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A STATISTICAL STUDY FOR FRICTION STIR WELDED ALUMINUM PARTS

Kaan Ozel

Trakya University, Faculty of Engineering, Department of Mechanical Engineering, Edirne, Turkey

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**Corresponding author: kaanozel@trakya.edu.tr*

Abstract
Statistical analysis is a fundamental research method used to ensure reliability and validity in experimental studies. The process of evaluating data and deriving meaningful conclusions through mathematical models forms the basis of statistical analysis. Friction stir welding stands out today as a significant example of modern welding technology. This welding method is particularly employed for joining non-ferrous metals, such as aluminum alloys, in the solid state. Following the welding process, various tests including hardness, tensile, and fatigue tests are conducted to determine the strength characteristics of the metallic materials. Evaluating the results of these mechanical tests, particularly from a statistical perspective, is of great importance.
In this study, data obtained from mechanical tests performed on aluminum alloys joined by friction stir welding were analyzed using the SPSS software package to assess reliability and validity. A series of statistical analyses based on tensile, hardness, and fatigue test results were conducted using the Regression Analysis Module, a component of SPSS.

Keywords: Statistical Analysis, SPSS Software, Friction Stir Welding, Aluminum Parts.

INTRODUCTION

Statistical analysis serves as a fundamental research methodology to guarantee the reliability and validity of experimental studies, enabling researchers to derive meaningful conclusions through rigorous mathematical modeling. In the field of advanced manufacturing, applying such analytical approaches is crucial for evaluating the integrity and performance of modern joining techniques. Notably, Friction Stir Welding (FSW) has emerged as a revolutionary solid-state joining technology. It is widely preferred for non-ferrous materials, particularly AA 5083 aluminum alloys, due to its ability to operate below the melting point. This eliminates common fusion welding defects such as porosity, hot cracking, and solidification shrinkage, which typically degrade the structural life of AA 5083 joints.

The final quality and mechanical integrity of AA 5083 FSW joints heavily depend on a complex interplay of various process parameters, primarily Tool Rotational Speed and Welding Speed. Extensive research has been dedicated to understanding how these variables govern heat generation, material flow, and subsequent grain refinement within the Stir Zone (SZ). A critical consensus in the literature reveals that these parameters exhibit a highly non-linear relationship with mechanical outcomes. For instance, several researchers demonstrated that as the tool rotational speed increases, the tensile strength initially improves due to enhanced material plasticization but subsequently drops at higher speeds due to excessive heat input and localized thermal softening. Similarly, variations in welding speed create a parabolic behavior; low welding speeds introduce high heat inputs

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that degrade the hardness profile in the heat-affected zone (HAZ), while excessive welding speeds lead to inadequate material flow, resulting in tunnel or wormhole defects that drastically compromise tensile integrity. In the literature, numerous scholars have utilized statistical and optimization tools to map these relationships. Taguchi-based Experimental Designs and Analysis of Variance (ANOVA) are frequently employed to identify the percentage contribution of process parameters on joint efficiency. Recent studies have also integrated advanced computational approaches, such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), to predict hardness profiles and ultimate tensile strength (UTS). Furthermore, investigations regarding the fatigue life of AA 5083 FSW joints have revealed distinct behavior under cyclic loading. [1-3]

To synthesize these historical benchmarks, Table 1 outlines the key findings from prominent literature regarding the multi-parametric optimization of AA 5083 FSW joints.

While advanced machine learning models and optimization frameworks offer exceptional predictive accuracy, there remains a critical research gap in providing standard, accessible empirical validation frameworks that linearize and clarify the direct correlations between multi-parametric FSW inputs and holistic mechanical outcomes specifically encompassing tensile strength, hardness variations, and fatigue life simultaneously using widespread statistical tools.

ANALYTICAL INVESTIGATION

In this study, the mechanical performance of friction stir welded AA 5083 aluminum alloys was statistically modeled and evaluated using SPSS linear regression analysis based on tool rotational speed and welding speed parameters.

Statistical Analysis of Data

The data obtained from the mechanical tests were examined using the SPSS software package within the scope of statistical analysis to assess reliability and validity. Utilizing the Regression Analysis Module, a core component of SPSS, a series of statistical analysis studies were conducted based on the tensile, hardness, and fatigue test outcomes.

