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RESEARCH ARTICLE

Friction Stir Welding in Aircraft Structures: Current and Future Prospects

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ABSTRACT

Friction stir welding (FSW) has significant potential to enhance the efficiency of air transportation systems; however, determining and applying its parameters continues to pose challenges. This article review explores current and future challenges, trends, and practices that facilitate the integration of competitive production into new aircraft structure joints. An overview of friction stir welding techniques used for the design and manufacture of aircraft structures are presented, focusing on product optimization through lightweight and high-strength properties. The implementation of various design solutions and advanced manufacturing technologies can enhance metallic fuselage systems' performance without compromising risk and cost. The paper presents examples of successfully addressed challenges and those driving the development of new practices, design solutions, methods, and tools. Ultimately, aircraft structure joints become more integrated when systems engineering approaches are linked with various design solutions and advanced manufacturing technologies (e.g., Vertical Compensation Friction Stir Welding) in a reusable manner, balancing product performance and producibility. Nevertheless, the field remains in active development, posing challenges for research, development, and practice.

Keywords: Friction stir welding, Aerospace structural application, Metallic fuselage, High-strength Al alloys, Dissimilar metals

1. Introduction

Friction stir welding techniques used for the design and manufacture of aircraft structures, including metallic fuselages, in addition to their desirable mechanical properties, they have the potential to be used in aerospace applications, making them ideal candidates for lightweight and high-strength materials [1–3]. However, despite its importance, the implementation of friction stir welding has not reached maturity in the aviation industry, partly due to the challenges associated with joining these structures using the FSW technique.

The abstract mentioned the potential of friction stir welding in improving air transportation systems' efficiency. For instance, a typical short-range jet aircraft designed for 50,000 flights could accumulate around 400,000 km (250,000 miles) on the ground during takeoff, landing, and taxiing. This example demonstrates the heavy loading history that aircraft structures must endure during their operational life, including accidental and operationally induced damages and cracks. The development and design of aircraft structures are inherently complex and multidisciplinary endeavors. The demand for technological advancements becomes apparent when considering

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the long life and extensive usage of civil aircraft structures.

Over the last several years, competition between composites and metallic structures has driven advancements in both fields. This study, however, focuses primarily on the experiences of metallic structures. Aerodynamic efficiency and cost-effectiveness have driven the development of more advanced materials and manufacturing technologies and the integration of fuselage subsystems into airframes. In order to make the most of advanced manufacturing techniques like additive manufacturing, it is crucial to understand their impact on both the aircraft system and its through-life behavior during the design process. Technologies for inspection and repair must advance as high-performance materials and weight-optimized designs become more prevalent [1].

While Systems Engineering (SE) focuses on the overall function of the fuselage as a system and its definition as a unit, Design for Manufacturing (DFM) addresses the relationships between engineering design and manufacturing capabilities. Systems engineering advancements are increasingly including lifetime elements of integrated models [2–4]. In more recent study focused on design and engineering elements in aerospace applications, the word "producibility," which refers to the robust creation of products that fulfill overall system requirements with cost-effective and functional performance solutions, has been explored [5–9].

Since its creation, friction stir welding has been regarded as a solid-state joining technique used largely for aerospace sector aluminum alloys. Years of extensive research and development are needed to introduce a technique for producing aircraft components. In order to specify, certify, and design processes, it is necessary to gather enough data regarding process parameters, tooling, and equipment. FSW was utilized in military and spacecraft before being employed in civil aviation [10]. This method is employed by aircraft producers including Boeing, Airbus, and Embraer for parts like floor panels, fuselage panels, and wing ribs [11–18].

This paper discusses the design of aircraft structures and advanced manufacturing techniques using friction stir welding for future civil aeronautical systems, aiming to fulfill the latest requirements and goals of all stakeholders. Achieving more eco-friendly air transportation necessitates advancements across various subsystems, including new propulsion fuels and systems, innovative structural concepts, and cutting-edge manufacturing technologies. This approach facilitates design for manufacturing within a system engineering framework. The primary research question (RQ) being addressed is whether friction stir welding of structural joints can serve as a viable alternative to riveted connections in the primary structures of aircraft.

Regarding FSW in airplane structures, nothing is known. The first section of this article gives a quick explanation of the FSW process, aircraft structures, and cutting-edge friction stir welding principles. Then, it assesses important problems in FSW of various high-strength aluminum alloys, concentrating on characterizations of the macro- and microstructure as well as the mechanical characteristics of these structural joints. Finally, conclusions are drawn, and recommendations for future research are provided.

2.1. Friction stir welding process and aircraft structures

A solid-state joining method known as friction stir welding has gained popularity because it can combine materials without melting them. A non-consumable spinning tool is used in the procedure to create frictional heat at the interface of the workpieces, which leads to the plasticized condition seen in Fig. 1 [18]. The plasticized material is then stirred and consolidated into a weld joint. This technique provides several advantages over conventional fusion welding processes, including reduced distortion, improved mechanical properties, and the ability to join dissimilar materials. Although, Friction Stir Welding (FSW) offers several advantages over conventional fusion welding processes, such as reduced distortion, improved mechanical properties, and the ability to join dissimilar materials, it is important to acknowledge its limitations. FSW is generally restricted to materials with good plastic deformation properties, like aluminum, magnesium, and copper, making it challenging to apply to harder materials such as steels or high-temperature alloys without specialized tools [19]. Additionally, the initial equipment cost is high, requiring heavy-duty machinery to generate the necessary pressure and rotational speed, which can lead to higher upfront expenses compared to conventional methods. Tool wear is another issue, as the FSW tool undergoes extreme stress and heat, particularly with harder materials, requiring frequent replacements and increasing operational costs. The process is also limited in its ability to handle complex geometries, as it is most suitable for flat or simple shapes where the rotating tool has sufficient access. Finally, while FSW typically results in a good weld quality, the surface finish may still require post-weld machining if aesthetic quality or tight dimensional tolerances are important. Recognizing these limitations helps clarify that while FSW excels in certain scenarios, its

