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Investigation of Processing Parameters on the Mechanical and Physical Properties of AA6061 Chip-Based Forged Parts Using MLR-GA Method

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Abstract

Solid-state recycling of aluminium offers an energy-efficient and environmentally friendly alternative to conventional melting-based methods. This study investigates the influence of processing parameters on the mechanical and physical performance of AA6061 chip-based forged components using Multiple Linear Regression (MLR) and Genetic Algorithm (GA) techniques. Aluminium chips produced by high-speed milling were consolidated through hot press forging at temperatures of 450°C, 500°C, and 550°C, with holding times of 60, 120, and 180 minutes. Tensile testing was conducted to assess the mechanical properties, with the ultimate tensile strength (UTS) selected as the main response variable. In addition, density testing was carried out to evaluate the physical properties of the forged samples. The MLR models successfully established correlations between forging parameters and UTS, while GA optimization identified the most favourable conditions for superior mechanical properties. The results showed that a higher forging temperature of 550°C and a longer holding time of 180 minutes improved the bonding between chips, resulting in higher UTS. The highest UTS was achieved at 550°C, 180 minutes, and a chip surface area of 73.77 mm^2. These findings highlight the potential of optimized solid-state recycling to produce high-quality aluminium components, thereby supporting sustainable manufacturing and efficient resource utilization in materials engineering.

1. Introduction

Aluminium is the second most widely used metallic element due to its excellent strength-to-weight ratio, corrosion resistance, and high recyclability (1,2). The global demand for aluminium continues to increase, particularly in the automotive, aerospace, packaging, and construction industries (3). However, primary aluminium production is highly energy-intensive, consuming about 200 GJ per tonne, and contributes significantly to greenhouse gas emissions (4,5).

Recycling aluminium is a sustainable alternative, as it requires only about 5-10% of the energy used in primary production and reduces carbon emissions by up to 95% (6,7). Conventional recycling, which involves remelting chips and scraps, faces challenges such as oxidation, impurity formation, and metal losses of up to 50% (8,9). This leads to deterioration of mechanical properties and limits the efficiency of the process.

Solid-state recycling, such as hot extrusion and hot press forging, avoids remelting and thus minimizes oxidation and material loss (10,11). Studies have shown that forging at higher temperatures improves tensile strength and ductility, while longer holding times enhance densification and reduce porosity (12,13,14). For AA6061 aluminium alloy, one of the most widely used engineering alloy, chip-based direct recycling using solid-state method has been reported to retain good mechanical properties (15,16).

Despite these advantages, limited studies have focused on predictive modelling and optimization of chip-based solid-state recycling. Advanced computational techniques such as Multiple Linear Regression (MLR) and Genetic Algorithms (GA) provide tools to model relationships between process parameters and mechanical outcomes, enabling more efficient optimization (17,18). Therefore, this research investigates the influence of processing parameters on the mechanical and physical properties of AA6061 chip-based forged parts using an MLR-GA hybrid approach.

2. Material Preparation and Processing

This section describes the procedures for preparing and treating the material before testing and analysis. The process includes selecting the raw material, cleaning, cutting, and shaping it into the desired form. The material is then treated using methods such as forging, heat treatment, or machining. Proper preparation and treatment are essential to ensure consistency, accuracy, and reliability of the results in the later stages of the study.

2.1 Preparation Chips

The raw material used in this study was AA6061 aluminium alloy chips obtained from a high-speed milling process. These chips, usually considered machining by-products or industrial waste, were reused as feedstock for direct recycling through a solid-state method. The high-speed milling technique was used to produce chips with consistent shape and good deformability, while machining parameters were adjusted to control chip formation. Continuous chips were formed at low feed rates, small depths of cut, and high cutting speeds, whereas discontinuous chips were formed at higher feed rates, larger depths of cut, and lower cutting speeds, resulting in rougher surfaces and larger chip sizes. The machining parameters used are listed in Table 1.

