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Joining Wood Plastic Composites Using a New Self-Reacting Friction Stir Toolset – A comparative study

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Abstract- **Wood-plastic composite (WPC) is an environmentally friendly material that promotes the recycling of wood and plastic waste. However, there is a notable lack of research on methods for joining these materials. This study introduces an innovative approach using a uniquely designed self-reacting friction stir toolset specifically for WPC joining. The performance of this new toolset is evaluated against prior research that employed a hot-shoe friction stir welding toolset on a WPC with a different composition. The study focuses on key parameters such as revolutions per welding line (RPWL), rotational speed, and welding speed, emphasizing their critical impact on the quality of the weld. The findings highlight the formation of a distinctive spherical macrostructure and report an impressive relative flexural strength of 99.18%, underscoring the potential of this method for high-quality WPC joining.**

Keywords- **Friction stir welding; Wood plastic composites; Low-density polyethylene; Polymers; Plastics; Welding; Stationary shoulders.**

I. INTRODUCTION

Wood plastic composites (WPCs) hold immense importance due to their ability to transform wood and plastic waste into a unified, sustainable material [1]. This dual-functionality not only addresses environmental concerns by promoting recycling but also results in a product that is both economical and efficient. Beyond their ecological and financial benefits, WPCs are renowned for their exceptional performance characteristics, including resistance to moisture absorption, which prolongs their durability. Additionally, they offer remarkable dimensional stability, ensuring that the material maintains its shape and form under varying conditions. Moreover, WPCs exhibit high relative stiffness, making them a strong and reliable choice for various applications where rigidity and structural integrity are essential. These attributes collectively highlight the versatility and value of WPCs in modern material science and engineering. Many types of polymeric materials, including thermosets and thermoplastics, are utilized in the WPCs fabrication process [2] such as High-Density Polyethylene (HDPE) [3], Polypropylene (PP) [4], Low-Density Polyethylene (LDPE) [5], Acrylonitrile Butadiene Styrene (ABS) [6], Polyvinyl Chloride (PVC) [7], and Polystyrene (PS) [8]. Also, various types of wood fibers are involved in the fabrication of WPCs like Bamboo wood [9], Poplar wood [10], Maple wood [11], Pine wood [12], and wood flour [13]. For their advantages, WPCs are used in many applications such as construction [14], automotive [15], and outdoor furniture [1].

The WPC ingredients undergo pre-processing treatments, which elevate the bonding between the cellulosic fibers and the plastic. The techniques used in this phase include; chemical, thermal, and mechanical treatment. In chemical pre-processing, coupling agents are added to the WPC ingredients which modifies the surface of the fiber to enhance its wetting in polymers and enhance the bonding between them. Some of the commonly used coupling agents are; maleic anhydride [16], glycidyl methacrylate [17], succinic anhydride [18], phthalic anhydride [19], hydroxy methyl methacrylate [20], and glycidyl methacrylate [21]. In mechanical treatment, the adhesion properties of the cellulosic fiber's surface are enhanced which in return the bonding between the fibers and the plastics is elevated. In this technique, the characteristics of the surface of the fiber are changed without changing its chemical composition and minimizing the need for chemicals. some of the methods used in mechanical treatments are; plasma treatment [22], electron beam irradiation treatment [23], and solid-state shear milling [24].

After pre-processing, the ingredients are blended by various methods to obtain a finished or semi-finished product. Generally speaking, the WPCs are manufactured by being extruded [25], mold-injected [26], or hot-pressed [27]. one of the extruders used in the manufacturing process is the single extruder [28]. Despite its simple components and the low running cost it needs, the production rate of this type is low, it needs a dryer to get rid of the moisture in the fibers, and the fibers are chemically decomposed during mixing. In order to overcome these drawbacks, a double-screw extruder [29] or co-kneader extruder [1] is used. In the double-screw extruder there is no need for an external dryer, as the moisture is removed through vents displaced on the extruder length and its mixing capability is

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high if compared to the single extruder. The co-kneader is a single extruder with fixed wiping pins fixed in the inner surface of the barrel. these pins wipe the extruder's screw surface to keep it clean. In this type, High production rates, low mixing temperatures, highly homogenous mix, and low energy consumption can be obtained.