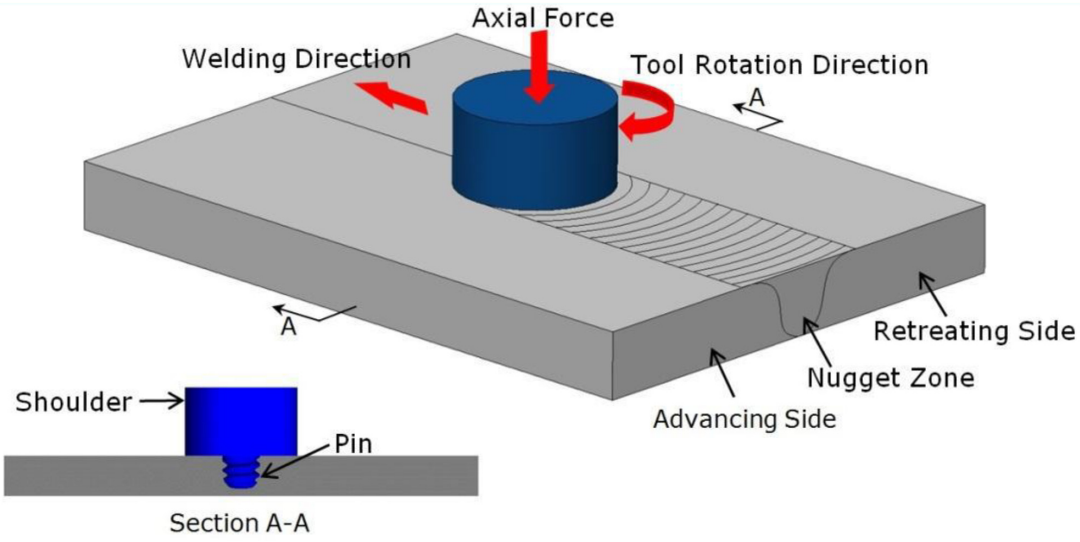

Fig. 1. Schematic drawing of FSW.

effectiveness can be constrained by material type, joint geometry, and economic considerations.

2.2. New concepts in friction stir welding for aircraft structures

The application of FSW in aircraft structures has led to the development of new concepts and techniques, such as Vertical Compensation Friction Stir Welding (VCFW) [19]. VCFW addresses the issue of compensation strip variations during the welding process. By maintaining a constant contact force between the tool and workpiece, VCFW helps to produce consistent weld quality and minimize the risk of defects [20–25].

2.3. Critical issues in FSW of high-strength aluminum alloys

The incorporation of high-strength aluminum alloys in aircraft structures poses several challenges for Friction Stir Welding (FSW). Key issues include the selection of appropriate welding parameters, the creation of suitable tool materials and designs, and the understanding of microstructural evolution during the welding process [26]. Recent studies have concentrated on optimizing welding parameters, developing advanced tools, and investigating the relationships between microstructure and properties to improve the weld quality and mechanical performance of FSW joints in high-strength aluminum alloys [27–30].

2.4. Macrostructure and microstructure characterizations

A thorough understanding of the macrostructure and microstructure of FSW joints in high-strength aluminum alloys is essential for effectively implementing this technology in aircraft structures. Research into grain structure, precipitation, and phase transformation behavior during the FSW process has yielded important insights into the factors that affect the mechanical properties of the welds [31].

2.5. Mechanical properties of FSW joints

FSW joints in high-strength aluminum alloys exhibit a range of mechanical properties depending on the specific alloy and welding conditions. Recent studies have demonstrated the potential for achieving superior strength, ductility, and fatigue performance compared to conventional riveted joints [32–35]. However, further research is needed to optimize the welding parameters and tool designs to maximize the mechanical properties of FSW joints in aircraft structures. High-strength aluminum alloys, particularly from the 2xxx (Al-Cu), 6xxx (Al-Mg-Si), and 7xxx (Al-Zn-Mg) series, are widely used in aerospace, automotive, and structural applications due to their excellent strength-to-weight ratio. For instance, 7075 aluminum, one of the strongest in the 7xxx series, exhibits a tensile strength of approximately 572 MPa, comparable to some steels but with a much lower density (about one-third that of steel). This makes it a popular choice in weight-sensitive applications. When compared to steel, aluminum alloys offer significant weight savings, but steel provides superior hardness, wear resistance, and overall strength, with tensile strengths often exceeding 1000 MPa in high-strength grades (e.g., 4340 steel). Steel is also less expensive and more readily available, though it is prone to corrosion without proper surface treatments.

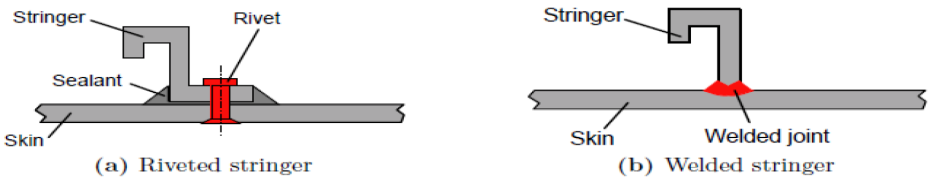

Fig. 2. Traditional (a) riveted-stringer and friction stir welded (b) plate-stringer joint configuration solution.

