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Effect of Squeeze Casting Parameters on Tensile Strength and Hardness of Aluminum Cast Part

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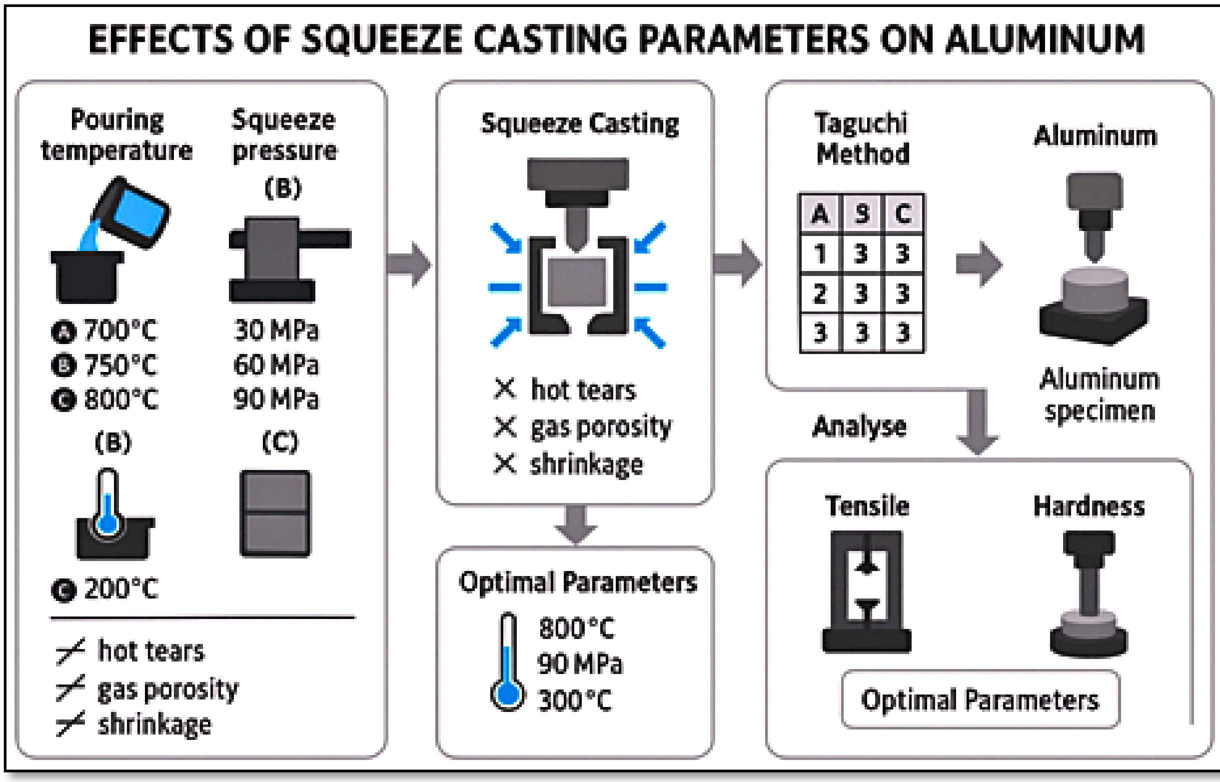
Abstract

Over the years, researchers have grown increasingly interested in how squeeze casting settings such as pouring temperature, squeeze pressure, and mould temperature influence the tensile strength and hardness of aluminium castings. Squeeze casting which forces metal into a die under high pressure cools more quickly than standard methods thus reducing defects such as hot tears, gas porosity, and shrinkage. To address these issues, this study uses the Taguchi statistical technique with an L9 orthogonal array, assigning three levels to each of the three factors: mould temperature (A) at 2000C, 2500C and 3000C; pouring temperature (B) at 7000C, 7500C and 8000C; and squeeze pressure (C) at 30, 60 and 90 MPa. Eighteen (18) aluminum specimens were produced from recycled aluminium scrap by repeating each trial twice for accuracy. Castings were tested for average tensile strength and hardness after standard machining to remove surface irregularities. The result showed that the combination of 90 MPa pressure, 8000C pouring temperature and 3000C mould temperature yield the strongest mechanical properties. The experimental result also shows that, squeeze pressure had the most significant impact on both tensile strength and hardness. Additional analysis of the signal-to-noise ratio substantiated this ranking and guided the optimal hardness of 90 MPa squeeze pressure, 800°C pouring temperature, and 300°C mould temperature. These findings demonstrate that careful control and optimization of squeeze casting parameters can significantly improve the quality and performance of aluminum cast products.

