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Hardness uniformity survey of butt joint from friction stir processing for magnesium-based aluminium alloy plate

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Abstract

In metal welding circles, it is commonly acknowledged that the ideal weld is one that appears to have no connections. The properties of the weld seam must not generate defects or unevenness that vary considerably from the original metal. The objective of this research was to explore into the hardness uniformity of the friction stir weld of AA5083-H112 aluminium composite plate, using factorial experimental design theory to determine the welding process. The experiment was carried out with the rotational speed and feed-rate of each variable adjusted at three levels. Afterwards, the statistical results of the hardness measured from the stirring friction weld were examined. At a 95% confidence level, an analysis revealed that a rotational speed of 4,500 rpm and a feed-rate of 72.91 mm/min resulted in a weld hardness equivalent to the original metal hardness. However, there are constraints on machinery and equipment. Therefore, the rotational speed of 4,500 rpm and feed rate of 55 mm/min were the testing parameters that produced the predicted hardness value of 38.49 HRB. Finally, the previously described weld zone remains subject to 197 MPa of residual compressive stress.

Keywords: AA5083-H112, Design of experiment, Friction stir welding, Hardness uniformity, X-ray diffraction

1. Introduction

Lightweight materials are highly sought after in the metal manufacturing industry, particularly in the fields of electric vehicles and aircraft [1, 2]. Weight attributes have a direct effect on energy consumption, workpiece size, and indirect production costs. However, it is essential in the design of such products to consider the mechanical properties of this lightweight material. This has the same influence as other expensive materials in terms of safety and efficiency of application. Aluminium alloys are one of the most commonly utilized light metals in the production of parts supporting this important capacity. Currently, aluminium alloy grade AA5083-H112, named according to ASTM B209-14, is one of the attractive materials of choice in the aforementioned manufacturing applications. It could be a material that serves to the aerospace, electrical vehicle, and automotive industries [3]. Because of its high strength-to-weight ratio, corrosion resistance, relatively inexpensive, and good weldability [4]. Nevertheless, the application of these alloys was constrained by significant restrictions in connectivity. In other words, conventional melting methods are ineffective for welding aluminium alloy grade AA5083-H112. It could cause undesired properties as a result of thermal influence (Heat affected zone: HAZ) or weld non - uniformity. Friction stir welding has been accepted for a long time in sheet metal since 1991 [5] and is still popular with butt joint products in sheet metal nowadays. Because this technology could connect the same or different materials without melting, the workpiece after joining has a low HAZ [6-9]. This heat effect would induce defects or unevenness in the workpiece, resulting in decreased performance [4, 10].

Optimizing the quality of friction stir welding by selecting the appropriate friction stir welding parameters is unavoidable in order to reduce production waste. This fundamental issue is still being researched by many groups of researchers in previously publications. The author proposed experimental studies of friction stir welding processes for aluminium alloys, where weld quality is frequently decided by mechanical properties. Tensile strength, surface hardness, and microstructure are examples of the mechanical properties mentioned [6, 11-13]. A variety of procedures are currently utilized to evaluate workpiece quality after friction stir welding. Recently, Suthar et al. [14] predicted the localized necking behavior of aluminium alloy friction stir welding parts using digital image correlation. As can be observed, research on the friction stir welding technology has been ongoing until now. This is because welding operations in each case study usually have various welding contexts. Therefore, thorough environmental control is required at all times in order to accomplish the most efficient production of friction stir welding workpieces. Collecting the data of investigations on variables controlling the friction stir welding process is therefore critical. In 2014, Cole et al. [5] and Guo et al. [15] investigated the effects of variables on aluminium alloy friction stir welding. It has been discovered that welding temperature and rotational speed have a direct impact on the quality of welded parts. Bergmann et al. [4] recently chose to investigate the effect of rotational speed on friction stir welding and confirmed that the rotational speed evaluated had a direct effect on the mechanical properties of the weld. However, it was discovered by gathering the variables in the current friction welding studies that rotational speed and feed rate were most frequently utilized to define conditions in friction stir welding [16-19]. And in process analysis, the statistical idea that could identify the optimal

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experimental conditions to be useful in evaluating the efficiency of the friction welding process was usually unavoidable. Khan et al. [16] and Campanella et al. [17] have conducted statistical analyses of the effect of hardness and other mechanical properties from friction stir welding experiments for aluminium alloy grades AA2024 and AA8090-T3, respectively. The results of this study confirmed that the statistical method could accurately and consistently select the most appropriate experimental conditions. To create a statistical model to evaluate an experiment, factorial design is an empirical modelling approach. Ashok Kumar and Thansekhar [20] employed analysis of variance (ANOVA) to investigate at the mechanical and wear properties of friction-welded AA6101-T6 and AA1350 alloys. Both, they discovered through ANOVA that offset distance and number of passes were welding parameters that substantially impacted wear and mechanical properties. The effects of traversing speed and axial load on the properties of friction stir welded dissimilar AA6101-T6 and AA1350 aluminium alloys were recently investigated by Ashok Kumar et al. [21] using ANOVA analysis. It underlines the application of ANOVA in experimental design and in the interpretation of experimental findings when the aforementioned control variables are included in the analysis.