In contrast, titanium alloys (such as Ti-6Al-4V) strike a balance between the lightweight nature of aluminum and the strength of steel, offering excellent corrosion resistance and a tensile strength around 900 MPa, while being almost twice as dense as aluminum. Titanium is preferred in environments requiring both high strength and corrosion resistance, though it is significantly more expensive than both aluminum and steel. This comparison highlights the trade-offs in selecting materials based on specific application requirements, such as strength, weight, corrosion resistance, and cost.

Friction stir welding shows great promise as an alternative to riveted joints in aircraft structures, offering potential improvements in weight reduction, structural performance, and manufacturing efficiency see Fig. 2. However, several challenges remain to be addressed, including the optimization of welding parameters and tool designs, the understanding of microstructural evolution during the process, and the development of robust quality control and inspection techniques. Future research should focus on these areas to facilitate the widespread adoption of FSW in the aerospace industry [36].

Friction stir welding (FSW) provides numerous advantages over other joining techniques for aluminum across a broad range of applications. Consequently, it is predominantly used with aluminum, particularly for large components that are challenging to heat-treat after welding to restore their temper characteristics. FSW enables the welding of material thicknesses from 0.5 to 65 mm from one side, achieving full penetration without porosity or internal cavities, allowing for the joining of aluminum sheets and plates without the need for filler wire or shielding gas. While FSW has traditionally focused on nonferrous alloys, recent advancements have broadened its applicability to a wider variety of materials [37].

2.6. A brief overview of aircraft structures

Aircraft structures work under erratic loads in a variety of settings, have extended service lifetimes, and are heavily employed. The goal of designers is to cost-effectively include the innate capacity to tolerate readily discernible harm. Damage-resistant materials, redundant load route design concepts, and careful attention to structural details are used to achieve this [38].

The buy-to-fly ratio, which is a key driving force in the aircraft sector, is weight reduction. This ratio is computed by comparing the final weight of a component to the weight of the raw materials needed to make it. This ratio for flying components can be as high as 15–20 [39] because of the importance of weight optimization and the resulting increase in material and production costs. Because FSW uses an advanced production technique, the buy-to-fly ratio might be significantly reduced. It can be challenging to strike a balance between weight reduction and prices, even though new materials used for weight reduction are typically more expensive and need for new design and production procedures.

The selection of materials is a critical aspect of airplane design, as it influences the joining, manufacturing, and assembly processes employed. Numerous studies have investigated the optimal materials for constructing fuselage structures and other aircraft components. Future aircraft structures are likely to incorporate a variety of materials to leverage the best properties of each [40].

In addition to material selection, researchers have provided systematic reviews of processes used to produce dissimilar joints of aluminum, magnesium, and titanium, as well as comprehensive reviews of state-of-the-art FSW of aluminum matrix composites.

It is important to consider the balance between safety and economic viability in aircraft design. While it is possible to invest indefinitely in safety and improvement, the increase in cost may outweigh the benefits. Consequently, the aerospace industry continues to focus on reducing costs while increasing reliability and performance. A trade-off between cost and safety is necessary to achieve an economically feasible product.

Aircraft structures are generally divided into primary, secondary, and tertiary structures, with each manufacturer defining these divisions. In addition, there are aerodynamic and special components, as well as repair-restrained structures. To keep metallic fuselages competitive against composite alternatives,

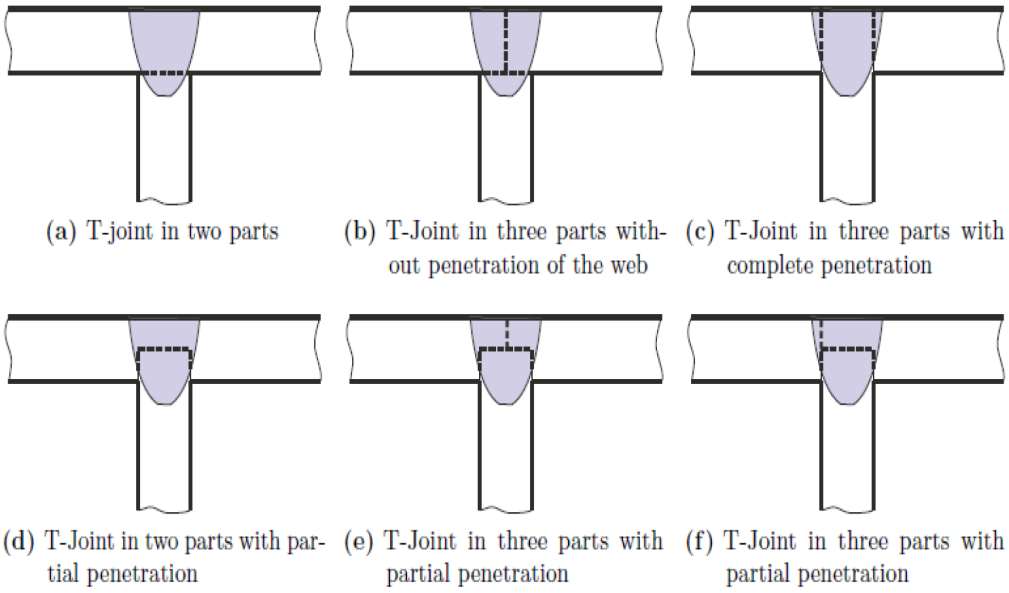

Fig. 3. Design solutions to produce T-joints by FSW.

emphasis should be placed on material selection, design procedures, and advanced manufacturing processes that enable the creation of airframe structures with reduced weight and cost.

