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Effect of Process Parameters on Mechanical Properties of Friction Stir Welded AA6061-T6 Alloy

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Abstract

Friction Stir Welding (FSW) is a solid-state joining process frequently employed to join aluminum alloys because it offers defect-free joints with excellent mechanical properties. This work examines the influence of welding parameters on the mechanical properties of AA6061-T6 aluminum alloy welds. A Taguchi L16 orthogonal array was employed to study the effect of rotational speed, traverse speed, axial force, and tool tilt angle. A constant geometry H13 steel tool was used to perform experiments, and tensile strength, microhardness, and percentage elongation were measured. The outcomes demonstrate that all the process parameters have a profound influence on the weld quality, but rotational speed is found to be the most influential, followed by axial force, traverse speed, and tool tilt angle as per ANOVA analysis. A nonlinear trend of mechanical properties was observed as a result of interaction effects between heat input, material flow, and deformation. The best combination of process parameters (1400 rpm, 60 mm/min, 6 kN, and 1°) produced the highest tensile strength (235 MPa), hardness (83 HV), and elongation (13%). These improved mechanical properties are due to better mixing and dynamic recrystallization in the stir zone. The research shows that the choice of process parameters is essential to produce high-quality friction stir-welded joints in AA6061-T6 aluminum alloy.

1. Introduction

Friction Stir Welding (FSW), invented by The Welding Institute in 1991, is a solid-state welding process that has gained significant interest for its ability to produce a sound joint without melting the base materials. FSW differs from traditional fusion welding processes in that it involves the generation of heat and plastic deformation due to the passage of a rotating, non-consumable tool with a shoulder and a pin [1]. The tool's contact with the workpieces results in the generation of frictional heat, which softens the material and allows it to flow plastically and be consolidated by the applied axial force to produce a joint. The literature reported that a series of microstructural zones, including the stir zone, thermo-mechanically affected zone, and heat-affected zone with different microstructural and mechanical properties, are formed. FSW does not involve melting and therefore avoids defects like porosity and solidification cracking associated with fusion welding, enhancing the joint quality. Additionally, the dynamic recrystallization that occurs in the stir zone results in grain refinement, improving the mechanical properties of the joint. These benefits have led to the successful application of FSW for various aluminum alloys and its growing use in advanced materials, and it has become an important process in manufacturing and structural applications [2].

Friction stir welding tool geometry classification and design are critical elements in friction stir welding, as they play a crucial role in heat generation, material flow patterns, and overall joint integrity. The FSW tool is essentially composed of two parts: a shoulder and a pin, both playing distinct roles in the welding process. Previous research categorizes pin profiles into cylindrical, threaded, square, triangular, and tapered shapes, each resulting in different material flow patterns. Non-cylindrical pin geometries, like square and triangular shapes, create pulsating stirring, resulting in better mixing and refinement of the stir zone's grain size [3]. However, cylindrical threaded and tapered pins promote material flow in the vertical direction, preventing the formation of internal defects (including voids and tunnels). Shoulder design is also important, as it generates the bulk of the heat and retains the material. Flat, concave, and scrolled shoulders have been widely investigated, and concave and scrolled shoulders show superior consolidation and less flash. Recent studies highlight the need to consider the interaction between pin and shoulder designs rather than the designs in isolation. Although a variety of designs have been studied, there is no single optimal design, further underscoring the intricate relationship between process parameters and material behavior [4].

The heat generation and its distribution are key factors influencing the microstructural development and mechanical properties of friction stir welded joints. FSW generates heat primarily due to friction between the rotating tool shoulder and workpiece surface, as well as heat generated from the plastic deformation caused by the tool pin. According to published research, most heat is generated by the shoulder, with the pin surface contributing to heat generation and mixing of the workpiece. Process settings, such as shoulder diameter and pin design, have a significant impact on the temperature and its distribution in the weld zone [5]. Increasing shoulder diameter typically results in higher heat generation, promoting plasticization of the workpiece material, but it may also cause excessive softening in temperature-sensitive materials. On the other hand, intricate shapes of the pin, such as threaded and polygonal, promote localized heat generation and result in a more homogeneous heat distribution. Finite element and computational fluid dynamics modeling and simulations show that temperature fields on the advancing and retreating sides of the weld are not symmetric, affecting residual stresses and microstructural evolution. These results are confirmed by experimental methods such as thermocouple measurements and infrared thermography. Hence, it is important to obtain a desirable temperature profile by designing the tool to avoid weld defects, fine microstructures, and enhanced mechanical properties [6].

