International Journal of Advances in Engineering Research http://www.ijaer.com

(IJAER) 2020, Vol. No. 19, Issue No. I, January **e-ISSN: 2231-5152, p-ISSN: 2454-1796**

MODELING AND OPTIMIZATION OF FRICTION STIR WELDING PROCESS PARAMETERS FOR DISSIMILAR ALUMINIUM ALLOYS

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ABSTRACT:

Friction Stir Welding (FSW) is a unique solid state welding technique that is rapidly gaining popularity due to its ability to produce strong joints. In this study, the friction stir welding technique is used to join 3.5 mm thick dissimilar aluminium alloys of AA 7075-O and AA 5454-O grades. The optimised Design of Experiments (DOE) is used to investigate the effect of tool pin profile and tool rotational speed on mechanical properties such as micro-hardness and tensile strength. The experiments are built on an L16 orthogonal array with TAGUCHI techniques for four design parameters and four parametric levels. The results of the experimental techniques are tabulated, and Minitab software is used to perform TAGUCHI analysis and Analysis of Variance (ANOVA).

Keywords: *Friction Stir Welding, Parameter Optimization, Microstructure, Grey relation analysis, Pin profile, Taguchi, Optimization, Process Parameters, AA 7075-O and AA 5454-O.*

INTRODUCTION:

Friction stir welding (FSW) is a popular joining technique that produces high-quality joints by joining materials at temperatures below their melting point. Because it is a solid-state process, FSW avoids many flaws associated with fusion welding processes, such as solidification cracking, liquid cracking, distortion, and porosity. A rotating cylindrical tool with a clamped workpiece is essential for carrying out the process. The tool consists of a pin and a profiled or non-profiled shoulder. The frictional heat required is produced by a rotating tool with a thinning contact between the shoulder and the surface of a material to be welded. The stirring operation is possible once the pin has reached the plastic deformation mode of the materials to be welded. The stirring quality in the weld zone is influenced by tool design and machine parameters. FSW has recently been used to join dissimilar aluminium alloys, aluminium to brass/copper, aluminium to steel, aluminium to magnesium, and aluminium to titanium [1-4].

Process parameter optimisation has increased the required joint quality. Inadequate levels of process parameters, on the other hand, may result in flaws. Regression analysis, design of experiments (DOE), analysis of variance (ANOVA), response surface methodology (RSM), and other approaches have been used for process optimisation. Using DOE techniques to reduce the number of trials reduces the cost and time required. Taguchi, a widely used DOE technique based on orthogonal arrays, has been extensively used as a process optimisation tool. Using Taguchi in conjunction with ANOVA, you can estimate the statistical significance of process parameters on responses. RSM is a fast way to create a mathematical model that predicts and represents the relationship between parameters and responses. The Taguchi approach has a major flaw in that the influences obtained are only relative and do not show which parameter has the greatest impact on the response value. It means that any change in experimental procedures, parameters, levels, or conditions will alter the outcomes and influences. Also, because of the array fraction, this method should not be used when all relationships between all parameters are required. Another limitation is that the Taguchi technique is an offline optimisation technique, which is incompatible with a dynamically adjusting operation [5-7].

TAGUCHI METHOD

The Taguchi Method consists of three stages: system design, parameter design, and tolerance design. The Taguchi method is used to improve product and process quality. When a higher level of performance is consistently achieved, quality improves. The best performance is achieved by determining the best combination of design factors. Performance consistency is achieved by making the product/process insensitive to the influence of the uncontrollable factor. The optimum design is determined using design of experiment principles in Taguchi's approach, and consistency of performance is achieved by carrying out the trial conditions under the influence of noise factors (Ross, 1988).

REVIEW OF LITERATURE:

Friction stir welding was invented in 1991 by Thomas and Nicholas at The Welding Institute in Cambridge, UK. It employs a rotating tool with a pin beneath the shoulder. The tool's pin and shoulder both contributed to heat generation. The shoulder controls the material flow while the pin mixes the base materials. The FSW has two welded sides; the first is known as the advancing side, in which the rotating tool and weld area are oriented in the same direction, and the second is known as the retreating side, in which the rotating tool and weld area are oriented in opposite directions [8-9].

Kumar et al. [10] performed friction stir welding of AA6061 and AA2024 alloys using various pin profiles. The results showed that the tensile strength of the joints performed with the squared-pin profile tool was higher than the strength obtained with the tapered and cylindrical pin profile tools.