Table 1 *Machining parameters and size of chips*

Parameters			Surface Area (mm^2/mm^3)
Cutting Speed (mm/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Average
35	0.5	0.02	99.30
35	1.0	0.02	73.77
35	1.0	0.05	24.19
35	1.5	0.02	51.78
35	0.5	0.04	52.60

2.2 Chip Size Measurement

The dimensions of the aluminium chips were measured to ensure uniformity of the raw material. Using a digital caliper, the average chip length, width, and thickness were recorded as approximately 4.18 mm, 1.68 mm, and 0.145 mm, respectively. Consistent chip size is important because uneven dimensions can cause variations in packing density and bonding during compaction and forging. Smaller chips may increase porosity, while larger chips may not bond properly, which can affect the mechanical properties of the forged parts.

2.3 Chips Cleaning and Drying

Before compaction, the aluminium chips were cleaned to remove machining lubricants, cutting fluids, dust, and other contaminants that could hinder metallurgical bonding during hot forging and reduce the material's mechanical properties. The cleaning process was carried out using Aceton A.R solution for 30 minutes in a Elmasonic S60H ultrasonic bath, followed by drying at 100 °C for 30 minutes.

2.4 Cold Compaction Process

The cleaned and dried chips were weighed at 12g and compacted into a dog bone-shaped billet using a cold compaction machine operating at 35 tons of pressure. This process converted the loose chips into a solid billet with sufficient green strength for handling. Cold compaction increased chip-to-chip contact, reduced voids, and produced preforms suitable for hot press forging. Proper pre-compaction also promoted better densification and minimized defects in the final product.

2.5 Hot Press Forging (HPF) Process

The compacted billets were hot press forged at three different temperatures (450°C, 500°C, and 550°C) and holding times (60, 120, and 180 minutes). As shown in Figure 1, the billets were placed in the HPF machine, where pressure and temperature were applied simultaneously. Forging above the recrystallization temperature of AA6061 promoted chip bonding, grain refinement, and improved densification. By varying the temperature and holding time, the effects on mechanical and physical properties were evaluated. Higher temperatures and longer holding times enhanced diffusion and chip consolidation, resulting in stronger and denser forged parts.

Fig. 1 *Hot press forging machine*

2.6 Tensile Test

Tensile testing was performed using a Universal Testing Machine (UTM) to obtain accurate and reliable mechanical data. The test was conducted at room temperature under a uniaxial load with an initial strain rate of $2.5 \times 10^{-3}\ s^{-1}$, and the specimens were pulled until fracture. The system enabled automated measurement and analysis of stress–strain data. From the stress–strain curves, key mechanical properties such as ultimate tensile strength (UTS) and elongation at break were calculated using Equations (1) – (4). UTS was identified as the main response variable for the Multiple Linear Regression (MLR) and Genetic Algorithm (GA) models. The tensile test results were used to evaluate the effects of processing parameters on the mechanical performance of the chip-based forged AA6061 components.

$$\sigma_E = \frac{F}{A_0} \tag{1}$$

$$\varepsilon_E = \frac{\Delta L}{L_0} \tag{2}$$

$$\sigma_T = \sigma_E(1 + \varepsilon_E)$$
$$\varepsilon_T = In\,(1 + \varepsilon_E) \tag{3}$$

$$\sigma_T = \frac{F(L_0 + \Delta L)}{A_0 L_0}$$
$$\varepsilon_T = In(\frac{L_0 + \Delta L}{L_0}) \tag{4}$$

2.7 Density Test

The density of the forged samples was measured using a precision density balance based on Archimedes' principle. Each specimen was weighed in air and then in distilled water to determine its actual density. The relative density was calculated by comparing the measured value with the theoretical density of AA6061, where any difference indicated porosity. Since porosity affects strength and durability, the density test served as an important evaluation of the forging process. Higher density values indicated better chip bonding and fewer voids, confirming the effectiveness of the selected processing parameters.