***Keywords**: Squeeze casting; mould temperature; pouring temperature; tensile strength; hardness.*

Graphical Abstract



1.0 INTRODUCTION

Aluminum and its alloys are very popular in automotive, aerospace and structural engineering due to their high strength to weight ratio, corrosion resistance and recyclability. These properties make them ideal for making light weight components. However traditional casting methods often lead to porosity, segregation and uneven microstructure which can affect mechanical performance and make the material unsuitable for high integrity applications. To overcome these challenges, squeeze casting also known as liquid metal forging has emerged as a promising alternative. This process involves pouring molten metal into a preheated die and applying high pressure as it solidifies. Squeeze casting improves microstructural uniformity, minimizes porosity and improves mechanical properties by increasing heat transfer rates. However, the success of this process depends on the precise control of the key parameters like melting temperature, pressure, solidification time and die temperature. Many researchers have studied how these parameters affect the casting results. Example includes: Mehat and Kamaruddin [1] who used Taguchi method to analyze injection molding parameters for recycled plastics. Shang et al. [2] studied the microstructure and mechanical behavior of aluminum matrix composites and found that Taguchi method is very effective in analyzing parameter interactions. Surappa [3] described squeeze casting as a multi stage process that requires careful execution while Muthu Kamatchi and Muraliraja [4] used Taguchi design to optimize aluminum composites with bone powder. They found that the optimal tensile strength and hardness was at 700°C melt temperature, 100 MPa pressure, 5% reinforcement and 600 rpm stirring speed. John et al. [5] optimized sand casting parameters for hardness and impact strength using ANOVA and found that pouring temperature was the most significant factor. Jamkar et al. [6] improved green sand casting by adjusting moisture, permeability and compression strength. Inegbedion et al. [7] used Taguchi L9 orthogonal array to study the effect of pouring temperature, mould temperature and squeeze pressure on aluminum alloy composites. They found that the optimal tensile strength and hardness was at 650°C pouring temperature and 700°C mould temperature, with pressure of 300 MPa and 200 MPa respectively. Deng et al. [8] did a systematic review of squeeze casting and highlighted the limitations and proposed future improvements in parameter design. Gugulothu et al. [9] used stir-squeeze casting (SSC) method to fabricate Al7475 composites with ceramic particles. Using Taguchi L16 design they found that reinforcement content had the highest influence on tensile strength,

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followed by squeeze pressure, stir speed and melt temperature. The optimal combination gave tensile strength of 325 MPa and hardness of 130.6 HV. Other significant studies include Srinivasan et al. [10] who investigated how pressure affects the microstructure and strength of LM6 aluminum. Sekar and Ananda Rao [11] focused on creating A7075 hybrid composites using stir and squeeze casting techniques. Karabulut et al. [12] delved into the drilling behavior of AA7039 composites that were reinforced with different ceramics. Christy et al. [13] examined recycled aluminum alloys produced through combined casting methods. Natrayan and Senthil Kumar [14] took an innovative approach by merging artificial neural networks with the Taguchi method to optimize the casting process for AA6061 composites reinforced with Al_2O_3, SiC, and graphite. Ojarigho et al. [15] also made strides in refining the squeeze casting parameters for the Al-12%Si alloy, identifying the optimal settings to enhance yield and tensile strength through detailed statistical analysis. Similarly, Manjunath et al. [16] and Shi-bo Bin et al. [17] utilized the Taguchi method to determine the best conditions affecting properties like tensile strength and elongation in LM20 and AlSi9Cu3 alloys. Finally, Souissi et al. [18] and Vijian et al. [19] highlighted the critical role of squeeze pressure in influencing both mechanical performance and surface finish, showing that careful parameter optimization can reduce defects and enhance casting quality. Though earlier research has examined squeeze casting parameters for aluminum composites and specific alloys, there remains a dearth of consensus on which factors most significantly impact tensile strength and hardness in unreinforced aluminum parts. This study seeks to addresses that gap by analyzing casting parameters like pouring temperature, squeeze pressure, and mould temperature. Some of the studies reviewed highlighted the need for better parameter design, but a comprehensive analysis of interactive effects remains underexplored.

