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Mechanical and Microstructural Evaluation of AA6082-T61 Joints Produced by Ultrasonic Vibration Assisted Friction Stir Welding Process

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ABSTRACT

Continuous improvement in the friction stir welding process (FSW) is still growing to improve the process capabilities and overcome certain drawbacks encountered in the process. Low welding speeds, high welding loads, and high torque needed are the main limitations of this process. Applying ultrasonic vibration is one of the versatile approaches that was proposed to tackle these issues. In this paper, a comparative study between the conventional friction stir welding process (CFSW) and the ultrasonic-assisted friction stir welding process (UAFSW) was conducted. The objective is to evaluate quantitively and qualitatively the influence of ultrasonic vibration waves on the weld surface quality, tensile strength, micro-hardness, microstructure, and weld formation of the joints. The results have demonstrated that ultrasonic vibration waves cause grain refinement action by 23.6% at the stirring zone (SZ) as well as its desirable role in enhancing the mechanical properties by a percentage up to 15% for ultimate tensile strength and eliminating weld defects, especially at high welding speed (120 mm/min). However, no profound effect was found for ultrasonic waves on the grain size in the thermomechanical affected zone (TMAZ) or the heat-affected zone (HAZ). A considerable reduction in the elongation % whether in CFSW or UAFSW compared to that of base metal was detected.

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1. INTRODUCTION

Materials joining technology has witnessed a lot of developments within the last three decades. One of the most influential innovations in this area is friction stir welding technique (FSW). Furthermore, FSW offers many pros over other fusion welding processes. Few distortions and residual stresses can result in from FSW. In addition, the process is environmentally friendly as it consumes less energy and emits fewer fumes and sputters which makes it overall more favorable than other fusion welding techniques. The process was invented by TWI at in the and the patent was filed in 1991 [1]. Since this date, the process has attracted the attention of many researchers around the world and has received considerable research effort. These efforts included establishing the theoretical approach for the process [2], optimizing the process parameters [3], and developing mathematical models to predict the characteristics of the joints [4]. However, the process still suffers from certain cons [5]. For instance, Low welding speed and limited productivity, high loading loads on the machine due to the huge friction between the tool and the workpiece and, the high torque needed to accomplish the operation are all drawbacks of the process. FSW process has undergone several modifications and improvements. These variations involved modifications in the tool, the machine, and the process itself [6-8]. As well as, integrating FSW process with a secondary energy source to provide more softening action, especially for welding hard materials [9]. In this regard, several auxiliary energy sources were used. electrical current [10], laser source [11], induction heat [12], electrical arc [13], and ultrasonic vibration [14] were integrated with the process. Among all these secondary energy sources, ultrasonic vibrations have shown specific advantages

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over the other approaches. For example, it consumes less energy and provides an efficient amount of softening without raising the temperature [9].

The influence of the ultrasonic vibration on the formation and mechanical properties of 2024Al-T4 joints was investigated. The results showed that by applying ultrasonic vibration, the weld formation was improved at high welding speeds and the stir zone was widened. Moreover, the mechanical properties in terms of strength, elongation, and micro-hardness were enhanced [15]. Similar results but for different aluminum alloys were reported, the microstructure of AA6061-T6 weld nuggets produced by UAFSW was compared to those produced by conventional FSW [16]. It was found that higher deformation characteristics are presented in the nugget zone of the joints produced by the UAFSW process and that was attributed to the ultrasonic softening effect. Furthermore, ultrasonic vibrations improved the recrystallization process and leads to better grain refinement. In another, study the welding forces, and weld thermal cycles in the UAFSW process of AA2024-T3 were analyzed to explore the role of ultrasonic vibration in the process [17]. It was concluded that the exerted ultrasonic vibrations lower both the traverse and axial forces and improve the material flow. On the other hand, ultrasonic vibrations do not have a significant effect on preheating the weld zone. The influence of the ultrasonic vibration on material flow and mechanical properties of AA2024-T3 was investigated. It was reported that the joints welded by the assistance of ultrasonic vibration have better material flow and higher mechanical properties than those joined by conventional FSW [18].