Based on the foregoing reasons and effects, the research focuses on weld uniformity as measured by the hardness obtained by friction stir welding of aluminium alloy grade AA5083-H112 containing magnesium as an alloying element. Using factorial design theory, analyse the optimum hardness of weld joints using statistical principles based on experimental conditions. The experiment was carried out with three different rotational speeds and feed rates. And this work produced tool pin profiles for friction welding using a combination of prototype shapes from Raturi et al. [12], Saad et al. [19] and Khalili et al. [22]. It has a cylindrical shape with a slightly bevelled tip and is equipped with the jigs required for friction stir welding process.

2. Materials and methods

2.1 Chemical composition

Aluminium alloy grade AA5083-H112 was used in this research to conduct a chemical separation test by surface melting at temperatures ranging from 650 °C to 750 °C [23], with the chemical composition shown in Table 1. The main alloying element in this grade of aluminium was magnesium with 4.59 wt.%. It has outstanding strength and corrosion resistance capabilities, and the percentage of magnesium in the range of 0.8 to 5.5 wt.% are regarded as medium to high strength, and the surface brightness is attributable to the alloy composition.

Table 1 Chemical composition of AA5083-H112 aluminium alloy plate

Element in wt.%							
Al	Mg	Si	Fe	Mn	Zn	Ti	Cr
Balance	4.59	0.10	0.18	0.60	0.02	0.04	0.07

2.2 Mechanical properties

Mechanical properties of 3 mm thick AA5083-H112 aluminium alloy plates used in this study experiments were received from local market distributors. Table 2 shows the properties of the AA5083-H112 aluminium alloy plate used, which has the yield stress with in rolling direction of 175.82 MPa, the ultimate tensile stress of 301.30 MPa, an elongation of 19.10 %, and a surface hardness of 37.10 (HRB).

Table 2 Mechanical properties of AA5083-H112 aluminium alloy plate

Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)	Hardness (HRB)
175.82	301.30	19.10	37.10

2.3 Friction stir welding

In this work, a semi-automatic milling machine model X6336 WA was used for welding in conformance with the friction stir welding pattern. The material plate was laser cut into a rectangle with a length of 50 mm and a width of 20 mm in the pre-welding process. The clamping tools on a semi-automatic milling machine were designed to execute the friction stir welding procedure under two of the studied welding factors: rotational speed and feed-rate. The experimental parameters that were not included for comparison were constant in all experimental conditions, i.e., the temperature before the welding feed was about 80 °C, with the temperature recording point positioned on the workpiece 1, which was 15 mm from the welding line. Besides, the depth of the agitator buried in the workpiece was 2 mm. The welding tool pin was formed of SCM440 tool steel, while the clamping tools were made of S40C carbon steel. In this regard, Figure 1 illustrates a 3D graphic of equipment installation for stir friction welding.

2.4 Design of experiment

According to friction stir welding, which describes the parameters studied in this study, each parameter in the stir friction welding experiment has three levels, as shown in Table 3, which employs the three-level factorial design (3^2). Rotational speed and feed-rate were taken into consideration for this design as controllable variables, while average hardness was taken into consideration as an output factor. A total of 27 tests were carried out, including a case of repetition for the experimental conditions that resulted in the optimum weld hardness.