To date, the body of literature addressing the methods for joining WPCs remains relatively sparse. Among the existing studies, some have explored techniques such as surface modification of WPCs to enhance adhesive bonding [30], laser transmission welding [31], ultrasonic welding [32], and friction stir welding (FSW) [33]. In one notable study focusing on FSW, Rahbarpour et al. [33] investigated the application of this method for welding a WPC material composed of 70% high-density polyethylene (HDPE) and 30% wood fibers. Their research utilized the hot shoe technique, which involves a stationary shoulder equipped with internal electric heaters to raise the temperature of the material during the welding process. This study identified temperature, rotational speed, and welding speed as critical factors that significantly influence the relative tensile strength of the welded joint. These findings underscore the importance of precise control over these parameters to achieve optimal weld quality in WPC materials.

In the field of plastic welding, advancements have been made in developing specialized tools for FSW. Initially, the same tool design used for welding aluminium, featuring a rotating shoulder with a pin, was adapted for use in plastics. The success of the FSW process in plastics hinges on several critical parameters, which are broadly categorized into machine parameters, welding tool parameters, and the properties of the material being welded. The machine parameters include key factors such as rotational velocity, welding speed, tilting angle, and plunging depth. These parameters are essential in regulating the heat input and controlling the degree of crystallinity within the welded area. The level of crystallinity, in turn, directly impacts the quality and integrity of the weld, making precise adjustment of these parameters crucial for achieving optimal welding outcomes in plastic materials. Zafar et al. [34] conducted a study on the welding of 10 mm thick Nylon-6 sheets, aiming to determine the optimal conditions for achieving the highest welding quality. Through their experiments, they identified that the ideal welding speed was 10 mm/min, while the optimal rotational speed was 1000 RPM. Their findings revealed that at lower rotational speeds, the quality of the weld was notably superior, resulting in strong and consistent joints. However, as the rotational speed and tilting angle increased, the peak temperature within the nugget zone rose significantly. This elevated temperature led to the formation of bubbles, which adversely affected the integrity and overall quality of the weld. The study highlighted the importance of carefully balancing these parameters to avoid defects and ensure a high-quality welding process in Nylon-6 materials. Bozkurt et al. [35] conducted a study focused on welding 4 mm thick HDPE sheets, with the goal of identifying the optimal parameters for producing a sound weld. Through their research, they determined that the best welding conditions were achieved at a welding speed of 115 mm/min and a rotational speed of 3000 RPM. The results of the study highlighted that rotational speed plays the most critical role in determining weld quality, making it the most significant parameter in the welding process. In contrast, the tilting angle was found to have the least impact on the weld quality, indicating that it is a less critical factor compared to other parameters. These findings emphasize the importance of prioritizing rotational speed adjustments to achieve optimal welding outcomes in HDPE materials. Payganeh et al. [36] explored the application of Friction Stir Welding (FSW) on a composite material composed of 30% glass fiber and 70% polypropylene (PP) with a thickness of 5 mm. Their study underscored the critical role that the tilting angle plays in influencing the joint strength. They found that an optimal tilting angle of 2 degrees resulted in the highest joint strength. However, when the tilting angle was improperly set, it led to the formation of tunnel defects, compromising the integrity of the weld. The study also identified the optimal welding speed and rotational speed as 8 mm/min and 630 RPM, respectively, for achieving the best weld quality. Additionally, the research highlighted the importance of various welding tool parameters, including shoulder diameter, pin diameter, pin topology, and pin length. Among these, the shoulder diameter was noted to be particularly significant, as it generates the majority of the frictional heat input during the welding process. However, the study pointed out a potential drawback—excessive heat input at the surface, which, due to the low thermal conductivity of plastics, tends to concentrate at the top surface. This concentrated heat can cause the material at the surface to melt and be squeezed out from the nugget zone, potentially leading to defects in the weld. These findings emphasize the need for careful control of tool parameters to optimize weld quality and avoid surface defects in FSW of composite materials. Jaiganesh et al. [37] investigated the effects of different pin profiles during Friction Stir Welding (FSW) in their study on welding 5 mm thick polypropylene (PP) sheets. The study focused on three distinct pin profiles: cylindrical pin, cylindrical tapered pin, and cylindrical grooved pin, each with a diameter of 5 mm. The results revealed that the cylindrical tapered pin was the most effective among the three. This pin profile resulted in fewer defects within the welding nugget, contributing to a more consistent and reliable weld. Additionally, the cylindrical tapered pin provided higher weld strength, which the researchers attributed to the larger contact area between the tool and the welded sheets. This increased contact