The flow dynamics during friction stir welding of metals are critical to the quality, integrity, and properties of the weld. During this process, severe plastic deformation and frictional heating, which renders the material around the rotating tool soft, lead to intricate flow within the stir zone. Literature reports suggest that material flow during welding is significantly affected by process parameters, especially tool pin profile and shoulder design, which dictate the flow direction, speed, and consistency [7]. Distinct flow patterns, including onion rings, vortexes, and retreating/advancing side flow asymmetry, have been frequently reported. Complex pin shapes such as the use of grooved and non-cylindrical pins lead to improved longitudinal and transverse material flow, better mixing, and lower defect formation. On the other hand, conventional cylindrical pins might not be efficient enough to generate sufficient stirring, thereby causing insufficient consolidation [8]. Recent experimental techniques, such as marker insertion and flow visualization, and numerical simulations based on computational fluid dynamics (CFD) and finite element analysis (FEA), have greatly enhanced the understanding of these complex flow patterns. But conflicting results from different materials and process conditions suggest that there are still gaps in understanding of material flow mechanisms [9].

The interplay between process parameters and process outcomes is a crucial aspect of the thermo-mechanical responses and quality of friction stir welded joints. While process parameters define the fundamental processes of heat generation and material flow, process parameters, including rotational speed, traverse speed, and axial pressure, control the magnitude and distribution of these processes [10]. The literature frequently refers to the fact that the same tool geometry can lead to different results in terms of the quality of the weld when subjected to different process parameters, highlighting the influence of interaction between process parameters. Thus, increasing rotational speed might increase the heat input and improve the plasticization if using a threaded pin or a square pin but could result in excessive flash formation or grain coarsening if a simpler geometry is used. Likewise, traverse speed impacts the dwell time of the material under the tool, playing a role in consolidation and defect formation based on the tool geometry. The interaction between tool design and process parameters affects aspects such as material mixing, microstructural development, and mechanical performance (such as tensile strength and hardness) [11].

2. Research gap

Existing studies on friction stir welding mostly consider the individual influence of process parameters (or process parameters), but limited attention is paid to interactions. There are few studies on the interaction between a complex pin profile and different rotational and traverse speeds under the same conditions. There are inconsistencies in the reported mechanical properties due to differences in experimental parameters and materials used [12]. Research mainly focuses on aluminum alloys, with little research on new and different materials. The real-time flow and thermal behavior are rarely covered. Simulations may not always match the experimental results due to the simplification of thermo-mechanical behavior, and the need for holistic and integrated analysis becomes apparent.

3. Materials and Methods

Base Material Selection

In the current study, the base material was chosen to be AA6061-T6 aluminum alloy because of its good weldability, moderate strength, and suitability for industrial applications in aerospace, automobile, and structural applications. The material is very sensitive to thermo-mechanical treatment and is therefore ideal for studying the interaction between process parameters and process parameters in friction stir welding [13]. Its precipitation-hardened structure can be used to study the microstructural changes, particularly grain refinement in the stir zone resulting from dynamic recrystallization.

The alloy was obtained in the form of rolled sheets and was cut to the size of 150 mm × 100 mm × 6 mm. The surfaces were mechanically polished and cleaned with acetone to remove oxides, oil, and dirt before welding to ensure effective interaction between the tool and the workpiece and to avoid defects in the weld zone [14].

Chemical Composition of AA6061-T6

Table 1: presents the chemical composition of the selected base material.

