

Advancements In Friction Stir Welding of Dissimilar Aluminum Alloys: A Comprehensive Review

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Abstract—A method known as friction stir welding is employed to join two or more distinct materials. This technique is utilized to weld various aluminum alloys, magnesium, and tough materials such as steel. These materials are lightweight, making it advantageous to use lightweight substances with robust mechanical properties. This study focused on the friction stir welding of two different aluminum alloys. The mechanical properties of the materials being joined remain intact in FSW. There are specific parameters that must be considered during this process. The input parameters include tool rotation speed, tool design, welding velocity, and axial force. The resulting output metrics are tensile strength and micro hardness. The aim of the regression models is to investigate how the influence of welding variables on the tensile strength and elongation of the tool, both the mechanical properties increase, reach a maximum level, followed by a decrease with further increase in the value of parameters. Then, using a scanning electron microscope (SEM), the surface topography of the welded piece is analyzed.

Index Terms—Friction Stir Welding (FSW), Tensile strength, Micro Hardness, Scanning Electron Microscope (SEM), Surface Topology.

I. INTRODUCTION

A solid-state joining technique called friction stir welding (FSW) was created in 1991 at The Welding Institute Ltd. The swift progress of contemporary manufacturing methodologies has stimulated the investigation of inventive joining strategies for an extensive array of materials, with aluminum alloys being a prime example. Friction stir welding (FSW) is one of these techniques that have shown promise in creating welds that are of superior quality and have improved mechanical characteristics. Scholars have been focusing more on the impact of process parameters on the microstructure and mechanical properties of FSW joints in an effort to attain the best

possible welding results [1]. The need for strong, lightweight components has driven metal joining technique research and development in the field of modern material engineering. The solid-state welding technique known as friction stir welding (FSW) has drawn a lot of interest because it may create welds with superior mechanical qualities, especially in aluminum alloys. The investigation of FSW's effect on aluminum alloy welds becomes more important as sectors such as automotive, aerospace, and marine engineering keep looking for cutting-edge solutions for their structural problems. The design of the welding tool, more especially the tool pin shape, is one of the numerous factors that affect the quality of FSW joints.

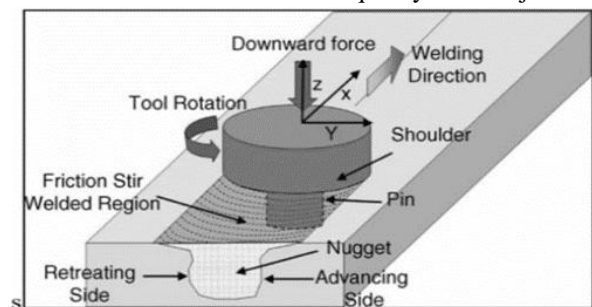


Figure 1: Schematic of FSW [1]

The microstructure and mechanical performance of the resulting welds can be greatly impacted by the geometry of the tool, which can also have a considerable impact on heat generation, mixing, and material flow during the welding process. Researchers have been prompted to investigate the subtle impacts of various tool pin profiles on weld strength increase due to the complex interplay between alloy qualities, process results, and tool design [2]. Friction stir welding (FSW) is one of the cutting-edge procedures that have been developed in the dynamic field of modern manufacturing as a result of the search for reliable and effective welding methods. The potential of this solid-state welding method to create excellent

joints in a range of materials, along with benefits like decreased distortion, higher mechanical qualities, and increased weld integrity, has attracted a lot of attention. The combination of experimental knowledge and numerical simulations appears to be a key strategy for comprehending and improving FSW processes as firms look for efficient ways to combine materials with different properties. Through the lenses of both empirical tests and numerical models, this research explores the friction stir welding process in great detail [3]. The knowledge gathered from this study will not only further our comprehension of FSW-induced residual stresses, but it will also offer useful recommendations for enhancing FSW procedures in many sectors [6]

II. SIGNIFICANCE OF FRICTION STIR WELDING

There are numerous benefits to friction stir welding over fusion-base joining techniques, particularly when combining comparable or dissimilar aluminum alloys. The procedure is safe for people to use, creates no hazardous emissions, and doesn't require any consumables (filler material fluxes, shielding gas etc.) for joining. The researches emphasized in the journals that are supplied emphasize the following crucial facets of the importance of FSW:

2.1. Improved Mechanical Properties:

Numerous scholarly papers [4] and [5] highlight the beneficial effects of FSW on the mechanical characteristics of welded joints. FSW creates joints that are tougher, more fatigue resistant, and have increased tensile strength. FSW joints are suited for demanding applications where structural integrity is crucial because to their increased mechanical properties.

