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Anova Analysis Of Mechanical Properties In Friction Stir Welding Joints Of Aa 7075 And Aa 6063 Alloys

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Friction Stir Welding (FSW) is a novel solid-state bonding technology that is widely used in the aerospace, automotive, and marine industries to improve the mechanical properties of different lightweight alloys. The purpose of this study is to investigate the mechanical properties of friction stir welded joints made of aluminum alloys AA 7075 and AA 6063. Mechanical characteristics such hardness, impact strength, elongation percentage, and tensile strength were tested to evaluate the welded joints' performance. Three primary parameters were optimized for the FSW process using the Taguchi L9 orthogonal array: welding speed (WS), expressed in mm/min; axial force (AF), expressed in kN; and tool rotation speed (TRS), expressed in rpm. The mechanical characteristics of the resulting welded joints were examined after AA 7075 and AA 6063 were bound using nine distinct combinations of these parameters. When ANOVA was used to examine the experimental data, it was easier to determine the ideal process parameters.After using the optimal parameter configuration discovered by RSM, the mechanical properties of the recently built welded joints were assessed against the predicted values. The strong agreement between the predicted and observed results validates the effectiveness of the optimization process. In order to produce high-quality welded joints, process factors must be optimized for better mechanical performance. This paper provides insightful new information on this process.

Keywords: Friction Stir Welding, Aluminum alloys, Mechanical properties, Taguchi method, ANOVA, Optimization, AA6063, AA7075

1. INTRODUCTION

Friction Stir Welding (FSW) constitutes a solid-state joining methodology extensively utilized for the joining of aluminum alloys, largely due to its proficiency in addressing the limitations associated with conventional fusion welding processes. In FSW, a non-consumable, rotating tool equipped with a specifically engineered pin and shoulder is inserted into the interface between two aluminum plates and is subsequently maneuvered along the welding seam. The mechanical friction generated between the rotating tool and the workpieces produces localized thermal energy, thereby softening the material without achieving its melting temperature.The softer material is stirred and packed under the tool shoulder as it advances, resulting in the creation of a strong metallurgical connection as it cools. FSW has several advantages for aluminum alloys since it lessens the possibility of typical defects including porosity, hot cracking, and solidification shrinkage, which are commonly observed in traditional welding techniques. The process also enhances mechanical properties, resulting in increased ductility, tensile strength, and fatigue resistance. These factors make it particularly suitable for use in the railway, automobile, aerospace, and marine sectors, where lightweight, high-strength joints are essential.

In contrast to fusion welding techniques, aluminum alloys like AA5754, AA6061, and AA7075 have undergone extensive research for friction stir welding (FSW) applications. FSW improves the microstructure in the weld zone by dissolving coarse grains and forming a fine, equiaxed grain structure, which improves the mechanical properties. In addition, the procedure delivers great repeatability, energy efficiency, and environmental friendliness. However, optimizing parameters of the process—encompassing rotational velocity, welding rate, axial load, and the configuration of the tool —is essential to prevent defects like tunnel voids, excessive flash, and surface grooves. Recent advancements in FSW, including the use of robotic arms and multi-axis CNC machines, have expanded its industrial applications. Additionally, hybrid techniques such as friction stir processing (FSP) and friction stir spot welding (FSSW) are gaining traction for surface modification and localized repairs in aluminum structures. FSW continues to evolve, with ongoing research focusing on further enhancing weld quality, understanding material flow behavior, and developing tools capable of welding dissimilar aluminum alloys efficiently. Recent developments in FSW have revealed that optimized parameters significantly improve the transformation of microstructures and the resultant mechanical characteristics of aluminum alloys by refining grain structure and eliminating common defects like porosity. Additionally, post-weld mechanical performance is enhanced, particularly in aerospace applications requiring lightweight yet durable joints [1]. Moreover, investigations into Al-Li alloy joints have demonstrated that FSW enhances joint strength and fatigue resistance by minimizing residual stress and promoting uniform grain size distribution. This contributes to the increasing application of Al-Li alloys within the aerospace and automotive sectors, the significance of elevated strength-to-weight ratios is paramount [2]. Similarly, novel methodologies in Friction Stir Welding (FSW), encompassing diverse tool configurations and welding trajectories, have been investigated to enhance the mechanical characteristics of lightweight aluminum alloys further. These advancements enhance joint quality while expanding the potential of FSW in high-precision industries [3]. Meanwhile, research on dissimilar alloys like 2017A and 5083 has shown that FSW produces strong joints by promoting metallurgical bonding at lower temperatures, reducing the likelihood of intermetallic layer formation, and enhancing corrosion resistance [4].

In another study, the welding of AA6061 and AA7075 alloys through FSW exhibited improved mechanical properties compared to traditional welding. Fine-tuned factors, including angular velocity and axial force, were imperative for achieving defect-free welds with superior tensile strength [5]. Interestingly, welding aluminum profiles using FSW achieved enhanced joint efficiency by ensuring uniform microstructure and minimizing heat-affected zones, resulting in improved ductility and mechanical reliability [6]. Process parameter the process of optimization is crucial in regulating weld configuration and its associated mechanical characteristics, as demonstrated in AA2024-AA7075 joints. Effective parameter control enhances weld strength while mitigating defects such as voids and flash formation [7].Additionally, investigations into AA6063-AA7075 dissimilar welds have shown that FSW can overcome challenges related to metallurgical incompatibility, enabling industries to leverage the strengths of different alloys in a single joint [8].