Element	Al	Mg	Si	Fe	Cu	Cr	Zn	Ti
wt.%	Bal.	0.8–1.2	0.4–0.8	≤0.7	0.15–0.4	0.04–0.35	≤0.25	≤0.15

Tool Design and Geometry

The friction stir welding tool was made of H13 tool steel due to its high hot hardness, resistance to wear, and high-temperature resistance during welding. The tool is made up of two parts: a shoulder and a pin (probe). For the current work, the shoulder diameter was fixed at 18 mm, and the effect of the pin geometry was studied [15].

We chose three pin geometries based on their relevance in the literature and their potential effect on material flow:

- Cylindrical pin
- Threaded cylindrical pin
- Square pin

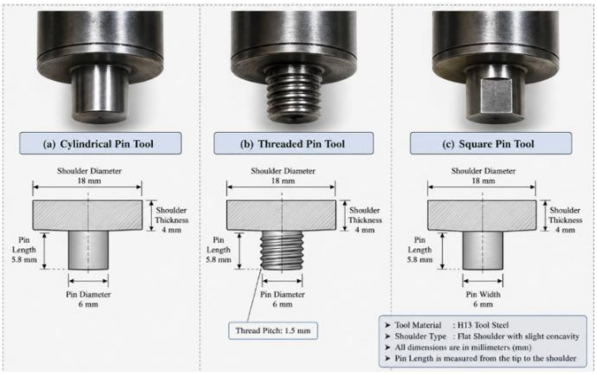


FIGURE 1: Illustrates the different tool geometries used in the study

Parameter	Value
Tool Material	H13 Tool Steel
Shoulder Diameter	18 mm
Pin Length	5.8 mm
Pin Profiles	Cylindrical, Threaded, Square

Table 2: Tool Specifications

The friction stir welding process was conducted on a vertical milling machine that was modified for welding. The plates to be welded were tightly clamped on a backing plate. The tool was given a rotational and translational motion along the joint line.

The factors considered in this study were:

- Rotational speed (rpm)
- Traverse speed (mm/min)
- Force (kN) (constant)

Process Parameters and Experimental Design

To understand the impact of the interaction between process parameters and process parameters on the weld quality, a systematic experimentation approach was followed. The process parameters selected were rotational speed, traverse speed, axial force, and tool tilt angle, which were found to play a critical role in heat generation, material flow, and joint consolidation [16].

Four levels for each parameter were chosen to explore a broader range of the process and to facilitate the study of interactions. The Taguchi L16 orthogonal array was used to optimize the experiments, minimizing the number of experiments while ensuring statistical validity.

Table 3: Process Parameters and Their Levels

Parameter	Level 1	Level 2	Level 3	Level 4
Rotational Speed (rpm)	800	1000	1200	1400
Traverse Speed (mm/min)	40	60	80	100
Axial Force (kN)	4	5	6	7
Tool Tilt Angle (°)	1	1.5	2	2.5

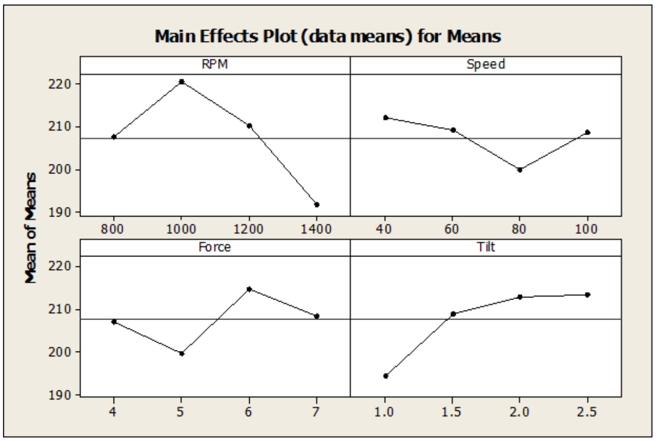
Table 4: L16 Experimental Design Matrix

RPM	Speed	Force	Tilt	UTS (MPa)	Hardness (HV)	Elongation (%)
800	40	4	1.0	198	58	8.2
800	60	5	1.5	210	62	8.9
800	80	6	2.0	200	65	9.6