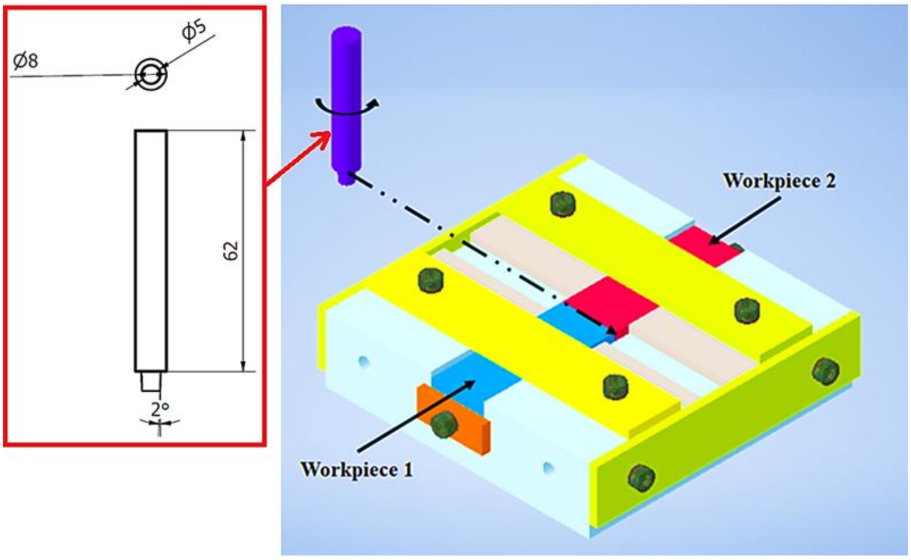

Figure 1 3D graphics setup of the friction stir welding process

Table 3 Parameters and their respective levels

Parameters	**Units**	**Levels**		
		1	**2**	**3**
Rotational speed	rpm	2900	4100	4500
Feed-rate	mm/min	30	55	100

3. Results and discussion

3.1 Hardness interface testing

The Rockwell hardness test technique was used in this study to examine the unevenness of the hardness of friction stir welded specimens based on the experimental conditions specified in the section of design of experiment. A semi-automatic surface hardness tester was used for hardness testing. The indenter is pressed on the surface of the specimen for 11 seconds under pressure during the test procedure. The Rockwell hardness (HRB) of the specimens was measured by processing the depth of pressure of the force dispersed to the surface area. The initial test force must really be 10 kgf (98.07 N) in order to comply with the B-scale Rockwell hardness testing standard. Using a 1/16" ball type indenter, the main load for the hardness test was set at 100 kgf (980.70 N). The hardness test results obtained under the experimental design conditions are depicted in Figure 2.

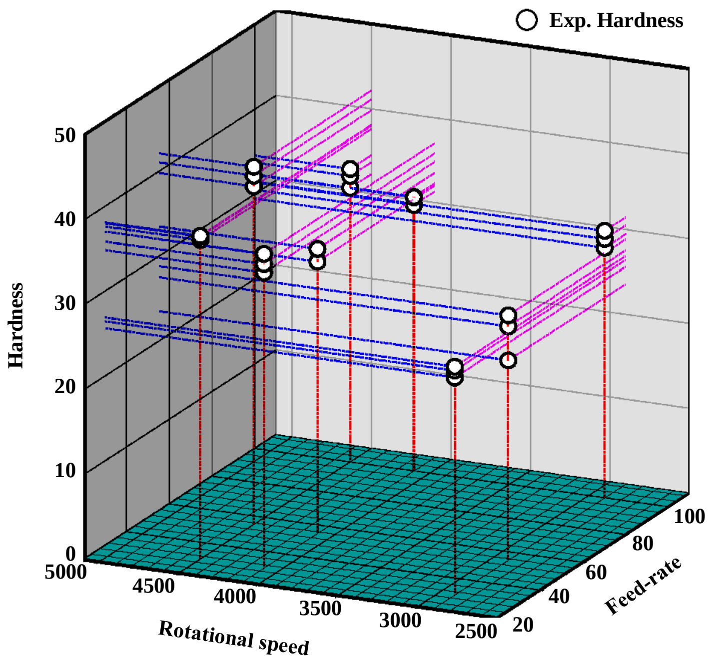

Figure 2 Mean hardness of joint in friction stir welding experiment plot

The modest inclination of the tool pin operating on the weld joint, or the use of a tool pin with a minor inclination, as proposed by Ghiasvand et al. [7] and Kubit et al. [8], improved in the smoothness of the welding process. It also prevents the formation of HAZ from heat build-up, which causes micro and macro unevenness within the weld, according to Su et al. [9] and Kumar and Maji [10]. The hardness at the weld area is both greater than and less than the original metal hardness as a result of this AA5083-H112 aluminium alloy friction stir welding. Unwelded aluminium has a hardness of 37.10 HRB.

3.2 Analysis of variance

As shown in Figure 3, the analysis of variance with Minitab 16 statistical software revealed that the hardness had a linear distribution and the P-value was 0.958, which was greater than the significance value (α = 0.05). This was clearly believed that the hardness test data was normally distributed.