2.2. Dissimilar Alloy Joining:

Studies like [2] & [1] show that FSW offers a special advantage when connecting dissimilar aluminum alloys. This ability allows engineers to harness the best properties of each alloy while avoiding fusion welding-related problems, which is essential in industries where the combination of several materials is required for certain attributes.

2.3. Optimization of Process Parameters:

One of the key components of FSW is process

parameter optimization. Better control over the weld quality, a decrease in defects, and improved joint performance are the results of this modification. The attainment of uniform and superior welds is contingent upon the proficiency in establishing accurate welding settings [6] & [7].

2.4. Reduced Heat Affected Zone:

The heat-affected zones produced by FSW are less than those produced by traditional fusion welding methods. This feature minimizes the requirement for post-welding treatments by reducing distortion and eliminating solidification-related problems.

2.5. Environment Friendly Welding:

FSW is a solid-state welding method that doesn't release any hazardous gasses or fumes. This is in line with current environmental standards and concerns, even though it isn't stated clearly in the articles that are presented.

2.6. Aerospace and Automotive Applications:

Studies published in these publications show that FSW is especially pertinent to the aerospace and automotive sectors, where strong, lightweight materials are essential. These industries benefit greatly from FSW's capacity to create high-strength joints in aluminum alloys with less weights and better structural integrity.

III. TOOL SELECTION

The friction stir welding tools are made from the high carbon steel H13 material. For welding, three distinct tool pin profiles—straight cylinder (a), taper pin (b), and threaded pin (c)—with a pin diameter of 6 mm and a shoulder diameter of 20 mm are utilized [8]. Heat treatment is used to the H13 FSW tools to increase their hardness and wear resistance. The tool pin has an average height of 3 mm, and figure displays the different tool pin profiles.

3.1. Straight cylinder tool:

A straight cylinder tool is cylindrical in shape. This kind of tool design is generally employed for specific materials or applications when more straight forward tool geometry is favorable or sufficient.

3.2. Taper pin tool:

A taper pin tool is used to make welding easier. In contrast to conventional cylindrical pin tools, taper

pin tools are shaped like a taper, with a different diameter at different points along its length.

3.3. Threaded pin tool:

One essential part of the FSW tool is the threaded pin. It enters the joint between the work pieces and extends from the tool's shoulder.

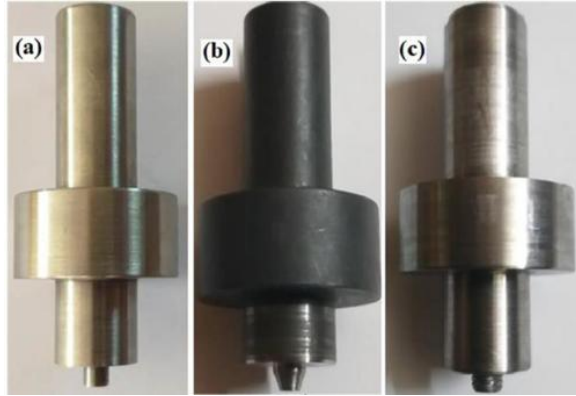


Figure 2: FSW Tools [8]

IV. EXPERIMENTAL PROCEDURE

Selection and Preparation of Materials, for that Select aluminum alloys (AA2014, AA6061, AA5052, AA5754, etc.) in accordance with the goals of the study and Cut aluminum plates from chosen alloys to the necessary sizes. Configure FSW hardware in accordance with published specifications. Using pertinent publications as a guide, define the welding parameters (rotation speed, welding speed, tool geometry). Put aluminum plates in a secure position for welding. Execute the FSW process while managing the chosen parameters. Launch the FSW equipment to begin the welding procedure. The instrument has to pierce the aluminum alloy plates in order to provide frictional heat and cause the material to become plastic. A weld joint is formed when the tool mechanically stirs and forges the material as it travels along the welding path. From an operational perspective, this procedure is further separated into three distinct sequences of activities based on the relative motion between the tool and work item.

Plunge and Dwell:

In the weld line, a rotating tool is permitted to dive into a stationary work piece until the tool shoulder comes into contact with the work piece's upper surface. The entire tool pin (probe) is inserted into the base metal at

this point. In addition to producing heat, the spinning tool pin inside the base metal and the rotating shoulder over its upper surface mix the plasticized material.

