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Design and Experimental Concept for Dissimilar Ultrasonic Welding Joints for Aluminum Alloy to Glass-Fiber-Reinforced Polymer Tubes

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Abstract

This conceptual study explores ultrasonic welding (UW) for creating joints between aluminum alloy A5052-H32 and glass-fiber-reinforced polymer (GFRP) cylindrical tubes, capitalizing on the method's advantages, such as low energy requirements, minimal heat-affected zones, and direct energy transfer to the weld interface. The research, conducted by the group with extensive expertise in solid-state joining and material deformation under extreme conditions, responds to the growing demand for reliable, fast, and cost-effective joining technologies. The proposed hybrid-UW technique introduces gradient functions at the joint interface, aiming to enhance the performance of Al/GFRP dissimilar joints. The manuscript not only outlines the technical approach and experimental methods employed but also highlights the distinctive aspects of the proposed technology. In addition to detailing the materials used and the design considerations for the ultrasonic welder's horn and anvil, the study provides a glimpse into the practical implementation of the proposed hybrid-UW technique. The limited joints made during the experimental phase serve as a proof-of-concept for the feasibility and potential effectiveness of the approach.

Keywords: Ultrasonic welding, Dissimilar joints, Aluminum alloy, Glass-fiber-reinforced polymers, Hybrid ultrasonic welding, Joint interface, Lightweight materials, Joining technology.

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Introduction

The demand for innovative joining technologies capable of joining dissimilar materials with varying properties has surged recently. Lightweight aluminum alloys, known for their structural advantages, and glass-fiber-reinforced polymer (GFRP) composites, prized for their high strength-to-weight ratio, present a compelling combination for diverse industrial applications. Joining these materials, however, remains a challenge, and it is this challenge that motivated the current study. This research is based on a comprehensive understanding of solid-state joining techniques, with a particular emphasis on ultrasonic welding (UW). The process of joining materials without the fusion of heat aligns seamlessly with the group's expertise (Shin et al., 2016). Over the years, the researchers have significantly contributed to the field, exploring various materials' deformation behaviors and developing novel joining techniques under extreme conditions (Shin et al., 2008; Shin & Jung, 2008; Shin, 2014, Shin & De Leon, 2015, Shin & De Leon, 2017, Chen et al., 2016). These conditions include high velocity and pressure, cryogenic temperatures, mechanical property testing, and high current conditions, making the researchers' experience different from the conventional studies in the field.

The industry's pressing need for dependable, efficient, and reasonably priced joining technologies designed for construction including fiber-reinforced polymer materials is what encouraged this research. Although mechanical joining techniques such as clinching (Zhang et al., 2016) and self-pierce riveting (Mandel & Krüger, 2012; Lambiase & Ko, 2017) facilitate quick assembly without requiring initial hole drilling (Ucsnik et al., 2010), the problem is that fasteners are prone to corrosion and their mass adds structural weight (Tan et al., 2015; Huang et al., 2013). On the contrary, adhesive bonding has disadvantages such as expensive costs, careful surface preparation, and long cure times even though it works well (Farahani & Dubé, 2017; Lionetto et al., 2017). Appropriate adhesion qualities are dependent on a temperature- and time-controlled crosslinking process (Arenas et al., 2013). Moreover, there are disadvantages to this technology, including the short lifespan of adhesive joints and the release of hazardous compounds into the environment (Lambiase et al., 2016; Pramanik et al., 2017).

Current research worldwide is addressing this need, but the group's advantage lies in the researchers' experience in solid-state joining, especially with dissimilar materials. Ultrasonic welding, chosen as the primary approach, offers distinct advantages, such as low welding energy requirements and minimal heat-affected

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zones (Shin & De Leon, 2017). In contrast to other techniques like resistance spot welding, UW and its hybrid variations possibly avoided the liquid phase reactions and directed energy precisely onto the weld interface (De Leon & Shin, 2017; De Leon & Shin, 2023; De Leon & Shin, 2022). This study builds upon the researchers' extensive knowledge and skills gained for several decades in the deformation behaviors of materials and the development of joining techniques under extreme conditions. The integration of ultrasonic welding into the group, extending even to the joining of high-temperature superconducting tapes, showcases the versatility of this technique (Shin et al., 2016; De Leon & Shin, 2020; Shin et al., 2020). The researchers' past contributions, such as investigations into dissimilar friction stir spot welding of metallic glass to lightweight crystalline metals (Shin, 2014) and ultrasonic spot welding of A5052-H32 alloy sheets (Shin & De Leon, 2017), mark steps towards addressing similar challenges. The current study, however, distinguishes itself by investigating the intricate details of ultrasonic welding joints between aluminum alloys and GFRP composites.

