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Effect of Friction Stir Welding Processing Parameters on the Mechanical Properties of AA1050 Aluminum Alloy

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Abstract: Friction stir welding (FSW) is gaining popularity in aluminum alloy joining due to its numerous advantages, such as creating high-quality joints with minimal heat input. This study examined the impact of different processing parameters, such as rotational and traverse speeds, on joints' quality and mechanical properties created through the FSW of AA1050 aluminum alloy. Various experiments were conducted to weld AA1050 aluminum alloy to investigate this, varying the rotational speeds (450-900 rpm) and traverse speeds (14-40 mm/min). The findings indicated that higher rotational speeds were associated with diminished joint quality, as indicated by heightened levels of porosity and the formation of intermetallic compounds. Moreover, an augmentation in traverse speed led to elevated tensile strength and hardness levels. The study determined that the processing parameters substantially impact the quality and mechanical properties of joints created through friction stir welding of AA1050 aluminum alloy. The study suggests that superior joints with favorable mechanical properties can be achieved by utilizing an intermediate rotational speed of 900 rpm and a traverse speed of 20 mm/min.

Keywords: Friction stir welding, Aluminum alloys, Microstructure, mechanical properties, AA1050.

1. Introduction

Friction stir welding is a solid-state welding method widely used to join heat-treatable aluminum alloys because it produces high-quality joints with low heat input. Several studies have investigated the effect of processing parameters on the quality and mechanical properties of joints made by FSW. A recent study investigated the impact of various processing parameters on the quality and mechanical properties of joints made by FSW using AA1050 aluminum alloy. The study examined the effect of processing parameters such as rotational speed, traverse speed, plunge depth, and dwell time on the joint properties [1]. It is essential to recognize and comprehend the potential interactions that can take place between the welding parameters to maximize the performance of the FSW joint that is produced as a result of the welding process [2]. Considering that the FSW results can be sensitive to variations in some of the welding parameters, it is essential to do so, as mentioned by many authors [3-5]. Welding factors, tool geometry, and joint design significantly impact heat distribution, material flow pattern, formed structure, and material connection quality [6]. When the rotation speed increases, the amount of heat generated increases, as does the size of the pieces removed from the material entering the matrix. As a result, the strength of the weld metal decreases [7]. Zhou et al.[8] they found that the tool rotating speed affected FSW joint tensile strength in Ti–6Al–4V alloy sheets. According to studies, when the rotation speed is raised to an ideal level while keeping the same traversal speed throughout the operation, the tensile strength of the joint increases [9]. A suitable bond will not be created owing to the drop in rotation due to a decrease in friction energy that will cause the object to pass through a minimum state speed [10]. According to [11], a high tool rotational speed produces smoother welding than a low tool rotational speed. [12] showed that if the rotating speed is set to 3000 rpm, all welds between AA 5052–O plates will have sound welded connections with smooth surface appearances. Additionally, [13] showed that increasing the rotating speed produced a uniform distribution of TiC particles inside the AA6082 matrix, while decreasing the rotational speed resulted in a poor distribution of TiC particles within the surface composite. Combined with each traverse speed, a certain rotation speed creates flawless welding. The construction of high-speed FSW welding was built on this basis [14]. During the friction stir processing of aluminum alloys, the axial force, the tool feed, and the rotational tool speed are the three process parameters that significantly impact the material's mechanical, microstructural, and formability properties [15, 16]. To determine the influence of welding conditions on aluminum alloy welds' mechanical and microstructural properties. According to their results, different rotation rates lead to different levels of hardness, whereas the connection's stiffness and level of hardness are not affected by the traverse speed [17, 18]. According to the results of [19], the effects of traverse speed on the mechanical properties of the joint, such as hardness and tensile strength, are more significant than the effects of rotational speed. When the traverse speed is increased, the interface between the two base metals (AA7020T651 and AA6060T6) becomes cyclical in the welding direction, but it gets disrupted in the cross-weld direction [20]. The tool rotation speed affects the heat input to the weld, which in turn affects the microstructure of the joint. A high rotation speed will result in a smaller heat affected zone and a finer grain size, which can improve the mechanical properties of the joint. However, a high rotation speed can also lead to defects in the joint, such as wormholes and tears [21]. The traverse speed affects the rate at which the tool is moving through the material. A high traverse speed will result in a shorter welding time, which can reduce the risk of defects. However, a high traverse speed can also lead to a lower quality weld, as the material may not have enough time to be properly plasticized [22].