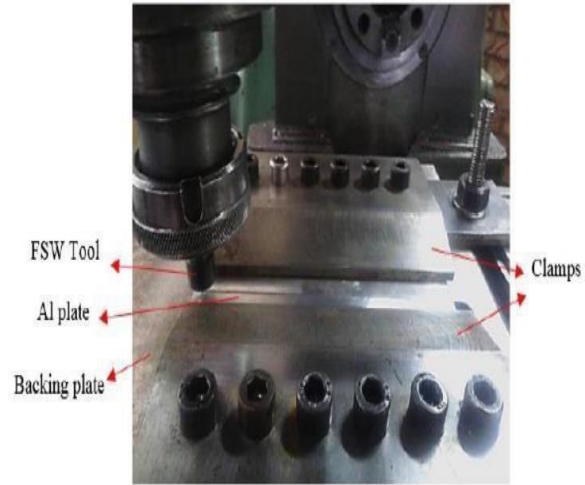


Figure 3: Experimental Setup [9]

Traverse:

The ability to move a rotating tool along a weld line. Since the joining of metal occurs along the weld line during this stage, this sequence of events is also referred to as the "weld stage". Joints with no defects arise from an ideal feed rate.

Retract: The revolving tool is pushed upward after the welding is complete. This is the last phase.

V. MECHANICAL PROPERTIES

5.1. Hardness

Many factors, including as the particular metals being welded, process parameters, tool design, and post-weld heat treatment, can affect the hardness of the weld zone in FSW of dissimilar aluminum alloys. Different microstructural zones like structural zone (SZ), thermomechanical affected zone (TMAZ), and heat affected zone (HAZ) are develop due to thermomechanical process during welding. The composition and metallurgical characteristics of various aluminum alloys differ, which causes variations in hardness. Welding dissimilar alloys together might result in a microstructure in the weld zone that is different from the basic materials in terms of hardness. The creation of intermetallic compounds, phase transitions, and grain refinement that occur during FSW can all have an impact on the weld's hardness. Achieving the required mechanical qualities

in the joint requires control over the microstructure. Friction stir welding of dissimilar aluminum alloys involves careful consideration of material selection, process parameters, tool design, and post-weld heat treatment procedures in order to provide homogeneous hardness in the weld zone. By optimizing these variables, one can lessen the difficulties posed by the FSW of dissimilar alloys and guarantee the creation of excellent welds with desired mechanical characteristics. In conclusion, mechanical performance and hardness distribution in joints made of dissimilar materials are closely related.

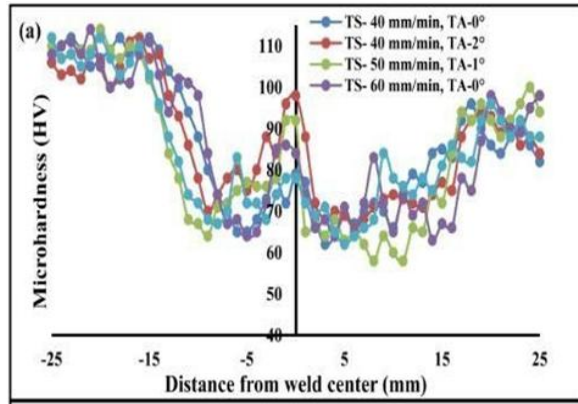


Figure 4: Micro hardness and welding speed's relationship [2]

5.2. Tensile Strength

The metals being welded, the welding conditions, the tool design, and the post-weld heat treatments all affect the tensile strength of friction stir welding (FSW) joints between different aluminum alloys. For the purpose of combining dissimilar aluminum alloys, FSW generally provides a number of benefits over traditional fusion welding processes, such as decreased distortion, improved mechanical characteristics, and increased corrosion resistance. The best parameters for FSW of different aluminum alloys are usually found through research and experimentation, and the mechanical characteristics of the resulting joints are evaluated. Tensile strengths of aluminum alloy combinations can vary because to variations in their compositions, microstructures, and metallurgical compatibility.

The ideal process parameters for welding dissimilar aluminum alloys in this FSW experiment are: 3, 6, and 9 KN of axial force; 1000, 1200, and 1400 rpm of rotation speed; 30, 45, and 63 mm/min of weld speed; and three distinct tool pin profiles, including threaded,

tapered, and straight cylinder pins. Using a laser cutting machine, the welded plates were transversely processed to create the tensile specimens in accordance with ASTM E8M-04 requirements. Universal testing equipment was used to perform the tensile test.