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area facilitated better heat distribution and material flow, enhancing the overall quality of the weld. These findings highlight the importance of selecting the appropriate pin profile to minimize defects and maximize the strength of the welded joint in FSW of PP materials.

The traditional FSW tool design proved inadequate for welding polymeric materials due to its limitations. In conventional tools, the shoulder, which generates heat by friction in metal welding applications, tends to melt the upper layer of polymeric materials. This melting occurs because polymers have poor heat conductivity, causing the heat to be concentrated at the surface. Consequently, this excess heat leads to the material being squeezed out from the nugget zone, resulting in defects and compromised weld quality. To address these challenges, modifications were made to the FSW tools specifically for polymeric materials. These modifications aimed to improve heat management and material flow, ensuring that the welding process is more effective and suitable for polymers, thereby enhancing the overall quality and integrity of the weld. Kumar and Roy.[38] introduced an innovative modification to the conventional FSW tool by developing a double-step shoulder tool designed specifically for improved performance with polymeric materials. This modified tool is constructed from H13 steel and features a shoulder diameter of 24 mm, a step-shoulder with a diameter of 16 mm, and a pin with a diameter of 6 mm. The pin profile is cylindrical with a right-hand thread. The tool was utilized for welding acrylonitrile butadiene styrene (ABS) sheets to polycarbonate (PC) sheets, both 6 mm thick, in a butt weld configuration. The design modification of the tool effectively reduced flash defects, which are common issues in polymer welding processes, and prevented the expulsion of material from the nugget zone. This enhanced performance was reflected in the joint efficiency achieved, which was 73.16%. The optimal welding conditions identified in this study included a rotational speed of 1600 RPM, a traveling speed of 0.2 mm/sec, and a tilt angle of 2 degrees. These parameters contributed to the successful application of the modified tool and demonstrated its effectiveness in improving the quality and reliability of the weld in polymeric materials.

Nelson et al. [39] introduced a novel FSW tool design featuring a stationary shoulder. The primary objective of this design modification was to prevent the expulsion of material from the nugget during the welding process. In this tool, while the pin rotates to generate the necessary frictional heat for welding, the shoulder remains stationary. This approach helps to maintain the material within the nugget zone, reducing the risk of void formation and enhancing the strength of the welded joint. By ensuring that the material does not escape from the nugget area, this tool design improves the overall quality and integrity of the weld, making it a significant advancement in the field of friction stir welding for various applications.

Azarsa and Mostafapour [40] advanced the concept of a stationary shoulder by creating a shoe-shaped shoulder that incorporates an internal heater along with a rotating pin. This innovative design allows the tool to generate heat through both the electrically heated shoulder and the frictional heat produced by the rotating pin. The dual heat sources enhance the welding process by providing more effective and controlled heating. The modified tool was employed for welding 10 mm thick high-density polyethylene (HDPE) sheets. The results demonstrated a significant improvement in weld quality, with a relative flexural strength of 95.69% achieved. This high strength was attained under specific conditions: the shoe temperature was set to 110°C, the travel speed was 25 mm/min, and the rotational speed was 1400 RPM. This development highlights the effectiveness of combining heating methods to optimize the welding process and achieve superior material properties in HDPE welding.