As it can be easily realized from the literature review that assessing the potentiality of exerting ultrasonic vibration waves during the FSW process of AA6082-T61 has not been well-established although the wide applications in which this alloy can be selected. This research aims to conduct a comparative study between conventional FSW and UAFSW processes of AA 6082-T61 to reveal the influence of ultrasonic vibration exertion on the tensile strength, microstructure, weld formation, and defects of the welded joints.

2. EXPERIMENTAL WORK

In the current study, aluminum alloy 6082-T61 was selected to be butt-joint welded using CFSW and UAFSW processes for comparing purposes. Due to having the highest strength of all 6xxx series alloys and its excellent corrosion resistance, AA 6082 is one of the most promising alloys. Besides, it has found its way into a wide range of applications such as cranes, bridges, beer barrels, ore skips, and trusses [19]. The composition and mechanical characteristics of AA6082-T61 in the as-received state are shown in Tables 1 and 2, respectively[1].

An abrasive water jet machine was utilized to cut the aluminum sheet into the required dimensions of the sample (160×100×3 mm). H13 hot work tool steel rod was machined to manufacture the FSW tool with a shoulder diameter and pin diameter of 14mm and 5mm, respectively. An ultrasonic processor (model up 400S) manufactured by Hielscher ultrasonics was used to obtain the required ultrasonic vibration waves. A sonotrode made of titanium with a 22 mm tip diameter and 100 mm in length was used to generate ultrasonic vibration waves at a frequency of 24 kHz, a power of 85 watts, and an adjustable amplitude up to 100 μm.

The ultrasonic processor was fixed to the head of a conventional milling machine via a suitable setup as shown in Figure 1. So that, the sonotrode can move freely along the welding line in front of the FSW tool by nearly 25 mm and with an angle of inclination of 60° between the axis of the sonotrode and the workpiece surface to keep it away from the tool. Thereby, the waves of ultrasonic vibration can be supplied directly into the localized area of the workpiece eliminating any loss in the transmitted energy compared to other methods for transmitting these waves.

2. 1. Process Parameters

In this paper, the experiments were designed and planned to perform a comparative study between conventional FSW and

TABLE 1. Chemical composition of AA 6082-T61, Wt%

Si	Fe	Cu	Mn	Mg	Cr	Ni	Ti	Al
1.1	0.5	0.1	0.7	0.9	0.25	0.2	0.1	REM

TABLE 2. Mechanical properties of AA 6082-T61

UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (HV)
270	185	21	112

UTS: Ultimate tensile strength; YS: Yield strength

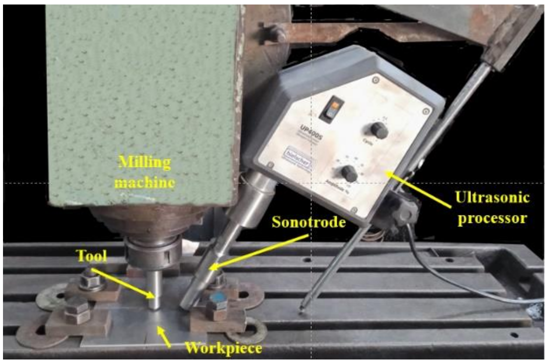

Figure 1. Experimental setup for UAFSW process

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UAFSW. For this purpose, the rotational speed was held constant at 800 rpm and at different welding speeds of (40, 80, 120, and 160 mm/min), to figure out how ultrasonic vibration waves can affect the joint performance. A set of experiments were performed according to Table 3. Where samples A, B, C, and D were compared to samples E, F, G, and H, respectively.

2. 2. Tensile Testing A universal testing machine (Shimadzu-1000KN) with a ram speed of 1 mm/s was utilized to measure the tensile strength of the welded joints. The specimens were prepared based on ASTM E8M-08 standard as shown in Figure 2. The specimens were cut from the transverse cross-section perpendicular to the welding line with an abrasive water jet machine to ensure good dimensional accuracy as well as to avoid any heat effect that may result in from the cutting operation.

2. 3. Micro-hardness Test Vickers micro-hardness test was performed to obtain the micro-hardness distribution of welded joints using micro-hardness tester (LM-700). A load of 100 grams and a holding time of 10 s were utilized. The measurements were taken along a horizontal line away from the specimen top surface by 1.5 mm, where reading is taken each 1 mm along the horizontal line.