The foundation of the Regression Analysis Approach relies on the assumption of a simplified linear model for the optimization parameter η, which is formulated as follows:

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \quad (1)$$

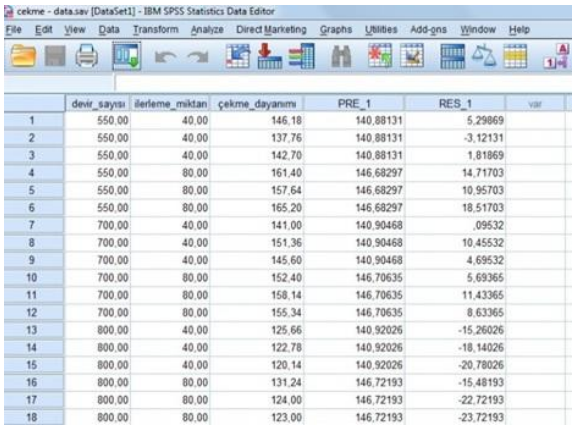
where x_1, x_2, … represent the independent factors upon which η depends, and β_0, β_1, β_2, … denote the 'true' values of the corresponding unknown parameters.

Following an experimental sequence consisting of a finite number of trials, sample estimates of the β coefficients can generally be obtained. These estimates are fitted into a linear regression equation expressed as:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \ldots \quad (2)$$

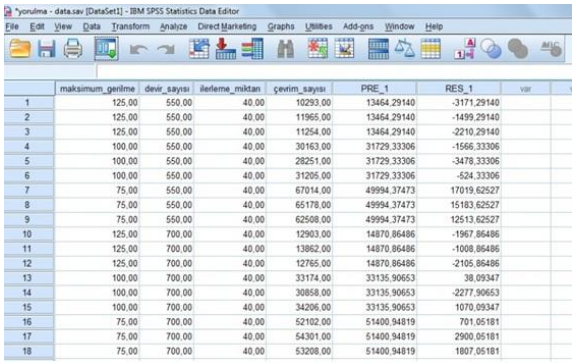
where “y” represents the response function, and the b values serve as the “estimated” values of the β parameters.

In simple terms, each coefficient represents the individual effect of its corresponding factor on the quality of the tensile strength expressed by the optimization parameter. The parameter optimization is carried out by utilizing the factorial design of experiments. The reliability and validity analyses of the results obtained from the mechanical tests were examined within the scope of statistical analysis using the SPSS Software Package. A series of statistical analysis studies were conducted utilizing the Regression Analysis Module in SPSS, based on the outcomes of the tensile, hardness, and fatigue tests. Representative examples of the analysis results and screenshots corresponding to these executed studies are presented in the figures below.



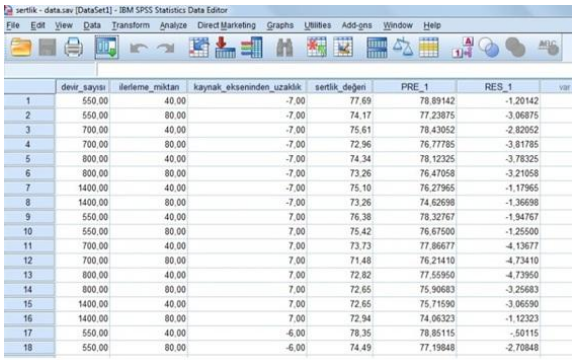
	devir_sayısı	ilerleme_miktarı	çekme_dayanımı	PRE_1	RES_1	var
1	550,00	40,00	146,18	140,88131	5,29869	
2	550,00	40,00	137,76	140,88131	-3,12131	
3	550,00	40,00	142,70	140,88131	1,81869	
4	550,00	80,00	161,40	146,68297	14,71703	
5	550,00	80,00	157,64	146,68297	10,95703	
6	550,00	80,00	165,20	146,68297	18,51703	
7	700,00	40,00	141,00	140,90468	,09532	
8	700,00	40,00	151,36	140,90468	10,45532	
9	700,00	40,00	145,60	140,90468	4,69532	
10	700,00	80,00	152,40	146,70635	5,69365	
11	700,00	80,00	158,14	146,70635	11,43365	
12	700,00	80,00	155,34	146,70635	8,63365	
13	800,00	40,00	125,66	140,92026	-15,26026	
14	800,00	40,00	122,78	140,92026	-18,14026	
15	800,00	40,00	120,14	140,92026	-20,78026	
16	800,00	80,00	131,24	146,72193	-15,48193	
17	800,00	80,00	124,00	146,72193	-22,72193	
18	800,00	80,00	123,00	146,72193	-23,72193	