The remaining sections of this manuscript will present the technical approach, methods, and experimental, and future industry integration of the study, offering a comprehensive exploration of dissimilar ultrasonic welding joints for aluminum alloy to GFRP tubes. Through this study, the researchers aim to present not only a novel contribution to the field but also a potential breakthrough for industrial applications in the near future.

Methods

The materials selected for these dissimilar UW joints are aluminum alloy (A5052-H32) and GFRP cylindrical tubes. The two primary components, aluminum, and GFRP, represent contrasting yet complementary elements in the structural landscape. The A5052-H32 is chosen for its lightweight properties and favorable mechanical characteristics, and serves as a critical element in the study. Typically provided in coupon-type sheets or cap-structured forms with a thickness not exceeding 2 mm, this alloy exemplifies the type of lightweight materials commonly used in various industrial applications, particularly in the automotive sector for its balance of strength and weight.

The GFRP material takes the form of cylindrical tubes with an internal diameter ranging from 50 mm to 300 mm and a thickness of less than 2 mm. Figure 1 shows the joint concept between these two materials. The joining positions are also indicated in Figure 1 as point A and point B. This configuration mirrors real-world structures, allowing for a representative study of joints that might be encountered in practical

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applications. The GFRP, characterized by its enhanced strength through the incorporation of glass fibers, brings a dimension of versatility to the joint configurations, encapsulating the aluminum coupons.

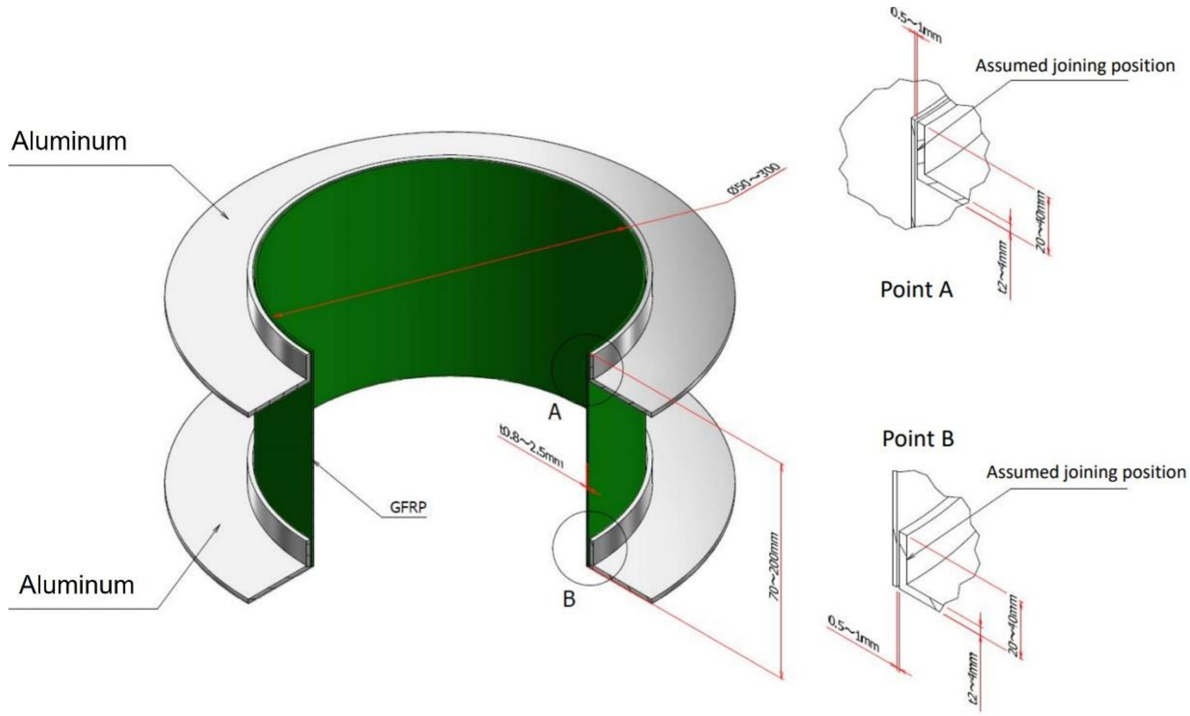

Figure 1. Joint assembly between aluminum A5052-H32 and glass-fiber-reinforced polymer.