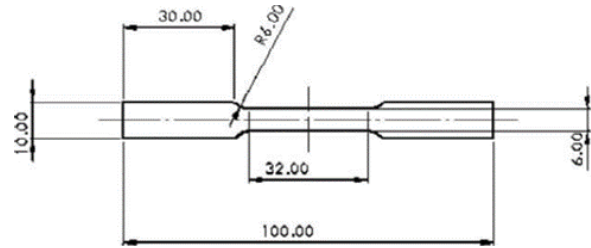


Figure 5: ASTM E8 Standard Tensile Specimen [8]

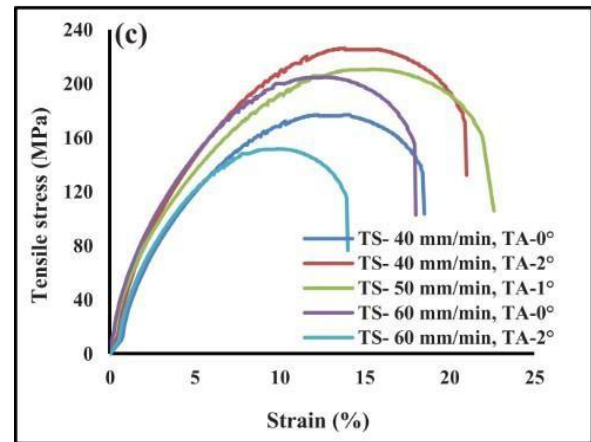


Figure 6: Stress-strain diagram of a dissimilar aluminum alloy FSW joint [2]

VI. MICROSTRUCTURAL ANALYSIS

Microstructural analysis of friction stir welding (FSW) of dissimilar aluminum alloys involves examining the changes that occur at the microscopic level during the welding process. When dissimilar aluminum alloys are joined using FSW, several key microstructural features can be observed:

6.1. Stir Zone (SZ)

The area where the welding really happens is called the stir zone. Its microstructure is different from that of the underlying materials. Because of the variations in the composition and characteristics of the alloys, the microstructure of the stir zone in dissimilar alloy welding can vary greatly. Grain refinement, plastic deformation, and dynamic recrystallization are usually observed in the stir zone.

6.2. Grain structure

In the stir zone, FSW frequently results in grain refinement relative to the base materials. Process variables including tool rotation speed, traverse speed, and material qualities affect the precise grain size and shape. Due to variations in the alloy compositions and thermal properties, the grain structure may change throughout the contact during dissimilar alloy welding.

6.3. Intermetallic compounds (IMCs)

Due to diffusion and reactivity between the alloying elements, intermetallic compounds may occur at the interface between the dissimilar aluminum alloys. The kind and distribution of IMCs affect the weld's mechanical characteristics and ability to withstand corrosion. Controlling the development of IMCs is essential since too much of them can cause brittleness and decreased weld strength.

6.4. Thermal gradient effect

Different thermal conductivities and melting temperatures of the dissimilar alloys could result in uneven heating and cooling during FSW. Temperature gradients have the potential to modify the grain size, phase distribution, and IMC formation of the microstructure close to the interface.

6.5. Heat affected zone (HAZ)

The HAZ is thermally cycled but does not deform plastically when it is next to the stir zone. The temperature attained during welding and the length of time exposed to high temperatures affect the microstructure of the heat-hazard zone. Because dissimilar materials interact differently in dissimilar alloy welding than in homogeneous alloy welding, the HAZ may show distinct microstructural changes.

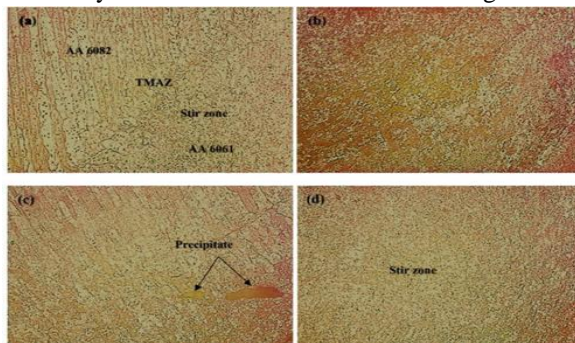


Figure 7: Optical microstructure of welded specimen [2]

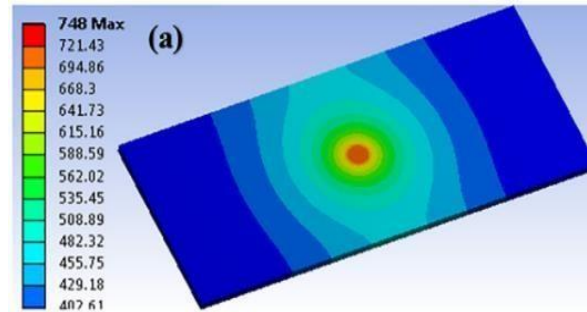


Figure 8: Temperature distribution friction stir welded joint at different zones [2]

VII. EFFECTS OF PROCESS PARAMETERS

Friction stir welding (FSW) of dissimilar aluminum alloy is a complex process, and the selection of process parameters plays a crucial role in determining the quality of the weld and the mechanical properties of the joint. The effects of various process parameters on FSW of dissimilar aluminum alloys include:

7.1. Rotation speed (rpm):

Rotational speed affects the heat generation in the weld zone. Higher RPMs generally result in higher heat input, which can lead to better material mixing and a finer grain structure. However, excessively high RPM can cause defects like tunneling and lack of material consolidation.