Eslami et al. [41] explored an alternative approach to enhancing heat generation in friction stir welding by incorporating a bronze heating sleeve inside a Teflon stationary shoulder, rather than adding a dedicated heater. In this design, heat is produced through two main sources: the frictional heat generated by the rotating pin and the additional frictional heat created by the interaction between the tool and the bronze sleeve. This configuration ensures a more uniform distribution of temperature across the thickness of the materials being welded, which helps to prevent the ingress of inclusions into the nugget zone. This innovative tool design was applied in welding a 1.2 mm thick polypropylene (PP) sheet to a 2 mm thick polyethylene (PE) sheet using a lap joint configuration. The results demonstrated that the weld seams achieved with this setup were robust and exhibited a smooth, flat appearance. The effective heat management provided by the bronze sleeve contributed to the high quality of the weld, highlighting the benefits of this approach in achieving sound welds in polymer materials.

Pirizadeh et al. [42] introduced a novel self-reacting FSW tool that draws inspiration from the bobbin tool used in metal welding [43]. Unlike the traditional bobbin tool, which features rotating shoulders, the self-reacting tool designed for plastics includes two stationary shoulders—one on the top and one on the bottom—with a rotating pin situated between them. This design modification addresses the issue of root defects, which are cracks that can compromise the integrity and strength of the welded seam. The effectiveness of this tool was evaluated in welding acrylonitrile butadiene styrene (ABS) sheets using a butt joint configuration. The results of the study indicated that the self-reacting tool successfully eliminated the root defect from the welded seam. Additionally, the tool achieved a maximum tensile strength of 20.7 MPa under optimal conditions, which included a rotational speed of 400 RPM, a travel speed

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of 40 mm/min, and a convex pin configuration. This development represents a significant advancement in FSW technology for plastics, enhancing weld quality and material performance.