However, it was discovered that the residual value distribution had an independent random pattern and was unable to determine the precise trend when the independence of the data under the level adjustment of each variable evaluated was examined. Therefore, it could be assumed that the data have an appropriate level of variance stability and that the investigated factors both significantly affect the experiment and are independent of one another, as shown in Figure 4. Since it meets these requirements, it can be used to produce a three-level factorial experiment condition.

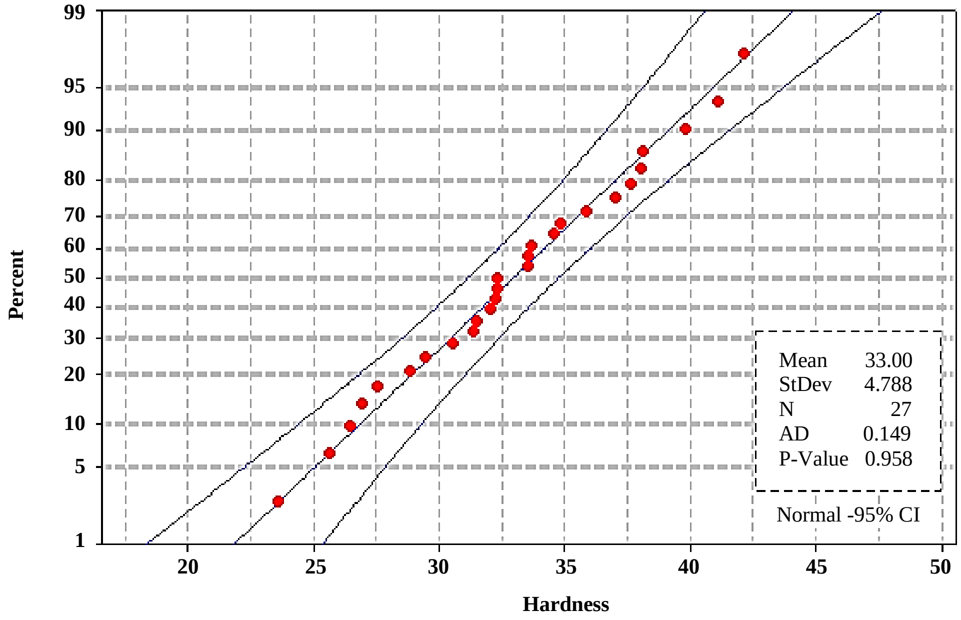

Figure 3 Normal probability plot of hardness

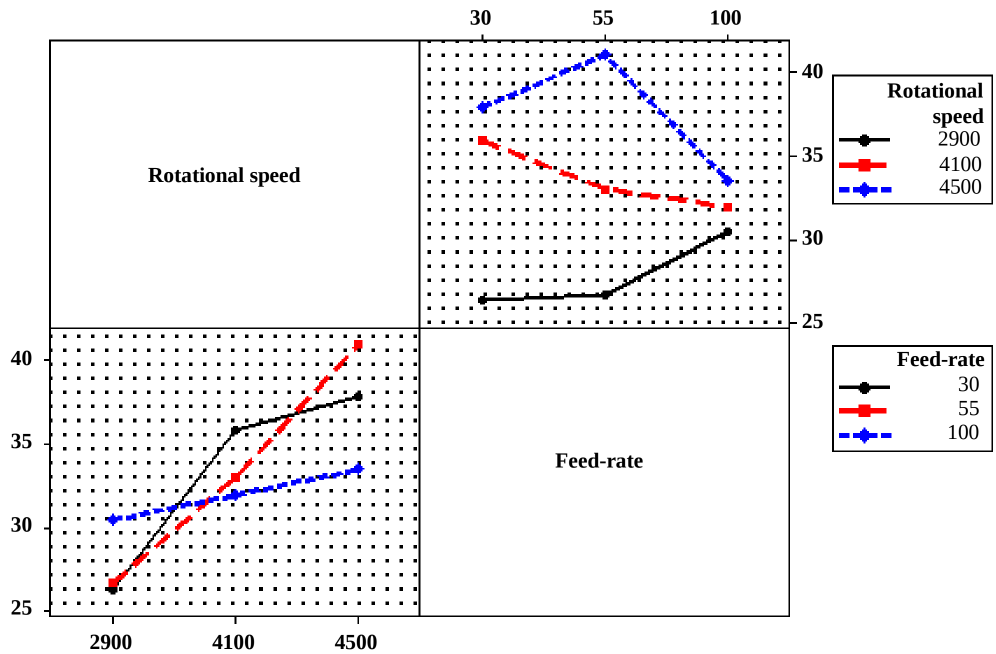

Figure 4 Interaction plot for hardness

Table 4 Analysis of variance for the hardness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Rotational speed	2	425.76	425.76	212.88	136.84	0.000
Feed-rate	2	13.49	13.49	6.75	4.34	0.029
Rotational speed*Feed-rate	4	128.83	128.83	32.21	20.70	0.000
Error	18	28.00	28.00	1.56		
Total	26	596.09				