2.7. New concepts of friction stir welding in aircraft structures

FSW was originally made available to a larger audience at the Schweissen and Schneiden Fair in 1997, and Boeing Company later purchased it for use in research and laboratories. In the Delta II and IV programs, where FSW has been used to make rocket fuel tanks, Boeing has been a pioneer in integrating FSW into industrial manufacturing. Time and money have been saved significantly as a result of this. Future designs for both commercial and military aircraft are taking into account FSW technology, with applications including carrier beams, floors, and entire fuselages and wings being examined.

As a lighter, less stressful, and more productive alternative to riveting in aircraft building, FSW has been hailed for its advantages over riveting. Together, these elements improve joint strength and manufacturing for contemporary joint designs, such as butt joints.

In conventional fuselage outer panel designs, stringers are riveted to an aluminum plate that acts as reinforcement. While riveting is commonly employed, it has several drawbacks, such as local stress concentration and requiring significant man-machine hours. Moreover, fusion welding processes for aluminum and its alloys can result in various issues, including loss of strength and the formation of defects.

These issues may be solved with FSW, which also provides increases in joint strength, fatigue resistance, corrosion resistance, and productivity by integrating design principles and cutting-edge production technology. For the stringer plate junction, a comparison of conventional and prospective innovative ways employing FSW reveals advantages including decreased weight, impermeability, cheaper production costs, and quicker production speeds.

It is important to note that to solve the problem of unwelded material at the T corners and improve mechanical qualities, a unique friction stir welding (FSW) method has been developed and tested.

Fig. 3 illustrates a variety of options for fabricating T-joints with FSW. When the web penetrates the flange, there is a reduced need for material flow, making it easier to remove cracks in the T corners without additional procedures. Additionally, the tool (or probe) can be designed with a wider diameter and shorter height, increasing its robustness.

Research was carried out and published that focused on a solution where the T-joint consists of three components and the web is placed between the two portions of the flange (as illustrated in Fig. 3a) [41]. This option was chosen because it allows for reinforcing plates during welding operations without special machining of plate edges (refer to Fig. 3a, Fig. 3b, and Fig. 3c). In actuality, (n-1) weldments are necessary to join n smaller plates together to make a huge plate of uniform thickness. With the specified T design

(Fig. 3c), a reinforced structure is produced at a cheaper cost with the same number of weldments. References [42] provide an overview of this arrangement and show how T-joints made with AA6082 were manufactured without cracks and with acceptable mechanical qualities.

Additionally, a novel method developed in response to the friction stir welding process' forging force offers a number of advantages over the bobbin tool idea, including the avoidance of root faults and fewer disadvantages for lengthy welds.

In the field of aeronautics, it is desirable to combine high strength and low weight. T-joint design solutions may be developed using a variety of options. These many design options (shown in Fig. 3).

Interestingly, the proposed Vertical Compensation Friction Stir Welding (VCFSW) technique appears suitable for joining aircraft structures (T-joints) as it addresses the negative effects caused by a large gap at the interface of two welded workpieces. According to references [43, 44, and 46], additional materials are positioned perpendicular to the horizontal surfaces of the workpieces at the interface.

Through changes to geometry and materials, the VCFSW approach improves joint behavior and increases joint strength. It is possible to create new structural solutions with improved designs and qualities by joining different metals together utilizing solid-state welding techniques like VCFSW. Reduced material use, cheaper prices, and a lessened environmental effect are anticipated benefits. Major aircraft producers like Boeing, Airbus, and Embraer ought to think about commercializing this method. Related studies on friction stir welding of dissimilar aluminum alloys used for aircraft structures.

2.8. Microstructural characterizations of dissimilar aluminum alloys

The stir zone (SZ), or weld nugget, exhibits complex vortex, whorl, and swirl patterns indicative of chaotic-dynamic mixing. This zone demonstrated significant mechanical mixing in the microstructural characterization of FSW joint surfaces for dissimilar aluminum alloys. Optimal processing conditions are vital for effectively joining different materials. Furthermore, the form and structure of the welding zone underwent considerable changes. To avoid defects, selecting the appropriate welding parameters is essential, and both the macrostructures and microstructures of FSW joints have been extensively studied. The microstructure and mechanical characteristics of dissimilar friction stir welds in the aviation aluminum alloys 2024-T351 and 6056-T4 were first investigated by Amancio-Filho et al. [46]. While maintaining constant axial force and tool shape, butt joints were produced by altering process variables, principally rotating speed (500–1200 RPM) and welding speed (150–400 mm/min). Sound joints could be produced at a rotational speed of 800 RPM and a welding speed of 150 mm/min, according to tests and macrographic analysis. The SZ was clearly visible in a cross-section of the weld (Fig. 4(a)), which also showed a lamellar pattern made up of both dark and bright lamellae. The samples evaluated at various locations along the weld seam of the analyzed joints also showed no signs of internal problems.

On two different types of aluminum alloys, 2024 and 7075, Da Silva [47] performed an FSW. The threaded pin on the FSW tool had dimensions of 4 mm in diameter, 2.85 mm in length, and 12 mm in flat shoulder diameter. While the force and rotation speed varied in accordance with three rotational speeds (400, 1000, and 2000 RPM) and forces (13.4, 12, and 9.8 KN, respectively), the tool feed rate remained constant at 254 mm/min. The AS was where the 7075-T6 aluminum alloy was placed. A 3° tilt angle FSW machine was utilized to manage the force. Fig. 5 depicts the microstructural analysis of the welds created at 1000 RPM. The FSW joint was seen to be devoid of flaws or other irregularities, such as porosity or a lack of penetration.