Dinaharan et al. [11] investigated the microstructure and tensile strength of the dissimilar friction stir welded, cast, and wrought aluminium alloy AA6061 as a function of material locations and tool rotational speed. They concluded that when the tool rotational speed was increased, the material placed on the advancing side (AS) occupied the majority of the weld zone, where the AS of the weld is hotter than the retreating side, as demonstrated by Cole et al. [12]. Sundaram and Murugan [13] investigated the effect of the pin profile used in FSW on the mechanical properties of dissimilar aluminium alloys 2024-T6/5083-H321 where the alloy with higher strength (2024) was located on the retreating side (RS). They demonstrated that when certain parameter combinations produce either very low or very high frictional heat, a plastic flow of material, lower tensile strength, and elongation are observed. Furthermore, Khodir and Shibayanagi [14] investigated the FSW of dissimilar materials, AA2024 and AA7075, and recommended that the low-strength material be used on the AS to produce better welds. Jata et al. [15] and Xue et al. [16], on the other hand, confirmed that locating hard materials at the AS improves joint strength. As a result, regardless of material placement, the material flow and joint performance are dependent on the welding conditions and their effects on generated heat and stir zone (SZ) temperatures [17]. Furthermore, heat dissipation is affected by material thickness, welding speed, and ambient temperature [18]. The use of high heat input, such as low welding speed and high rotation rate, can result in improper tool/material contact conditions (slipping conditions), resulting in defective joints [19]. Otherwise, El-Sayed et al. [20] demonstrated, both experimentally and theoretically, that tool pin profile has a minor effect on the maximum temperature of the welded joints when welding at the same speed.

OBJECTIVES:

- Modeling of Friction Stir Welding Process Parameters for Dissimilar Aluminium Alloys
- Optimization of Friction Stir Welding Process Parameters for Dissimilar Aluminium Alloys
- Analysis of Variance (ANOVA)
- Main effects of the plot for SN ratio.

RESEARCH METHODOLOGY:

The base metals used in this work were a heat treatable aluminium alloy of 7075-O and a strain hardening aluminium alloy of 5454-O. The chemical compositions of the metals used were examined using an X-ray fluorescence spectrometer (XRF). The chemical compositions and mechanical properties of both alloys are detailed in Table 1. For standardization, the base metals were machined to 138 × 81 × 3.5 mm by a vertical milling machine. Because of its high S/W ratio and acceptable corrosion resistance, AA7075-O has numerous applications in aerospace, defence, marine, and automobile, but there are concerns about reliability and lifetime when used in variable marine environments. In such cases, combining this alloy with another that has excellent corrosion resistance in marine environments will be beneficial. One of these alloys is AA5454-O. AA5454-O is used in a variety of welded assemblies, tanks, pressure vessels, trucking, and dump bodies [21,22].

Table 1 Chemical Composition of base materials AA5454-O and AA7075-O

Material	Si	Fe	Cu	Mn	Mg	Cr	Ti	Zn	Al
AA 5454	0.25	0.4	0.1	0.65	2.8	.076	0.2	0.25	Bal.
AA 7075	0.40	0.50	1.25	0.30	2.7	0.19	0.2	5.2	Bal.

Table 2: Mechanical properties of base materials AA5454-O and AA7075-O

Material	UTS (Mpa)	% Elongation	Micro Vickers hardness (VHN)
AA 5454	260	15 %	70
AA 7075	402	10 %	175

Figure 1 depicts the machine used (a), sheet dimensions with clamp positions (b), welded joints after test specimen machining (c), and test specimens (d). A classic WMW ECKERT vertical milling machine was used to make the joints (Fig. 1a). Two clamps were used to secure the sheets above a steel backing plate, as shown in Fig. 2b. To complete the process, four tool actions were required: rotation, penetration and plunging, translation, and retraction. The speeds were calibrated using a tachometer.