Fig. 1. *An example of data entry for tensile tests utilized for regression analysis in SPSS*



	maksimum_gerilme	devir_sayısı	ilerleme_miktarı	çevrim_sayısı	PRE_1	RES_1	var
1	125,00	550,00	40,00	10293,00	13464,29140	-3171,29140	
2	125,00	550,00	40,00	11965,00	13464,29140	-1499,29140	
3	125,00	550,00	40,00	11254,00	13464,29140	-2210,29140	
4	100,00	550,00	40,00	30163,00	31729,33306	-1566,33306	
5	100,00	550,00	40,00	28251,00	31729,33306	-3478,33306	
6	100,00	550,00	40,00	31205,00	31729,33306	-524,33306	
7	75,00	550,00	40,00	67014,00	49994,37473	17019,62527	
8	75,00	550,00	40,00	65178,00	49994,37473	15183,62527	
9	75,00	550,00	40,00	62508,00	49994,37473	12513,62527	
10	125,00	700,00	40,00	12903,00	14870,86486	-1967,86486	
11	125,00	700,00	40,00	13862,00	14870,86486	-1008,86486	
12	125,00	700,00	40,00	12765,00	14870,86486	-2105,86486	
13	100,00	700,00	40,00	33174,00	33135,90653	38,09347	
14	100,00	700,00	40,00	30858,00	33135,90653	-2277,90653	
15	100,00	700,00	40,00	34206,00	33135,90653	1070,09347	
16	75,00	700,00	40,00	52102,00	51400,94819	701,05181	
17	75,00	700,00	40,00	54301,00	51400,94819	2900,05181	
18	75,00	700,00	40,00	53208,00	51400,94819	1807,05181	

Fig. 2. *An example of data entry for fatigue tests utilized for regression analysis in SPSS*



	devir_sayısı	ilerleme_miktarı	kaynak_ekseninden_uzaklık	sertlik_değeri	PRE_1	RES_1	var
1	550,00	40,00	-7,00	77,69	78,89142	-1,20142	
2	550,00	80,00	-7,00	74,17	77,23875	-3,06875	
3	700,00	40,00	-7,00	75,61	78,43052	-2,82052	
4	700,00	80,00	-7,00	72,96	76,77785	-3,81785	
5	800,00	40,00	-7,00	74,34	78,12325	-3,78325	
6	800,00	80,00	-7,00	73,26	76,47058	-3,21058	
7	1400,00	40,00	-7,00	75,10	76,27965	-1,17965	
8	1400,00	80,00	-7,00	73,26	74,62698	-1,36698	
9	550,00	40,00	7,00	76,38	78,32767	-1,94767	
10	550,00	80,00	7,00	75,42	76,67500	-1,25500	
11	700,00	40,00	7,00	73,73	77,86677	-4,13677	
12	700,00	80,00	7,00	71,48	76,21410	-4,73410	
13	800,00	40,00	7,00	72,82	77,55950	-4,73950	
14	800,00	80,00	7,00	72,65	75,90683	-3,25683	
15	1400,00	40,00	7,00	72,65	75,71590	-3,06590	
16	1400,00	80,00	7,00	72,94	74,06323	-1,12323	
17	550,00	40,00	-6,00	78,35	78,85115	-,50115	
18	550,00	80,00	-6,00	74,49	77,19848	-2,70848	

Fig. 3. *An example of data entry for hardness tests utilized for regression analysis in SPSS*

In the regression analysis study, dependent variables representing tensile, hardness, and fatigue test results "y", independent estimated constant coefficients b_0, and independent estimated parameters such as rotational speed and feed rate b_1, b_2, b_3, … were derived using Equation (2).