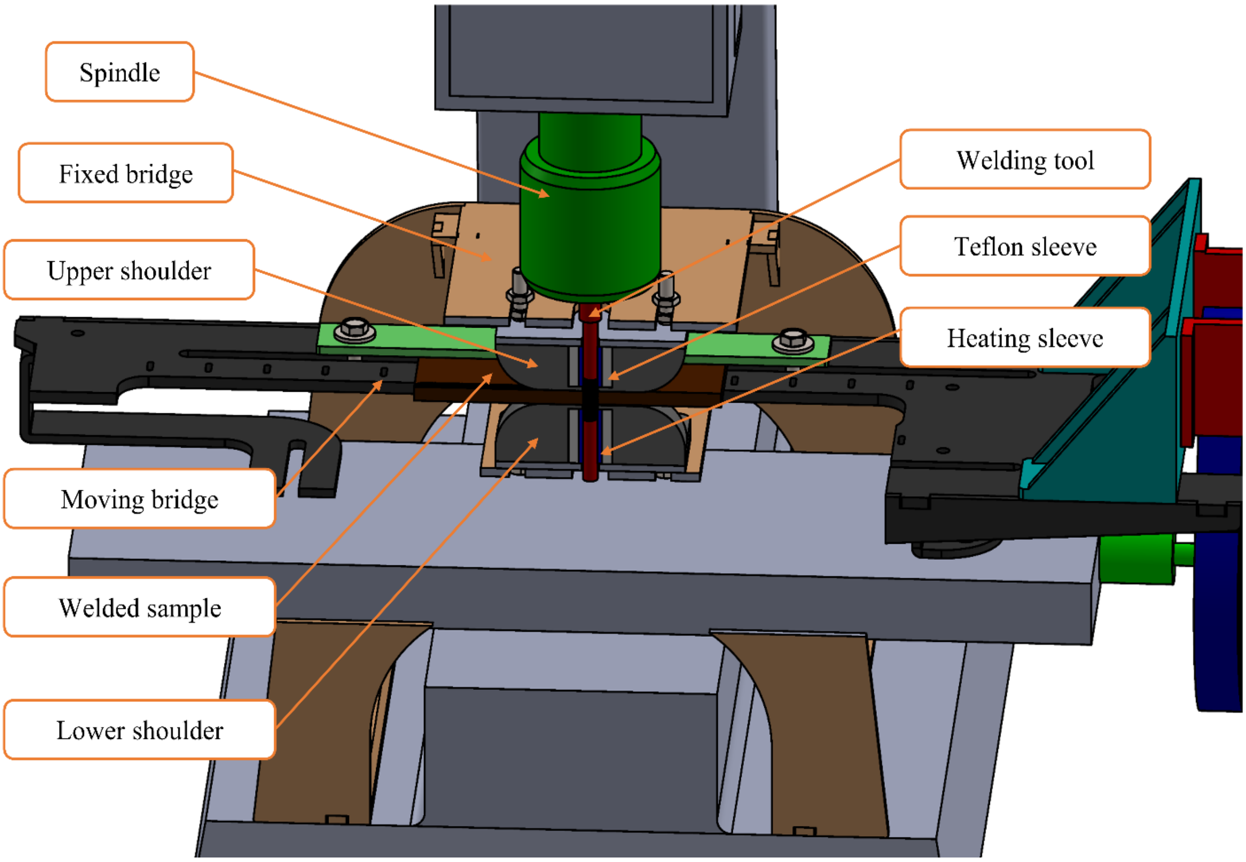

Figure 1 The toolset used in the study

II. MATERIALS AND METHODS

A. Materials

The WPC used in this study consists of the following weight ratios: 44% rice straw fibers with a mesh size of 25, 46% recycled low-density polyethylene (LDPE), 6% calcium carbonate, 0.7% maleic anhydride, 0.7% antimony trioxide, and the remainder is wax. The preparation process begins with blending these components in an extruder at a temperature of 170°C. The blended mixture is then processed through a hammer mill to crush it into smaller pieces and subsequently ground in a grinding machine to achieve a finer consistency. To ensure uniformity in the blend, the ground mixture is subjected to the same blending and processing steps again. Following this, the composite material is hot-pressed at 180°C using a 50-ton hydraulic press. This hot-pressing stage consolidates the components, resulting in a homogeneous WPC that is ready for further applications or testing.

The WPC used in the study is formulated with the following weight ratios: 44% rice straw fibers with a mesh size of 25, 46% recycled low-density polyethylene (LDPE), 6% calcium carbonate, 0.7% maleic anhydride, 0.7% antimony trioxide, with the remainder consisting of wax. The preparation process begins by blending these components in an extruder at a temperature of 170°C. The resulting mixture is then processed through a hammer mill to break it into smaller particles, followed by grinding in a grinding machine to achieve a finer texture.

To ensure a consistent and uniform blend, the ground mixture is subjected to the same manufacturing process once again. Finally, the composite is hot-pressed at 180°C using a 50-ton hydraulic press. This hot-pressing step consolidates the materials into a uniform WPC, ready for further use or testing.

B. Toolset Design

The toolset utilized for the welding process is a modified version of the self-reacting toolset proposed by Pirizadeh et al. [42]. In this updated design, the upper and lower stationary shoulders are mounted onto a fixed bridge, which is securely

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attached to the bed of a drilling-milling machine. Concurrently, the workpiece is fixed onto a separate moving bridge that traverses through the fixed bridge. The welding tool is mounted on the machine spindle and is designed to pass vertically through heating brass sleeves integrated into both shoulders. These brass sleeves are encased in Teflon sleeves to prevent overheating of the shoulders during the welding process. The welding tool itself is a shank with a diameter of 10 mm, featuring two sets of reverse threads with a 1.5 mm pitch located in the middle of the shank. The reverse threading is specifically engineered to push the stirred material into the nugget zone, enhancing the vertical blending of the welded material and thereby improving the homogeneity of the nugget. Figure 1 illustrates the setup, showing how the bridges are attached to the machine and how the welding tool is integrated with the stationary shoulders.