2. 4. Microstructure Evolution It was essential to evaluate the microstructure of the welded joints to find out the influence of ultrasonic vibration on the grain size and hence the mechanical performance of the joints. The microstructure was revealed mainly using optical light Microscopy (see Figure 3). The samples of dimensions ($30 \times 5 \times 3\ mm$) were cut from the transverse section of the joint using an abrasive water jet machine. To remove oxide films, scratches, and other impurities, the samples were ground in several stages, ranging from coarse to fine grinding using a different set of silicon carbide papers grades i.e. (220, 500, 800, and 1000) mounted on rotating water-lubricated disc. The samples were finally polished using abrasives suspended in a water solution on an electrically powered wheel covered by a cloth. The etching process was carried out in two immersion stages. In the first stage, the specimen was immersed for 60 s in 0.5M sodium hydroxide solution. In the second stage, the specimen was etched in a composition of 0.25M sodium hydroxide solution with 4% potassium permanganate ($KMnO_4$) for 15 s [20].

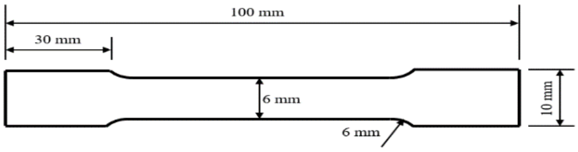


Figure 2. Standard tensile test specimen

TABLE 3. Process parameters for comparison at a constant rotational speed of (800 rpm)

Weld speed (mm/min)	Amplitude (μm)	Sample
40	Without Ultrasonic vibration	A
80		B
120		C
160		D
40	20	E
80		F
120		G
160		H

3. RESULTS AND DISCUSSION

3. 1. Influence of Ultrasonic Vibration on Weld Appearance The quality of the weld line is an effective indicator of the success of the welding operation. The absence of visible surface imperfections refers to selecting the process parameters properly leading to generating adequate heat input and proper material flow. On the other hand, external defects such as large grooves, voids, and flashes result from poor material flow. In this respect, the weld surfaces of CFSW and UAFSW joints were compared at different welding speeds as shown in Figure 4. As can be noticed from the figure, the weld line appearance at low welding speeds such as 40 and 80 mm/min is sound and free of external defects for both CFSW and UAFSW. On the other hand, the difference in surface quality started to appear at higher welding speeds. The weld line surface resulting from CFSW had voids defect at a welding speed of 120 mm/min and large grooves at a welding speed of 160 mm, while the weld line appearance in UAFSW was better as it contained less density of defects. This improvement in the weld line appearance can be attributed to the enhanced material flow due to the applied ultrasonic

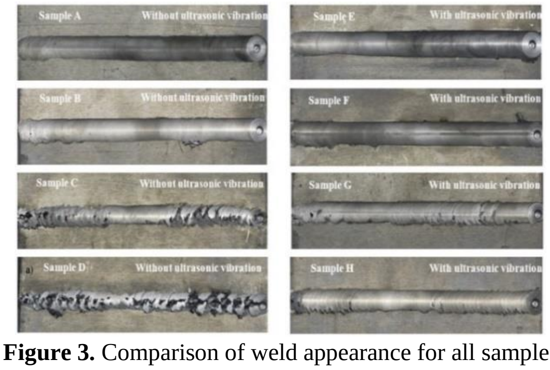


Figure 3. Comparison of weld appearance for all samples

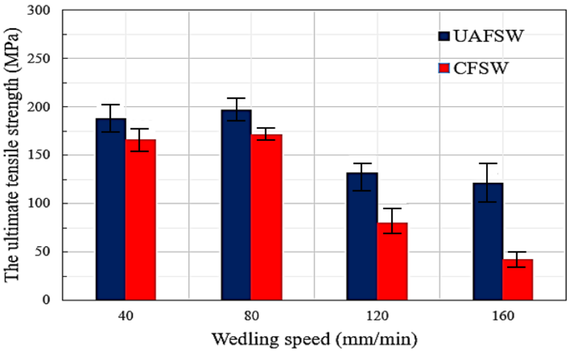


Figure 4. Comparison of UTS for CFSW and UAFSW at different welding speeds

vibrations and this effect is much more profound at high welding speeds [21].