The ultrasonic welding process is performed using a specialized ultrasonic welder, carefully chosen to optimize the joint performance. It is a lateral-drive UW machine (KORMAX, model KM-2035) in time control mode, capable of generating the necessary vibratory energy for effective welding. Additional details about this welder are available elsewhere (Shin & De Leon, 2017). This welder has a single transducer system, so oscillating motion is generated on only the horn side of the overlapped sample to be joined. Nevertheless, it has the capability of generating up to 3.5 kW of power at a frequency of 20 kHz. The equipment allows precise control over the welding parameters, including frequency, amplitude, and weld duration.

In addition to conventional ultrasonic welding, a hybrid-ultrasonic welding technique was introduced. This original technology incorporates a gradient function at the joint interface, enhancing the transversal oscillation in the weld zone. The hybrid technique involves several modifications and designs, including specialized horn and anvil configurations, proper mounting, and clamping through a vise tailored for the joint structure. A horn and anvil with a pyramidal tip pattern were used as shown in Figure 2(a) and (b), respectively. The vibration direction was applied parallel to the

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surface of the jointed materials. The horn was made of high-speed steel, having circular and square surface shapes on both ends, which had dimensions of 14 mm diameter and 12 mm x 12 mm square shape (please see Figure 2a). Figure 2(b) shows the specially designed anvil with its respective tips and dimensions. The tips' patterns were designed according to the dimensions and physical properties of the materials to be welded through the preliminary test selections and in the researchers' previous study (Chen et al., 2016).

Also, appropriate material interlayers are used to provide gradient functions, and specific pre- and post-processing methods for both samples and joints. The combination of these factors, along with careful selection of machine parameters and material properties, is expected to optimize the hybrid effects on joint performance and quality.

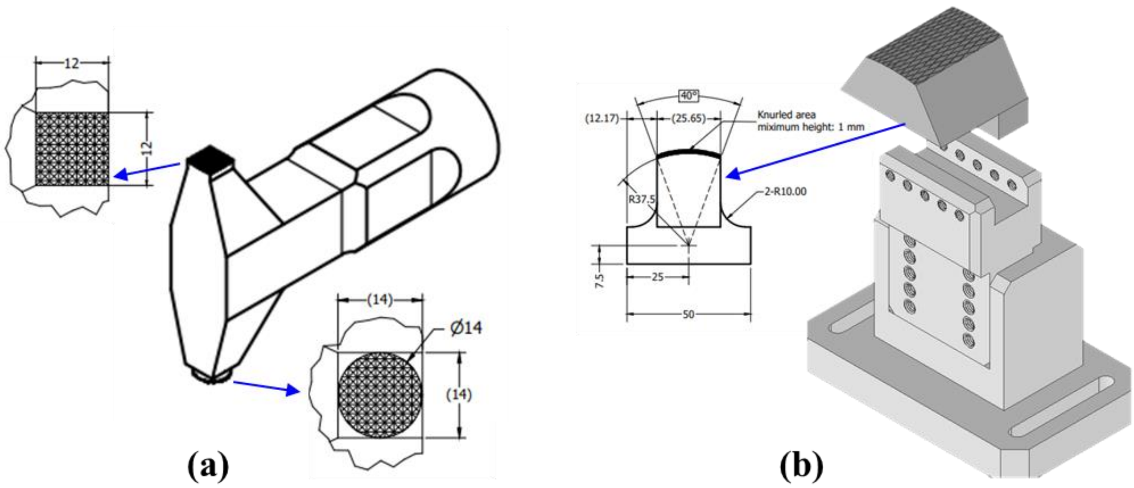

Figure 2. (a) Horn with square and square shape surface and (b) cylindrical-shaped anvil with radius of curvature of 100 mm. Note: all linear dimensions are in mm.

Result and Discussion

From encapsulating GFRP tubes with A5052-H32 caps to integrating A5052-H32 coupons within GFRP structures, the researchers' study pursued to optimize the UW adaptability. Figure 3 shows the cylindrical GFRP- A5052-H32 UW assembly. To provide a uniform and continuous application of ultrasonic vibration, a rotary welding positioner is coupled to the welder setup. This can be controlled at different rotating speeds, making the joint uniform and systematic. By incorporating this hybrid-ultrasonic welding technique, the researchers elevated the transversal oscillation within the weld zone. This approach, achieved through meticulous design

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modifications, clamping strategies, and material interlayers, not only optimized joint performance but opened new doors for dissimilar material bonding.