The plunge depth affects the amount of material that is displaced by the tool. A deep plunge depth will result in a wider weld zone, which can improve the mechanical properties of the joint [23]. However, a deep plunge depth can also lead to defects in the joint, such as lack of fusion [24].

The optimum welding parameters will vary depending on the material being welded and the specific mechanical properties being measured [25]. However, in general, a high rotation speed, a low traverse speed, and a shallow plunge depth will produce a joint with good mechanical properties [26]. In addition to the welding parameters, the microstructure of the joint also affects its mechanical properties [27]. The microstructure of the joint is influenced by the heat input to the weld, the cooling rate, and the alloy composition. A fine-grained microstructure with a uniform distribution of phases is generally desirable for good mechanical properties [28].

This study contributes to the growing research focused on optimizing friction stir welding parameters for superior joint quality and mechanical properties. The research investigates the effect of various processing parameters on the quality and mechanical properties of joints made by FSW using AA1050 aluminum alloy. In addition to optimize the FSW parameters which will led to significant improvements in the mechanical properties of aluminum alloy welds, making it a promising technique for various industrial applications.

2. EXPERIMENTAL WORK

The experimental setup and the preliminary tests were conducted to evaluate the effect of FSW parameters on the resulting mechanical properties and microstructure observation of AA1050 welded sheets. The materials used are described, and the methods used for producing the FSW samples, and characterizing the grain and particle structure, are explained. The mechanical properties of the welded joints are measured via hardness, impact, and tensile testing. The chemical composition of the base metal is obtained using Optical Emission Spectroscopy. Sparks were ignited at various locations of the base metal sample, and their spectrum was analyzed to estimate alloying elements. The chemical composition (in weight percent) of the commercial base metal and the standard AA 1050 alloy material is presented in Table 1.

The present investigation employed AA 1050 wrought plates, whose elemental composition (as presented in Table 1) was verified through inductively coupled plasma optical emission spectroscopy. The processing parameters are listed in Table 2.

Samples with dimensions of 150 mm x 50 mm x 8 mm were cut using a wire-cutting machine. Friction stir welding was conducted utilizing an automated vertical milling apparatus. A fixture that was specifically designed and constructed for friction stir welding was utilized for the purpose of clamping. The cutting tools employed in the FSW process were fabricated from K110 tool steel (Table 3). Subsequent to the machining procedure, the hardness of the tool was augmented through the process of oil hardening, commonly referred to as "quenching." The instrument featured a pin possessing a conical and cylindrical profile concurrently. A non-consumable tool made of high-carbon steel was fabricated and implemented. The tool's rotation was observed to be effective, leading to its endorsement by previous researchers [29-31]. The diameter of the terminal end is 5.5 mm, accompanied by a shoulder diameter of 25 mm and a pin length of 6 mm, as illustrated in Figure 1. The tool's tilt angle was consistently maintained at 2 degrees during the operation.

TABLE 1. Chemical composition of the as-received AA1050 alloy (weight %)

Element	Cu	Mg	Mn	Zn	Fe	Si	Ti	Al
%	0.04	0.05	0.038	0.071	0.32	0.25	0.014	remain

TABLE 2. The processing parameters used in this work.

	level			
Too rotational speed, rpm	450	560	710	900
Travel speed mm/min	12	20	28	40
Tilt angle	Fixed at 2°			

TABLE 3. Chemical composition of K110 tool steel.

Alloy K110	Chemical Composition wt. %						
	C	Mn	Cr	V	Mo	Si	Fe
	1.55	0.75	11.3	0.75	0.75	0.3	Bal.

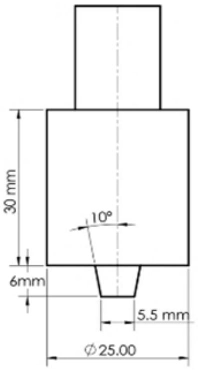

FIGURE 1. Schematic drawing of the FSW tool design

Microstructure characterization

The specimens for metallographic examination were sectioned perpendicular to the processing directly to the required sizes (Figure 2a). The area of interest that must be concluded in the cut specimens is the region comprising FSW zone, TMAZ, HAZ and base metal regions. Specimens were ground progressively using grinded under water on a Metasery Grinder 2000 rotating disc. Each stage progressively removes and replaces the larger surface scratches with smaller ones using silicon carbide abrasive discs (180, 220, 320, 400, 600, 800, 1000, 1500, 2000, 2400, and 1200 grit). Then they were polished using 10 µm alumina paste and 3 µm diamond paste. The samples were etched with classical Keller's reagent (2 ml HF(48%) + 6 ml HNO_3+ 91 mL distilled water) at room temperature for a few seconds. Microstructural characteristics of FSP specimens are investigated using an Olympus optical metallurgical microscope GX41.

