



ORIGINAL RESEARCH ARTICLE

EFFECT OF SEMI- SOLID SQUEEZE CASTING PARAMETERS ON MECHANICAL PROPERTIES OF RECYCLED ALUMINIUM ALLOY SCRAP

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ABSTRACT

The growing demand for sustainable materials has heightened interest in recycling aluminium alloys for engineering applications. This study investigated the recycling of aluminium alloy from automobile cylinder head scrap using semi-solid squeeze casting, optimized via a Taguchi $L_9(3^3)$ design. Adopted process parameters were squeeze pressure (100–140 MPa), slurry temperature (590–630 °C), and die preheating temperature (220–240 °C). Their effects on tensile strength and hardness were analyzed using signal-to-noise ratios and ANOVA. Also, the recycled alloy was identified as an Al–Si type, containing 6.75% Si and 0.36% Mg, along with trace amounts of Fe, Cu, Mn, and Zn. In addition, tensile strength ranged from 228 to 233 MPa, while hardness ranged from 72 to 78 BHN. The maximum tensile strength of 233 MPa was achieved at 100 MPa squeeze pressure, 590 °C slurry temperature, and 220 °C die preheating temperature. The maximum hardness of 78 BHN occurred at 140 MPa squeeze pressure, 630 °C slurry temperature, and 220 °C die preheating temperature. Similarly, the ANOVA revealed that die preheating temperature had the greatest influence on tensile strength (64.76% contribution), while squeeze pressure and slurry temperature most strongly affected hardness (49.57% each). Furthermore, confirmation tests at optimal parameters yielded 231 MPa tensile strength and 77 BHN hardness values comparable to those of commercial A356 alloy (258.5 MPa tensile strength, 75 BHN hardness). These findings demonstrate that Taguchi-optimized semi-solid squeeze casting can produce recycled aluminium components with excellent mechanical properties, promoting sustainable manufacturing.

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1.0 Introduction

Aluminium (Al) and its alloys are widely used in engineering applications such as aerospace, transportation, electronics, and the automotive industry because of their excellent technological properties, lightweight nature, and high performance in both wrought and cast forms. Their increasing adoption has been driven by the growing demand for lightweight structural materials capable of reducing vehicle weight and CO₂ emissions, with studies showing that the use of aluminium and magnesium alloys alongside innovative engineering design strategies provides an effective approach to weight reduction in modern engineering applications (Soundararajan *et al.*, 2015; Alam and Ansari, 2017; Ojarigho *et al.*, 2024; Guo *et al.*, 2024). These properties include corrosion resistance, high strength, excellent castability, good formability, favourable specific stiffness, high thermal conductivity, and low density (Muresan, 2023). These characteristics make aluminium alloys suitable for innovative applications in automotive components. Although the casting process is highly versatile, flexible, economical, and one of the fastest methods of converting raw materials into finished products, not all casting techniques are suitable for aluminium alloy components that require superior mechanical properties (Manjunath *et al.*, 2019). In addition, traditional casting techniques such as sand casting and high-pressure die

casting, which have historically been used in the production of aluminium alloy components, are often associated with defects including shrinkage, centreline segregation, oxide inclusions, porosity, blistering, underfilling, and hot tearing. These defects compromise the quality of the final products, making such methods less suitable for manufacturing high-performance aluminium automotive components. To minimise these defects and enhance the mechanical performance of cast aluminium alloys, semi-solid squeeze casting has been introduced (Kleiner *et al.*, 2019; Imanze *et al.*, 2025).