Thermal and mechanical studies on AA6061-AA7075 FSW joints highlight that proper heat management is critical to prevent distortion, ensuring the joint retains mechanical integrity under various loading conditions [9]. The weldability of similar and dissimilar aluminum alloys through FSW improves significantly with optimized process parameters, providing a cost-effective and high-quality alternative to conventional fusion welding methods [10]. Furthermore, predictive models developed for optimizing FSW of dissimilar alloys demonstrate the effectiveness of simulation tools in achieving superior mechanical properties, promoting the widespread adoption of this technique in industrial applications [11]. Studies on the influence of tool pin profiles reveal that specialized tool designs can significantly impact microstructural refinement and tensile strength, particularly in dissimilar alloy joints [12]. Interestingly, incorporating Al_2O_3 nanoparticles into the FSW process has shown to enhance the microstructural properties of AA7075-T6 and AA6061-T6 joints, contributing to higher wear resistance and mechanical performance [13]. The influence of welding parameters on the mechanical and corrosion resistance of AA6082-T6/7075-T6 joints emphasizes the importance of fine-tuning process variables to meet specific operational demands in harsh environments [14].Then, thermo-mechanical analysis of FSW in AA6063 alloy reveals that controlling heat input throughout the procedure, it assumes a crucial function in attaining enhanced mechanical characteristics, contributing to higher productivity and joint reliability [15].

2.MATERIALS AND METHODS

2.1 Base metals

The AA 7075 with AA 6063 joined by using the friction stir welding methodology is depicted in Figure 1, illustrating the process of FSW through the manipulation of tool rotational velocity, axial load, and welding pace.

Figure. 1 Photographic views of clamped specimen

2.2Study of Mechanical Properties FS welded AA 7075 with AA 6063

The examination of the mechanical properties associated with friction stir welding AA 7075 with AA 6063 is imperative for the progression of lightweight structural applications in aerospace, automotive, and marine sectors. These particular aluminum alloys exhibit commendable strength-to-weight ratios; however, their distinct dissimilarity presents obstacles in conventional welding methodologies. Friction stir welding (FSW) presents a solid-state joining methodology that possesses the capability to surmount these obstacles, yielding welds with exceptional mechanical attributes. Comprehending the microstructure, tensile strength, fatigue endurance, and corrosion performance of these welded connections is vital for refining process variables, projecting joint functionality, and ensuring the dependability and security of structures crafted from these materials. This investigation contributes to the enhancement of more effective and resilient lightweight constituents, ultimately resulting in enhanced fuel efficiency and diminished environmental footprint across diverse transportation domains.

3.Testing

3.1Tensile Strength

The tensile strength of joints formed by friction stir welding of AA 7075 and AA 6063 alloys plays a vital role as a critical parameter indicating both weld quality and structural integrity. This characteristic directly signifies the joint's capacity to endure external forces, a fundamental necessity for their utilization in aerospace, automotive, and similar sectors employing these lightweight metal alloys. Through the assessment of tensile strength, engineers can finely tune welding variables, juxtapose joint efficacy against original materials, and judiciously determine design choices. Such a feature aids in the anticipation of potential failure mechanisms, the establishment of stringent quality assurance protocols, and the assurance of compliance with mandatory safety criteria for welded components (figure 2). Ultimately, the enhancement and comprehension of tensile strength in these dissimilar alloy joints contribute significantly to the advancement of more dependable, effective, and high-performance lightweight frameworks, thereby fostering innovation across diverse engineering domains.

Figure. 2. Tensile strength specimens of FS welded AA 7075 with AA 6063

3.2 Elongation

The elongation percentage serves as a crucial parameter in the evaluation of friction stir welded connections between AA 7075 and AA 6063, representing the ductility and formability of the materials post-welding. This attribute is crucial for assessing the joint's response to various loading conditions, appraising the comprehensive integrity of the weld, and determining the extent of plastic deformation the joint can endure prior to failure. Elevated weld ductility, which is often associated with improved fatigue endurance and superior functionality under dynamic loading circumstances or when post-weld alterations are required, is signified by higher elongation ratios. When it comes to dissimilar joints—like AA 7075 coupled with AA 6063—the elongation % provides important information about how different material qualities may be successfully integrated at the weld contact. Such insights are instrumental in optimizing welding parameters, comprehending the microstructure of the weld, and ensuring the durability of the assembled components under designated service conditions to avert premature failure. Ultimately, the examination of elongation percentage aids engineers in crafting safer and more dependable structures and components utilizing these heterogeneous aluminum alloys interconnected via friction stir welding (table 1).

Table 1. Elongation of AA 7075 with AA 6063

S. No.	TRS (rpm)	AF (kN)	WS (mm/min)	Elongation (%)

1	1000	4	30	10.35
2	1000	5	45	11.54
3	1000	6	60	11.26
4	1100	4	45	12.21
5	1100	5	60	11.28
6	1100	6	30	10.04
7	1200	4	60	10.26
8	1200	5	30	14.62
9	1200	6	45	11.24

3.3 Study of Impact Strength

Impact strength represents a critical characteristic in friction stir welded interface between AA 7075 and AA 6063 utilizing the FSW methodology. When suddenly exposed to dynamic stresses, it serves as an essential parameter for assessing the material's capacity to absorb energy and resist fracture. This specific characteristic is very important for heterogeneous alloy joints because it shows how resilient the weld is to shock loads and how long it can last before failing catastrophically (figure 3). Elevated impact strength indicates a well-coalesced weld zone with higher energy absorption characteristics. This kind of capacity is necessary in industries like aircraft and automotive, where parts are expected to withstand sudden hits or accidents. When it comes to friction stir welding AA 7075 and AA 6063, engineers may evaluate the joint's susceptibility to fracture initiation and propagation by understanding impact strength. This is crucial because of the unique mechanical properties of these alloys. This insight contributes to the development of more robust and secure structures, as well as the optimization of welding parameters and joint performance predictions across diverse operational conditions. Enhancing impact strength is crucial for fabricating lightweight components that are both reliable and durable, thereby augmenting the overall performance and safety of products designed for critical applications.