2.0 MATERIALS AND METHODS

2.1 Materials

The primary material utilized in this research was aluminum obtained from recycled aluminum scraps. Prior to use, the scraps were sorted and weighed. The mould employed for casting was fabricated from mild steel, with dimensions of 180 mm in length, 140 mm in width, and 100 mm in thickness. A cavity was machined into the die to achieve the required shape for casting. The key equipment used during the study included a crucible furnace, graphite crucible, crucible tongs, a squeeze casting machine, a thermocouple, and a melting furnace.

2.2. Methods

2.2.1 Squeeze Casting Process

Nine experimental runs were performed, each producing two specimens, totaling 18 cast samples. The dies (moulds) were fabricated prior to casting. 4kg of aluminum scrap was weighed and melted using a graphite crucible furnace, and squeeze casting was conducted under different process conditions. The molten aluminum was poured into the die at three different temperatures 700°C, 750°C, and 800°C corresponding to various combinations of die preheat temperatures and applied pressures. The furnace was maintained at 10°C above each target pouring temperature. Prior to pouring, the dies were preheated to enhance metal flow and reduce casting defects, with die temperatures set at 200°C, 250°C, and 300°C. Squeeze pressure was also varied, with values of 30 MPa, 60 MPa, and 90 MPa applied using the casting machine's plunger. After solidification, castings were removed from the mould cavities. The tensile strength of each sample was measured using a Denison universal testing machine, while hardness was evaluated using the Brinell Hardness Test. The Brinell Hardness Number (BHN) was calculated using the standard BHN formula provided in equation 1.

$$BHN = \frac{2P}{\pi D\left(D - \sqrt{\left(D^2 - d^2\right)}\right)} \quad (1)$$

where, P = Load (kg), D = Diameter of indenter (mm), d = Diameter of indentation (mm)

Signal to noise ratio (S/N) for tensile strength and hardness is calculated using equation 2. Since the aim of the study is to optimize casting parameters, the "larger the better (LB)" S/N ratio is used.

$$S/N_i = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (2)$$

where, y = the observed data, n = number of observation (trials)

The tensile strength is calculated using equation 3

$$Tensile\,\text{Strength} = \frac{F_{max}}{A_0} \quad (3)$$

where,

F_{max} = Maximum force applied before fracture (in Newtons, N)

A_0= Original cross-sectional area of the specimen (in mm²)

2.2.2 Taguchi optimization method

An L9 orthogonal array design of experiment was employed for the Taguchi optimization method. The L9 orthogonal array was chosen because it minimizes the number of experiments trials required and also helps identify the combination of parameters that optimizes

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performance, improve the system's reliability, reproducibility and reduces variability. The technique employs a generic signal-to-noise (S/N) ratio with HB (higher is better) characteristics to quantify the present variation. The input parameters considered are squeeze pressure, mould temperature, pouring temperature while the output parameters are tensile strength and hardness. Table 1 show the range of the process parameters employed while Figure 1 depict the schematic representation of the squeeze casting setup.