Mechanical properties characterization

To evaluate the tensile properties of the processed stir zone, flat (*dog bone*) tensile specimens were cut to the required dimensions from the center of the processed zone, parallel to the processing direction as per ASTM (American Society for Testing of Materials), the specimen's geometry illustrated in Figure 2. A 300 KN capacity Universal Testing Machine was employed to conduct the tensile testing

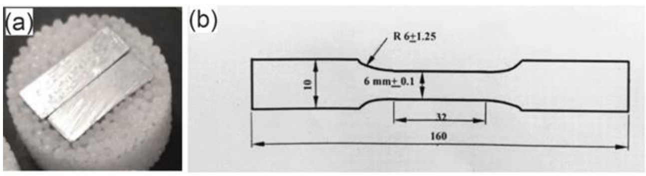

FIGURE 2: (a) Microstructure samples **(b)** Tensile test ASTM standard sample dimension

The Impact test was conducted to evaluate the impact energy of the welded materials. The following is a recommended procedure for conducting impact testing on friction stir welded specimens:

First, prepare the FSW specimens according to the standard procedure. Next, ensure the specimens are properly labeled and identified for easy tracking. Then, inspect the specimens visually to check for any visible defects or irregularities. After visual inspection, conduct a pre-test measurement of the dimensions and mass of each specimen to ensure consistency among them. For impact testing, we use the ASTM E23 (Charpy) standard. The specimens were tested at room temperature, and the pendulum's velocity was adjusted to 5.4 m/s. Three specimens are tested for each set of welding parameters, and the average value of absorbed energy must be reported along with the standard deviation. WP410 GUNT device is used to perform the test Figure 3

FIGURE 3. Impact test machine and sample setup

3. RESULTS AND DISCUSSIONS

3.1 MICROSTRUCTURE OBSERVATION

Processing parameters, including tool speed and longitudinal travel speed, influence the material's flow behavior. The microstructural behavior was affected. Examining welds at various rotational and travel speeds reveals a notable influence of rotational speed on the weld surface-to-travel speed (ω/v) ratio. To attain a defect-free and smooth surface weld, it is necessary to enhance the value of the ratio between the welding speed (v) and the frequency of the welding current (ω). The high heat input during welding can cause a significant amount of material to be displaced into the weld area. To achieve high-quality welding and a favorable weld surface, it is necessary to modify the speed ratios (ω/v) within the range of 11 to 32 according to the literature to provide the suitable generated heat in the stirred zone [2,5]. Various welding parameters were employed to examine the cross-sectional characteristics of welded joints. Figure 4-a displays the optical microstructure image of the AA1050 alloy base metal in the form of a rolled sheet. The grains in the image appear elongated horizontally and exhibit a small thickness. The FSW process results in the formation of three zones: the Heat Affected Zone (HAZ), the Thermo-mechanically Affected Zone (TMAZ), and the Stirred Zone (S.Z.). These zones are illustrated in Figure 4-b. Based on the observations in Figure 4c, it can be concluded that there is no discernible presence of cracking or porosity in the joints, suggesting that the quality of the joints is exceptional. The material's dynamic recrystallization occurred due to its strong plastic deformation and high temperature. [32, 33].