Furthermore, Tae et al. [48] investigated the process variables influencing the microstructure and mechanical properties of Al-Li alloys. Rotation and travel speeds were the main process parameters considered in this study. The tool featured a cone-shaped threaded pin, a shoulder with a 22 mm-diameter threaded surface, and a threaded surface. Al-Li 2195-T8 was the material used in this research, with a thickness of 7.4 mm. The process had rotational speeds ranging from 300 to 800 RPM and travel speeds from 120 to 420 mm/min. Fig. 6 shows the macro- and microstructure of the FSW joint. A distinct line separates the parent material and stir zone on the advancing side. A thermomechanical affected zone exists between these areas.

The stirring action in Friction Stir Welding (FSW) resulted in enhanced particle dispersion and refinement in the microstructure of welded aircraft structures. Additionally, a dynamic recrystallization process facilitated grain formation influenced by varying process parameters.

2.9. Mechanical properties of dissimilar aluminum alloys

The mechanical characteristics of welds made of different aluminum alloys are covered in this

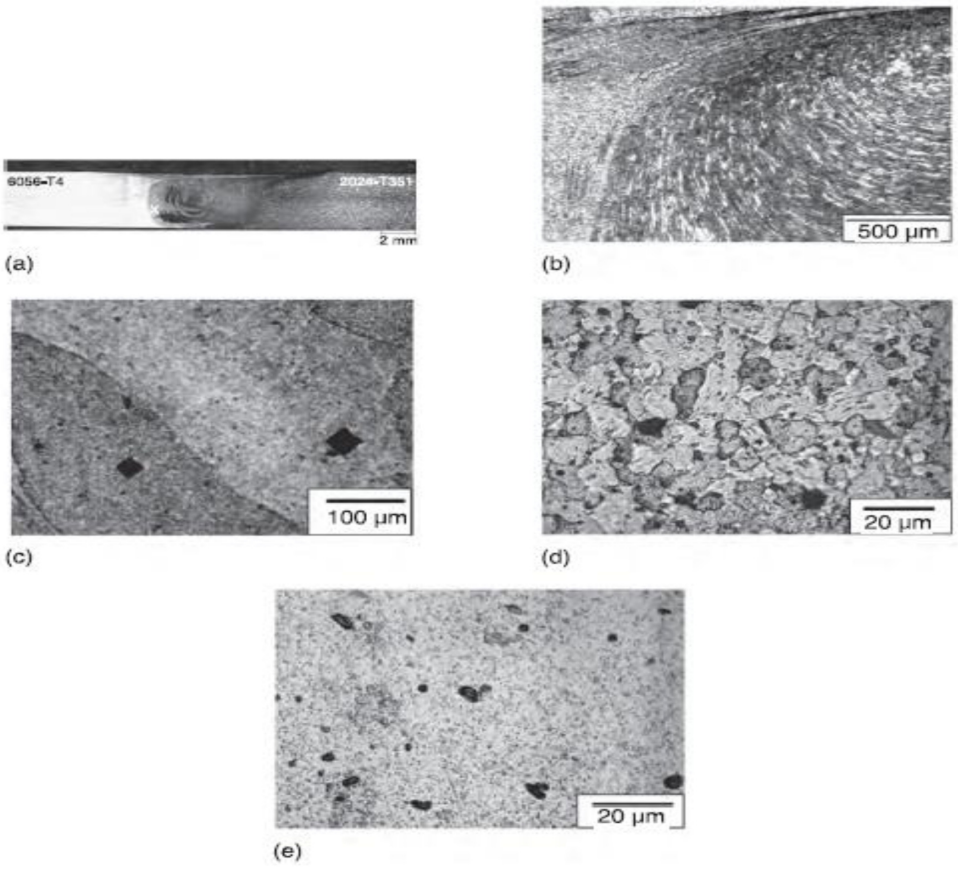

Fig. 4. (a) Cross-section of the weld between dissimilar AA2024-T351 and AA6056-T4; (b) transition region between TMAZ and stir zone; (c) enlarged view of the weld cross-section shown in (a) at the position marked 'X' in the nugget area; (d) dark lamella formed at the interface; and (e) bright lamella formed at the interface [46].

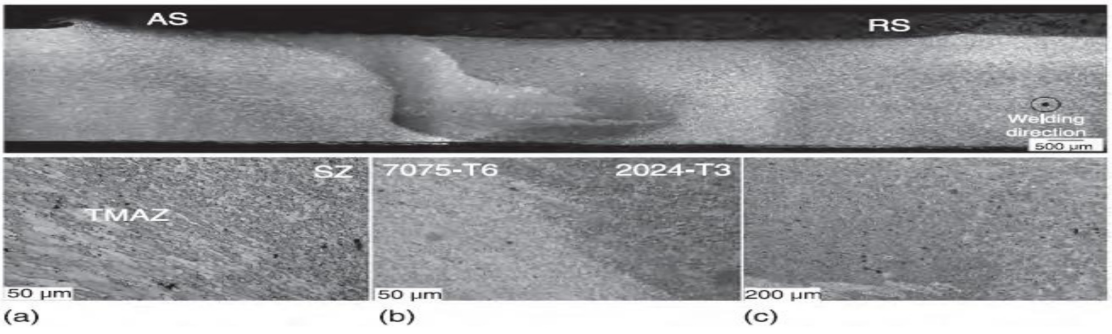

Fig. 5. Optical micrograph of the cross-section of condition 7075/2024: (a) TMAZ-SZ boundary on the advancing side; (b) SZ-SZ interface between 7075-T6 and 2024-T3; and (c) TMAZ-SZ boundary on the retreating side [47].

subsection, with an emphasis on microhardness profiling and the tensile behavior of the welds.