Table 1: Input parameters and levels

Input parameters	Symbols	Level 1	Level 2	Level 3
Squeeze pressure	MPa	30	60	90
Pouring temperature	^{0}C	700	750	800
Mould temperature	^{0}C	200	250	300

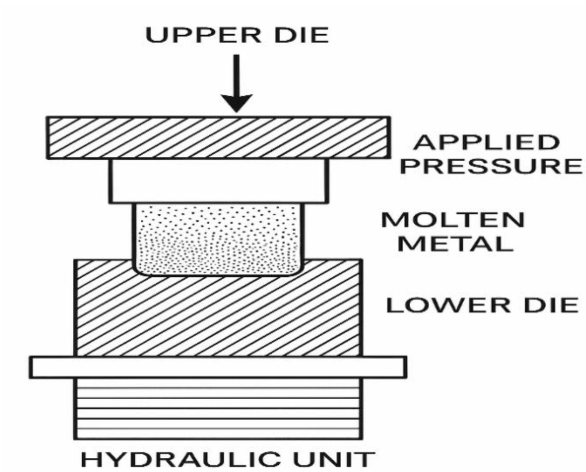

Figure 1: schematic representation of the squeeze casting setup.

The Taguchi experimental design and orthogonal array is depicted in Table 2 and 3 respectively.

Table 2: Taguchi Experimental Design

Table 4: Result of the tensile strength test experiment

Trail number	Squeeze pressure	Pouring temperature	Mould temperature
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3: Taguchi orthogonal array

Trail number	Squeeze pressure	Pouring temperature	Mould temperature
1	30	700	200
2	30	750	250
3	30	800	300
4	60	700	250
5	60	750	300
6	60	800	200
7	90	700	300
8	90	750	200
9	90	800	250

3.0 RESULTS AND DISCUSSION

The aluminum specimen obtained from the experiment was tested and the responses in terms of tensile strength and hardness were noted and tabulated accordingly in Table 4 and 5.

The squeeze casting results show that tensile strength is most improved by squeeze pressure (C), with values ranging from 94.32 to 96.62 MPa, indicating enhanced densification and reduced porosity. Pouring temperature (B) also positively influenced strength, especially in B3 samples reaching up to 95.83 MPa. Mould temperature (A) produced the lowest strengths, with A1 as low as 73.99 MPa, suggesting poor microstructural integrity. Overall, optimal squeeze pressure had the greatest effect on mechanical performance, followed by pouring temperature, while inappropriate mould temperature significantly reduced the tensile strength of the cast aluminum parts. The Brinell Hardness Number (BHN) results shown in Table 5 further confirm that squeeze pressure (C) significantly enhances material properties, with C3 showing the highest hardness values (412.54 and 401.77), indicating superior surface strength and resistance to deformation. Here mould temperature (A) produced the lowest hardness values, especially A1 at 121.07 and 138.00, revealing weak material compaction. Pouring temperature (B) offered moderate hardness, with B2 reaching up to 285.49. Combined with tensile results, it is clear that squeeze pressure has the greatest positive effect on mechanical performance, followed by pouring temperature, while reduced mould temperature settings lower both strength and hardness.

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Specimen label	**Diameter of sample (mm)**	**Load at break (KN)**	**Cross sectional area (mm^2)**	**Cross sectional area (m^2)**	**Tensile strength (MPa)**
C1	15.02	17.12	177.19	0.00017719	96.62
C1	15.37	17.91	185.54	0.00018554	96.53
C2	15.90	19.05	198.56	0.00019856	95.94
C2	15.82	18.80	196.56	0.00019656	95.64
C3	15.26	19.85	207.65	0.00020765	95.59
C3	16.26	17.89	189.67	0.00018967	94.32
A1	15.78	14.47	195.57	0.00019557	73.99
A1	16.17	15.20	205.36	0.00020536	74.02
A2	15.24	16.00	182.41	0.00018241	87.71
A2	16.09	16.40	203.33	0.00020333	80.66
A3	16.00	17.20	201.06	0.00020106	85.55
A3	15.78	17.00	195.57	0.00019557	86.93
B1	15.79	14.79	195.82	0.00019582	75.52
B2	15.20	16.76	181.46	0.00018146	92.36
B3	15.13	16.00	179.79	0.00017979	95.83
B3	15.11	16.80	179.32	0.00017932	93.69