S= 1.24727, R-Sq = 95.30%, R-Sq(adj) = 93.21%

Table 4 displays the results of the analysis of variance, confirming that both rotational speed and feed-rate have a significant impact on the surface hardness of the friction stir weld with a P-value less than 0.05. According to the data, the rotational speed had the most impact on the hardness at weld center, which is in agreement with the results of Ashok Kumar and Thansekhar [24, 25]. By defining the variance of the model and the variance of the residual values side by side, the F value was utilized to explain the importance of the components in the ANOVA table. Additionally, it was discovered that the cofactor had a sizable impact on the surface hardness of the friction stir weld when the interaction of the parameters was taken into account. The R-square designation coefficient was 95.30 %, meaning that in this analysis 95.30 % of the experimental parameters were under control and only 4.70 percent were uncontrolled variables. This supports the reliability of the variable selection used to explore frictional welding in this work. However, there could be certain factors that were not considered into account in this study but only had a slight influence on the outcomes.

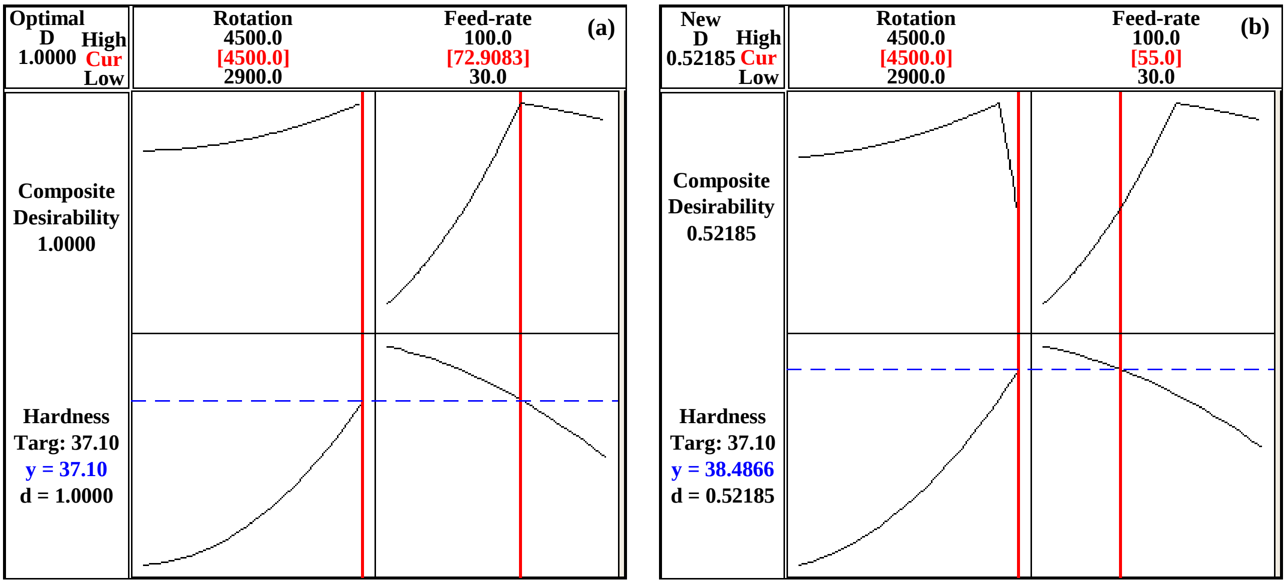

Figure 5 Parameter hardness prediction plot (a) optimal conditions from statistical analysis (b) condition closest to ideal condition