The dependent variables are expressed as functions for

- tensile tests;

$$y_1 = f(n,V) \quad (3)$$

- fatigue tests;

$$y_2 = f(n,V,\sigma_{max}) \quad (4)$$

- hardness tests;

$$y_3 = f(n,V,d) \quad (5)$$

y_1 : dependent variable for tensile strength (MPa)

y_2 : dependent variable for number of cycles (N)

y_3 : dependent variable for hardness value (HV)

n : rotational speed (rpm)

V : feed rate (mm/min)

d : distance from the weld axis (mm)

σ_{max} : maximum stress (MPa)

The formulas derived from the functions provided above are given below;

The formula for the dependent variable obtained for tensile tests;

$$y_1 = b_0 + b_1.n + b_2.V \quad (6)$$

The formula for the dependent variable obtained for fatigue tests;

$$y_2 = b_0 + b_1.n + b_2.V + b_3.\sigma_{max} \quad (7)$$

The formula for the dependent variable obtained for hardness tests;

$$y_3 = b_0 + b_1.n + b_2.V + b_3.d \quad (8)$$

Subsequently, the results of the regression analysis for the tensile, fatigue, and hardness tests are presented below.

```
GET
  FILE='F:\çalışma\altı aylık raporlar\anova - tez\cekme - data.sav'.
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REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA
  /CRITERIA=PIN(.05) POUT(.10)
  /NOORIGIN
  /DEPENDENT çekme_dayanımı
  /METHOD=ENTER devir_sayısı ilerleme_miktarı
  /SAVE PRED RESID.
```

Regression

```
[DataSet1] F:\çalışma\altı aylık raporlar\anova - tez\cekme - data.sav
```

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	ilerleme_miktarı, devir_sayısı[b]	.	Enter

a. Dependent Variable: çekme_dayanımı

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,221[a]	,049	-,042	13,65562

a. Predictors: (Constant), ilerleme_miktarı, devir_sayısı

b. Dependent Variable: çekme_dayanımı

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	202,017	2	101,008	,542	,590[b]
	Residual	3915,996	21	186,476		
	Total	4118,013	23			

a. Dependent Variable: çekme_dayanımı

b. Predictors: (Constant), ilerleme_miktarı, devir_sayısı

Fig. 4. *Tensile tests' SPSS regression analysis result - 1*

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	134,994	11,539		11,698	,000
	devir_sayısı	,000	,009	,004	,018	,986
	ilerleme_miktarı	,145	,139	,221	1,041	,310

Coefficients[a]

Model		95,0% Confidence Interval for B Lower Bound	95,0% Confidence Interval for B Upper Bound
1	(Constant)	110,996	158,992
	devir_sayısı	-,018	,018
	ilerleme_miktarı	-,145	,435

a. Dependent Variable: çekme_dayanımı

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	140,8813	146,8154	143,8308	2,96367	24
Residual	-23,72193	18,51703	,00000	13,04840	24
Std. Predicted Value	-,995	1,007	,000	1,000	24
Std. Residual	-1,737	1,356	,000	,956	24

a. Dependent Variable: çekme_dayanımı

Fig. 5. *Tensile tests' SPSS regression analysis result - 2*

The formula for the dependent variable, obtained from the statistical analysis of tensile tests, is as follows:

$$y_1 = 134{,}994 + 0{,}145.V \qquad (9)$$

```
REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA
  /CRITERIA=PIN(.05) POUT(.10)
  /NOORIGIN
  /DEPENDENT çevrim_sayısı
  /METHOD=ENTER devir_sayısı ilerleme_miktarı maksimum_gerilme
  /SAVE PRED RESID.
```

Regression

```
[DataSet1] F:\çalışma\altı aylık raporlar\anova - tez\yorulma - data.sav
```

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	maksimum_gerilme, ilerleme_miktarı, devir_sayısı[b]	.	Enter

a. Dependent Variable: çevrim_sayısı

b. All requested variables entered.