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$$Density = \left(\frac{A}{|B|}\right) \times the\ density\ of\ the\ distilled\ water \quad (5)$$

Where A = the weight of specimen on air, B = the weight of specimen in distilled water

3. Result and Discussion

This chapter presents the findings on the mechanical and physical performance of hot-forged AA6061 chip-based samples under various processing conditions. Tensile testing was used to evaluate mechanical properties, with ultimate tensile strength (UTS) as the main response variable. A total of 45 experiments were conducted using a full factorial design to study the effects of forging temperature, holding time, and chip surface area. Multiple Linear Regression (MLR) and Genetic Algorithm–MLR (GA-MLR) methods were applied to predict and validate the influence of these parameters on UTS. The results showed that processing parameters significantly affected strength through chip bonding and diffusion mechanisms. Overall, the findings highlight the potential of solid-state recycling to produce high-performance aluminium components, promoting sustainable and efficient manufacturing.

3.1 Ultimate Tensile Strength

The ultimate tensile strength (UTS) was selected as the main response variable to evaluate the mechanical behavior of the forged AA6061 chip-based parts. The results showed that forging temperature, holding time, and chip surface area significantly influenced UTS. Higher temperatures combined with longer holding times improved chip bonding and metallurgical integrity. The lowest UTS was recorded at 450°C, 120 minutes, and a chip surface area of 73.77 mm^2, while the highest UTS of 128.41 MPa was achieved at 550°C, 180 minutes, and the same chip surface area. The UTS results are illustrated in Figure 2.

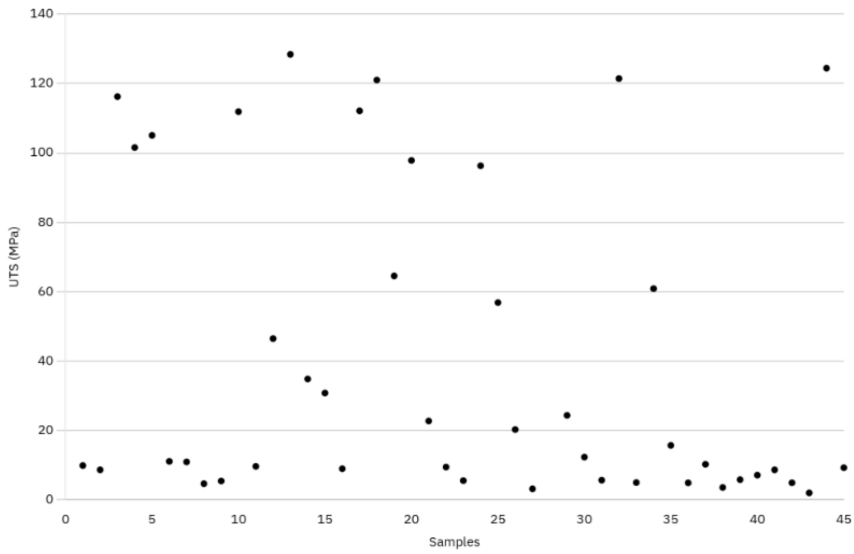

Fig. 2 *UTS result from different process parameters*

3.2 Analysis of Variance (ANOVA) for UTS

The differences in findings and outcomes can be significant for improving process control and optimization. Final ANOVA for tensile strength is shown in Table 2. In ANOVA analysis, the p-value or probability values are crucial for determining the significance of each component in the model.

Table 2 *ANOVA results of UTS*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	64201.4	10700.2	14.06	0.000
Temp	1	17	17	0.02	0.882
HT	1	504.8	504.8	0.66	0.420
CSA	1	1282.1	1282.1	1.68	0.202

Temp*HT	1	1158.9	1158.9	1.52	0.225
Temp*CSA	1	2899.7	2899.7	3.81	0.058
HT*CSA	1	3289.4	3289.4	4.32	0.044
Error	38	28918.2	761		
Total	44	93119.6			

The ANOVA Pareto chart Figure 3 illustrates the standardized effect contribution ratios of the input factors and their interactions. The letters A, B, and C represent forging temperature, holding time, and chip surface area, respectively. The length of each bar indicates the relative influence of each factor. The interaction between holding time and chip surface area (BC) showed the largest effect on UTS with a ratio of 2.024, followed by the interaction between temperature and chip surface area (AC). The chip surface area (C) alone was also a significant contributor. Although the interaction between temperature and holding time (AB) had a noticeable influence, it was less dominant compared to the other factors.