2.9.1. Microhardness profile of welds made from different aluminum alloys

The micrograph of Vickers microhardness profile measurements taken on the weld created at 800 RPM and 150 mm/min supported the cause of the lamellae pattern formation visible in the weld. Dark lamellae displayed higher microhardness values than dazzling lamellae, according to the microhardness profiles shown in Fig. 7 [46]. Based on the previous study, the microhardness profiles were divided into four typical microstructural zones: BM, HAZ, TMAZ, and SZ.

Fig. 8 clearly depicts the microhardness profile of the weld that Da Silva et al. [47] executed at

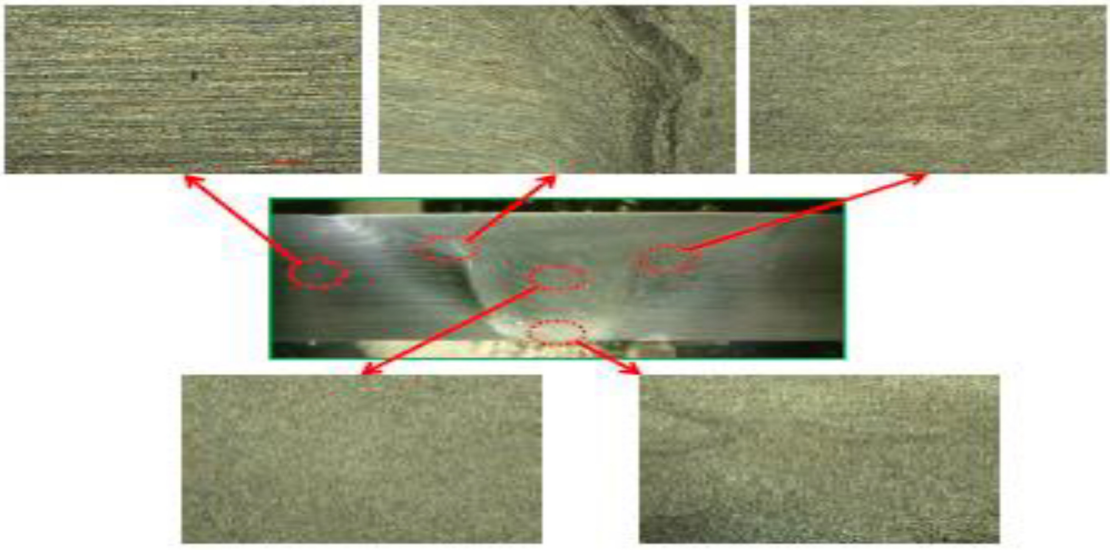

Fig. 6. Macro and microstructure of the FSW joint (600 RPM, 300 mm/min) [48].

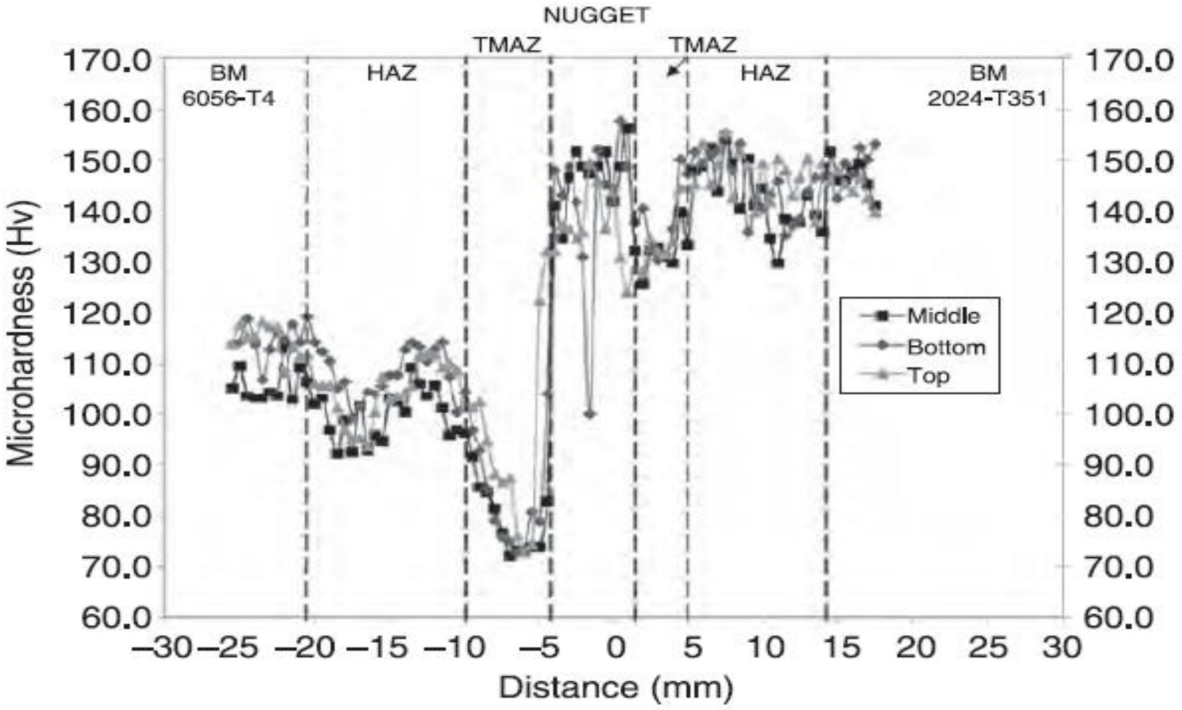

Fig. 7. Microhardness profiles of the weld cross-section [46].

1000 RPM and a feed rate of 254 mm/min, done at the mid-thickness line as well as 1 mm above and below the 4 mm mid-thickness line of different 2024 and 7075 aluminum alloys.