Semi-solid squeeze casting (SSSC) of aluminium alloys is an advanced manufacturing technique with considerable potential for industrial applications and research development. This process can produce near-net-shape castings with minimal defects, enabling the products to withstand heat treatment and welding processes without issues such as out-gassing or burning (Ashley, 2025; Martinec *et al.*, 2020). Compared with conventional casting methods, SSSC provides significant advantages because it combines the benefits of both casting and forging, thereby improving the mechanical properties of the resulting components (Omagu *et al.*, 2020). In this process, a semi-solid slurry is first injected into the die cavity, after which solidification occurs under applied pressure (Shi-bo *et al.*, 2013). The controlled processing environment associated with SSSC improves microstructural uniformity, reduces common casting defects such as porosity and shrinkage, and promotes finer grain structures, which ultimately enhance mechanical properties (Vijian *et al.*, 2007). The superior characteristics observed in semi-solid squeeze casting compared to conventional liquid casting are largely attributed to the higher heat transfer rate achieved during the process. As a result, this casting technique meets the requirements for producing aluminium alloy components for automotive structural applications (Senthil and Natrayan, 2020). In addition, the advantages offered by SSSC in manufacturing critical automotive components made from lightweight materials with improved structural and mechanical performance have attracted considerable research interest. Shi-bo *et al.* (2013) applied the Taguchi method to evaluate the effects of process parameters such as pouring temperature, die preheating temperature, filling speed, and squeezing pressure on the tensile strength, elongation, and hardness of squeeze-cast $AlSi_3Cu_3$ alloys. Similarly, Vijian *et al.* (2007) used the Taguchi experimental design approach to investigate the influence of squeeze pressure, die preheating temperature, and squeeze time on the hardness and ultimate tensile strength of squeeze-cast LM24 alloy.

Senthil *et al.* (2020) also employed the Taguchi parametric design technique to enhance the tensile strength and hardness of AC2A alloy by controlling process variables such as die preheating temperature, die insert material (including copper, brass, stainless steel, and hot die steel), semi-solid slurry temperature, squeeze pressure, and holding time. The success of the squeeze casting process largely depends on proper control of several critical process parameters, including melt pouring temperature, squeeze pressure, solidification time, die preheating temperature, and filling velocity, among others (Shang *et al.*, 2006; Belay *et al.*, 2024). In this study, the primary objective was to optimise the key parameters of the semi-solid squeeze casting process using Taguchi's experimental design method. Taguchi's systematic approach to parameter and tolerance design is recognised as a robust technique for achieving high-quality products (Muthu and Muraliraja, 2023). Also, Mehat *et al.* (2011) applied the Taguchi design method to analyse the influence of injection moulding parameters on recycled plastics. Similarly, Shang *et al.* (2006) used the Taguchi method to investigate the interactions between process variables affecting the microstructural and mechanical behaviour of aluminium matrix composites, concluding that the technique is highly effective for evaluating parameter interactions.

Also, Muthu and Muraliraja (2023) utilised the Taguchi design approach to optimise aluminium composites reinforced with bone powder. Their study revealed that optimum tensile strength and hardness were achieved at a melt pouring temperature of 700 °C, a squeeze pressure of 100 MPa, a reinforcement level of 5%, and a stirring speed of 600 rpm. In another investigation, John *et al.* (2013) optimized sand casting parameters to improve hardness and impact strength, with analysis of variance indicating that the melt pouring temperature had the most significant influence on the properties. Also, Inegbedion *et al.* (2022) used a Taguchi L9 orthogonal array to examine the effects of squeeze pressure, melt pouring temperature, and mould temperature on the properties of aluminium alloy composites. Their findings showed that optimal tensile strength and hardness were achieved at a melt pouring temperature of 650 °C, a squeeze pressure of 300 MPa, and a mould temperature of 200 °C. Deng *et al.* (2023), in their process review, highlighted certain limitations of squeeze casting and proposed recommendations for improving future parameter design. In addition, Gugulothu *et al.* (2022) employed the Taguchi L16 design to study Al7475 composites reinforced with ceramic particles produced through the stir squeeze casting (SSC) process. The results indicated that ceramic particle reinforcement had the greatest influence on tensile strength, followed by squeeze pressure, stirring speed, and melt pouring temperature. Under optimal conditions, a tensile strength of 325 MPa and a hardness of 130.6 HV were achieved. While, Rahman *et al.* (2023) investigated the effects of processing parameters on squeeze-cast LM25 alloy composites reinforced with silicon carbide (SiC) particles. The experimental

conditions included melting temperatures between 600 °C and 700 °C, SiC contents of 4–8 wt%, and stirring speeds of 550–750 rpm. The maximum tensile strength of 211 MPa and hardness of 91 HV were obtained at a stirring speed of 750 rpm, a SiC content of 8 wt%, and a melting temperature of 650 °C. The Taguchi analysis revealed that stirring speed played a more significant role than other factors such as SiC weight fraction or melting temperature in achieving uniform dispersion of reinforcement particles in the composite.