Fig. 6. *Fatigue tests' SPSS regression analysis result - 1*

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,954[a]	,910	,906	4919,37515

a. Predictors: (Constant), maksimum_gerilme, ilerleme_miktarı, devir_sayısı

b. Dependent Variable: çevrim_sayısı

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	16706172197	3	5568724066	230,110	,000[b]
	Residual	1645617129	68	24200251,90		
	Total	18351789326	71			

a. Dependent Variable: çevrim_sayısı

b. Predictors: (Constant), maksimum_gerilme, ilerleme_miktarı, devir_sayısı

Fig. 7. *Fatigue tests' SPSS regression analysis result - 2*

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	100985,980	3718,475		27,158	,000
	devir_sayısı	9,377	1,796	,190	5,222	,000
	ilerleme_miktarı	-33,848	28,988	-,042	-1,168	,247
	maksimum_gerilme	-730,602	28,402	-,934	-25,724	,000

Coefficients[a]

Model		95,0% Confidence Interval for B	
		Lower Bound	Upper Bound
1	(Constant)	93565,878	108406,083
	devir_sayısı	5,794	12,961
	ilerleme_miktarı	-91,692	23,996
	maksimum_gerilme	-787,277	-673,926

a. Dependent Variable: çevrim_sayısı

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	12110,3750	57964,9570	33982,7361	15339,43284	72
Residual	-10227,41602	17019,62500	,00000	4814,32301	72
Std. Predicted Value	-1,426	1,563	,000	1,000	72
Std. Residual	-2,079	3,460	,000	,979	72

a. Dependent Variable: çevrim_sayısı

Fig. 8. *Fatigue tests' SPSS regression analysis result - 3*

The formula for the dependent variable, obtained from the statistical analysis of fatigue tests, is as follows:

$$y_2 = 100985{,}980 + 9{,}377.n - 33{,}848.V - 730{,}602.\sigma_{max} \quad (10)$$

```
GET
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DATASET NAME DataSet1 WINDOW=FRONT.
REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA
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  /NOORIGIN
  /DEPENDENT sertlik_değeri
  /METHOD=ENTER devir_sayısı ilerleme_miktarı kaynak_ekseninden_uzaklık
  /SAVE PRED RESID.
```

Regression

```
[DataSet1] F:\çalışma\altı aylık raporlar\anova - tez\sertlik - data.sav
```

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	kaynak_ekseninden_uzaklık, ilerleme_miktarı, devir_sayısı[b]	.	Enter

a. Dependent Variable: sertlik_değeri

b. All requested variables entered.

Fig. 9. *Hardness tests' SPSS regression analysis result - 1*

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,443[a]	,196	,176	2,67961

a. Predictors: (Constant), kaynak_ekseninden_uzaklık, ilerleme_miktarı, devir_sayısı

b. Dependent Variable: sertlik_değeri

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	203,646	3	67,882	9,454	,000[b]
	Residual	832,915	116	7,180		
	Total	1036,561	119			

a. Dependent Variable: sertlik_değeri

b. Predictors: (Constant), kaynak_ekseninden_uzaklık, ilerleme_miktarı, devir_sayısı

Fig. 10. *Hardness tests' SPSS regression analysis result - 2*

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	
		B	Std. Error	Beta	t
1	(Constant)	81,952	1,013		80,928
	devir_sayısı	-,003	,001	-,338	-4,055
	ilerleme_miktarı	-,041	,012	-,281	-3,378
	kaynak_ekseninden_uzaklık	-,040	,057	-,059	-,711

Coefficients[a]

Model		Sig.	95,0% Confidence Interval for B	
			Lower Bound	Upper Bound
1	(Constant)	,000	79,946	83,958
	devir_sayısı	,000	-,005	-,002
	ilerleme_miktarı	,001	-,066	-,017
	kaynak_ekseninden_uzaklık	,478	-,152	,072

a. Dependent Variable: sertlik_değeri

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	74,0632	78,8914	76,8230	1,30817	120
Residual	-5,81731	6,89046	,00000	2,64562	120
Std. Predicted Value	-2,110	1,581	,000	1,000	120
Std. Residual	-2,171	2,571	,000	,987	120

a. Dependent Variable: sertlik_değeri

Fig. 11. *Hardness tests' SPSS regression analysis result - 3*

The formula for the dependent variable, obtained from the statistical analysis of hardness tests, is as follows:

$$y_3 = 81{,}952 - 0{,}003.n - 0{,}041.V - 0{,}040.d \quad (11)$$

To evaluate the predictability of the mechanical properties of friction stir welded AA 5083 aluminum alloys based on the process parameters, a systematic linear regression analysis was executed using SPSS. The input variables utilized in this study were the primary source parameters, specifically tool rotational speed and welding speed The established linear models exhibited vastly different degrees of determination across the evaluated mechanical tests.

