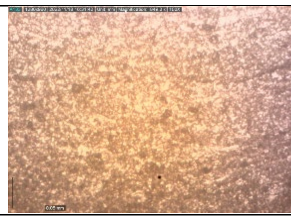
			Exp. 2.1
BM (100x)	2.1. BM+welded joint (100x)	2.1. welded joint (100x)	

Fig. 4 Microscopic appearance: base material BM, FSW and SFSW welded joints (Exp. 2.1)

4. FUTURE RESEARCH: FSP/SFSP PROCESSING FOR DIFFERENT ROLLED AND CAST ALUMINUM ALLOYS

Following the research on Friction Stir Welding (FSW) and Submerged Friction Stir Welding (SFSW) for EN AW 6082 and EN AW 7075 alloys, a significant area for future research involves expanding Friction Stir Processing (FSP) and Submerged Friction Stir Processing

(SFSP) to a wider range of rolled and cast aluminum alloys. FSP and SFSP hold considerable potential for optimizing the mechanical and structural properties of both rolled and cast aluminum alloys.

For rolled alloys, FSP can lead to substantial improvements in microstructure refinement and the elimination of inhomogeneities caused by rolling. On the other hand, cast alloys, which often suffer from issues such as porosity or uneven dendritic structures, could greatly benefit from the plasticization and recrystallization achieved through FSP or SFSP. This would result in parts with enhanced mechanical properties, finer grain structure, and reduced internal defects.

Another area to explore in future research is the adaptation of FSP and SFSP processes for aluminum alloys with varying chemical compositions. Alloys from, 5xxx (aluminum-magnesium), and 6xxx (aluminum-magnesium-silicon) and 7xxx (aluminum-zinc-magnesium) series may respond differently to these processes due to variations in their thermomechanical behaviour. It is important to investigate how processing parameters such as tool rotation speed, welding speed, and water temperature in the case of SFSP influence the final properties of the material.

Furthermore, future research could examine in detail the effects of FSP and SFSP processing on the mechanical properties of various aluminum alloys.

Additionally, integrating FSP and SFSP processes with other advanced technologies, such as heat treatment or additive manufacturing, could open new research directions. Combining these technologies could offer innovative solutions to produce high-performance aluminum alloy components with enhanced strength and superior performance in extreme conditions.

Thus, future research in the area of FSP and SFSP for rolled and cast aluminum alloys will contribute to expanding the applicability of these technologies, improving the quality and performance of materials used in critical industries such as aerospace, automotive, and marine.

5. CONCLUSIONS

The comparative study of Friction Stir Welding (FSW) and Submerged Friction Stir Welding (SFSW) for EN AW 6082 and EN AW 7075 aluminum alloys highlighted key differences in their performance.

EN AW 7075, known for its high strength, benefited from SFSW, which improved surface quality and reduced defects due to underwater cooling, though with a slight reduction in mechanical properties like hardness and tensile strength. EN AW 6082, a more weldable alloy, performed similarly with both processes, with SFSW offering minor improvements in surface quality and grain refinement.

SFSW showed potential for high-strength materials like EN AW 7075 by better controlling material plasticization. For weldable alloys like EN AW 6082, both FSW and SFSW were effective, with slight advantages for SFSW.

Future research should focus on expanding FSP/SFSP processing for various rolled and cast aluminum alloys to enhance material properties such as microstructure refinement and defect minimization.

This could benefit industries like aerospace, automotive, and marine, with stronger and more durable aluminum components.

In conclusion, both FSW and SFSW are efficient for aluminum alloy welding, with SFSW offering enhanced control and surface quality in specific applications. The study lays the groundwork for further exploration of advanced welding techniques to improve high-performance aluminum component fabrication.

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REFERENCES

[1] M. Nicolae, M. G. Sohaciu, R. Dumitrescu, S Ciucă & A. Nicolae, Vectors of Sustainable Development and Global Knowledge in the Metallic Materials Industry in Romania, *Sustainability*, **14**(16), 9911, 2022.

[2] R. Rai, A. De, H. K. D. H. Bhadeshia & T. Debroy, Friction stir welding tools, *Science and Technology of welding and Joining*, **16**(4), 325-342, 2011.

[3] L. N. Botila, et al., Development of the Working Techniques Required to Apply Friction Stir Welding in Liquid Environment, *Materials Science Forum*, Vol. *1096*, Trans Tech Publications Ltd, 2023.

[4] M. Vahdati, M. Mahmoud and S. Mahmoud, Modeling and optimization of the yield strength and tensile strength of Al7075 butt joint produced by FSW and SFSW using RSM and desirability function method, *Transactions of the Indian Institute of Metals* **73**, 2587-2600, 2020.

[5] N. Ethiraj, S. Meikeerthy and T. Sivabalan, Submerged friction stir welding: An overview of results of experiments and possible future works, *Engineering and Applied Science Research* **47**.1, 111-116, 2020.

[6] C. Rathinasuriyan, et al., Current status and development of submerged friction stir welding: a review, *International Journal of Precision Engineering and Manufacturing-Green Technology*, **8**, 687-701, 2021.

[7] M. M. Ahmed, et al., Friction stir welding of aluminum in the aerospace industry: the current progress and state-of-the-art review, *Materials*, **16**.8, 2971, 2023.

[8] Y. N. Zhang, X. Cao, S. Larose & P. Wanjara, Review of tools for friction stir welding and processing, *Canadian Metallurgical Quarterly*, **51**(3), 250-261, 2012.

[9] S. Emamian, M. Awang, F. Yusof, P. Hussain, M. Mehrpouya, S. Kakooei & A. Zafar, A review of friction stir welding pin profile, In *2nd International conference on mechanical, manufacturing and process plant engineering* (pp. 1-18), Springer Singapore, 2017.

[10] E. D. Nicholas, W. M. Thomas, A review of friction processes for aerospace applications, *Int. J. Mater. Prod. Technol.*, 13, (1–2), 45–55, 1998.

[11] A. Heidarzadeh, M Jabbari & M. Esmaily, Prediction of grain size and mechanical properties in friction stir welded pure copper joints using a thermal model, *The International Journal of Advanced Manufacturing Technology*, **77**, 1819-1829, 2015.

[12] * * * TWI Ltd., Friction Stir Welding for Aerospace Applications ,2021.

[13] L. N. Boțilă, I. A. Perianu, M. Marin-Corciu, E. Dobrin, I. Duma, R. N. Popescu, Submerged friction stir welding compared to friction stir welding of EN AW 6082 aluminum alloy, *14th International Conference Innovative Technologies for Joining Advanced Materials TIMA* **23**, 9-10.11.2023, Timișoara, România.

[14] L. N. Boțilă, I. A. Perianu, M. Marin-Corciu, E. F. Binchiciu, I. Duma, R. N. Popescu, Experimental research on FSW and SFSW welding of EN AW 7075 aluminum alloy, *14th International Conference Innovative Technologies for Joining Advanced Materials TIMA* **23**, 9-10.11.2023, Timișoara, România.