7.2. Traverse Speed:

The traverse speed determines the rate at which the tool moves along the joint. A higher traverse speed typically leads to less heat input and faster cooling rates. However, it can also affect the mixing of materials. Slower traverse speeds may promote better mixing but could increase the heat input.

7.3. Tool Geometry:

The shape and size of the FSW tool shoulder and pin can significantly affect the weld quality. Tool design should be optimized for the specific dissimilar aluminum alloys being welded to ensure proper material flow and mixing.

7.4. Plunge Depth:

The weld quality may be affected by how deeply the FSW tool enters the work pieces. Better material consolidation may result from a longer plunge depth,

but there may be a higher chance of flaws as well, particularly when welding dissimilar metals with different characteristics.

7.5. Tool Tilt Angle:

During FSW, the tilt angle can be changed to regulate the material flow. While a negative tilt angle might enhance material mixing, a positive tilt angle can aid in decreasing the development of tunnel flaws. The particular alloys being welded determine the ideal tilt angle.

7.6. Backing Material and Support:

Heat dissipation and deformation during FSW can be impacted by the choice of backing material and support structures. Sufficient support is necessary to keep joints aligned and prevent distortion.

7.7. Clamping and Fixturing:

In order to guarantee the alignment and stability of the work parts during welding, proper clamping and fixturing are essential. Accurate clamping might cause flaws and misalignment of the joints.

To achieve a high-quality weld with desired mechanical qualities, it is imperative to optimize these process parameters for the particular dissimilar aluminum alloys being welded. FSW of dissimilar aluminum alloys requires careful control of these parameters, process monitoring, and experimentation. In addition, process parameter optimization might benefit from sophisticated methods such as numerical modeling and simulation.

VIII. CONCLUSION

Finally, it should be noted that friction stir welding (FSW) of dissimilar aluminum alloys is a flexible and exciting joining process with a number of benefits over conventional fusion welding procedures. Because it can provide high-quality, flawless welds with exceptional mechanical qualities, it has been extensively used in a variety of industries, including aerospace, automotive, and marine. The following are some important lessons learned:

Material Compatibility:

Dissimilar aluminum alloys that are often difficult to weld using traditional fusion welding procedures can be joined together successfully with FSW. This makes

it possible to design lightweight structures with certain material characteristics.

Improved Mechanical Properties:

High tensile strength, fatigue resistance, and improved corrosion resistance are just a few of the mechanical qualities that FSW welds often have. These qualities are critical for applications in harsh environments.

Low Heat Input:

Since FSW is a solid-state welding method, it produces less heat than fusion welding. Because of the low heat input, there is less chance of deformation, less unwanted metallurgical phases will emerge, and the base materials' microstructure will be preserved.

Reduced Defects:

FSW is renowned for its capacity to create welds devoid of defects, including hot cracking and porosity, which are frequent problems in fusion welding. Reliability rises as a result, and post-weld inspection and maintenance are reduced.

Environmental Benefits:

Since FSW is solid-state, it produces fewer pollutants and is therefore an eco-friendly welding technique. Because of its efficiency, it may also result in a decrease in material waste.

Process Parameter Sensitivity:

It is essential to carefully optimize process parameters like rotational speed, traverse speed, tool shape, and tool material for the successful joining of different aluminum alloys using FSW. Selecting the right parameters is essential to producing welds that are high-quality.

Research and Development:

The capabilities and uses of FSW technology are still being expanded through ongoing research. Cutting-edge equipment, supplies, and process tracking methods are always being developed to further enhance the procedure.

Industry Applications:

FSW has been effectively used in a number of industries, including automotive and aerospace, where it helps produce lightweight components and is used to manufacture aircraft structures. Its possible uses are

only expanding.

In conclusion, friction stir welding offers a practical way to combine these challenging materials with several benefits, including improved mechanical properties, fewer defects, and environmental advantages. Research and development are expected to be used increasingly more extensively in many different industry sectors.

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