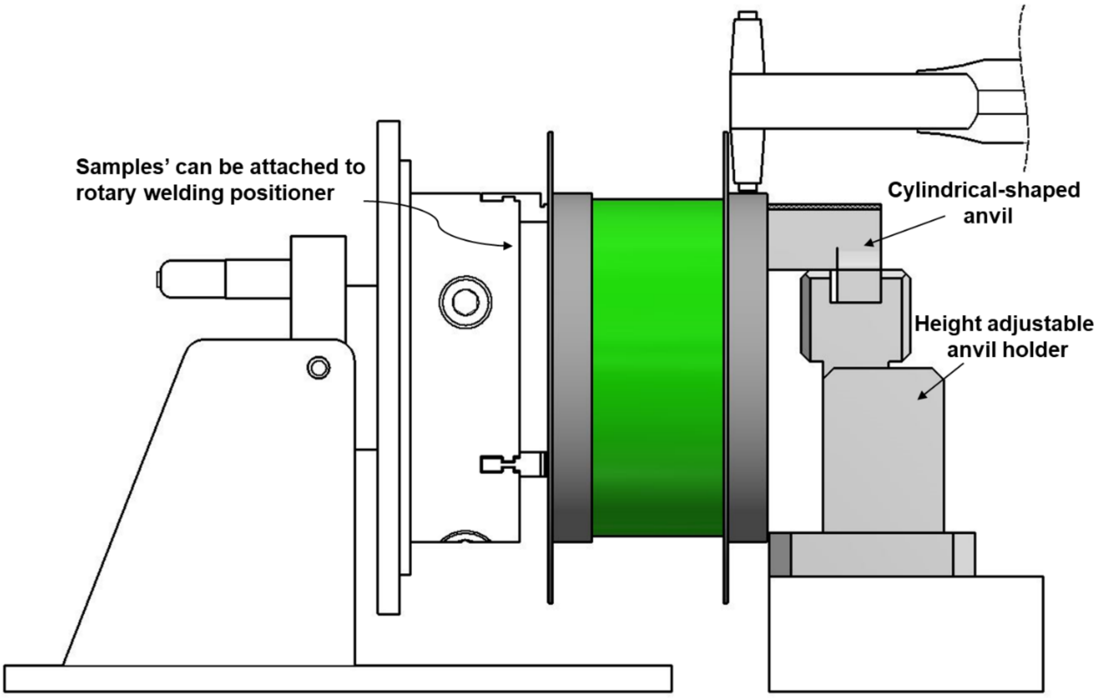

Figure 3. A customized cylindrical-shaped anvil is utilized coupled with the samples' positioner for uniform and continuous application of ultrasonic vibration.

Acknowledging the need for reliable joints, especially in the tensile strength aspect, coupon-shaped sheets were first tried to join. Figure 4 shows the A5052-H32 and GFRP samples with surface modifications through abrasive polishing (Figure 4a) and with an Indium sheet, 100 μm in thickness as interlayer (Figure 4b).

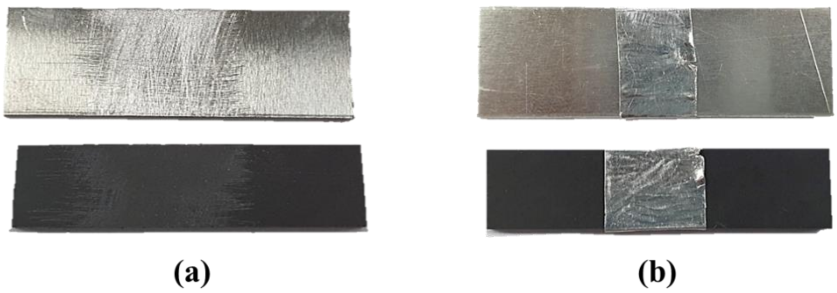

Figure 4. (a) Coupon-shaped A5052-H32 and GFRP samples with polished surfaces and (b) an Indium sheet inserted between the samples as interlayer material.

Two joints with different weld parameters are presented in Figure 5 (a) and (b). The possibility of joining these two different materials was materialized. At different

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welding parameter conditions, two distinct welds can be observed after the sample separation, one with a more abrasive joint interface than the other. The use of interlayer material and varying welding parameters affects the joint interface. By further adjusting the welding parameters and finely tuning the interlayer material, an optimized weld can be achieved.