Figure. 3. Impact tested specimens of FS welded AA 7075 with AA 6063

3.4 Micro Hardness

Microhardness constitutes a crucial attribute in the examination of friction stir welded connections comprising AA 7075 and AA 6063, offering significant insights into the localized mechanical properties within distinct regions of the weld. The significance of this characteristic is particularly pronounced in dissimilar alloy joints due to its capacity to unveil the hardness profile in the fusion nugget, thermally and mechanically influenced region (TMIR), and thermally impacted zone (TIZ), reflecting the intricate microstructural alterations brought about by the welding operation (table 2). The analysis of microhardness aids in deciphering the influence of welding parameters on the particular strength and ductility of the joint is a subject of great importance given the divergent nature of the properties of AA 7075 and AA 6063. This data proves instrumental in enhancing the welding procedure to attain a more uniform distribution of hardness, thereby reducing vulnerabilities in the joint.

Table 2. Micro Hardness of AA 7075 with AA 6063

S. No.	TRS (rpm)	AF (kN)	WS (mm/min)	Micro Hardness
1	1000	4	30	110.4
2	1000	5	45	129.1
3	1000	6	60	124.3
4	1100	4	45	130.2
5	1100	5	60	117.8
6	1100	6	30	120.8
7	1200	4	60	118.4
8	1200	5	30	129.2
9	1200	6	45	108.2

Moreover, microhardness findings are interconnected with other mechanical attributes such as tensile strength and wear resistance, rendering it a valuable instrument for forecasting the overall performance of the joint. Through an examination of microhardness fluctuations, engineers can enhance their comprehension the influence of welding variables on the particular strength and ductility of the joint, a subject of, and ultimately devise more dependable and robust friction stir welded components suitable for applications in industries like aerospace, automotive, and others necessitating lightweight structures with high performance capabilities.

4.Microstructural Analysis

4.1 SEM analysis

Scanning Electron Microscopy (SEM) analysis of aluminium alloys AA6063 and AA7075 reveals distinct microstructural characteristics due to their different compositions and heat treatments. AA6063, a medium-strength alloy with high corrosion resistance, typically shows a uniform distribution of α-Al grains with secondary phases like Mg2Si precipitates dispersed along grain boundaries, enhancing mechanical properties. In contrast, AA7075, a robust alloy predominantly utilized in the aerospace sector demonstrates a more intricate microstructure characterized by coarse grains and the occurrence of intermetallic phases such as Al2CuMg (S-phase) and Al7Cu2Fe. These precipitates, along with η-phase (MgZn2) particles, contribute to its superior strength but lower corrosion resistance compared to AA6063. SEM analysis also highlights the surface morphology and fracture patterns, with AA6063 displaying ductile fracture features (dimples) and AA7075 showing more brittle fracture characteristics due to the hard intermetallic phases.

5.Result and discussion

5.1 Tensile strength

Figure 4 depicts a contour plot illustrating the Tensile Strength (MPa) concerning X1 (A: TRS - Tool Rotational Speed in rpm) on the horizontal axis and X2 (B: AF - Axial Force in kN) on the vertical axis. It constitutes a fundamental element of a RSM analysis directed towards the enhancement of variables related to the friction stir welding of aluminum alloys 6063 and 7075. Achieving a Tool Rotational Speed (TRS) approaching 1200 rpm.with a notable Axial Force (AF) of approximately 6 kN results in the highest tensile strength. Conversely, low TRS values combined with moderate to high AF levels are associated with the lowest tensile strength. The rise in both TRS and AF indicates a steady improvement in tensile strength. One specific variable, C, is held constant at 45 and is probably the welding speed. This graphical depiction facilitates the understanding of the interplay between Tool Rotational Velocity and Axial Load in influencing the Tensile Integrity of the welded interface. This indicates that the refinement of these variables can markedly improve the tensile integrity of the friction stir welded joint comprising the designated aluminum alloys.