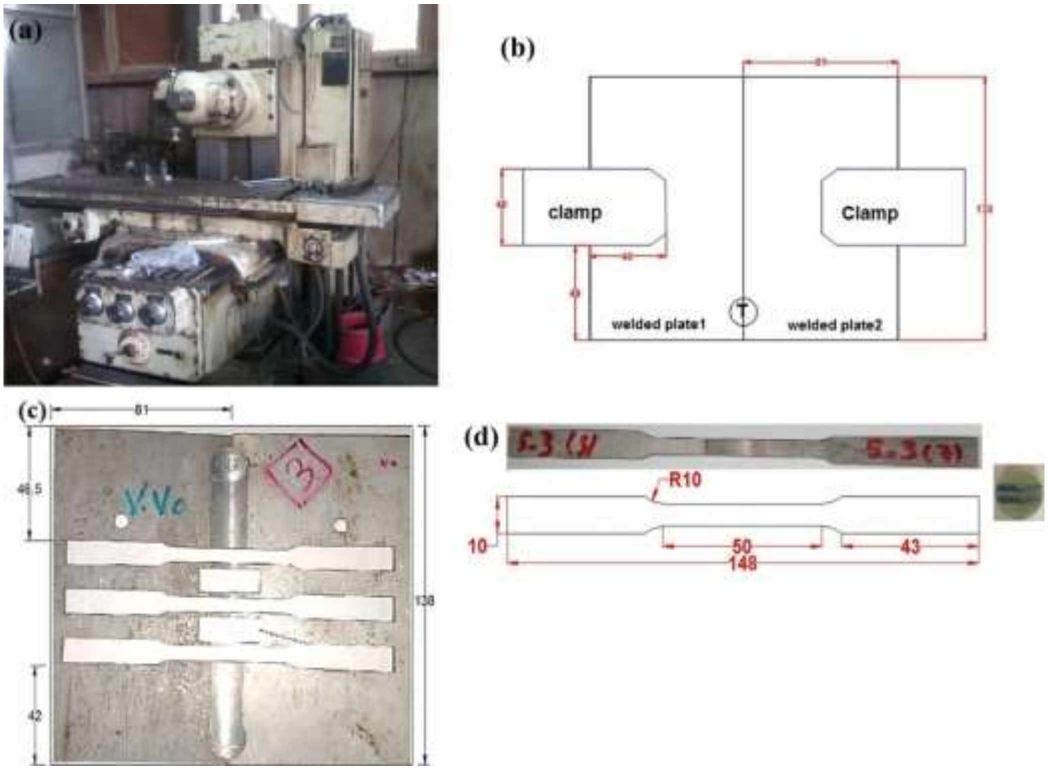


Figure 1: WMW ECKERT machine used (**a**), clamping system (**b**), welded joints after machining of test specimens (**c**), and test specimens (**d**)

The outputs used to evaluate the process were ultimate tensile strength (MPa) and elongation%. Transverse tensile specimens were taken in accordance with ASTM B557-Sub size to evaluate joint strength. [Conclusion and Discussion:

The Taguchi method's main goal is to design a robust system that is reliable under noise conditions. This method adjusts design parameters to their optimal levels, rendering the process insensitive to noise. The noise parameters are either uncontrollable or extremely difficult (expensive) to control. The goal of using the signal to noise (S/N) ratio is to achieve a state in which the influences of controllable parameters can eliminate or weaken the effect of noise (uncontrollable). To maximise the outputs (strength and elongation) to uncontrollable noises, the S/N criterion (higher is better) is used. According to this criterion, the levels with the highest ratio are optimal. It is available as follows: [23]

$$\frac{\mathrm{S}}{\mathrm{N}} ratio = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad \text{……………………. (1)}$$

where y_i is the ith observation of a treatment combination and n is the number of replications.

The mean, standard deviation (SD), and S/N ratio of UTS (MPa) and elongation% are shown in Figure 2. The range of UTS results is 165.003 MPa at trial No. 11 (T11) to 212.193 MPa at trial No. 2. When compared to the strength of the softer side (AA5454), the joint efficiency ranges from 63.5 to 81.6%. The elongation varies between 4.266 (T11) and 11.7333% (T8). In comparison to the AA5454 side, the elongations range from 106.65 to 293.33%. Based on UTS results, the S/N ratio domain ranges from 44.20 at T11 to 46.53 at T2. Elongation varies from 12.5077 at T11 to 21.3256 at T2.