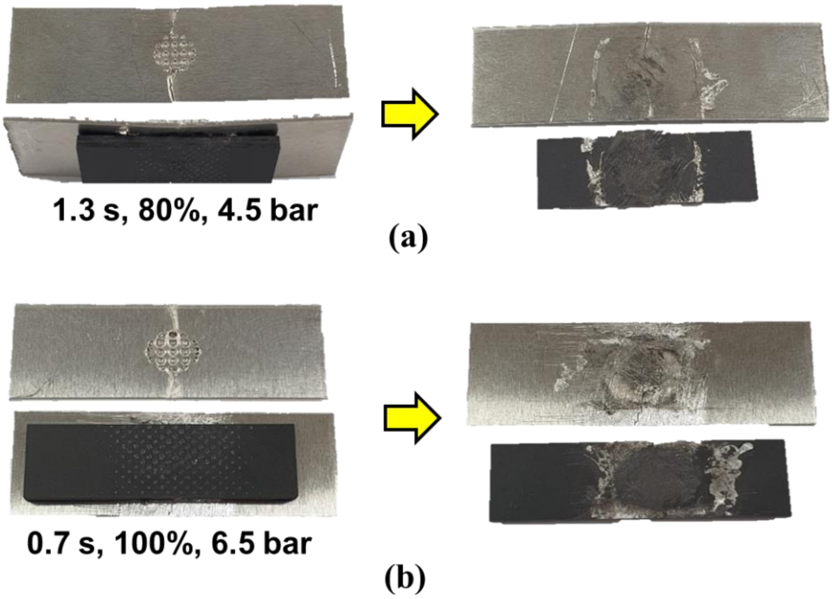

Figure 5. Ultrasonic welded A5052-H32 and GFRP with two different welding parameters. The images on the right show the joint interface after the joint separation. (a) welding time of 1.3 s, 80% vibration amplitude, and 4.5 bar of welding pressure. (b) welding time of 0.7 s, 100% vibration amplitude, and 6.5 bar of welding pressure.

In the initial results, the dissimilar ultrasonic welding joints emerged not just as a scientific achievement but as a preparation for potential industrial transformation. The hybrid-ultrasonic welding technique, the adaptability to real-world conditions, and the vision for future advancements collectively provided the possibilities for improvement.

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Conclusion and Recommendation

In conclusion to this study, an investigation into dissimilar ultrasonic welding joints between A5052-H32 and GFRP cylindrical tubes set sights on the future. This study represents more than an achievement, it aligns with the ongoing evolutionary trends in manufacturing and joining technologies. As industries evolve towards lightweight materials and composite structures, the demand for reliable, efficient, and adaptable joining techniques becomes increasingly in demand. The dissimilar ultrasonic welding joints presented here could be promising in transforming industrial practices. With a hybrid-ultrasonic welding technique that enhances joint properties, these joints could become essential in the assembly of structures crucial to sectors such as automotive, aerospace, and renewable energy. This study sets the stage for a future where ultrasonic welding becomes a versatile tool for joining other dissimilar materials across various industries.

As industries embrace the era of Industry 4.0 (What is Industry 4.0 and how does it work?), the adaptability of ultrasonic welded joints to automation becomes a pivotal aspect. The integration of simulation tools for virtual optimization and non-destructive testing procedures that detect faults early in the welding process foretell a future where efficiency and quality intertwine. Crucially, the adaptability of ultrasonic welding in in-line manufacturing assembly suggests reduced setup times, increased weld productivity, and higher-quality joints. The vision of a manufacturing process that predicts failures, configures automatically, and adapts to changes signifies a leap toward a more streamlined and economical industrial future. Although not presented in this study, the concept of broader mechanical property testing involving the joints subjected to adaptive vacuums and varying temperatures could be of importance. Several tests could assess the joints against thermal shock, vibration, and dynamic loading conditions.

The dissimilar ultrasonic welding joints presented here, with their performance, adaptability, and potential for automation, symbolize a stepping stone towards a future where the joining of dissimilar materials is not just a challenge but an opportunity for innovation. As industries increasingly prioritize efficiency, sustainability, and adaptability, the techniques developed in this study could become instrumental. The dissimilar ultrasonic welding joints may well become a cornerstone in the construction of structures that define the future of industries, ushering in an era where innovation and practicality converge for the betterment of industrial practices.

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