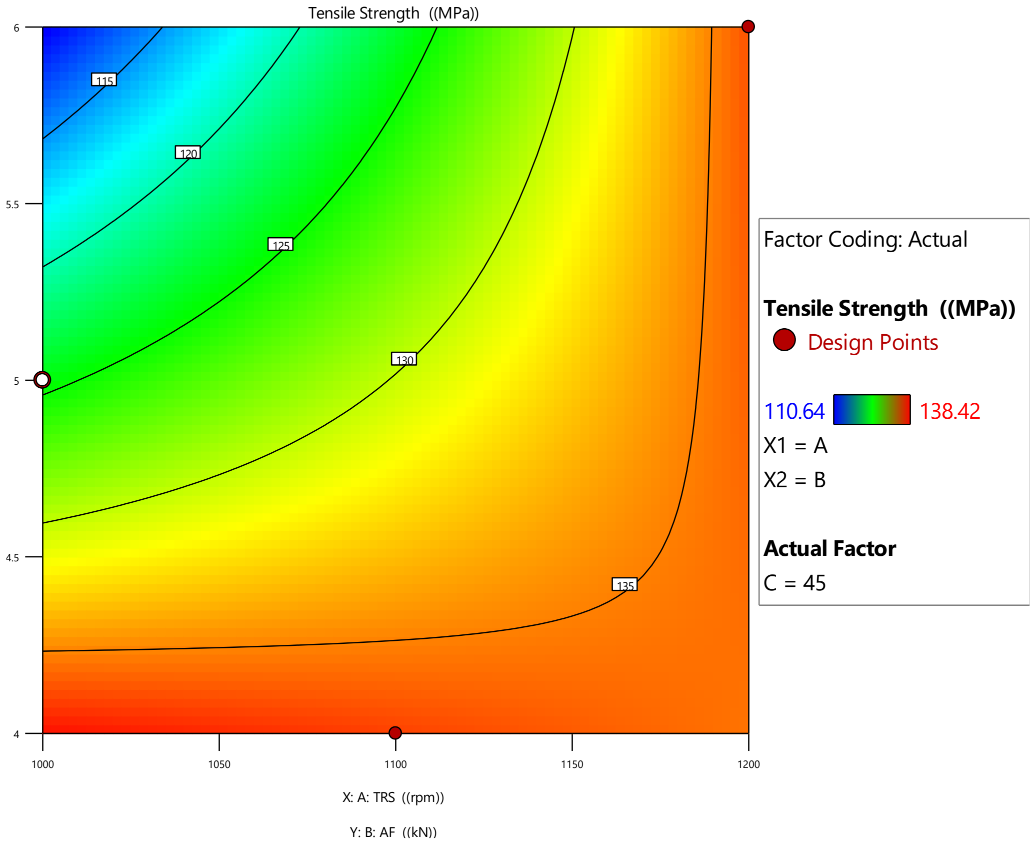

Figure. 4 Contour plot for Tensile Strength of FSW Joint with AFand TRS

The figure 5 Ilustre the 3D surface plot that demonstrates an an examination employing Response Surface Methodology (RSM) to assess the tensile strength quantified in MPa. The study centers on two variables, specifically X1 (A-TRS, varying from 1000 to 1200 ppm) and X2 (C-WS, fluctuating between 30 to 60 mm/min). By observing the response surface, one can observe the manner in which tensile strength fluctuates in response to variations in these two factors, showcasing values that span from 110.64 to 138.42 MPa, visually represented through a color spectrum transitioning from blue to red. Within the plot, there are two specific design points highlighted: one positioned above the surface (depicted in red) and another below (depicted in white). This graphical representation employs actual factor coding, maintaining factor B at a constant value of 5. Such visualization serves to enhance comprehension regarding the correlation between A-TRS and C-WS with regard to the tensile strength of the material, a relationship likely intertwined with the formulation or processing of Formulated Waste Simulant (FWS) as discussed in preceding analyses.

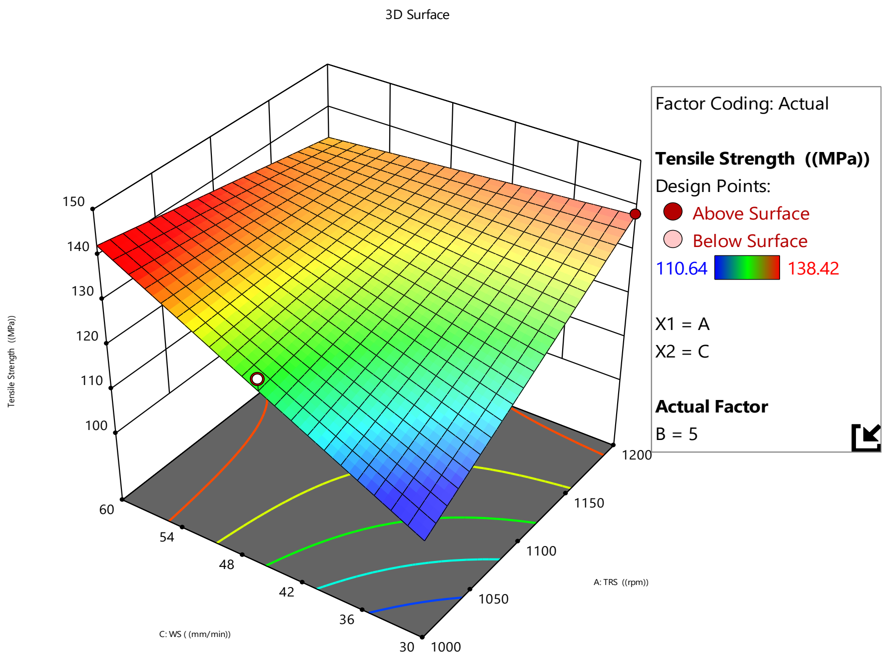

Figure. 5. 3D surface plot between Tensile Strength,Welding speed and TRS

5.2 Impact strength

Factor coding is represented through coding, while the sum of squares follows the Type III – Partial approach. The Model F-value of 10.25 suggests that there exists a 9.15% the likelihood of encountering an F-value of this magnitude purely as a result of random fluctuations. Model components are regarded as statistically significant when P-values are below 0.0500. In the present analysis, terms A, B, C, AB, and BC are deemed statistically significant. In contrast, P-values exceeding 0.1000 suggest a lack of significance in the model components. When multiple model components are classified as insignificant (excluding those required for the preservation of hierarchy), the model refinement could enhance the overall model, please refer to table 3 for more details.

Table 3. ANOVA for 2FI model Response 3: Impact Strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	27.33	6	4.56	10.25	0.0915	significant
A-TRS	15.48	1	15.48	34.83	0.0275	
B-AF	11.01	1	11.01	24.76	0.0381	
C-WS	12.60	1	12.60	28.34	0.0335	

AB	8.60	1	8.60	19.34	0.0480	
AC	6.88	1	6.88	15.48	0.0589	
BC	17.36	1	17.36	39.05	0.0247	
Residual	0.8889	2	0.4444			
Cor Total	28.22	8				

The illustration depicted in figure 6 presents a 3D surface plot that elucidates the correlation between Impact Strength, measured in Joules, and two variables i.e. Axial force (AF) and tool rotational speed (TRS) are important variables in the field of friction stir welding techniques. The X-axis shows TRS values between 1000 and 1200 RPM, the Y-axis shows AF values between 4 and 6 kN, and the Z-axis shows Impact Strength, which varies between around 16 and 30 Joules. Blue to red color gradients represent decreasing to increasing Impact Strength levels. The graphical representation shows a significant gain in Impact Strength along with an increase in TRS and AF. There is a discernible change from low Impact Strength (low TRS and low AF) in the lower-left quadrant to raised Impact Strength (high TRS and high AF) in the upper-right quadrant.