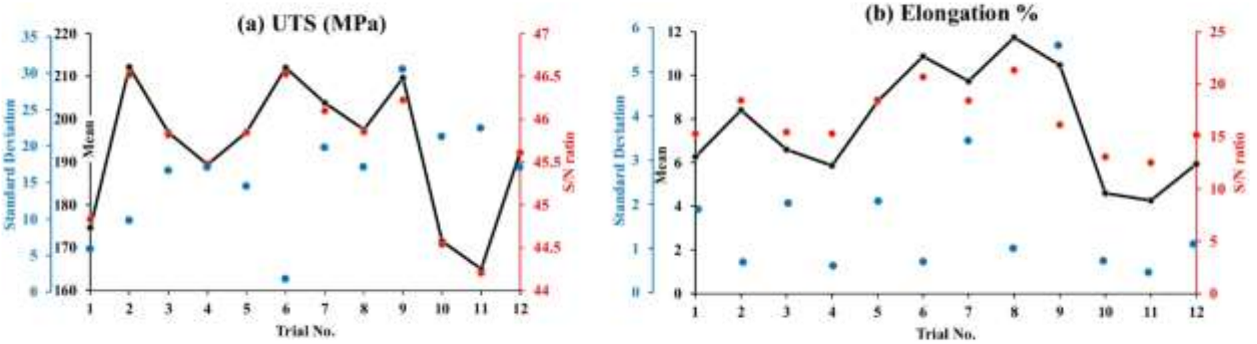


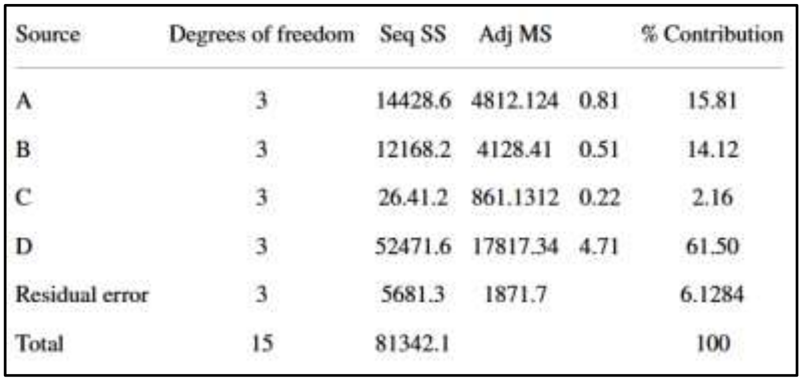
Figure 2: The mean, S/N ratio, and standard deviation of experimental UTS (**a**) and elongation (**b**)

When using a traditional milling machine, the most likely noise in FSW is an uncontrollable axial force. Because surface conditions of a workpiece and machine linkages deflect under loading conditions, using the plunge depth without a force controller may result in the formation of some defects or the production of different weld qualities in the same operation. As a result, the tool cannot adjust its position during the process without further digging into the workpiece, resulting in significant weld flash. In contrast, the force controller can revise the tool's position by maintaining a constant contact force and preventing flashing. It also explains why the results of the same trial can vary so much [24].

ANALYSIS OF VARIANCE (ANOVA)

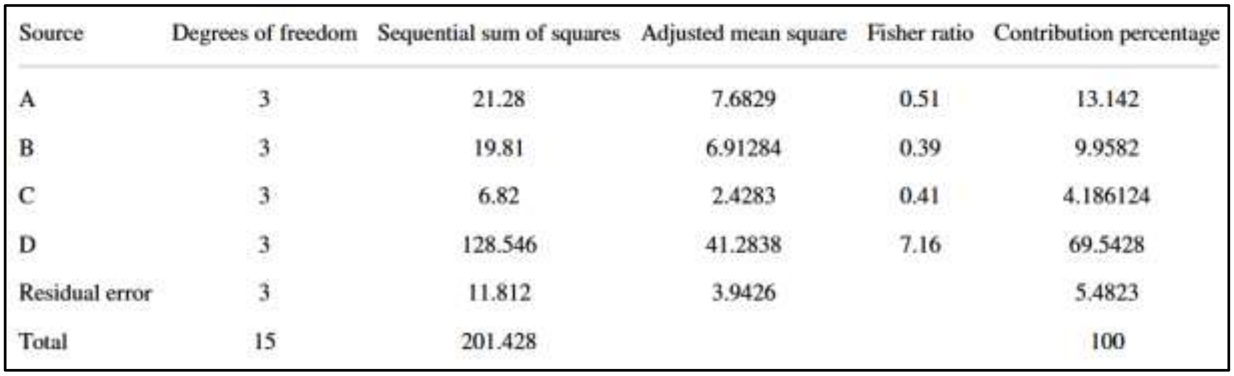
The technique of analysis of variance determines which variables are statistically significant. So, you can see how much and how significantly the process parameter influences your reaction. Tables 3 and 4 contain ANOVA tables for the mean and the noise to signal ratio, respectively. Figure 3 depicts the results in terms of mean and SN ratio. The F test is being used to determine the performance parameters in this study, which are extremely important. A higher F value indicates that the factor has a greater influence on the process's outcome. Throughout our investigation, we discovered that the D/d ratio had a significant impact on the tensile strength of the weld. [25]

Table 3 Means-variance analysis.