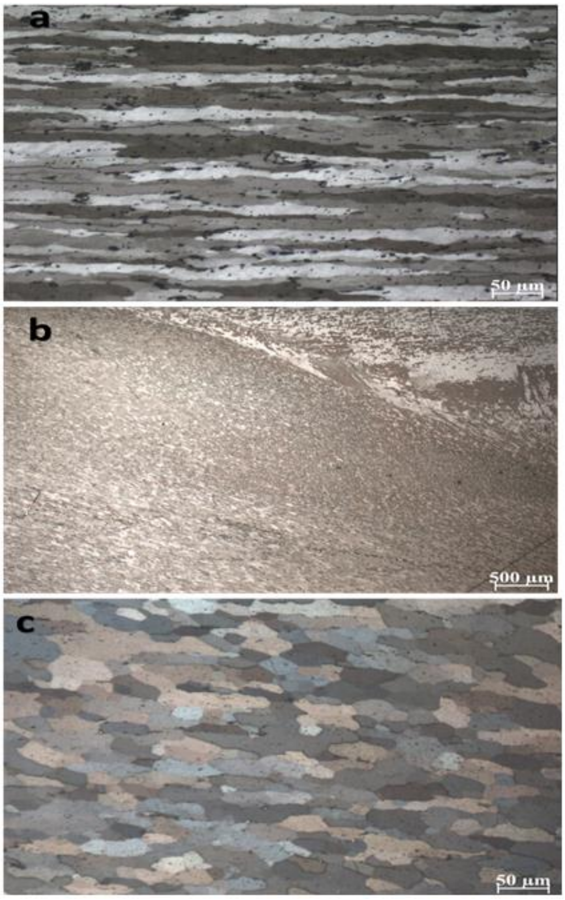

FIGURE 4. Microstructure of the (a) base alloy, (b) processed zone HAZ, TMHAZ, (c) stirred zone SZ.

3.2 MECHANICAL PROPERTIES

Tensile testing is a widely used mechanical testing method that can provide important information about the mechanical behavior of materials under tension. The tensile test results of a Friction Stir Welding sample made of AA1050 aluminum alloy at different welding speeds can also provide insights into the effect of welding speed on the tensile properties of welded joints. This study subjected the AA1050 aluminum alloy FSW samples to tensile testing at various welding speeds.

After applying the tensile test, we noticed that all samples were cut in the gauge region, as shown in Figure 5. Hence, the samples confirmed that all conditions are welded perfectly without defects.

The stress-strain curve of the base alloy AA1050 was performed and plotted as shown in Figure 6. Thus, the maximum tensile stress and maximum elongation were recorded in the tested samples compared with the welded samples.

FIGURE 5. The samples after tension test.

3.3 EFFECT OF THE TOOL ROTATION SPEED ON THE TENSILE PROPERTIES

The effect of tool rotation speed on the tensile test results of FSW samples has been studied at various welding speeds. Figure 7 shows that the tool rotation speed significantly impacts the mechanical properties of FSW samples made of AA1050 aluminum alloy at different welding speeds. At a constant traverse speed, an increase in tool rotation speed results in increased tensile strength and elongation values, but it decreases the fracture toughness of the FSW samples. Furthermore, it was found that increasing the welding speed and decreasing the tool rotation speed leads to a reduction in the heat input required for joining, which decreases the size of the heat-affected zone (HAZ) and improves the mechanical properties of FSW samples. The test results also suggested that at higher tool rotation speeds, such as 710 and 900 rpm, the FSW joint exhibited superior mechanical strength compared to the FSW joint produced at higher welding speeds, such as 560 and 450 rpm. This study highlights the importance of selecting an optimal welding speed in FSW to obtain optimum tensile properties for AA1050 aluminum alloy joints. Therefore, it can be concluded that the optimal tool rotation speed and welding speed must be carefully chosen based on the specific requirements of the FSW application to achieve the desired mechanical properties of the joint. Various parameters, including traverse speed, affect the mechanical properties of FSW joints. The traverse welding speed in FSW refers to the speed at which the tool moves along the joint line during welding. The transverse welding speed is expressed in millimeters per minute (mm/min). The welding speed affects several aspects of FSW, including heat input, material flow, microstructure, and mechanical properties. In the case of AA1050 aluminum alloy, the effect of traverse speed on the tensile test results revealed that traverse speed significantly affects the tensile test results of welded samples. Specifically, as the traverse speed increases, the tensile strength of FSW samples decreases while the elongation at break increases. The welding speed is a critical parameter affecting the welded joints' quality and mechanical properties. The tensile test is a standard mechanical test used to determine the strength and ductility of materials. The test involves applying a uniaxial force to a specimen until it fractures. At low traverse welding speeds, there is more time for heat to dissipate from the weld zone. This results in a narrower heat-affected zone (HAZ) and finer grain structure in the weld nugget. As a result, low-speed welds tend to have higher strength and ductility than high-speed welds. On the other hand, high traverse welding speeds result in wider HAZs and coarser grain structures in the weld nugget. This can lead to reduced strength and ductility due to increased porosity, cracking, or other defects caused by insufficient material flow or inadequate heat input. In general, there is an optimum range of traverse welding speeds for each material that produces optimal mechanical properties. For AA1050 Aluminium alloy welded using FSW process, studies have shown [1] that an optimum range of 20-28 mm/min produces good quality welds with high strength and ductility.