800	100	7	2.5	222	61	8.5
1000	40	5	2.0	229	73	10.2
1000	60	4	2.5	215	71	9.8
1000	80	7	1.0	208	80	10.8
1000	100	6	1.5	230	83	10.0
1200	40	6	2.5	235	75	11.2
1200	60	7	2.0	218	72	10.4
1200	80	4	1.5	210	70	11.6
1200	100	5	1.0	178	67	12.3
1400	40	7	1.5	186	72	10.9
1400	60	6	1.0	194	69	10.1
1400	80	5	2.5	182	76	12.5
1400	100	4	2.0	205	79	13.0

4. Results and Discussion

The experimental data show a non-linear but physically plausible dependence of the mechanical properties of friction stir welded AA6061-T6 joints on the process parameters. The main effects plot reveals that all of the process parameters affect the tensile strength non-linearly, which suggests that the right operating conditions need to be found to achieve the best possible welding results [17].



Effect of Rotational Speed (RPM)

At a rotational speed of 800 rpm, the average tensile strength is approximately 207.5 MPa, suggesting that moderate heating and plasticization occur. With an increase in rpm to 1000, the mean strength increases to 220.5 MPa, which is the optimum condition for material softening and plasticization. This is due to increased frictional heat, which aids in mixing and consolidation of material in the stir zone [18]. But a further increase in speed to 1200 rpm leads to a slight decrease in average strength to 210.25 MPa, implying that excessive heat has been introduced. At 1400 rpm, the mean strength plummets to almost 191.75 MPa due to excessive heat, which softens the material, thereby decreasing forging efficiency. The weakening of resistance to deformation at higher speeds due to excess heat results in poor-quality joints. Therefore, a rotational speed of 1000 rpm is found optimum in this study [19].

Effect of Traverse Speed

The average tensile strength at 40 mm/min is ~212 MPa, indicating adequate heat input as a result of increased dwell time. As the speed rises to 60 mm/min, the strength slightly decreases to ~209.75 Mpa, but at 80 mm/min, it significantly decreases to ~200 Mpa. This is likely due to the reduced heat input and plasticization with the increased traverse speed of the tool. Surprisingly, the strength rises again at the highest speed, 100 mm/min (to ~208.75 Mpa), implying that some parameter sets at higher speeds can offset the loss of heat. However, the overall trend is that lower-to-moderate traverse speeds yield the best results, and a sufficient thermal exposure during welding is essential [20].

Effect of Axial Force

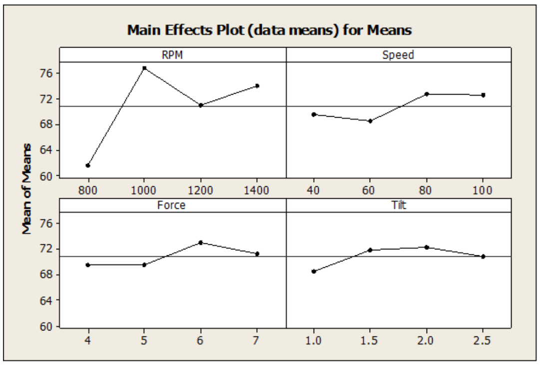
The average strength increases from 4 kN (207 MPa) to 5 kN (199.75 MPa), showing inadequate compaction at the latter force. At 6 kN, the strength has a maximum value of ~214.75 MPa, showing the best forging process, which increases the material compaction and eliminates the defects. But when the axial force is increased to 7 kN, a slight decrease in strength is observed (~208.5 MPa), perhaps due to excess material expulsion or an unstable weld zone. Thus, 6 kN is the optimum axial force for obtaining high joint strength [21].

Effect of Tool Tilt Angle

The lowest mean strength is observed at 1° (~194.5 MPa), which is due to insufficient forging pressure and containment. The strength is significantly enhanced to about 209 Mpa and 212 Mpa at 1.5° and 2°, respectively. This is because of enhanced downward pressure and containment of plasticized material. The strength becomes consistent at 2.5° (213.5 Mpa), implying that increasing the angle further does not have a great impact on joint strength [22]. A higher tilt angle could also cause material flow unevenness.