Additionally, the basic metals 2024-T3 and 7075-T6 have microhardnesses of around 137 and 172 HV0.2, respectively. The HAZ area of the RS had the lowest hardness values, which were in the range of 123 HV0.2, or nearly 90% of the base metal's hardness value. The microhardness distribution is clearly varied, particularly in the SZ [47].

Evaluating mechanical properties such as microhardness and tensile strength is crucial for FSW joints used in aeronautical applications, particularly for critical components of, for example, aircraft structures. Furthermore, it is feasible to optimize the welding settings by evaluating these qualities, which represent the joint efficiency (the ratio of the tensile

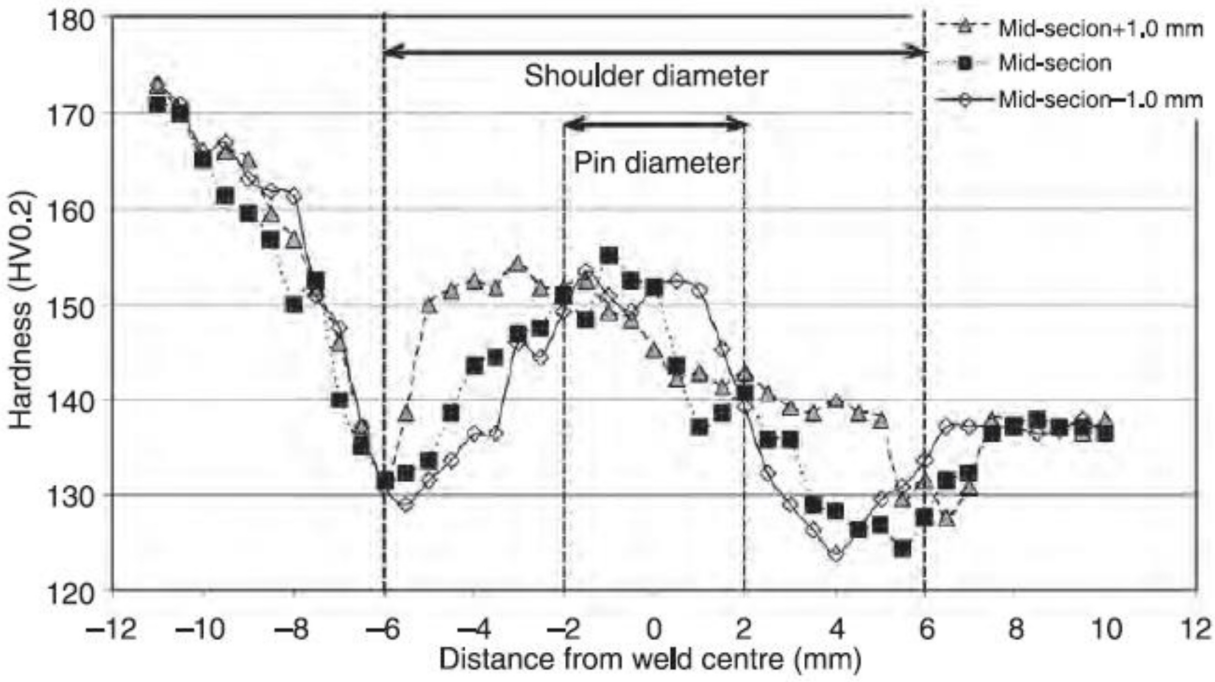

Fig. 8. Microhardness distributions of FSW cross-section joints performed at mid-thickness as well as 1 mm below and above the mid-thickness line [47].

strength of the junction to the tensile strength of the base metal) of the weldment.

2.10. Tensile properties of dissimilar aluminum alloys

The tensile strength of FSW samples is frequently evaluated in order to compare the strength and ductility of the welded samples with the base metals. When assessing the integrity of joints in dissimilar welding, it is usual practice to look for failure in the weaker of the two base metals connected, distant from the weld interface. In this part, various aluminum alloys' tensile properties are displayed.

When characterizing the tensile behavior of their welds, Amancio-Filhoa et al. [46] noted that tensile testing findings indicated strength up to 90% of the weakest connecting partner, 6056-T4. In the TMAZ of alloy 6056-T4, where the annealed structure resulted in a drop in microhardness, tensile samples broke. (for instance, see Fig. 7). Micro-flat tensile testing was able to validate this trend, showing that the tensile strength was lower and the strain was higher in the microhardness drop zones. According to the study, in dissimilar FSW, the weaker component controls joint performance, with failure occurring in regions where there has been a significant loss of strength due to annealing processes.

Additionally, Saad Ahmed Khodir et al. [49] Friction stir welding was used to achieve the T3 and T8 conditions, studied the effects of welding speed and fixed base metal placement on the quality, structure, and static mechanical characteristics of welded dissimilar junctions in AA2024 and AA7075, respectively. They claimed that when the 2024 Al alloy plate was positioned on the advancing side, the maximum tensile strength of 423 MPa was attained at a welding speed of 1.7 mm/s. Localized fractures occurred at the weak alloy's lowest hardness in sound joints and in the NZ in damaged joints.

Furthermore, the impact of welding speed and tool pin profile on the friction stir processing zone of formation in AA2219 was investigated by Balasubramanian V. et al. [50]. They observed that the square pin profile tool at a welding speed of 45.6 mm/min generated welds with maximum tensile strength and greater hardness as well as mechanically sound, metallurgical defect-free welds.

Interestingly, The junction produced employing the taper screw thread pin at a welding speed of 70 mm/min demonstrated better tensile strength (92.30% of base metal ultimate strength) and 27.58% elongation in AA6082-O aluminum, according to Patil H. S. et al. [51].