3.4 EFFECT OF THE WELDING PROCESSING PARAMETERS ON THE ULTIMATE TENSILE STRESS (UTS)

One of the significant advantages of FSW is its ability to produce defect-free welded joints without affecting the base materials' properties. However, the success of FSW in producing high-quality welded joints depends heavily on several processing parameters, such as rotational tool speed, welding speed, axial force applied, and tool design. These processing parameters directly affect the mechanical properties of the welded joints, specifically the ultimate tensile stress (UTS). Figure 8, demonstrates that using 710 and 900 rpm rotational speeds throughout all conducted transverse resulted in better mechanical properties for both friction stir welding and friction stir process in AA1050 alloy. While the low rotational speeds have the minimum tensile properties overall, the tested samples.

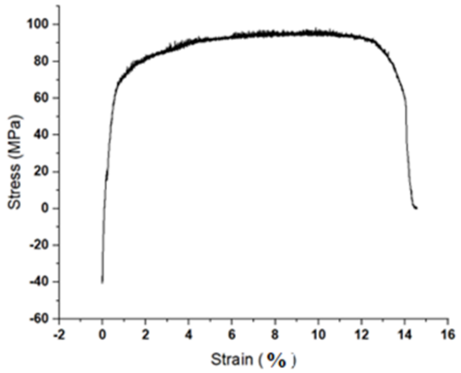

Figure 6. Stress-strain curve of the base alloy AA1050

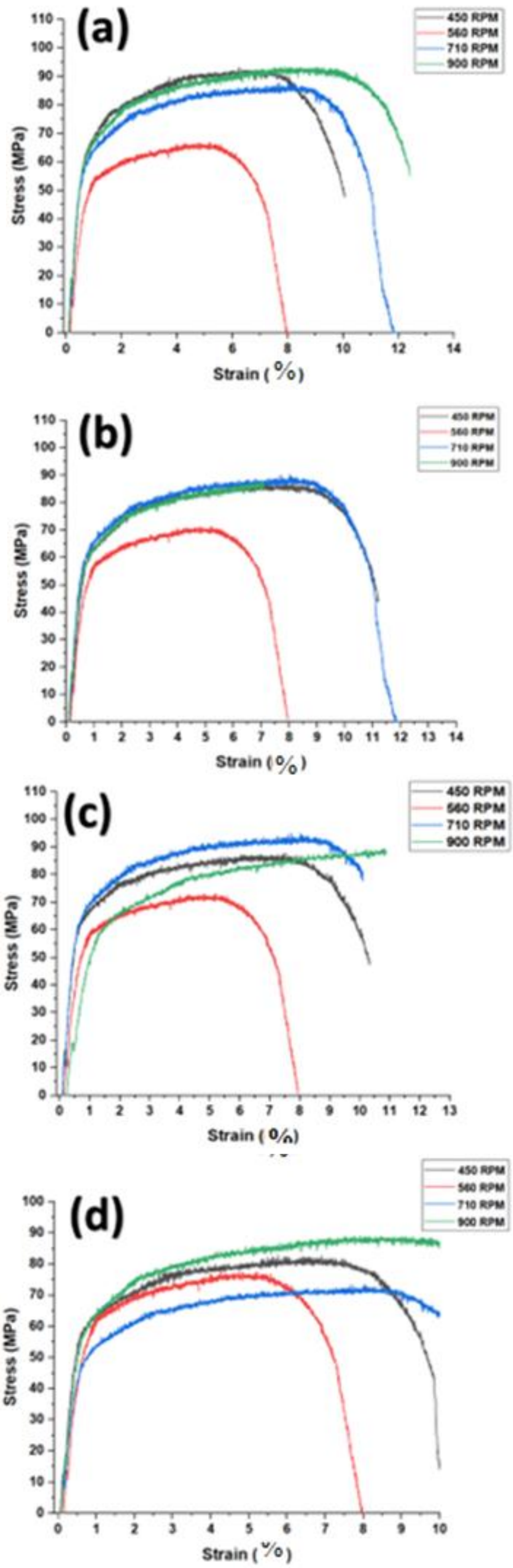

FIGURE 7. Effect of tool rotation speeds on the tensile properties at constant welding traverse speed at (a) 14 mm/min, (b) 20 mm/min, (c) 28mm/min, and (d) 40 mm/min