Of course, the ideal weld is one that has the same properties as the original material and prevents defects from appearing on the workpiece and creating unevenness that could damage its usage. According to statistical analysis, the weld in this work must be near to 37.10 HRB in order for the hardness to be comparable to the original material. For a 3 mm thick AA5083-H112 aluminium alloy plate, the optimum conditions for the friction stir welding process were found to be a rotational speed of 4,500 rpm and a feed-rate of 72.91 mm/min, as illustrated in Figure 5(a). This statistical analysis predicts a weld surface hardness of 37.10 HRB, the same as the hardness of the original material, under optimal conditions. However, the actually friction welding experimental settings, where the feed-rate of 72.91 mm/min cannot be implemented, place constraints on the optimal condition determined by this statistical analysis. But, when the friction stirs welding experiment's setup parameters were adjusted to be nearly as well as possible, i.e., a rotational speed of 4,500 rpm and a feed-rate of 55 mm/min, the prediction result showed that the hardness was 38.49 HRB, as shown in Figure 5(b). This induced a 3.74 percent error that deviated from the stated goals. The statistical analysis in the Section 3.2 clearly demonstrated that rotational speed and feed-rate had an effect on weld property, as previously demonstrated by Kumar et al. [1], Jamali and Mirsalehi [18] and Saad et al. [19]. According to the statistical analysis principle, the hardness of the friction stir weld was carefully selected as the response variable in this study. At the 0.05 level, the results of this study showed that rotational speed and feed-rate had a significant effect on the hardness of the friction stir weld in aluminum alloy AA5083-H112. Importantly, this is consistent with the findings of Rajkumar et al. [11], Raturi et al. [12] and Campanella et al. [17].

3.3 X-ray diffraction

The residual stress measurement method, which cannot be used by normal observation methods, was employed to thoroughly analyses the friction stir welded specimens from the experimental design under appropriate weld surface hardness circumstances. By using X-ray diffraction (XRD), the residual stress at the weld joint was measured and represented in the mathematical mean stress form, as shown in Figure 6. The technique used in this study to detect the residual stress of the friction stir weld region is consistent with that proposed by Raturi and Bhattacharya [6]. This indicates that a weld can cause unevenness across the entire weld line even with proper quality control. Throughout the operation, a portable X-ray diffractometer (μ -x360) was used to quantify the residual stress on the elements and the residual stress on the welds of the experimental specimens. The distance between the XRD equipment and the specimen was 67 mm, and the angle of incidence of the X-rays was adjusted at 35 degrees. Based on the results of the residual stress measurement performed on the experimental specimens weld joints at 4500 rpm of rotational speed and 55 mm/min of feed-rate, which were determined by statistical analysis to be the ideal circumstances, has a residual compressive stress of 197 MPa. The unwelded workpiece, on the other hand, contains a residual stress of -59 MPa, as shown in Table 5. It is obvious that even though optimal welding conditions for friction stir welding result in a weld joint with hardness that is almost equal to the hardness of the original workpiece. But it will be unable to prevent residual stress from affecting the weld, though. The X-ray examination of friction stir welds in this study found residual stresses near the welds, similar to the assumptions made by Swathi et al. [26].

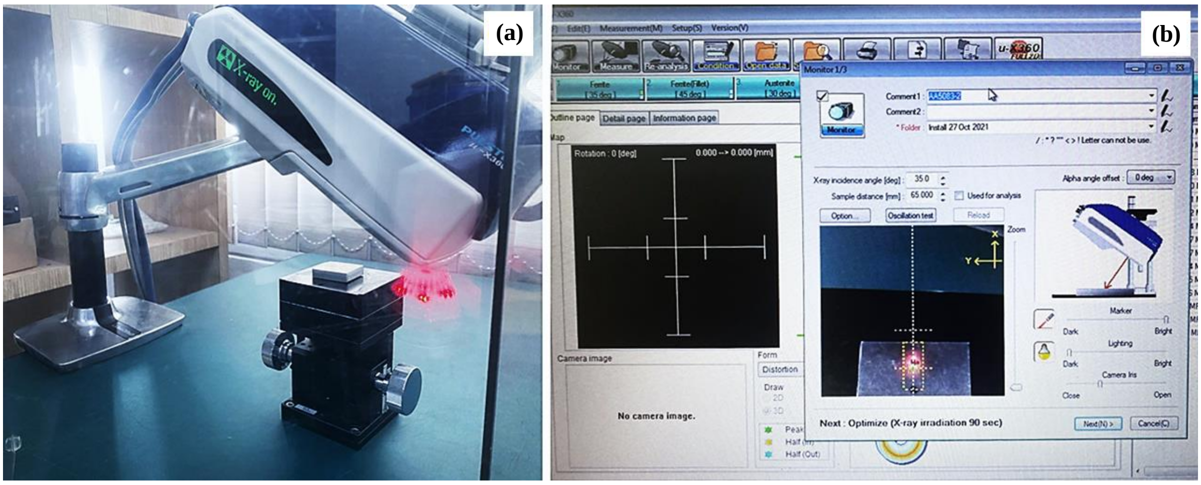

Figure 6 Measurement of residual stresses by X-ray diffraction method (a) specimen position and X-ray source (b) example of software residual stress analysis

Table 5 Example of compressive residual stress result of specimen

Specimen	Rotational speed (rpm)	Feed-rate (mm/min)	Residual Stress (MPa)
Original material	-	-	-59
Optimal of FSW	4500	55	-197

4. Conclusions

The objective of this study was to examine the hardness uniformity at the friction stir weld area for aluminium alloy plates of grade AA5083-H112, which were parameterized using the factorial design approach with 32 tiers. Three different rotational speeds and three different feed-rate levels were used to vary the experimental conditions. Surface hardness measurements and statistical analyses were performed on the specimens following friction welding under these test circumstances.