3. 2. Influence of Ultrasonic Vibration on Tensile Properties

The ultimate tensile strength (UTS) for both CFSW and UAFSW samples was evaluated over a range of welding speeds to figure out the effect of ultrasonic vibration on the tensile strength and elongation percentage (elongation %) at different welding speeds. As shown in Figure 5, at a welding speed of 40 mm/min, the CFSW and UAFSW joints have an UTS of 166 and 188 MPa, respectively; showing an enhancement in UTS with a percentage of approximately 13% when ultrasonic vibration is on. Moreover, a similar trend was recorded at a velocity of 80 mm/min, where the UTS of the UAFSW joint is higher than that of CFSW by 15%. This improvement in the UTS can be demonstrated by the grain refinement action which has been detected in the microstructural analysis of the SZ. Conversely, a significant decrease in the UTS was recorded at high welding speeds i.e., 120 and 160 mm/min for both CFSW and UAFSW. But the fall in the UTS was more dramatic for CFSW joints recording values of 80 MPa at a speed of 120 mm/min and 42 MPa at 160 mm/min, which means that joints had failed. This failure of joints at such high welding speeds is mainly because of the lack of time available for material to absorb heat and soften hence the material flow is poor and severe defects are produced. On the other hand, the situation for UAFSW was much better as the UTS at a speed of 120 mm/min and 160 mm/min were 132 MPa and 121 MPa respectively. This performance of UAFSW joints compared to CFSW is evidence of the significant role the ultrasonic waves played in providing the material with more softening action.

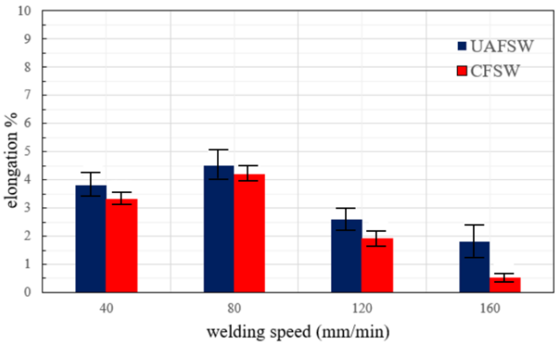
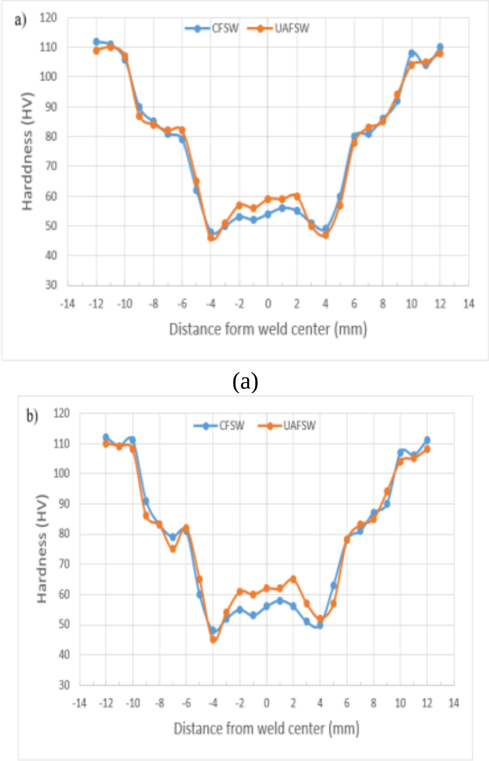


Figure 5. Comparison of elong% for CFSW and UAFSW

Regarding the elongation%, as shown in Figure 5, there is a considerable reduction in the elongation % whether in CFSW or UAFSW compared to the base metal. This is because of the lower morphological homogeneity in CFSW and UAFSW, as different microstructural zones namely, SZ, TMAZ, and HAZ are formed which are morphologically different. A similar finding was reported by other researchers.