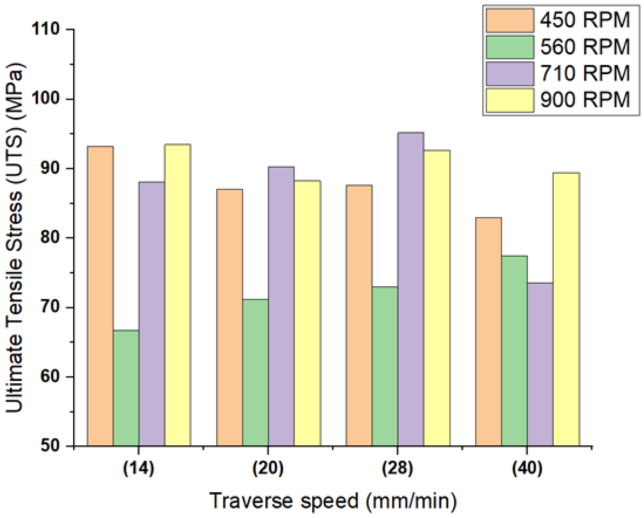

FIGURE 8. Effect of welding process parameters on the UTS

3.5 IMPACT TEST RESULTS

The present research investigated the impact of FSW parameters, including welding speed and tool rotational speed, on the impact properties of AA1050 alloy. The study's findings demonstrate that the impact properties of AA1050 alloy were significantly influenced by both the welding speed and tool rotational speed. The study revealed that a rise in welding speed resulted in a decline in impact toughness. In contrast, an escalation in tool rotational speed resulted in an enhancement in impact toughness, as depicted in Figure 9. The findings indicate that all four welding parameters significantly influenced the impact energy absorbed by the samples. The attainment of the optimal impact energy was observed to occur at a reduced tool rotational speed and an increased traverse speed. The present investigation holds significance for industries that heavily depend on the welding of AA1050 alloys. It offers crucial insights into the impact of various processing parameters on the properties of welded samples, particularly their impact resistance.

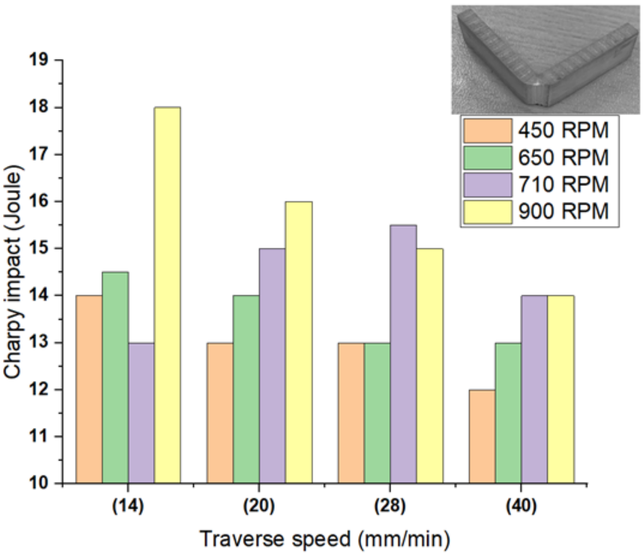

FIGURE 9. Effect of processing parameters on the impact test

4. Conclusions

- The current work investigated the effect of the FSW process parameters on the mechanical properties of AA1050 Aluminum alloy. The welding processing parameters significantly affect FSW joints' impact test, mechanical properties, and microstructure. From the investigated work, we can conclude the following findings:
- - Tensile testing is a widely used mechanical testing method that can provide important information about the mechanical behavior of materials under tension. The tensile test results of a Friction Stir Welding (FSW) sample made of AA1050 aluminum alloy at different welding speeds can also provide insights into the effect of welding speed on the tensile properties of welded joints. This study subjected the AA1050 aluminum alloy FSW samples to tensile testing at various welding speeds.
- The results indicated that, as the welding speed increased, the ultimate tensile strength (UTS) and yield strength of the FSW joint decreased. The reduction in the strength properties of FSW joints with increased welding speed can be attributed to several factors, including reduced heat input and insufficient material mixing due to the fast travel speed.
- The FSW parameters significantly influenced the impact energy absorbed by the samples. The attainment of the optimal impact energy was observed to occur at a reduced tool rotational speed and an increased traverse speed.

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