The rotational speed of 4500 rpm and the feed-rate of 72.91 mm/min are the optimum welding conditions, according to the results of the weld hardness analysis of friction stir welding based on statistical considerations. It was the welding condition that makes the hardness of the weld near the original metal with a predicted weld hardness of 37.1 HRB. Some limitation of this stirring friction welding experiment was that the machine and equipment could not be adjusted for the feed-rate of 72.91 mm/min. The experimental settings, however, were very close to the optimum conditions when the friction stir welding condition was adjusted at a rotational speed of 4,500 rpm and a feed-rate of 55 mm/min. The prediction results showed that the hardness of the friction stir weld was 38.49 HRB, signifying a 3.74 percent error from the projected value. According to the ANOVA results, both the rotation speed and the feed-rate had a significant effect on the hardness of the friction stir weld, with a P-value less than 0.05. Furthermore, the interaction of these two parameters had a significant impact on the hardness of the stirred friction weld. Importantly, this research takes into account the surface of the weld joint formed by friction welding at the optimum condition for an in-depth examination of the residual stress using the X-ray diffraction method proposed by Swathi et al. [26]. To control the suitability of the friction stir welding process, which is a technique for observing weld line uniformity that is finer than that observed by conventional methods. Even though the friction stir weld at the optimum welding conditions had the same hardness as the original metal, the mentioned weld area nevertheless had the influence of residual compressive stress in the amount of 197 MPa. This represents a 258 percent increase in residual compressive stress, which may be significant enough to influence a decision to use this friction welding part in a potential application.

Friction stir welding under constrained conditions can be optimized to improve quality and reduce production costs. Finally, a future research objective is to analyses the crystallographic orientation of the ultra-high-strength steel (UHSS) friction stir weld using the electron back-scattered diffraction (EBSD) detection technique. A method for assessing the properties of materials at the microstructure level is gaining popularity in the field of material engineering and is being utilized in the industrial sector to fabricate metal parts.

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6. References

[1] Kumar R, Singh J, Sharma S, Li C, Królczyk G, Wojciechowski S. Neutrosophic entropy-based ingenious measurement for fast fourier transforms based classification of process-parameters and wear resistance of friction-stir processed hybrid AA7075-B4C aluminium metal-matrix composites. J Mater Res Technol. 2022;20:720-39.

[2] Ahmed MM, El-Sayed Seleman MM, Ahmed E, Reyad HA, Alsaleh NA, Albaijan I. A novel friction stir deposition technique to refill keyhole of friction stir spot welded AA6082-T6 dissimilar joints of different sheet thicknesses. Mater. 2022;15(19):6799.

[3] Ghaffarpour M, Aziz A, Hejazi TH. Optimization of friction stir welding parameters using multiple response surface methodology. Proc Inst Mech Eng L: J Mater Des Appl. 2017;231(7):571-83.

[4] Bergmann LA, Batistão BF, de Alcântara NG, Gargarella P, Klusemann B. Effect of rotational speed and double-sided welding in friction stir–welded dissimilar joints of aluminum alloy and steel. Weld World. 2022;66(9):1747-56.

[5] Cole EG, Fehrenbacher A, Duffie NA, Zinn MR, Pfefferkorn FE, Ferrier NJ. Weld temperature effects during friction stir welding of dissimilar aluminum alloys 6061-t6 and 7075-t6. Int J Adv Manuf Technol. 2014;71(1):643-52.

[6] Raturi M, Bhattacharya A. Mechanical strength and corrosion behavior of dissimilar friction stir welded AA7075-AA2014 joints. Mater Chem Phys. 2021;262:124338.

[7] Ghiasvand A, Suksatan W, Tomków J, Rogalski G, Derazkola HA. Investigation of the effects of tool positioning factors on peak temperature in dissimilar friction stir welding of AA6061-T6 and AA7075-T6 aluminum alloys. Mater. 2022;15(3):702.

[8] Kubit A, Trzepieciński T, Kluz R, Ochałek K, Slota J. Multi-criteria optimisation of friction stir welding parameters for EN AW-2024-T3 aluminium alloy joints. Mater. 2022;15(15):5428.