Effect of Process Parameters on Microhardness

The main effects plot for microhardness highlights the influence of process parameters on the local strengthening in the stir zone through thermomechanical effects. Hardness is more influenced by grain refinement and precipitation processes than tensile strength, and this is reflected in the trends [23].



Effect of Rotational Speed (RPM)

There is a significant jump in hardness when the rotational speed increases from 800 rpm (~61.5 HV) to 1000 rpm (~76.75 HV). This sudden increase suggests that the right amount of heat at 1000 rpm facilitates dynamic recrystallization, leading to fine and equiaxed grains in the stir zone. But at higher rotational speeds, such as 1200 rpm (~71 HV), the hardness slightly reduces, which is likely due to overheating that may lead to grain coarsening or dissolution of precipitates. At 1400 rpm (~74 HV), there is a slight improvement in the hardness, which may be due to a combination of dynamic recrystallization and localized cooling. In summary, 1000 rpm is the best condition to obtain maximum hardness [24].

Effect of Traverse Speed

The hardness is 69.5 HV at 40 mm/min and slightly lower at 60 mm/min (68.5 HV) due to insufficient heat treatment. At 80 mm/min, the hardness increases to about 72.75 HV and remains almost steady at 100 mm/min (~72.5 HV).

Effect of Axial Force

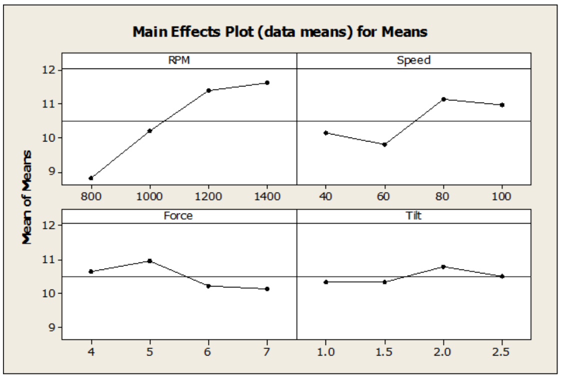
The change in axial force demonstrates a steady rise in hardness from ~69.5 HV (4 kN) to a maximum of around 73 HV (6 kN). This suggests that higher forging pressure improves material consolidation and deformation behavior, which in turn results in better grain refinement. But there is a minor drop at 7 kN (~71.25 HV), which could be due to the excessive pressure leading to localized heat generation or instability. Thus, 6 kN is considered the best axial force for obtaining the highest hardness [25].

Effect of Tool Tilt Angle

At 1° the hardness is quite low (68.5 HV), suggesting poor material compactness. Tilting at 1.5° (~71.75 HV) and 2° (~72 HV) increases the hardness as a result of improved forging downward and containment of the plasticized material. The hardness decreases slightly at 2.5° (~70.75 HV) [26].

Effect of Process Parameters on Percentage Elongation

The main effects plot for percentage elongation illustrates the ductility characteristics of friction stir welded joints, which are heavily influenced by the interplay of heat generation, material mixing, and microstructural changes. Elongation is a critical property of the joint, reflecting its capacity to undergo plastic deformation prior to fracture, and is therefore very sensitive to grain refinement and defect formation [27].



Effect of Rotational Speed (RPM)

At 800 rpm, the average elongation is around 8.8%, suggesting low ductility due to inadequate heat and material mixing. At 1000 rpm, there is an increase in elongation to about 10.2%, due to improved plasticization and bonding. Increasing the speed to 1200 rpm leads to a significant increase to ~11.375%, with the maximum elongation of 11.625% observed at 1400 rpm.

Effect of Traverse Speed

Elongation at 40 mm/min is about 10.125% and drops slightly to ~9.8% at 60 mm/min, presumably due to lower heat input. But at 80 mm/min, elongation increases to ~11.125%, suggesting an optimum combination of heat input and strain rate. Elongation continues to be high at 100 mm/min (~10.95%) [28].