C. The study parameters

To determine the parameters for the study and establish the working range, a series of bead-on-plate experiments were conducted. These experiments revealed that the slope of the relationship between rotational speed and welding speed, referred to as revolutions per weld line (RPWL) and measured in revolutions per 0.1 mm, significantly impacts the quality of the welded joint. Figure 2 illustrates the various RPWLs examined in the study. The five RPWL values, labeled RPWL1 through RPWL5, represent the slopes of lines that divide the working range into equal sectors of the same area. Each line is positioned as the average between two adjacent sectors. For each RPWL line, four equal segments are defined, with each segment bounded by five distinct points representing different combinations of rotational and welding speeds. These points are used as the parameter set during the welding process to optimize the welding conditions and ensure high-quality welds.

III. EXPERIMENTAL SETUP

A. Samples manufacturing and welding procedure

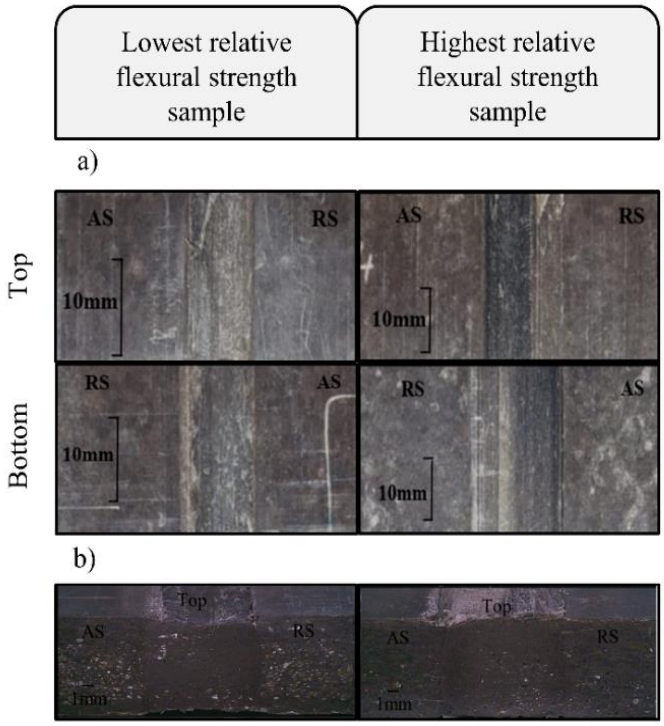

Figure 2 Visual & macrostructural views

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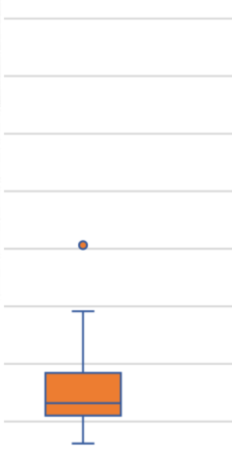
RPWL1 = 3.5 rev/0.1mm	
N, RPM	V, mm/sec
600	0.28
769	0.36
936	0.44
1105	0.52
1273	0.6

RPWL2 = 4.7 rev/0.1mm	
N, RPM	V, mm/sec
600	0.21
875	0.31
1150	0.41
1425	0.5
1700	0.6

RPWL3 = 5.9 rev/0.1mm	
N, RPM	V, mm/sec
702	0.2
1053	0.3
1404	0.4
1755	0.5
2106	0.6

RPWL4 = 7.1 rev/0.1mm	
N, RPM	V, mm/sec
852	0.2
1193	0.28
1534	0.36
1874	0.44
2200	0.52

RPWL5 = 9.3 rev/0.1mm	
N, RPM	V, mm/sec
1116	0.2
1387	0.25
1657	0.3
1928	0.35
2200	0.39



izadeh, et al. [41]

l self-reacting tool [41].

Figure 3 The parameters used in welding

Figure 5 Relative flexural strength of each RPWL group.