[9] Su M, Qi X, Xu L, Feng Q, Han Y, Zhao L. Microstructural and mechanical analysis of 6063-T6 aluminum alloy joints bonded by friction stir welding. J Mater Sci. 2022;57(31):15078-93.

[10] Kumar G, Maji K. Forming limit analysis of friction stir tailor welded AA5083 and AA7075 sheets in single point incremental forming. Int J Mater Form. 2022;15(3):1-23.

[11] Rajkumar T, Radhakrishnan K, Rajaganapathy C, Jani SP, Ummal Salmaan N. Experimental investigation of AA6063 welded joints using FSW. Adv Mater Sci Eng. 2022;2022:1-10.

[12] Raturi M, Garg A, Bhattacharya A. Joint strength and failure studies of dissimilar AA6061-AA7075 friction stir welds: effects of tool pin, process parameters and preheating. Eng Fail Anal. 2019;96:570-88.

[13] Jabraeili R, Jafarian HR, Khajeh R, Park N, Kim Y, Heidarzadeh A, et al. Effect of FSW process parameters on microstructure and mechanical properties of the dissimilar AA2024 Al alloy and 304 stainless steel joints. Mater Sci Eng A. 2021;814:140981.

[14] Suthar H, Bhattacharya A, Paul SK. DIC-based approach to predict post necking behavior for AA6061, AA7075 and their friction stir welded joints. Mech Mater. 2022;172:104364.

[15] Guo JF, Chen HC, Sun CN, Bi G, Sun Z, Wei J. Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters. Mater Des. 2014;56:185-92.

[16] Khan AS, Badheka VJ, Chaudhari AB, Gadakh VS. Experimental investigation of friction stir welding of aluminum alloy AA8090-T3 using taguchi method. J Mater Eng Perform. 2022:1-9.

[17] Campanella D, Marcon G, Lombardo A, Buffa G, Fratini L. The role of thermal contribution in the design of AA2024 friction stir welded butt and lap joints: mechanical properties and energy demand. Prod Eng. 2022;16(2):247-259.

[18] Jamali A, Mirsalehi SE. Investigation on effects of traverse speed and number of passes on mechanical and abrasive properties of AA7075-T6/ZrO2 surface nanocomposite produced using friction stir processing. Weld World. 2022;66(11):2297-313.

[19] Saad F, Ibrahem K, Abu-Okail M, Khairaldien WM, Allah MH. An investigation of post-weld heat treatment of friction stir welded aluminium blanks AA2024 embedded with AA7075. In: Abdalla AE, editor. 20th International Conference on Applied Mechanics and Mechanical Engineering (AMME-20); 2022 Mar 29-31; Cairo, Egypt. Bristol: IOP Publishing; 2022. p. 1-15.

[20] Ashok Kumar R, Thansekhar MR. Mechanical and wear properties of friction stir welded dissimilar AA6101-T6 and AA1350 alloys: effect of offset distance and number of passes. J Mech Sci Tech. 2018;32(7):3299-307.

[21] Ashok Kumar R, Pandiyarajan R, Raghav GR, Nagarajan KJ, Rengarajan S, Pandian SD, et al. Role of traversing speed and axial load on the properties of friction stir welded dissimilar AA6101-T6 AND AA1350 aluminium alloys. J Chin Inst Eng. 2023;46(1):81-5.

[22] Khalili M, Eivani AR, Seyedein SH, Jafarian HR. The effect of multi-pass friction stir processing on microstructure and mechanical properties of dual-phase brass alloy. J Mater Res Technol. 2022;21:1177-95.

[23] Li H, Xu W, Li L, Xia H, Chen X, Chen B, et al. Enhancing the wettability for 4043 aluminum alloy on 301L stainless steel via chemical-etched surface texturing. J Mater Process Technol. 2022;305:117577.

[24] Ashok Kumar R, Thansekhar MR. Reinforcement with alumina particles at the interface region of AA6101-T6 and AA1350 alloys during friction stir welding. Mater Res Express. 2018;5(4):046521.

[25] Ashok Kumar R, Thansekhar MR. Property evaluation of friction stir welded dissimilar metals: AA6101-T6 and AA1350 aluminium alloys. Mater Sci. 2017;23(1):78-83.

[26] Swathi IB, Raju LS, Rao KV. Optimization of ultrasonic vibration assisted friction stir process to improve mechanical properties of AA7075-nano B4C surface composite. Proc Inst Mech Eng C: J Mech Eng Sci. 2022;236(16):1-15.