Semi-solid squeeze casting offers strong potential for producing near-net-shape aluminium components with reduced energy use and material waste, making it important to study the influence of key process parameters (Christy et al., 2020). Therefore, this study investigates the effects of squeeze pressure, slurry temperature, and die preheating temperature on recycled aluminium scrap, including its chemical composition, purification, and mechanical properties. To manage the complexity of the process, statistical techniques were adopted to reduce experimental runs, time, and cost (Natrayan and Senthil, 2020; Gaurav and Priyank, 2023). A Taguchi L9 (3³) orthogonal array under the Design of Experiments (DOE) framework was used to predict Signal-to-Noise (S/N) ratios and analyse parameter interactions, while Pareto ANOVA was applied to determine the significance and contributions of each factor

2. Materials and Method

2.1 Materials

Aluminium scraps (1.5 kg) from the top cylinder head of an automobile petrol engine (Plate 1), was obtained from a scrap vendor and used in this study. The mould used for the casting was fabricated from mild steel with dimensions of 0.16 m in length, 0.14 m in width, and 0.10 m in height. A cavity of the required shape for the casting was machined into the die. Also, the main equipment used in this study included a Hand-held XRF metal analyser (Niton XLp 300, Thermo Fisher Scientific, USA), tabletop Monsanto tensometer testing machine (Bench Model Horizontal Tensile Testing Machine, Kudale Instruments Pvt Ltd, India), coreless induction melting furnace (SFI/OFI/122012, Strayfield International, India), Brinell hardness testing machine (Model A200, Officine Galileo, Italy), 25 T hydraulic press (Model 219604, Shun Fu Europe B.V., Netherlands), benchtop muffle furnace (Omega LMF-A550/240V Series, Omega Engineering, England), and K-type thermocouple (Chromega Nickel/Chromium, Omega Engineering, England).



Plate 1: Top cylinder head of an automobile petrol engine

2.2 Method

The experimental procedures involved chemical analysis and refining of aluminium alloy scraps, semi-solid processing using squeeze pressure, slurry temperature, and die preheating temperature as variables, specimen preparation, and mechanical testing according to ASTM B557-23 for tensile testing and ASTM E10-23 for hardness evaluation.

2.2.1 Chemical composition of aluminium alloy scraps

A hand-held XRF metal analyzer (Niton XLp 300 Series) was used to determine the chemical composition of the aluminium alloy scrap. The analyzer's window was placed firmly against the surface of the metal sample to ensure that the X-ray beam covered as much of the sample as possible. The trigger of the XRF handheld gun was pulled and held to initiate the test, which activated a high-energy, short-wavelength X-ray beam. The test was stopped by releasing the trigger once the analysis was completed.

2.2.2 Refining of aluminium scrap

Recycled aluminium scrap served as an alternative source of aluminium (Al) and aluminium alloys for the production of aluminium alloy components. Aluminium alloy scrap obtained from the top cylinder head of an automobile petrol engine, weighing 1.5 kg, was broken into smaller pieces. The scrap pieces were thoroughly washed, dried, and charged into a 3 kg graphite crucible. The crucible and its contents were then placed in an open-air charcoal-fired furnace for melting. The molten metal was subsequently cast into cylindrical ingots with a diameter of 0.025 m and a length of 0.12 m using a green sand mould.

After melting and prior to casting into cylindrical ingots of size 0.25 m diameters by 0.12 m length. (Plate 2), the molten aluminium was refined to remove impurities such as dissolved hydrogen gas and entrapped non-metallic inclusions of Al₂O₃. Fluxing was carried out at a temperature of 600 °C by sprinkling 2.5 wt.% of Lite Salt (a 50/50 mixture of sodium chloride and potassium chloride) relative to the total weight of the melt onto the surface of the molten metal and stirring it thoroughly. The addition of the fluxing agent to the melt resulted in the formation of dross, which consisted of non-metallic oxides and other impurities floating on the surface of the melt. Thereafter, degassing was performed using hexachloroethane (C₂Cl₆) tablets as the degassing agent after the dross was skimmed off from the surface of the melt.