The accompanying legend indicates that the Welding Speed parameter is maintained consistently at 45 mm/min. Three distinct data points are identifiable on the graph. The Impact Strength associated with the welding process typically exhibits enhanced results with increased values of both parameters, whilst keeping the Welding Speed constant at 45 mm/min.

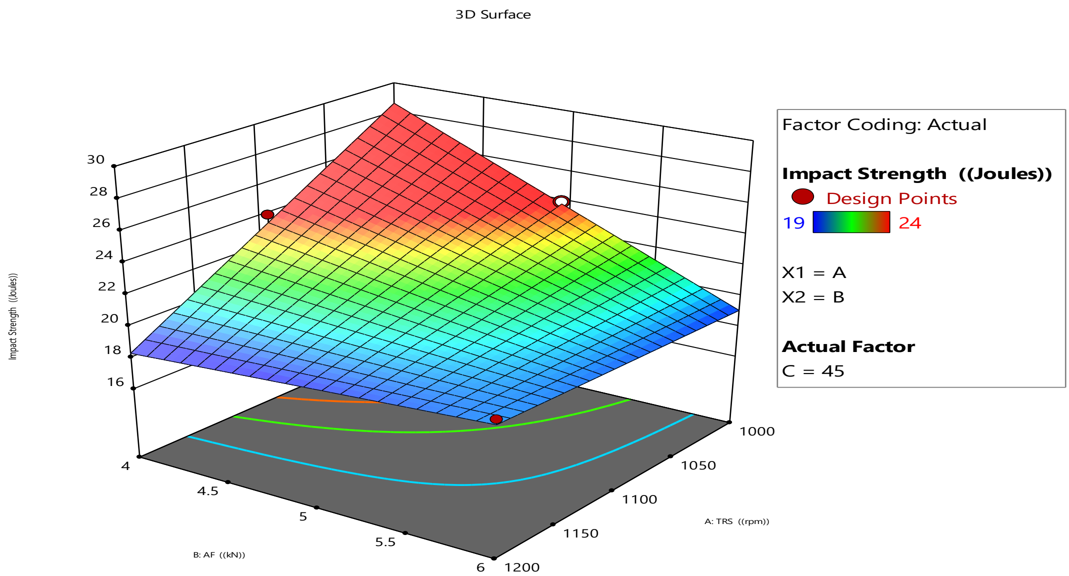

Figure.6. 3D surface plot for Impact strength with TRS and AF

5.3Elongation

The Figure 7 illustrates a contour plot derived from an analysis by using Response Surface Methodology (RSM), with a focus on elongation (%) as the response parameter. Specifically, the plot shows the correlation between two variables, X1 as TRS spanning from 1000 to 1200 ppm on the horizontal axis and X2 as AF ranging from 4 to 6 kN on the vertical axis. The elongation percentages range between 10.04% and 14.62%, distinguished by a color spectrum. The contours visible in the plot imply a general trend of increasing elongation with higher levels of both TRS and AF, with the maximum elongation values concentrated in the top right corner of the plot. This visual representation aids in comprehending the impact of alterations in TRS and AF on the elongation characteristics of the material, which are likely associated with the FWS analys

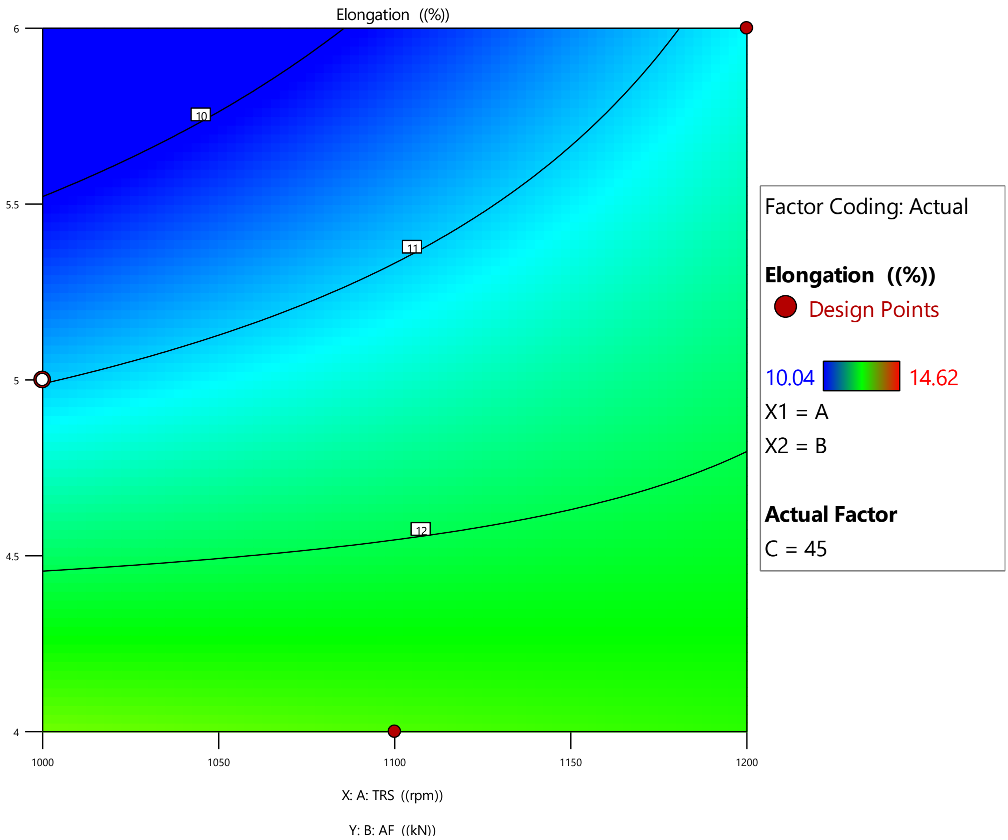

Figure.7. Contour plot for elongation (%) with AF and TRS

The figure 8 depicts 3D surface plot showcasing the outcomes of an analysis conducted using Response Surface Methodology (RSM), in the context of Friction Stir Welding