Source	Degrees of freedom	Seq SS	Adj MS		% Contribution
A	3	14428.6	4812.124	0.81	15.81
B	3	12168.2	4128.41	0.51	14.12
C	3	26.41.2	861.1312	0.22	2.16
D	3	52471.6	17817.34	4.71	61.50
Residual error	3	5681.3	1871.7		6.1284
Total	15	81342.1			100

Table 4: Statistical ANOVA for the correlation between signal and noise. [26]



Source	Degrees of freedom	Sequential sum of squares	Adjusted mean square	Fisher ratio	Contribution percentage
A	3	21.28	7.6829	0.51	13.142
B	3	19.81	6.91284	0.39	9.9582
C	3	6.82	2.4283	0.41	4.186124
D	3	128.546	41.2838	7.16	69.5428
Residual error	3	11.812	3.9426		5.4823
Total	15	201.428			100

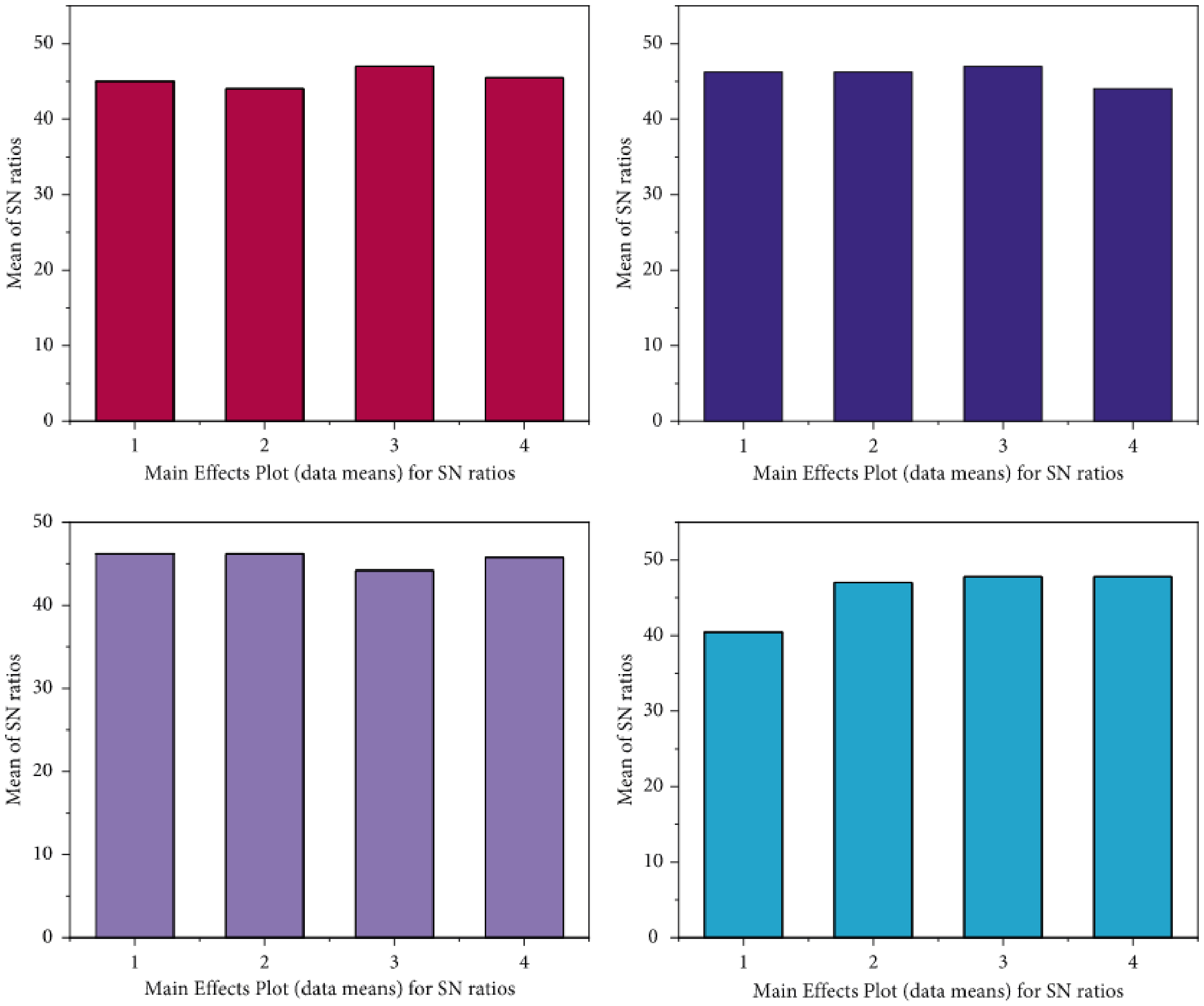


Figure 3: Main effects of the plot for SN ratio.

Particles of second-phase intermetallic were discovered in both materials used in the study. Iron/manganese aluminides were found in alloy 7075's second-phase particles, while eutectic Al-2Cu $^{(\theta)}$particles were found in alloy 5454. Particles in the alloy's second phase 7075 were smaller and finer than those in alloy 5454. The weld contained three unique microstructural zones: SZ, TMAZ, and HAZ. There was a clearly defined SZ/TMAZ and TMAZ/HAZ boundary on the forward-moving side of the TMAZ. Dispersion of these contacts was greater on the retreating side. In comparison to the non-affected foundation materials, the grain structure of the weld nugget did not appear to have changed significantly in the HAZ. Vickers microhardness tests were performed at 0.25 mm intervals across the weld to identify any differences in properties between the various areas of the weld. The hardness of the weld nugget boundaries was significantly reduced when using unmodified 5454. The weld nugget's hardness was significantly lower because it was softer than the 5454 base material. The hardness of the weld nugget retreating side was only marginally reduced in comparison to the 7075-