Table 5: Result of hardness test experiment

Specimen label	Diameter of indenter D (mm)	Diameter of indentation d (mm)	Load (kg)	BHN (10/1000)
C1	10.00	1.98	1000	321.56
C1	10.00	1.97	1000	342.86
C2	10.00	2.05	1000	299.75
C2	10.00	2.08	1000	291.08
C3	10.00	1.75	1000	412.54
C3	10.00	1.80	1000	401.77
A1	10.00	3.20	1000	121.07
A1	10.00	3.00	1000	138.00
A2	10.00	2.54	1000	194.12
A2	10.00	2.50	1000	200.48
A3	10.00	2.47	1000	207.69
A3	10.00	2.48	1000	205.48
B1	10.00	2.13	1000	277.42
B1	10.00	2.12	1000	280.07
B2	10.00	2.11	1000	282.77
B2	10.00	2.10	1000	285.49
B3	10.00	2.07	1000	203.08
B3	10.00	2.05	1000	299.75

3.1 Result of the Experimental Setup

For the practical experimental runs, two trials were carried out for tensile strength in order to ascertain the integrity of the casting process and their average were computed. The experimental trial test result with replication for tensile strength and hardness is presented in Table 6

Table 6: Experiment test result for tensile strength and hardness

		Responses					
Experiment	**Number**	**Tensile strength (MPa)**			**Hardness (BHN)**		
		T_1	**T_2**	**Average**	**T_1**	**T_2**	**Average**
	1	96.62	96.53	96.58	321.56	342.86	332.21
C	2	95.94	95.64	95.79	299.75	291.06	295.41
	3	95.59	94.32	94.96	412.54	401.77	407.18
	4	73.99	74.02	74.01	121.07	138.00	129.54
A	5	87.71	80.66	84.19	194.12	200.48	197.03
	6	85.55	86.93	86.24	207.69	205.48	206.59
	7	75.52	88.67	82.09	277.42	280.07	278.75
B	8	92.36	95.83	94.09	282.27	285.49	284.13
	9	88.99	93.69	91.34	293.08	299.75	296.42

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The combined analysis of tensile strength and hardness shows that squeeze pressure (C) yields the highest and most consistent mechanical performance, with average tensile strengths of 96.58 MPa and highest hardness of 407.18 BHN, indicating strong, dense material. Mould temperature (A) resulted in the lowest values, with tensile strength averaging as low as 74.01 MPa and hardness at 129.54 BHN, revealing poor structure. Pouring temperature (B) produced moderate improvements, with best tensile values reaching 94.09 MPa and hardness up to 296.42 BHN. Overall, squeeze pressure had the most positive effect, followed by pouring temperature, while mould temperature performed worst. Table 7 represent the signal-to-noise (S/N) ratio for tensile strength and hardness.

Table 7: Average S/N ratio for tensile strength and hardness

	Tensile Strength			Hardness		
Level	**A**	**B**	**C**	**A**	**B**	**C**
1	39.61	38.42	39.28	50.66	47.16	48.59
2	38.19	39.18	38.73	44.79	48.24	47.00
3	38.95	39.15	38.74	49.13	49.30	48.99
Max - Min	1.42	0.76	0.55	5.87	2.14	1.99
Rank	1	2	1	1	2	3
Optimum level	A1	B2	C1	A1	B3	C3

The highest S/N ratio for tensile strength (39.61) was at A1 followed by 38.95 at A3 and 38.19 at A2. So A1 is the best pouring temperature. For mould temperature (B) the maximum S/N ratio is 39.18 at B2 slightly higher than B3 (39.15) and much higher than B1 (38.42). For squeeze pressure (C) the highest tensile strength was at C1 with a mean S/N ratio of 39.28. So the optimal parameter combination for tensile strength is A1B2C1 which correspond with the result obtained by [7]. The hardness values show the highest S/N ratio at A1 (50.66) followed by A3 (49.13) and the lowest at A2 (44.79) again A1 is the best for hardness as well. For mould temperature (B) B3 is the highest hardness (49.30) which is different from tensile strength (which favors B2). For squeeze pressure (C) C3 is the highest hardness (48.99) which is different from tensile strength optimum (C1). So there is a trade off when we optimize for different mechanical properties. The optimal parameter combination for hardness is A1B3C3. Figure 2 and 3 show the signal-to-noise (S/N) ratio plot for tensile strength and hardness. These plots help visualize how each factor level significantly influence the performance characteristics, helping in selecting the best combination for optimization.