Plate 2: Cylindrical alloy ingot

2.2.3 Experimental design via Taguchi optimization technique

The Taguchi optimization technique was employed to optimize the selected casting process parameters affecting the mechanical properties of aluminium alloy scrap. Nine experimental runs were conducted using the L₉(3³) orthogonal array based on Taguchi’s parametric design. The process parameters considered as input variables during the experimental design were squeeze pressure, die preheating temperature, and slurry temperature, while the output responses evaluated were tensile strength and hardness. The slurry temperature levels were set at 590 °C, 610 °C, and 630 °C; die preheating temperatures were 220 °C, 230 °C, and 240 °C; and squeeze pressures were 100 MPa, 120 MPa, and 140 MPa. The control factors and their respective levels are presented in Table 1, while the Taguchi experimental design matrix is shown in Table 2. However, since the objective of the study was to investigate the influence of semi-solid squeeze casting parameters on the mechanical properties of recycled aluminium alloy scrap, the “larger-the-better” Signal-to-Noise (SN) ratio criterion was adopted to evaluate the optimal conditions for responses, as expressed in Equation 1.

$$SN \text{ (dB)} = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{R_i^2} \right) \quad 1$$

where; dB-decibel, i-observation, n-total number of observation and R_i-response

Table 1: Control Factors and Their Levels.

| Factor | Notation | Control Factor | Level 1 | Level 2 | Level 3 |
|--------|----------|---------------------------------|---------|---------|---------|
| A | | Squeeze pressure (MPa) | 100 | 120 | 140 |
| B | | Slurry temperature (°C) | 590 | 610 | 630 |
| C | | Die preheating temperature (°C) | 220 | 230 | 240 |

2.2.4 Semi-Solid Squeeze Casting of Aluminium Alloy Components

Semi-solid squeeze casting of the aluminium alloy components was carried out in accordance with the experimental conditions specified in the Taguchi design matrix presented in Table 2. Cylindrical aluminium alloy ingots were first cut into smaller pieces and remelted in a coreless induction furnace equipped with an

improvised mechanical stirring system. The stirring system consisted of a motor-driven coated stainless steel stirrer. The furnace was heated to a temperature above the melting point of the alloy to ensure complete melting of the ingot pieces. After complete melting, the temperature of the molten alloy was gradually reduced to obtain the semi-solid slurry state. During the experiments, the slurry temperature was controlled at the levels specified in the Taguchi design (590 °C, 610 °C, and 630 °C). Mechanical stirring was then performed for 5 minutes at a stirring speed of 500 revolutions per minute using a one-horsepower electric motor (DC YL802.4, 100 % copper wire, Viking type) to ensure uniform slurry formation.

Table 2: Taguchi experimental design matrix

| Run | Squeeze Pressure, (MPa) | A | Slurry Tmpt. B (°C) | Die Preheat Tmpt. C (°C) |
|-----|-------------------------|---|----------------------|--------------------------|
| 1 | 100 | | 590 | 220 |
| 2 | 100 | | 610 | 230 |
| 3 | 100 | | 630 | 240 |
| 4 | 120 | | 590 | 240 |
| 5 | 120 | | 610 | 220 |
| 6 | 120 | | 630 | 230 |
| 7 | 140 | | 590 | 230 |
| 8 | 140 | | 610 | 240 |
| 9 | 140 | | 630 | 220 |

Before pouring the slurry into the die cavity, the internal surfaces of the dies were coated with graphite die/core coating to reduce sticking and improve casting quality. The dies were subsequently preheated in a Bench Top Muffle Furnace (Omega LMF-A550/240 V Series) to the required temperatures of 220 °C, 230 °C, and 240 °C, as specified by the experimental design. For each experimental run, a pre-measured quantity of the semi-solid aluminium alloy slurry at the specified temperature was poured directly into the preheated die cavity. Squeeze pressure was then applied using a 20-tonne hydraulic press at the levels defined in the Taguchi design (100 MPa, 120 MPa, and 140 MPa) and maintained for the corresponding pressure duration indicated in the experimental matrix. The casting was allowed to solidify under pressure before removal from the die. A schematic diagram of the semi-solid squeeze casting experimental setup is presented in Figure 1.