3. 3. Influence of Ultrasonic Vibration on Hardness

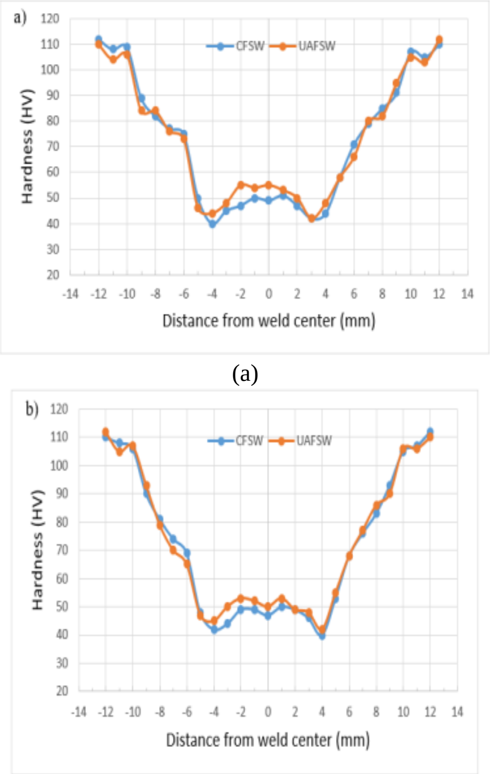
A comparison between the micro-hardness profile in CFSW and UVAFSW at different welding speeds is shown in Figures 6 and 7. In general, the micro-hardness profile resulting from FSW process is characterized by W-shape. Where the values of micro-hardness slightly decrease in the HAZ due to dissolution and coarsening of precipitates compared to the values at the SZ and then rise again until reaching its maximum value at the base metal.



(a)

(b)

Figure 6. Comparison of microhardness for a) Samples A and E , b) Samples B and F



(a)

(b)

Figure 7. Comparison of microhardness for a) Samples C and G b) Samples D and H

As shown from figures the micro-hardness profiles for CFSW and UAFSW are close in most of the regions except the stirring zone, where the values of micro-hardness are higher in UAFSW than CFSW. This improvement in micro-hardness values in the stirring zone are predicted because of the grain refinement in the stirring zone.

3. 4. Influence of Ultrasonic Vibration on Microstructure

Microstructure evolution is of great importance as it controls the properties of the weld joint. Many microstructural alterations happen during the FSW process because of the thermal cycles and plastic deformation. there are mainly three distinct regions in FS-welded joints, namely, stir zone (SZ), thermo-mechanically affected (TMAZ), and heat-affected zone (HAZ). In this section microstructure samples extracted from CFSW and UAFSW joints were prepared according to standard procedure and examined using light optical microscopy to find out the potentiality that ultrasonic vibration waves have on controlling the microstructure of the welded joints in terms of the grain size and weld formation.

3. 4. 1. The Microstructure of the Base Metal

Firstly, the microstructure of the parent metal AA 6082-T61 in the as-received status was viewed using LOM and SEM to determine the average grain size and examine the precipitate state as shown in Figures 8(a) and (b). The grain size for the base metal was found by applying the line intercept method. In this manner, image J software was utilized and average grain size of 14 μm was obtained. The hardening precipitates of type Mg_5Si_6 were revealed using SEM.

3. 4. 2. Microstructural Map of FS-Welded Joint

To ensure the appropriateness of all preparation steps for microstructural analysis and thereby the clarity of all microstructural, a microstructural map was established using LOM as shown in Figure 9. All microstructural zones i.e., stir zone which has experienced an intense plastic deformation with very equiaxed fine grains, TMAZ with its distinguished elongated grains, and HAZ which has coarse grains were obtained obviously.

3. 4. 3. Influence of Ultrasonic Vibration on Different Microstructural Zones

The influence of ultrasonic vibration waves on the grain size at various microstructural zones was investigated by comparing the microstructure of sample B which has been conventionally friction stir welded with sample F which has been ultrasonically assisted friction stir welded. Both samples are welded at the same welding condition of 800 rpm and 80 mm/min. Figures 10(a) and (b) presents the microstructures of samples B and F, respectively. Investigating the SZ of both samples showed a grain refinement due to the high plastic deformation in this region. The average grain sizes calculated were 3.8 μm and 2.9 μm for samples B and F, respectively. Thereby, it is clear that imposing ultrasonic vibration waves during the FSW process causes a grain size reduction by 23.6% at the stirring zone. This grain refinement action can be