Joint geometry is crucial to the design of welds. For different aluminum alloy butt joints and T-joints, Tavares et al. [52] compared the yield strength (YS), ultimate tensile strength (UTS), elongation, and fatigue strength of FSW welds. Both designs had

Table 1. Welding variables and tensile properties of aircraft joints welded by FSW.

Base metals	Base metals condition	Plate thickness (MM)	Rotation speed (rpm)	Traverse speed (mm/min)	Axial force (kN)	Tool shape	UTS (MPa)	Yield stress (MPa)	EL (%)	Joint efficiency (%)	Refs.
Al-Li 2195T8	Rolled	7.4	300–800	120–420	–	Tapered threaded	446.2	413.3	12.9	73.9	[48]
2024T3 -7075T6	Rolled	2.5	700	160	–	Cylinder	424	325	6	74.12	[53]
7075T6	Rolled	12	250	25	–	Tapered threaded	394	335	12	70	[54]
5083H32	Extruded	4	1600	250	–	Tapered	301	150	17	98	[55]
6061T6	Extruded	4	1200	200	–	Tapered	234	144	13	74.3	[55]
5052H34-7075T6	Rolled	4.83	400	187	9	Tapered threaded	198	143	9	86.8	[36]
2024-2024T3	Rolled	0.8	1810	460	–	Cylinder	429.4	314.6	9.8	91	[37]
6082-6082T6	Rolled	0.8	1810	460	–	Cylinder	226.4	152.4	6.7	69	[37]
2024T3-6082T6	Rolled	0.8	1810	460	–	Cylinder	228.9	159.4	4	69	[37]
2024T3	Rolled	3.8 and 4	700	200	18	Tapered threaded	464.7	320.4	14	98	[38]
2024T3-7075T6	Rolled	2for 2024 1.2 for 7075	400	100	12	Conical	551	490	9.5	84.8	[39]
2024T3	Rolled	1.6	1800	20	–	Spiral flute shoulder	398.7	312.6	9	82	[56]
6061-7075 T6	Rolled	6.3	1200	30	6.7	Threaded Conical	215	177	6	79	[40]

EL: Elongation; joint efficiency: the ratio of the tensile strength of joint to the tensile strength of base metal.

comparable yield and ultimate tensile strengths, although T-joints had somewhat lower elongation and fatigue strengths. Before a weld arrangement is used commercially, mechanical property characterization is crucial.

According to research by Tae et al. [48], the high strength of Al-Li 2195-T8 was shown to be present between 400 and 600 RPM and 240 and 300 mm per minute. When the process departed from this range, strength diminished. The welded junction had a maximum ultimate strength of 73.9% of the parent material and a minimum of 63.3%.

Finally, the tensile strength of FSW-fabricated aircraft structural joints was contrasted with that of the base metal. FSW joints are more effective than those made using traditional welding techniques. The design of the tool, the welding settings, the PWHT, and the creation of intermetallic compounds are some of the variables that affect the tensile strength of AMC joints. The tensile characteristics of AMCs welded by FSW are summarized in Table 1.

The ultimate tensile strength (UTS) of the aircraft structural joints is largely influenced by welding process variables such tool rotation speed, traverse speed, and axial force. Rotation speed has the most overall effect on joint efficiency, even if traverse speed and axial force also have an impact on the tensile strength of airplane structural joints.

No universal trend can be applied to the welding process parameters for all joint connections in the aircraft industry. As a result, each material requires a dedicated study to attain the maximum tensile strength of the FSW joint.

3. Discussion

The difficulties and complexity brought on by the adoption of novel technological advancements and design ideas for lightweight aircraft components are discussed in this study. Design for Manufacturability (DFM) methods and general engineering processes must advance in order to produce a product that is well-balanced from a performance and production standpoint. In response to the research question, multiple reasons have been presented to adapt to the emerging engineering situation. Traditional rivet joints present issues such as local stress concentration, the need for thousands of rivets, extensive man or machine hours, increased joint weight, and fluid permeability. Alternative design solutions offer benefits such as the creation of T-joints, elimination of cracks in T corners without special operations, simultaneous reinforcement of plates with welding operations without unique plate edge machining, fabrication of large uniform thickness, and the capacity

to control the friction stir welding process' forging force.

On the other hand, the use of friction stir welding, specifically vertical compensation friction stir welding (VCFSW), enables decision-making for most aspects throughout development through two mechanisms: geometric and material modifications. These mechanisms help address the issue of unwelded material in T corners, mitigate the adverse effects caused by a large gap at the interface between two welded workpieces, introduce additional materials at the interface of two workpieces perpendicular to their horizontal surfaces, and utilize a more robust tool (or probe) with a larger diameter and lower height. These factors contribute to improved joint strength [57].

4. Conclusions and future work

This paper addresses the evolving requirements and goals of various stakeholders seeking significant advancements in aircraft structure subsystems. To achieve more eco-friendly air travel, the coming years will see the development of new propulsion fuels and systems, innovative structural concepts, and advanced manufacturing technologies.

In particular, new structural solutions that optimize design and production can utilize various alloys joined through solid-state welding processes, such as vertical compensation friction stir welding. The anticipated advantages of this approach include reduced material consumption, lower costs, and minimized environmental impact. Major aircraft manufacturers like Boeing, Airbus, and Embraer should consider the commercial adoption of this technology.

In summary, this article explores and presents the current and future possibilities for designing and manufacturing advanced aircraft structures using friction stir welding. It evaluates design solutions for producing these structures with cutting-edge manufacturing technologies, alongside the microstructural characterizations and mechanical properties influenced by various process parameters. The findings highlight areas where future technical and methodological advancements are expected, paving the way for further research and innovation in the field.

Conflict of interest

The authors declare no conflict of interest.

Author contribution

All authors contributed equally.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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