(FSW) procedure. This graphical representation elucidates the correlation among three variables of X1 as TRS in rpm on the x-axis ranging from 1000 to 1200 rpm, X2 as WS in mm/min on the other x-axis ranging from 30 to 60 mm/min, and Elongation (%) on the y-axis spanning from 10.04% to 14.62%. The morphology of the surface reveals the impact of TRS and WS combinations on elongation percentage, with greater elongation seemingly achievable with elevated TRS values and moderate to high WS values. The curvature of the surface implies a multifaceted interplay between the input parameters, showcasing a peak in elongation at specific combinations of TRS and WS. This visual representation facilitates prompt identification of optimal process parameters for maximizing elongation in the FSW process, elucidating how the two input variables interact to influence the final result.

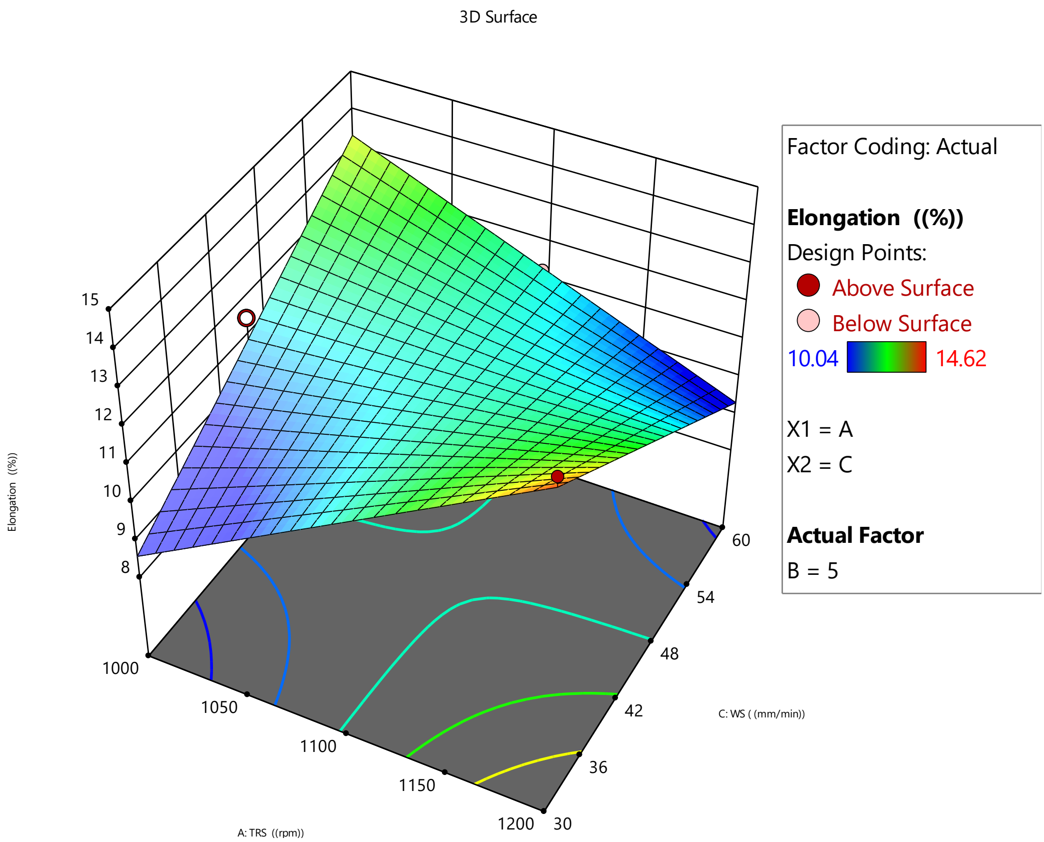

Figure. 8. 3D surface plot between Elongation (%),WS and TRS

5.4 Microhardness

The graph depicted in Figure 9 illustrates a "Predicted vs. Actual" chart displaying Micro Hardness values. The x-axis corresponds to the measured values, while the y-axis illustrates the predicted values. Each data point is color-coded according to its Micro

Hardness value, varying from blue (108.2) to red (130.2). The diagonal line symbolizes ideal prediction, where the predicted values align perfectly with the actual values. The majority of points are closely grouped around this line, indicating a generally high level of predictive accuracy exhibited by the model. A noticeable pattern emerges from the lower values (blue points) at the lower left to the higher values (red points) at the upper right. Some points exhibit slight deviations from the line, indicating minor inaccuracies in prediction. An outlier point (white with a dark outline) stands out, displaying a more significant deviation from the overall trend. In conclusion, this plot suggests that the predictive model for Micro Hardness performs admirably, with predictions closely resembling actual values across the measurement spectrum, albeit with some minor discrepancies