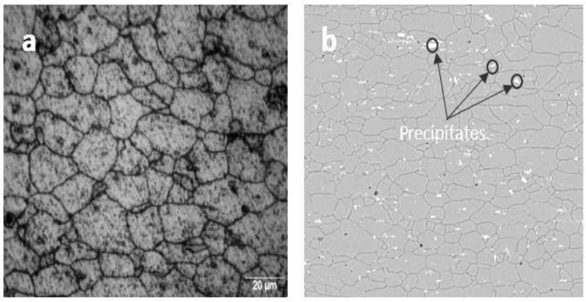


Figure 8. Microstructure of base metal using a) LOM, b) SEM

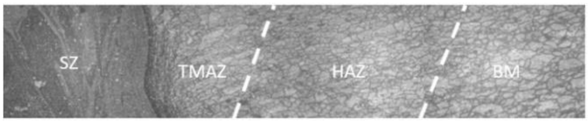


Figure 9. Microstructural map for FS-welded sample

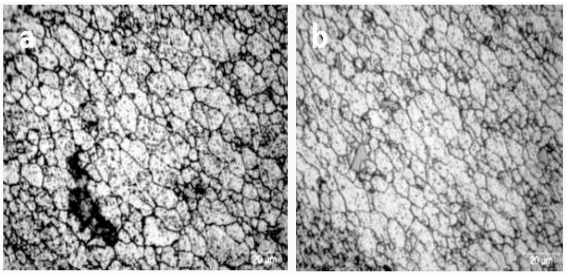


Figure 10. Microstructure of a) sample B at TMAZ, b) Sample F at TMAZ

mainly attributed to the acoustic softening phenomena furthering welding operation and Its role in improving plastic deformation [16]. From this finding, it is expected that the mechanical properties of UAFSW joints will be superior compared to CFSW according to Hall-Petch equation. These results agree with similar findings by other researchers [22].

The microstructure of the TMAZ at samples B and F was obtained as shown in Figures 11(a) and (b), respectively. The grain size of 7.8 μm and 7.6 μm in average, was calculated for samples B and F, respectively. Thereby, it can be stated that ultrasonic vibration waves do not have a significant influence on the grain size at the TMAZ.

The average grain size at the HAZ was also calculated for samples B and F after viewing their microstructure as shown in Figures 12(a) and (b). The average grain size of 14 μm and 14.1 μm was obtained for samples B and F, respectively. The two values are approximately equal and hence we can demonstrate that ultrasonic vibration does not have any effect on the grain size at the HAZ.

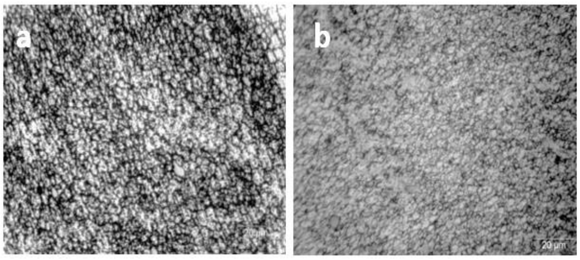


Figure 11. Microstructure of a) sample B at SZ, b) sample F at SZ

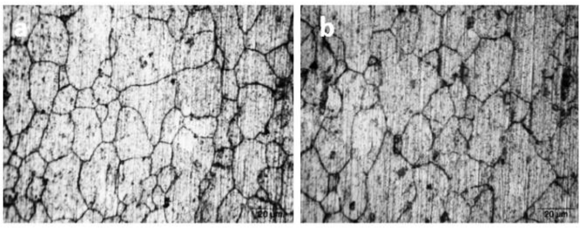


Figure 12. Microstructure of a) sample B at HAZ, b) Sample F at HAZ

3. 5. Influence of Ultrasonic Vibration on the Weld Formation

The weld formation at the stirring zone was examined at high welding speed to find out the role of ultrasonic vibration waves on the material flow. Hence, the microstructures of samples C and G which have been welded at a welding speed of 120 mm/min were viewed and compared as shown in Figures 13(a) and (b). At the SZ of sample C, which was conventional welded, a large defect of tunnel type was detected as shown in Figures 13(a). This defect mainly results from the low heat input, which is corresponding to high welding speed, leading to insufficient softening and improper material flow [23]. On the contrary, the microstructure of sample G which has been ultrasonically assisted during the FSW process is defect-free and onion rings which express the proper material flow are clear in Figures 13(b). This enhancement in the material flow when ultrasonic vibration was applied can be explained by the acoustic softening effect which is responsible for providing the FSW process with an additional amount of softening during the welding operation. Subsequently, it can be stated that ultrasonic vibration plays a critical role in eliminating some welding defects at the SZ due to the extra softening it provides [24]. The microstructure data, grain sizes, and a scatter of grains sizes are summarized in Table 4.