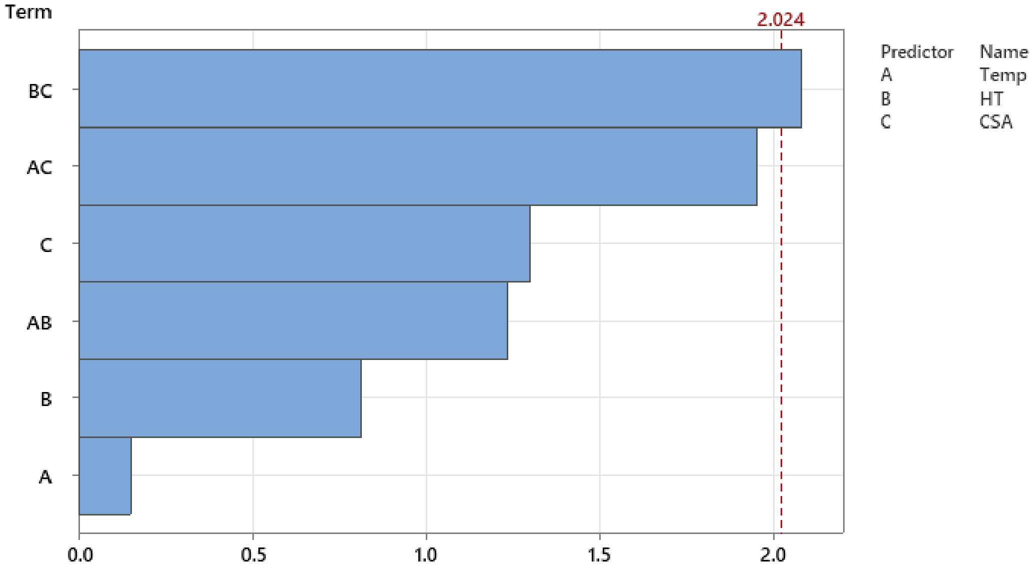

Fig. 3 *Factor contribution effect ratio on UTS in a Pareto chart*

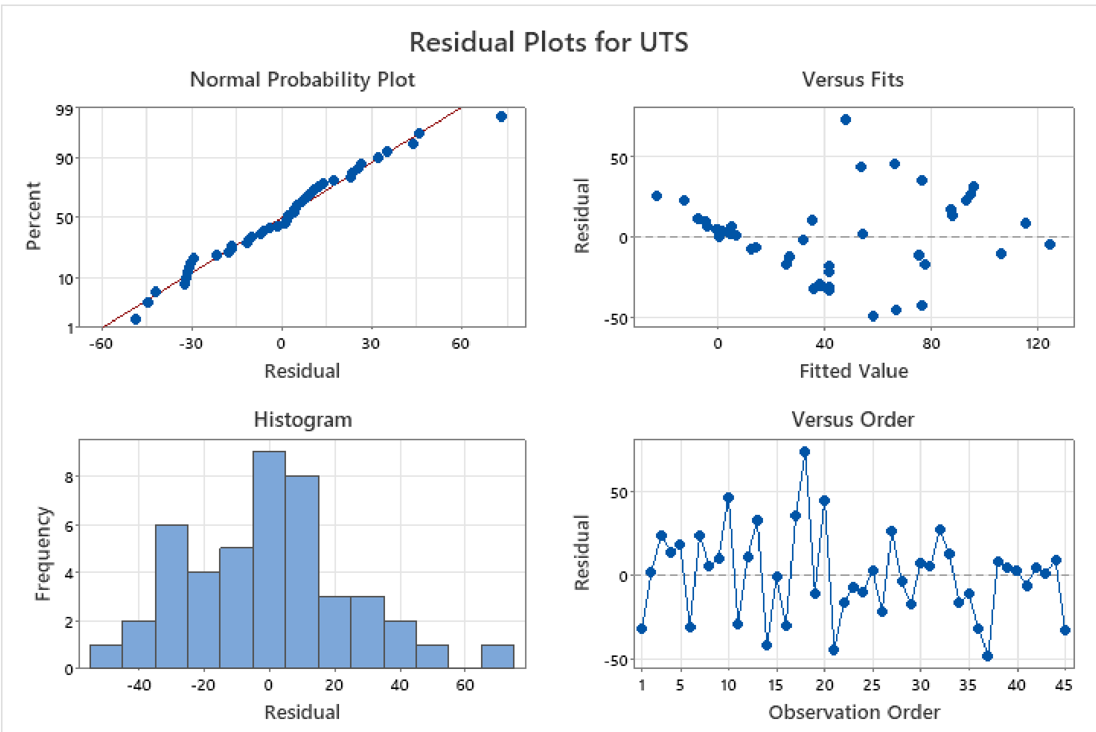

Fig. 4 *Residual plot for UTS*

Figure 4 presents the residual plots for UTS, which are used to assess the adequacy and reliability of the regression model. The Normal Probability Plot shows that the residuals lie close to the straight line, indicating that they are normally distributed. The Histogram displays a bell-shaped distribution, further confirming normality. The Residuals versus Fits plot shows that the points are randomly scattered