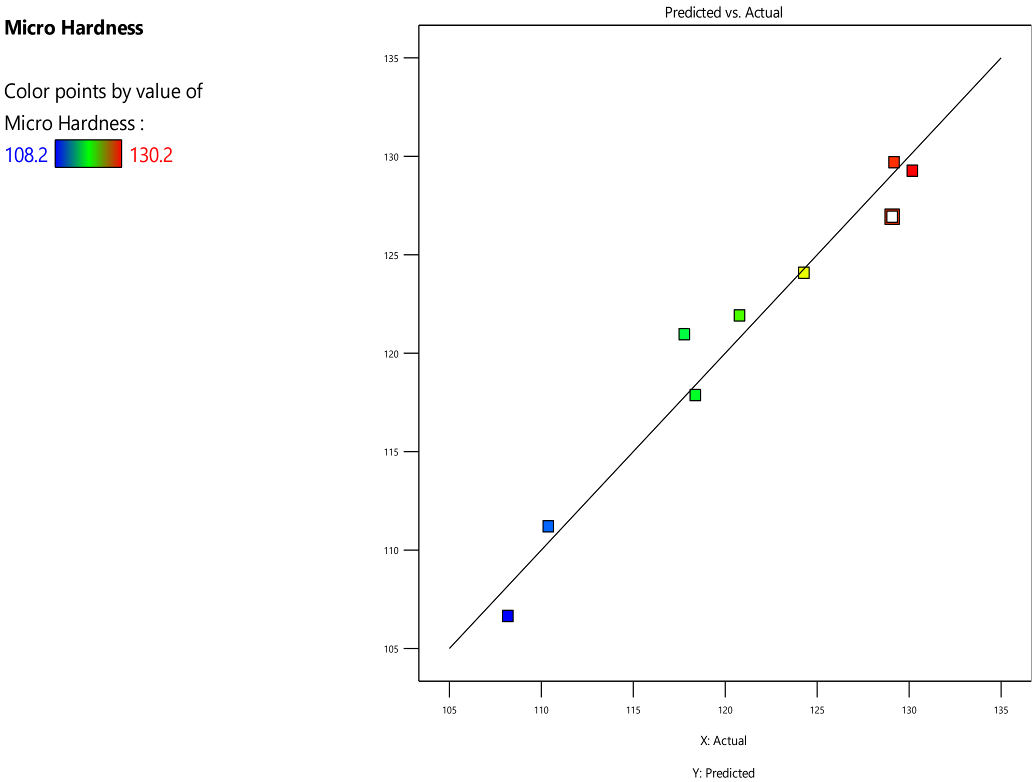

Figure.9. Predicted vs. Actual for Micro Hardness

The diagram in figure 10 depicts a 3D surface plot that illustrates the correlation between Micro Hardness (on the vertical axis) and two variables: X1 (A: TRS) and X2 (B: AF). The surface gradient spans from blue (with lower values at approximately 108.2) to red (with higher values at around 130.2). The range of X1 (TRS) is from 1000 to 1200, while X2 (AF) varies between 4 and 6. The plot reveals a trend where Micro Hardness generally rises with increases in both X1 and X2, reaching peak values in the top right quadrant. Three specific design points are indicated: two above the surface and one below it. An observation of "Actual Factor C = 45" is included, indicating that this plot showcases a segment of a more intricate dataset where C remains constant. This graphical representation facilitates the examination of how variations in factors A and B influence changes in Micro Hardness within a context that seems to relate to materials science or engineering.

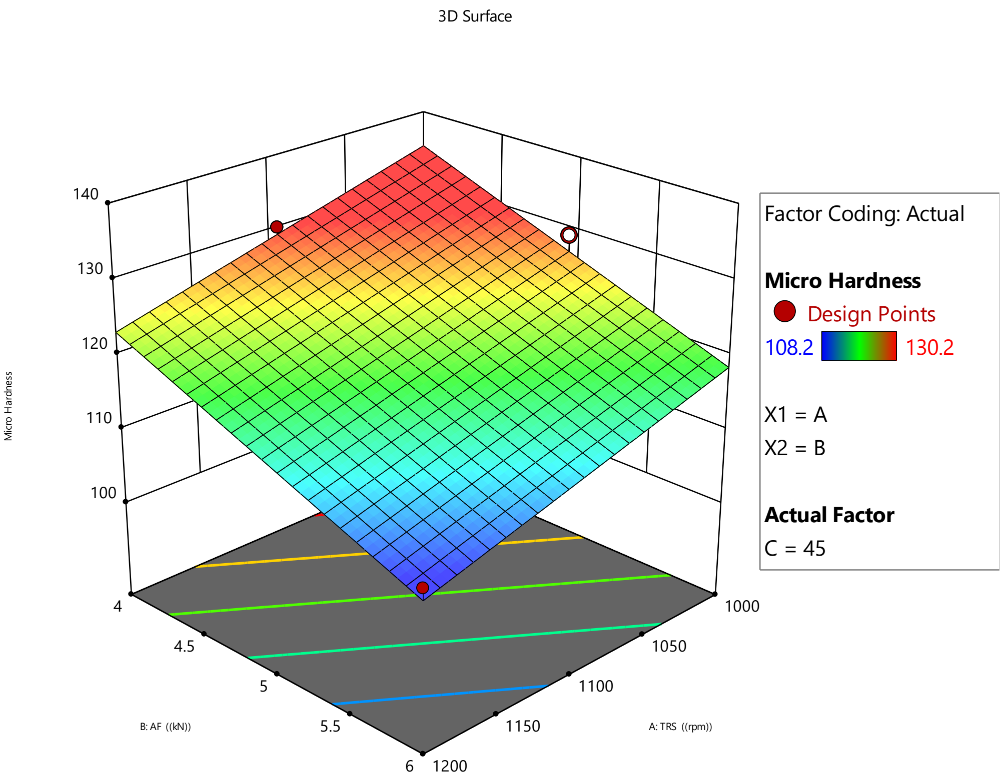

Figure. 10. 3D surface plot for Micro Hardness with AF and TRS

5.5 Microstructural Analysis

Microstructural analysis of FSW joints is essential for optimizing weld quality by examining grain size, orientation, and distribution across zones like the nugget zone, TMAZ, and HAZ. This analysis helps detect defects, understand the relationship between process parameters and joint properties, and predict performance under stress, fatigue, or corrosion. SEM analysis of fracture surfaces reveals patterns affected by the velocity of tool rotation, the rate of welding, and the axial force applied, affecting ductility and elongation (figure 11). Joints with higher tool speeds and forces exhibit larger spacing between pitch lines, indicating lower ductility, while closer markings suggest better elongation. Ductile fractures show dimples, and early void formation correlates with tensile strength variations, with cleavage patterns more visible under lower axial forces