base material. When compared to a 7075 basic material, the weld nugget had a higher hardness. The predicted hardness rating for base material 5454 was much higher than the actual hardness rating for base material 5454. [27]

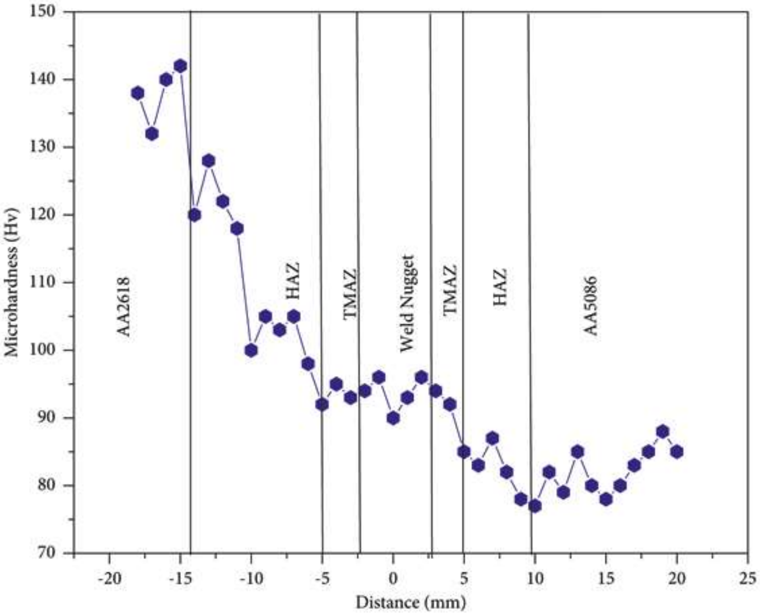


Figure 4: Welding microhardness profile.

FSW was discovered to be the case for producing acceptable butt welds between the two aluminium alloys investigated, demonstrating its ability to weld incompatible aluminium alloys. Despite the fact that FSW of aluminium alloys from various families has been established in previous studies, one distinguishing feature of the welds formed in this work is insufficient metal mixing to cause significant corrosion. [28]

CONCLUSION:

In this study, a statistical optimisation based on experimental work was performed to consider ultimate tensile strength (UTS) and elongation of dissimilar joints by friction stir weld (FSW) between AA5454 and AA7075. A fractional-factorial Taguchi L16 orthogonal array was used to arrange four FSW parameters at four levels. ANOVA was used to determine the main effects and the degree of significance of each parameter on the responses. Furthermore, using optical and scanning electron (SEM) microscopes, the researchers investigated the microstructure and fractography of dissimilar joints and base metals. The main contribution of this work is the development of a comparative study of FSW parameter optimisation using various orthogonal arrays.

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