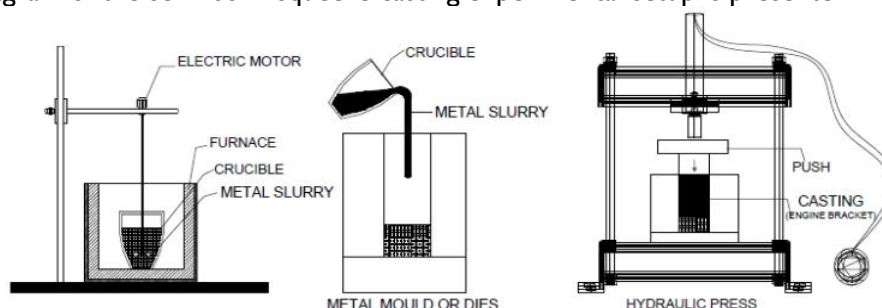


Figure 1: Schematic diagram of the squeeze casting experimental setup (a) Coreless Induction with Stirring Mechanism, (b) Dies with Metal Slurry and (c) Hydraulic Shop Press (Model 219604 25T)

2.2.5 Mechanical Testing

After the casting process, the mechanical properties of the produced components were evaluated through tensile strength and hardness tests using specimens machined from the cast samples. The tensile strength test was performed using a Monsanto Tensometer (Bench Mode; Kudale Instruments (P) Ltd., India). Tensile test specimens were machined from the cast components in accordance with the specifications of the American Society for Testing and Materials standard ASTM International, specifically ASTM B557-23. The geometry and dimensions of the tensile specimen are illustrated in Figure 2.

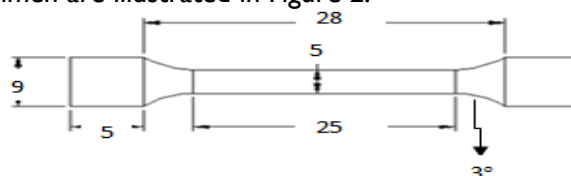


Figure 2: Tensile Test Specimen (All Dimensions in mm)

In addition, the hardness of the samples was determined using a Brinell hardness tester (Officine Galileo Hardness Tester. Model A200; Servizio Assistenza Technica; Italy). For each sample, hardness measurements

were taken at three different locations on the surface, and the average Brinell Hardness Number (BHN) was calculated in accordance with ASTM E10-23. The Brinell hardness value was determined using Equation 2:

$$\text{BHN} = \frac{W}{\left(\frac{\pi}{2}D\right)\left(D - \sqrt{D^2 - d^2}\right)} \quad 2$$

Where W-load on the indenter (kg), D-diameter of the steel ball (mm) and d-average measured diameter of indentation (mm).

3. Results and Discussion

3.1 Chemical Composition of Aluminium Alloy Scraps

Table 3 shows the results of the analysis of composition of the aluminium alloy scrap. The analysis indicates that the alloy contains Silicon (Si) at 6.75%, Iron (Fe) at 0.15%, Copper (Cu) at 0.15%, Manganese (Mn) at 0.10%, Magnesium (Mg) at 0.36%, and Zinc (Zn) at 0.10%, while the remaining percentage (92.44%) constitutes Aluminium (Al). The relatively high silicon content suggests that the scrap material belongs to the Al–Si alloy family, which is commonly used in casting applications due to its good fluidity, improved castability, and enhanced wear resistance. The presence of magnesium further contributes to strengthening through solid solution and precipitation hardening, while small amounts of copper and manganese can improve strength and hardness. However, iron is generally considered an impurity element in aluminium alloys and is typically maintained at low levels to avoid the formation of brittle intermetallic phases that may reduce mechanical performance. In addition, the composition obtained from the analysis confirms that the aluminium scrap is suitable for recycling and casting applications, particularly for semi-solid squeeze casting processes where Al–Si based alloys are widely used due to their favorable casting characteristics and mechanical properties.