The hot-pressed wood-plastic composite (WPC) specimens will be divided into four quarters, with pairs of quarters being welded together. After welding, specimens will be extracted from the welded section, with each specimen being cut 15 mm from the entry point of the weld. These extracted specimens will be subjected to mechanical testing to determine their flexural strength. Additionally, a sample will be taken from the middle of the welded joint for macroscopic examination to assess and identify any defects present in the weld.

B. Comparative Study

For comparison, the results of the new toolset modification will be evaluated against those reported by Rahbarpour et al. [33], who employed a hot shoe technique for welding wood-plastic composite (WPC) specimens consisting of 30%-wt. wood fibers, 70%-wt. high-density polyethylene (HDPE), and approximately 3%-wt. maleic anhydride grafted polyethylene. Additionally, the new modification will be compared to the method proposed by Pirizadeh et al. [42], which utilized a self-reacting toolset for welding WPCs. This comparison will help assess the effectiveness and improvements offered by the new toolset relative to these established methods.

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IV. RESULTS AND DISCUSSIONS

A. Weld Appearance and Macrostructure

The visual inspection of the welded joints, as shown in Figure 3(a), indicates that both specimens with the lowest and highest relative flexural strength exhibit defect-free welded lines, with no visible tunnels or flashes.

The macroscopic investigation of the specimens, depicted in Figure 3(b), confirms that both specimens are free from root defects, which are typically a primary cause of cracking. The specimens are nearly devoid of other defects, except for a shallow landing observed in the specimen with lower relative flexural strength. This shallow landing is attributed to the presence of pores in the middle thickness of the parent material and the dual-reverse threading of the tool, which compresses the nugget and contributes to this imperfection.

Additionally, the specimens exhibit small bores on the right and left sides of the tool, which are indicative of stress concentration areas. These bores are responsible for localized stress, leading to fractures on both the advancing and retreating sides of the tested specimens. This explains why fractures occurred in these specific areas of the specimens.

B. Mechanical Properties

The specimens were tested to determine their flexural strength according to the ASTM D7264 Standard [44]. the box plot shown in Figure 4 shows the results of the tested specimens against the results of the studies made by Rahbarpour, et al. [33] and Pirizadeh, et al. [42]. From the figure, the new modification shows a superior performance against the hot-shoe method done by Rahbarpour, et al. [33] that was applied to the aforementioned WPC with a plastic composition higher than that used in the presented study, or the self-reacting tool method suggested by Pirizadeh, et al. [42] which was applied to acrylonitrile-butadiene-styrene (ABS). Over three-quarters of the welded specimens have relative flexural strength of over 80% and a maximum of 99.18% relative flexural strength was achieved.

C. Effect of RPWL

The RPWL parameter was found to have a considerable effect on weld quality. Higher RPWL values, achieved by either increasing the rotational speed or decreasing the welding speed, led to better material mixing and a more consistent weld nugget. The optimal RPWL value was identified as RPWL3 (5.85 revolutions per 0.1 mm), where there is an effective balance between heat input and material flow. Figure 5 presents a box plot illustrating the relative flexural strength values for each RPWL group. The plot visually demonstrates how different RPWL values impact the joint's relative flexural strength, highlighting the significant influence of the RPWL parameter on the overall weld quality.

VI. CONCLUSION AND FUTURE WORK

This This study details the development and application of a novel self-reacting friction stir toolset designed for joining wood-plastic composites (WPCs). The new toolset, along with the introduction of the revolutions per weld line (RPWL) parameter, demonstrated effective joining capabilities, producing welds with high mechanical strength and excellent quality. A comparative analysis with the traditional hot-shoe friction stir welding method underscored the advantages of the self-reacting toolset, particularly in terms of enhanced control and adaptability. The results indicate that the self-reacting toolset provides a more viable and robust solution for joining WPCs, offering significant improvements over conventional methods.

Future research should concentrate on optimizing the design of the toolset for various WPC compositions and investigating the long-term performance of the welded joints under different environmental conditions. Additionally, exploring the scalability of the process for industrial applications will be crucial for advancing the practical use of this technology.

Conflicts of Interest: The authors declare no conflict of interest.

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