around zero without any clear pattern, suggesting constant variance and no systematic errors. Finally, the Residuals versus Order plot shows no specific trend or sequence effect, meaning that the data were collected independently. Overall, these plots confirm that the regression model provides a good fit and accurately represents the relationship between the variables and UTS.

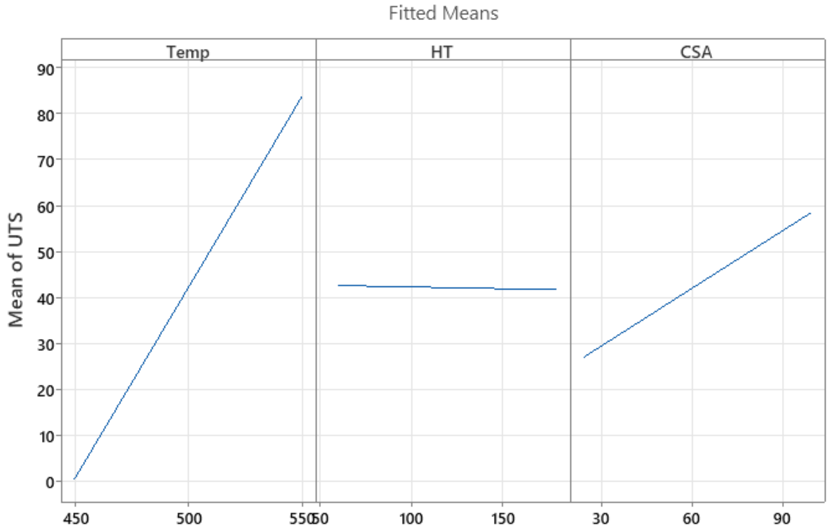

Fig. 5 *Main effect plot for UTS*

As shown in the ANOVA main effect plot in Figure 5, UTS has a positive relationship with forging temperature, and chip surface area (CSA).