Table 3: Compositions of aluminium scrap

| Elemental Composition | Si | Fe | Cu | Mn | Mg | Zn | Al |
|-----------------------|------|------|------|------|------|-----|---------|
| Percentage (%) | 6.75 | 0.15 | 0.15 | 0.10 | 0.36 | 0.1 | Balance |

3.2 Experimental Results

The experimental results obtained from mechanical testing of samples are shown in Table 4. It shows the combinations of the casting process parameters; squeeze pressure, slurry temperature, and die preheating temperature and their effects on the mechanical properties of the semi-solid squeeze cast aluminium alloy. The S/N ratios were calculated using the “larger-the-better” criterion in order to determine the optimal parameter settings that maximize the mechanical properties. Again Table 4 shows the tensile strength of the cast samples ranged between 228-233 MPa, while the hardness values varied from 72-78 BHN. These variations indicated that the mechanical properties of the recycled aluminium alloy are influenced by the selected process parameters used during the semi-solid squeeze casting process. From the results presented in Table 4, the first sample produced one of the highest tensile strengths of 233 MPa at a squeeze pressure of 100 MPa, slurry temperature of 590 °C, and die preheating temperature of 220 °C, although its hardness value was relatively lower (72 BHN). Similarly, the eight sample also recorded a tensile strength of 233 MPa at higher squeeze pressure (140 MPa) and slurry temperature (610 °C) with a die preheating temperature of 240 °C, showing that different parameter combinations can produce comparable tensile strength values. In addition, the highest hardness value (78 BHN) was obtained in Run 9, corresponding to a squeeze pressure of 140 MPa, slurry temperature of 630 °C, and die preheating temperature of 220 °C. This suggests that higher squeeze pressure and higher slurry temperature contribute positively to the hardness of the cast aluminium alloy due to improved densification and reduced porosity during solidification.

3.3 Analysis of Experimental Results

3.3.1 Signal to noise (SN) ratios

The signal-to-noise (S/N) ratio values, calculated using the “larger-the-better” criterion to determine the optimal parameter settings that maximizes the mechanical properties, are presented in Table 5, while Figures 3a and 3b show the main effect plots for tensile strength and hardness, respectively. These plots help illustrate how each factor level significantly influences the performance characteristics and assist in identifying the optimal parameter combination for process optimization (Balaji *et al.* 2023). From Table 5, the highest S/N

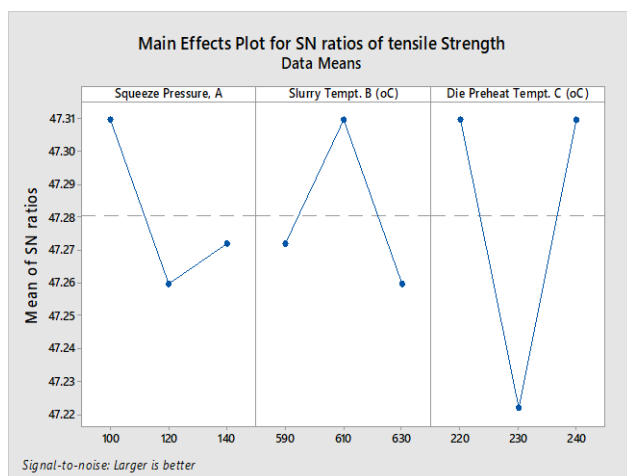
ratio for tensile strength (46.49 dB) was obtained in the seventh sample. In agreement with this result, Figure 5a indicates that the parameter combination of squeeze pressure (100 MPa), slurry temperature (610°C), and die preheat temperature (240°C) provides a relatively stable and optimal condition for improving the tensile strength of the cast alloy. In addition, for hardness, the maximum S/N ratio (15.26 dB) was recorded in ninth sample. Figure 5b further confirms that the parameter combination of squeeze pressure (140 MPa), slurry temperature (630°C), and die preheat temperature (230°C) yields the most stable and improved hardness performance among the tested conditions. Overall, the results demonstrate that increasing squeeze pressure and slurry temperature generally enhances the hardness of the aluminium alloy, whereas tensile strength shows moderate variation across the different parameter combinations. These findings highlight the importance of carefully selecting processing parameters in order to achieve the desired mechanical properties during the semi-solid squeeze casting process.