For the fatigue life tests, the linear regression model demonstrated an exceptionally high goodness-of-fit, yielding a coefficient of determination of $R^2 = 0{,}910$. This confirms that approximately 91,0% of the variance in the fatigue behavior can be directly accounted for by the linear variations of the input source parameters (rotational speed and welding speed). This strong dependency underscores that cyclic loading resistance is highly sensitive to macro-parametric adjustments in a predictable, linear manner, making first-order equations reliable for fatigue life forecasting.

Conversely, the hardness tests resulted in a relatively low coefficient of determination $R^2 = 0,196$, meaning that only 19,6% of the hardness variability is explained by the linear model. This indicates that hardness variations across the distinct weld zones (Stir Zone, TMAZ, and HAZ) are predominantly governed by localized microstructural attributes—such as dynamic recrystallization, grain size refinement, and secondary phase precipitations—rather than straightforward linear combinations of the rotational and welding speeds.

Most notably, the linear regression model for the tensile tests
exhibited a negligible correlation, with an R^2 value of 0,049. This critical outcome proves that ultimate tensile strength (UTS) does not follow a simple linear trajectory relative to the FSW input source parameters. In friction stir welding of AA 5083 alloys, heat generation and plastic deformation are highly non-linear phenomena driven by the coupled effects of rotational and traverse speeds. High tool rotational speeds increase heat input but lead to thermal softening in the weld zone, whereas insufficient rotational speeds or excessive welding speeds cause inadequate material flow and consolidation defects. Consequently, tensile strength typically exhibits a parabolic or optimal peak relationship rather than a continuous linear trend.

The low R^2 values obtained for tensile strength and hardness strongly demonstrate that a first-order linear approach is inadequate for capturing these specific mechanical properties. While the current linear model successfully mapped the fatigue performance, it highlights a crucial limitation in predicting tensile and hardness behaviors. Therefore, as a recommendation for future work, it is essential to transition from first-order linear frameworks toward higher-order non-linear polynomial modeling, specifically quadratic analysis via Response Surface Methodology (RSM). Integrating quadratic square terms and multi-variable interactions into the statistical matrix will allow researchers to mathematically capture the peak interaction thresholds and provide a comprehensive optimization model for FSW process parameters.

CONCLUSION

The primary conclusions derived from this research are as follows:

- High Predictability in Fatigue Life: The linear regression model for fatigue tests demonstrated a superior goodness-of-fit with an R^2 value of 0,910. This confirms that approximately 91,0% of the variance in cyclic loading performance can be directly predicted via first-order linear equations of the input source parameters.
- Microstructural Dominance on Hardness: The hardness regression model yielded a low coefficient of determination $R^2 = 0,196$, proving that linear adjustments of macro process parameters account for only 19,6% of hardness variations. The remaining variance is heavily dictated by localized microstructural phenomena such as dynamic recrystallization and grain refinement in the weld zones.
- Non-Linear Behavior of Tensile Strength: A negligible linear correlation $R^2 = 0,049$ was obtained for the ultimate tensile strength. This critical finding scientifically demonstrates that the tensile efficiency of AA 5083 FSW joints does not follow a continuous linear trend, but rather a complex, non-linear trajectory driven by thermal softening and material flow characteristics.
- Inadequacy of First-Order Models: The study successfully delineates the boundaries of linear statistical tools in friction stir welding, proving that while first-order models are sufficient for fatigue prediction, they fail to map tensile and hardness behaviors accurately.
- Recommendation for Future Frameworks: To capture the optimal peak parameters and multi-variable interactions, future research must transition from linear regression toward higher-order non-linear polynomial modeling, specifically quadratic analysis

via Response Surface Methodology (RSM).

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