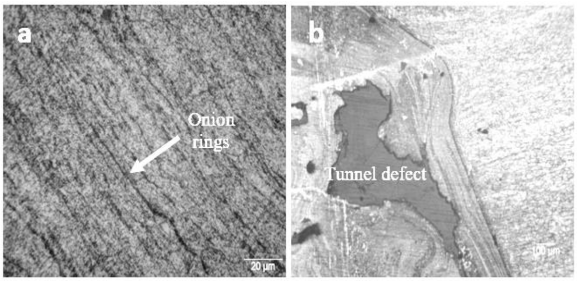


Figure 13. a) Free-defective microstructure at sample G, b) Tunnel defect in sample C

TABLE 4. The microstructure data and grain sizes

Specimen type	Average Particle size	Microstructure zone
Base Material	14μm	Through the sample
CFSW	3.8 μm	SZ
UAFSW	2.9 μm	
CFSW	7.8 μm	TMAZ
UAFSW	7.6 μm	
CFSW	14 μm	HAZ
UAFSW	14.1 μm	

4. CONCLUSIONS

In the present study, a microstructural investigation showed that integrating ultrasonic vibration with the FSW process can reduce the grain size at the stirring zone by 23 %. While ultrasonic vibration does not affect the grain size at the HAZ nor at the TMAZ. As a result of grain refinement at SZ, the strength of joints produced by the UAFSW process was higher than its counterparts made by CFSW. In addition, examining the weld formation showed that ultrasonic vibration acted a dominant role in enhancing the material flow and eliminating some specific weld defects at high welding speeds such as tunnel defect. The effect of ultrasonic vibration on the UTS is more profound at higher welding speeds, where acoustic softening can provide FSW process with additional softening and thereby, the material flow is improved. Ultrasonic vibration has helped also in improving the elongation percentage by 7%. On the contrary, at these high welding speeds, the weld appearance of conventional FS-welded joints contain large defects due to the low heat input, and fewer defects were detected when ultrasonic vibration was applied.

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Persian Abstract

چکیده

فرآیند جوشکاری اصطکاکی اغتشاشی (FSW) هنوز در حال رشد است تا قابلیت‌های فرآیند را بهبود بخشد و بر اشکالات خاصی که در فرآیند با آن مواجه می‌شویم غلبه کند. سرعت های جوشکاری کم، بارهای جوشکاری بالا و گشتاور مورد نیاز بالا از محدودیت های اصلی این فرآیند هستند. استفاده از ارتعاش اولتراسونیک یکی از رویکردهای همه کاره ای است که برای مقابله با این مسائل پیشنهاد شده است. در این مقاله، یک مطالعه مقایسه ای بین فرآیند جوشکاری اصطکاکی اغتشاشی معمولی (CFSW) و فرآیند جوشکاری اغتشاشی اصطکاکی به کمک اولتراسونیک (UAFSW) انجام شد. هدف ارزیابی کمی و کیفی تأثیر امواج ارتعاشی اولتراسونیک بر کیفیت سطح جوش، استحکام کششی، میکروسختی، ریزساختار و تشکیل جوش اتصالات است. نتایج نشان داده‌اند که امواج ارتعاشی اولتراسونیک باعث عمل پالایش دانه در ناحیه هم‌زن (SZ) و همچنین نقش مطلوب آن در افزایش خواص مکانیکی و از بین بردن عیوب جوش، به‌ویژه در سرعت جوشکاری بالا (۱۲۰ میلی‌متر در دقیقه) می‌شود. همچنین، کاهش قابل توجهی در درصد کشیدگی چه در CFSW و چه UAFSW در مقایسه با فلز پایه وجود دارد. این به دلیل همگنی مورفولوژیکی کمتر در مناطق مختلف ریزساختاری در CFSW و UAFSW است. با این حال، هیچ اثر عمیقی برای امواج مافوق صوت بر روی اندازه دانه در منطقه تحت تاثیر حرارت مکانیکی (TMAZ) یا منطقه متاثر از حرارت (HAZ) یافت نشد.