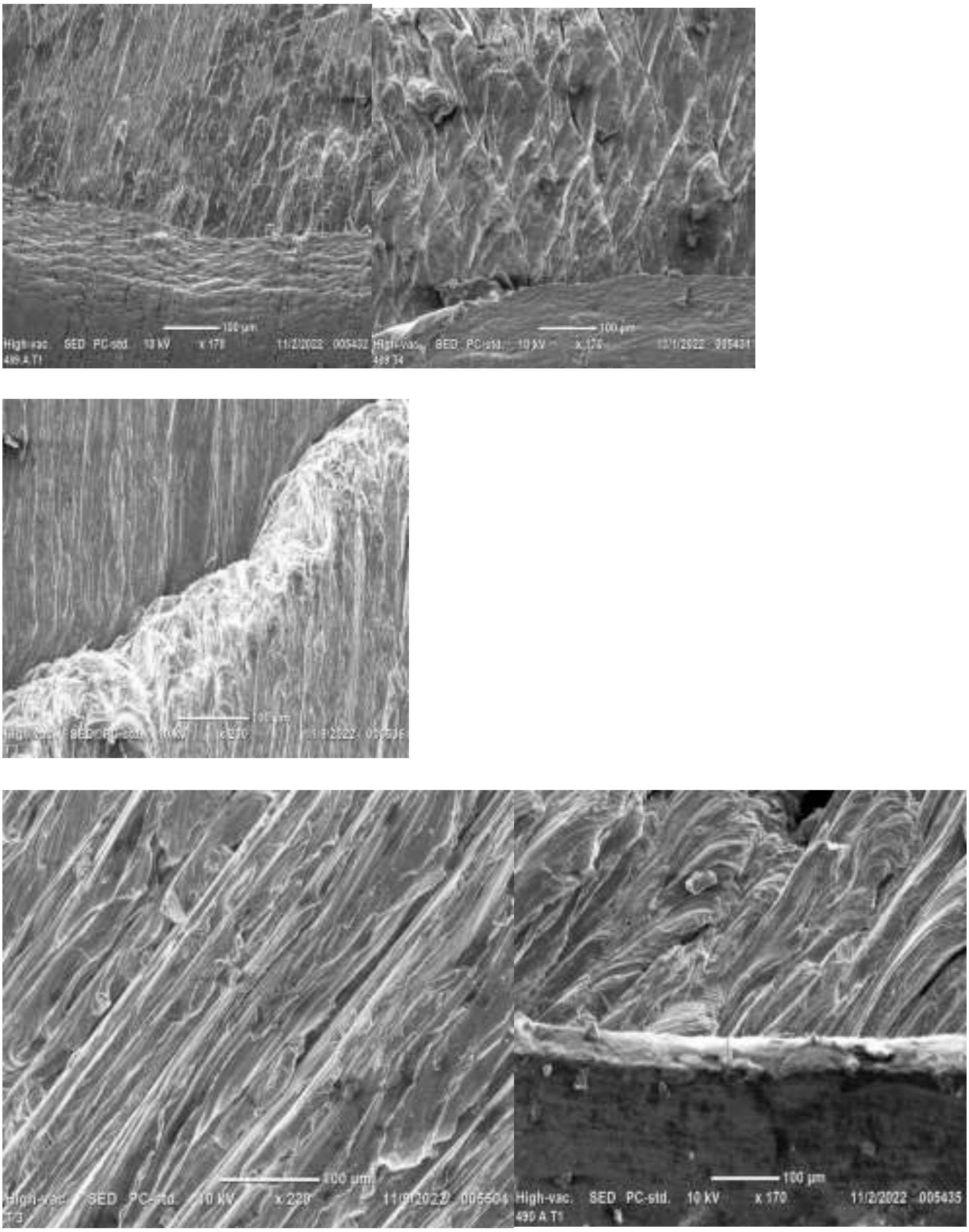

Figure. 6.11. SEM fractographs tensile specimens in Sample 1 to 5

6.Conclusion

This paper primarily focuses on the mechanical characteristics of friction stir welded (FSW) joints made of AA7075 and AA6063 aluminum alloys. The evaluation of critical mechanical qualities includes hardness, tensile strength, impact resistance, and percentage elongation. These are crucial indicators of the lifespan and functionality of the welded joints. The Analysis of Variance (ANOVA) method was used to determine process variables such tool design, traverse speed, and rotation speed in order to guarantee the best possible quality in the welding process. The importance of different process factors and their interactions may be established with the use of ANOVA, which helps determine the best circumstances for welding AA7075 and AA6063.Following the mechanical testing of the FSW specimens, Response Surface Methodology (RSM), a statistical approach investigating the connection between process parameters and mechanical qualities, was used to further evaluate the data. Following the creation of more FSW joints using the optimal parameter set identified by ANOVA, the mechanical properties of the welded materials were evaluated and compared to the values predicted by the statistical models. This comparative study validates the prediction models and shows that optimal parameters result in improved mechanical performance, providing valuable insights into the design of reliable, high-strength joints for industrial applications.

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