Table 4: Summary of experimental results

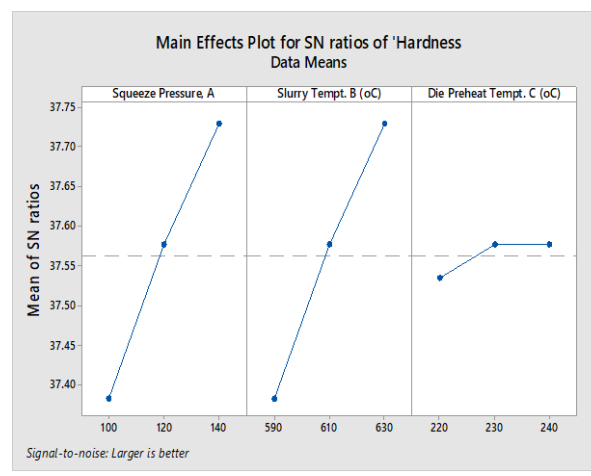
| Experimental matrix | | | | Experimental results | |
|---------------------|---------------------------|----------------------|---------------------------|------------------------|----------------|
| Run | Squeeze Pressure, A (MPa) | Slurry Tempt. B (°C) | Die Preheat Tempt. C (°C) | Tensile Strength (MPa) | Hardness (BHN) |
| 1 | 100 | 590 | 220 | 233 | 72 |
| 2 | 100 | 610 | 230 | 232 | 74 |
| 3 | 100 | 630 | 240 | 231 | 76 |
| 4 | 120 | 590 | 240 | 232 | 74 |
| 5 | 120 | 610 | 220 | 231 | 76 |
| 6 | 120 | 630 | 230 | 229 | 77 |
| 7 | 140 | 590 | 230 | 228 | 76 |
| 8 | 140 | 610 | 240 | 233 | 77 |
| 9 | 140 | 630 | 220 | 232 | 78 |

Table 5: Signal to noise (SN) ratio values

| Experimental matrix | | | | Signal to noise (SN) ratios (dB) | |
|---------------------|---------------------------|----------------------|---------------------------|----------------------------------|----------|
| Run | Squeeze Pressure, A (MPa) | Slurry Tempt. B (°C) | Die Preheat Tempt. C (°C) | Tensile Strength | Hardness |
| 1 | 100 | 590 | 220 | 43.97 | 9.83 |
| 2 | 100 | 610 | 230 | 44.86 | 10.10 |
| 3 | 100 | 630 | 240 | 45.34 | 10.63 |
| 4 | 120 | 590 | 240 | 45.48 | 12.04 |
| 5 | 120 | 610 | 220 | 45.98 | 12.46 |
| 6 | 120 | 630 | 230 | 44.30 | 12.66 |
| 7 | 140 | 590 | 230 | 46.49 | 13.98 |
| 8 | 140 | 610 | 240 | 44.51 | 14.15 |
| 9 | 140 | 630 | 220 | 45.20 | 15.26 |



(a)



(b)

Figure 3: Main effect plots for (a) Tensile Strength (b) Brinell Hardness

3.3.2 Analysis of variance

Analysis of Variance (ANOVA) was performed to determine the contribution of individual casting parameters to the responses. The analysis was carried out at a 95% confidence level with a significance level of 5%. The ANOVA results for tensile strength and hardness are presented in Tables 6 and 7, respectively. The contribution of each casting parameter to the tensile strength is presented in Table 6. The parameters considered include squeezing pressure (A), slurry temperature (B), and die preheating temperature (C). The results indicate that die preheating temperature is the most influential factor affecting tensile strength, contributing 64.762% of the total variation. In comparison, slurry temperature and squeezing pressure each contribute 17.619%. This suggests that the tensile strength of the cast alloy is highly sensitive to the die preheating temperature. Based on the Signal-to-Noise (S/N) ratio analysis, the optimal combination of process parameters for maximizing tensile strength was determined to be A1B2C1. Similarly, the ANOVA results for hardness are presented in Table 7, showing the influence of squeezing pressure, slurry temperature, and die preheating temperature. The results reveal that squeezing pressure and slurry temperature have the most significant effect on hardness, each contributing 49.574% to the total variation. In contrast, die preheating temperature contributes only 0.852%, indicating that it has a negligible effect on the hardness of the cast material. Based on the S/N ratio analysis, the optimal parameter combination for achieving maximum hardness was found to be A3B3C2.