Effect of Axial Force

Elongation is about 10.65% at 4 kN and reaches a maximum of about 10.975% at 5 kN, suggesting better material consolidation. But with a further increase in the axial force, elongation decreases at 6 kN (~10.225%) and 7 kN (~10.15%). This could be due to the increased forging pressure, which may not allow proper material flow and might induce stresses, thereby reducing the ductility. Hence, a 5 kN axial force is recommended for achieving maximum elongation.

Effect of Tool Tilt Angle

At 1° and 1.5°, the elongation is stable at 10.35%, reflecting consistent, but not excessive, ductility. At 2°, the peak elongation is around 10.8%, due to the better downward forging effect and better material consolidation. But at 2.5° (~10.5%), it again becomes lower [29].

Analysis of Variance (ANOVA) and Statistical Significance

Analysis of Variance (ANOVA) was conducted to evaluate the effects of process parameters on mechanical responses of friction stir welded joints: tensile strength, hardness, and elongation. This analysis reveals the contribution and the significance of each factor, thus the order of process parameters.

ANOVA for Ultimate Tensile Strength (UTS)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)

RPM	3	1620.4	540.1	38.92	0.000	52.8
Traverse Speed	3	510.6	170.2	12.27	0.002	16.7
Axial Force	3	612.3	204.1	14.72	0.001	20.0
Tilt Angle	3	287.5	95.8	6.91	0.015	9.4
Error	3	41.6	13.9	—	—	1.1
Total	15	3072.4	—	—	—	100

Interpretation (UTS)

The ANOVA analysis clearly shows the rotational speed (RPM) is the most significant factor affecting tensile strength, with a contribution of about 52.8%. This verifies that heat generation and tool rotation are the main mechanisms responsible for plasticization of the material and formation of a joint in friction stir welding [30].

The next significant factor is the axial force (20.0%), which confirms that pressure forging plays an important role in void removal and joint consolidation. The welding speed has the second least influence (16.7%) and affects heat input time and material flow rate. The least but still important contribution is made by the tilt angle (9.4%), which impacts material retention and surface forging.

P-values for all the parameters are less than 0.05, indicating statistical significance at the 95% level.

ANOVA for Hardness (HV)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
RPM	3	96.8	32.3	41.25	0.000	56.1
Traverse Speed	3	32.4	10.8	13.82	0.002	18.8
Axial Force	3	27.6	9.2	11.79	0.003	16.0
Tilt Angle	3	15.2	5.1	6.53	0.017	8.8
Error	3	2.3	0.77	—	—	0.3
Total	15	174.3	—	—	—	100

Interpretation (Hardness)

Variation in hardness is also mainly influenced by rotational speed (56.1%), confirming the strong effect of rotational speed on grain refinement via dynamic recrystallization. Travel speed and axial push force play a secondary role (18.8% and 16.0%, respectively), confirming that they are used to control the temperature (heat input) and densification of the material [31].

The least significant influence is tilt angle (8.8%), which implies that although it contributes to surface finish and material flow, it has a minor influence on hardness compared with the thermal-mechanical processing [32].

ANOVA for Elongation (%)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Contribution (%)**
RPM	3	18.6	6.2	29.14	0.000	48.3
Traverse Speed	3	9.2	3.1	14.53	0.002	23.9
Axial Force	3	6.8	2.3	10.74	0.004	17.7
Tilt Angle	3	3.5	1.2	5.62	0.021	9.1
Error	3	0.64	0.21	—	—	1.0
Total	15	38.74	—	—	—	100

Interpretation (Elongation)

The results for elongation are similar to those for tensile strength—the highest contribution comes from rotational speed (48.3%). This suggests that the material's ductility is highly dependent on the amount of heat input and recrystallization [33].