3.3 Multiple Linear Regression (MLR) Model for UTS

The MLR empirical model was created to explain how the model's input elements and output response relate to one another. Regression analysis of experimental data served as the basic for the model's development. For fresh values of the input variables (Temp, HT, and CSA), the model is able to predict the UTS. The completed regression model is expressed in (6).

$$UTS = -60 + 0.054(Temp) - 0.86(HT) - 2.67(CSA) + 0.00254(Temp)(HT) + 0.00785(Temp)(CSA) - 0.00697(HT)(CSA) \quad (6)$$

The MLR empirical model offered important insight into predicting tensile strength and successfully predicted the UTS of chip-based forged parts for several untested situations. Performance evaluation based on the coefficient of determination (R^2), mean square error (MSE), root mean square error (RMSE), and mean absolute error (MAE) metrics, which were articulated in Eqs 7-11, has been given.

$$R^2 = \frac{\sum_{i=1}^{n}(y_{ai} - y_{pi})^2}{\sum_{i=1}^{n}(y_{pi} - y_{a.mn})^2} \quad (7)$$

$$R^2 adjusted = [(1 - R^2) \times \frac{n-1}{n-k-1}] \quad (8)$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_{pi} - y_{ai})^2 \quad (9)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_{pi} - y_{ai})^2} \quad (10)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(y_{ai} - y_{pi})\right| \quad (11)$$

In the equations, and represent the actual and predicted values, respectively, while denotes the mean of the observed response. The terms *k* and *n* refer to the number of input factors and data points, respectively. As shown in Table 3, the MLR model's accuracy evaluation yielded promising results: an MSE of 643.16%, RMSE of 25.36%, MAE of 19.82%, and an R^2 of 0.69%. These metrics indicate that the model performed well in predicting UTS values. Figure 6 illustrates the strong agreement between the predicted and experimental UTS results, while Table 4 lists the observed UTS, input parameters, predicted UTS values, and the corresponding percentage errors for the MLR model.

Table 3 *MLR evaluation metrics of UTS prediction using MATLAB*

Metrics	Values
MSE %	643.16
RMSE %	25.36
MAE %	19.82
R^2 %	0.69

Table 4 *Actual and Predicted values of UTS by MLR models*

Sample	Input Factors			Actual UTS	Predicted UTS (by MLR)	% error x 100
	Temp (°C)	HT (min)	CSA (mm/mm²)			
1	500	180	51.78	9.78	40.82071	-317.39
2	450	180	24.19	8.54	5.755101	32.61
3	550	60	73.77	116.22	92.60546	20.32
4	550	180	52.60	101.52	87.02654	14.28
5	550	180	51.78	105.05	86.70436	17.46
6	500	180	52.6	10.99	40.82104	-271.44
7	450	180	73.77	10.84	13.68522	-26.25
8	450	120	24.19	4.54	1.108641	75.58
9	450	180	52.60	5.32	5.38446	-1.21
10	550	60	51.78	111.88	65.57315	41.40
11	500	120	51.78	9.55	37.87511	-296.60
12	500	60	51.78	46.41	34.9295	24.73
13	550	180	73.77	128.41	95.34423	25.75
14	550	120	51.78	34.74	76.13876	-119.15
15	550	60	24.19	30.69	31.65677	-3.15
16	500	120	52.60	8.85	38.21836	-331.85
17	550	180	24.19	112.11	75.86425	32.32

18	500	120	73.77	121.01	47.08012	61.09
19	500	60	99.30	64.48	74.69424	-15.85
20	500	60	73.77	97.81	53.33074	45.48
21	550	60	52.60	22.62	66.58118	-194.35
22	450	60	99.30	9.34	25.39899	-171.94
23	500	60	24.19	5.43	11.84219	-118.09
24	550	180	99.30	96.26	105.375	-9.47
25	550	120	24.19	56.79	53.76051	5.33
26	500	180	99.30	20.17	40.83972	-102.48
27	450	180	99.30	3.06	23.69553	-674.36
28	550	60	99.30	120.47	123.9895	-2.92
29	500	180	24.19	24.26	40.80968	-68.20
30	450	60	52.60	12.22	4.65018	61.95
31	450	120	51.78	5.56	0.388542	93.01
32	550	120	73.77	121.43	93.97485	22.61
33	450	60	24.19	4.87	7.972383	-63.70
34	550	120	52.60	60.82	76.80386	-26.29
35	500	120	24.19	15.59	26.32593	-68.93
36	500	60	52.60	4.78	35.61568	-645.10
37	500	120	99.30	10.13	57.76698	-470.36
38	450	180	51.78	3.45	5.062938	-46.75
39	450	120	99.30	5.71	0.85173	85.08
40	450	60	51.78	7.01	4.285854	38.86
41	450	60	73.77	8.54	14.05601	-64.59
42	450	120	52.60	4.80	0.36714	92.35
43	450	120	73.77	1.88	0.185397	90.14
44	550	120	99.30	124.42	114.6822	7.83
45	500	180	73.77	9.15	40.82951	-346.22