Table 6: Pareto ANOVA Calculation for Tensile Strength (MPa)

| Factor | A | B | C | Total | |
|--------------------------------|---------|---------|---------|--------|--------|
| Sum of Factor Level | 1 | 141.93 | 141.82 | 141.93 | 425.53 |
| | 2 | 141.78 | 141.93 | 141.67 | |
| | 3 | 141.82 | 141.78 | 141.93 | |
| Sum of Square Difference (SSD) | 0.037 | 0.037 | 0.136 | 0.21 | |
| Degree of Freedom (D.O.F) | 2 | 2 | 2 | 6 | |
| Contribution Ratio (CR %) | 17.619% | 17.619% | 64.762% | 100 | |
| p-value | 0.048 | 0.051 | 0.012 | — | |
| Optimum Level | A1 | B2 | C1 | | |

Table 7: Pareto ANOVA Calculation for Hardness (BHN)

| Factor | A | B | C | Total | |
|--------------------------------|--------|--------|--------|--------|--------|
| Sum of Factor Level | 1 | 112.15 | 112.15 | 112.61 | 338.07 |
| | 2 | 112.73 | 112.73 | 112.73 | |
| | 3 | 113.19 | 113.19 | 112.73 | |
| Sum of Square Difference (SSD) | 1.630 | 1.630 | 0.852 | 3.288 | |
| Degree of Freedom (D.O.F) | 2 | 2 | 2 | 6 | |
| Contribution Ratio (CR%) | 49.574 | 49.574 | 0.852 | 100 | |
| p-value | 0.008 | 0.008 | 0.041 | - | |
| Optimum Level | A3 | B3 | C2 | | |

3.4 Confirmation Test

A confirmation test was conducted using the optimal factor levels obtained from the Signal-to-Noise (S/N) ratio analysis. This test represents the final step in the Taguchi experimental design approach and is performed to validate the reliability of the predicted optimal conditions. In this study, the confirmation experiment was carried out using the optimal combinations of the casting parameters obtained from the S/N ratio analysis: A1B2C1 for tensile strength and A3B3C2 for hardness. These parameter combinations were used to produce semi-solid squeeze cast samples, which were subsequently characterized by measuring their tensile strength and hardness using the procedures described in the earlier section. Furthermore, the tensile strength and hardness of a commercially available cylinder head aluminium alloy (A356) used as the control sample were also determined for comparison. The results of the confirmation test are presented in Table 8.

The results show that the semi-solid squeeze cast sample produced at the optimal parameter combination exhibited a tensile strength of 231 MPa. Although this value is slightly lower than that of the control sample (258.5 MPa), it still demonstrates that the optimized process parameters produced a material with reasonably high strength suitable for engineering applications. In terms of hardness, the optimal sample produced at parameter combination A3B3C2 recorded a hardness value of 77 BHN, which is slightly higher than that of

the control sample (75 BHN). This improvement suggests that the optimized semi-solid squeeze casting parameters contributed to enhanced resistance to plastic deformation. Overall, the confirmation test validates the effectiveness of the Taguchi optimization approach, showing that the selected parameter combinations can produce semi-solid squeeze cast aluminium alloys with mechanical properties comparable to those of commercially available A356 cylinder head alloys.

Table 8: Results of confirmation test

| Properties | Optimal sample | Control sample |
|------------------------|----------------|----------------|
| Tensile strength (MPa) | 231 | 258.5 |
| Hardness (BHN) | 77 | 75 |

4. Conclusion

This study established that the mechanical performance of recycled aluminium alloy derived from automobile cylinder head scrap can be effectively tailored through careful control of semi-solid squeeze casting parameters. The findings confirm that process variables play distinct and significant roles in determining specific mechanical properties, and that their optimization is essential for achieving a balanced performance.

The application of the Taguchi optimization technique proved to be a reliable and systematic approach for identifying suitable processing conditions, thereby enhancing the efficiency and consistency of the casting process. The results further demonstrate that recycled aluminium alloys can attain mechanical properties that are sufficiently competitive for engineering applications, reinforcing their viability as sustainable alternatives to primary alloys.

Overall, the study validates semi-solid squeeze casting as a promising and practical route for recycling aluminium scrap into value-added components. It highlights the potential of integrating process optimization techniques with advanced casting methods to support sustainable manufacturing while maintaining acceptable material performance standards.

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