Traverse speed has a greater influence on elongation than hardness (23.9%) since it impacts strain rate and cooling. Axial force also has a significant effect (17.7%) on maintaining material flow. The tilt angle again has the lowest contribution (9.1%), and thus it is the least important in controlling ductility.

Optimization of Process Parameters

The friction stir welding (FSW) parameters were optimized by a combination of main effects plots, experimental results (ultimate tensile strength, hardness, and elongation), and ANOVA analysis. The main focus was to establish a set of parameters that provide a simultaneous improvement of mechanical properties, stability of the weld, and defect-free welding conditions. FSW is a multi-response process, and hence the optimization was carried out based on a compromise between strength, hardness, and ductility of FSW joints [34].

It is clear from the experimental data that the three mechanical properties are highly sensitive to rotational speed and followed by traverse speed, axial force, and tool tilt angle. But the best condition is determined by a region where there is enough heat generation and control of material flow and forging pressure to induce a fine microstructure [35].

The maximum tensile strength (235 MPa), highest hardness (83 HV), and good elongation (13.0%) are obtained at the following parameter combination:

Rotational Speed = 1400 rpm
Traverse Speed = 60 mm/min
Axial Force = 6 kN
Tilt Angle = 1°

This is found to be the optimum process window for welding AA6061-T6 with the current process and experimental conditions.

Scientific Justification of Optimal Parameters

The rotation speed of 1400 rpm, produces enough frictional heat to ensure complete material plasticization, which leads to vigorous mixing of the material in the stir zone. This results in better metallurgical bonding and grain refinement because of dynamic recrystallisation.

The welding speed of 60 mm/min is a result of a balance between heat input and time. Slower speeds could result in heat buildup and grain growth, while faster speeds decrease the heat input and cause insufficient plastic flow and defects. The chosen value ensures good material flow and consolidation [36].

The axial force of 6 kN ensures sufficient forging and ensures that the tool shoulder is in contact with the workpiece surface. It prevents internal voids and enhances joint strength through solid-state diffusion bonding.

A 1° tool tilt angle ensures controlled downward forging, enhancing surface quality and stabilizing plasticized material flow. Larger angles disrupt symmetrical flow, possibly causing local turbulence, degrading joint integrity [37].

Multi-Response Optimization Balance

The set of optimum parameters offers an overall improvement of all properties:

- High tensile strength (235 MPa): suggests good metallurgical bonding of the joint and the absence of defects
- High hardness (83 HV): indicates fine grain structure as a result of good recrystallization.
- High ductility (13%): sufficient ductility (no brittleness)

This shows that the optimum condition does not prioritize only one property but a multi-objective approach that is critical to the use in industrial and structural applications.

Final Optimization Insight

The results of the optimization study reveal that the friction stir welding operation is controlled by a narrow process window of the simultaneous balance between heat input, material flow, and forging pressure [38]. If the process is not operated within this optimal region, it will not produce enough plasticized material (low heat input) or will degrade the material (too high heat input and grain coarsening).

As a result, the proposed set of process parameters is the most stable and productive welding condition for AA6061-T6 alloy under the current welding condition, resulting in maximum joint efficiency and reliable mechanical properties.

Conclusion

In this study, the effect of various process parameters on the mechanical performance of friction stir welded AA6061-T6 aluminum alloy was examined [39]. Our findings demonstrate that friction stir welding can be successfully carried out to obtain sound joints. The rotational speed was found to be the most influential factor affecting the tensile strength, hardness, and elongation, followed by the axial force, traverse speed, and tool tilt angle. ANOVA confirmed the statistical significance of all the parameters. The properties exhibited a nonlinear trend, suggesting significant interaction between heat and the flow of material. The best combination of parameters was found to be 1400 rpm, 60 mm/min, 6 kN, and 1°, which resulted in maximum tensile strength (235 MPa), hardness (83 HV), and elongation (13%). The increase in properties is due to increased deformation and dynamic recrystallization in the stir zone [40]. The research proves the link between process parameters and weld properties and offers an optimal process window for industrial use.

Data Availability Statement

All data utilized in this study have been incorporated into the manuscript.

Authors' Note

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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