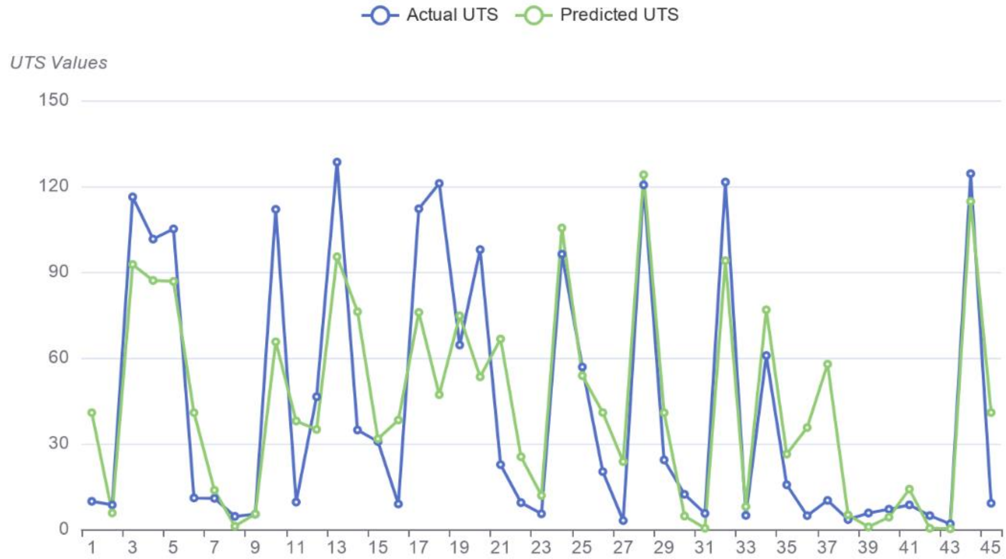

Fig. 6 *Actual vs Predicted UTS Values by MLR Model*

4. Conclusion

This study examined the mechanical and physical performance of AA6061 aluminium chip-based forged parts, focusing on forging temperature, holding time, and chip surface area as key processing parameters. A total of 45 experiments were carried out using a full factorial design, with tensile testing conducted to determine the ultimate tensile strength (UTS) as the main response. The highest UTS value of 128.41 MPa was achieved at a forging temperature of 550°C, a holding time of 180 minutes, and a chip surface area of 73.33 mm², indicating that higher temperatures and longer holding times improved chip bonding and mechanical integrity. Density measurements supported these findings by showing better consolidation under optimized conditions. The Multiple Linear Regression (MLR) model demonstrated strong predictive accuracy for UTS, while the Genetic Algorithm–MLR (GA-MLR) optimization validated the optimal parameter settings, closely matching the experimental results. The GA-MLR model achieved an optimum UTS of 123.99 MPa at 550°C, 60 minutes, and a chip surface area of 99.3 mm². Overall, the results confirm that chip-based solid-state recycling can produce high-performance aluminium components while reducing material waste and energy consumption, highlighting the potential of sustainable recycling practices to support a circular economy and environmentally responsible aluminium manufacturing.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Muhammad Adib, PM Dr Shazarel; data collection: Muhammad Adib; analysis and interpretation of results: Muhammad Adib PM Dr. Shazarel; draft manuscript preparation: Muhammad Adib, PM Dr Shazarel . All authors reviewed the results and approved the final version of the manuscript.

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