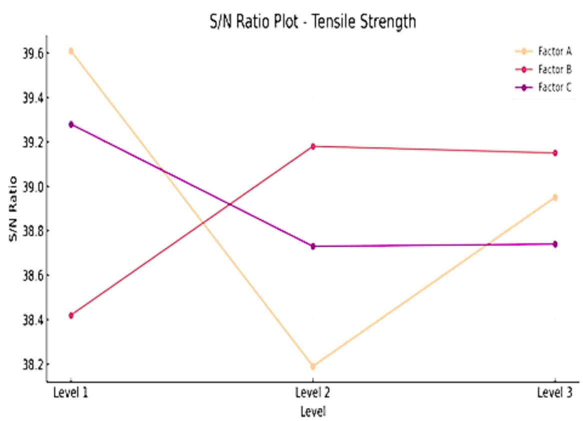

Figure 2: Signal-to-noise (S/N) ratio plot for tensile strength

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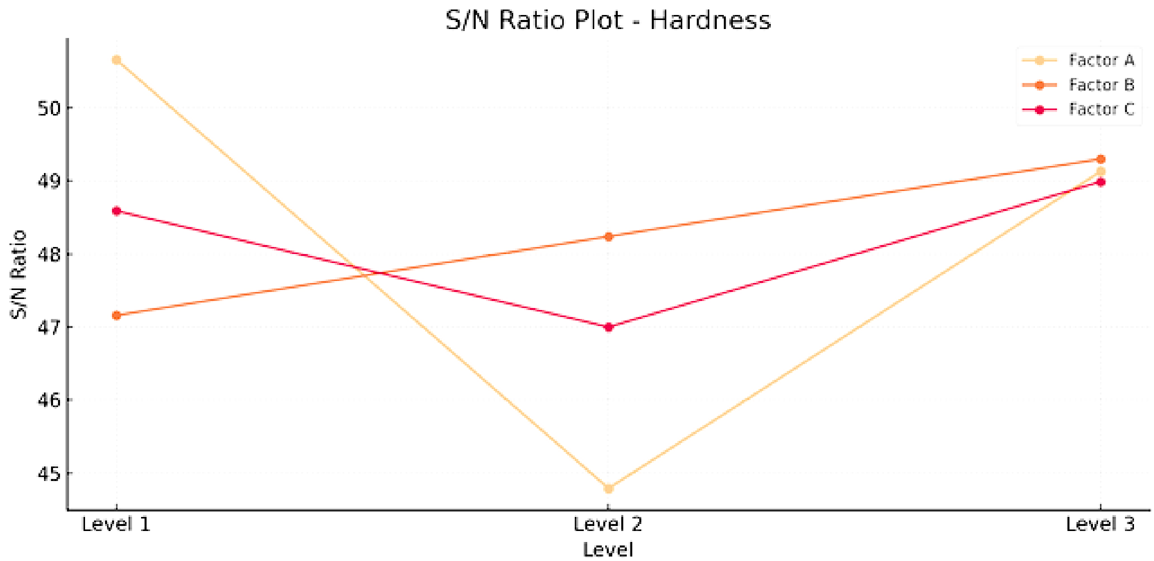

Figure 3: Signal-to-noise (S/N) ratio plot for hardness

Figure 4 and 5 show the response graphs for the signal-to-noise (S/N) ratios of tensile strength and hardness across different levels of each factor. The bar chart shows the influence of factors A (pouring temperature), B (mould temperature), and C (squeeze pressure).

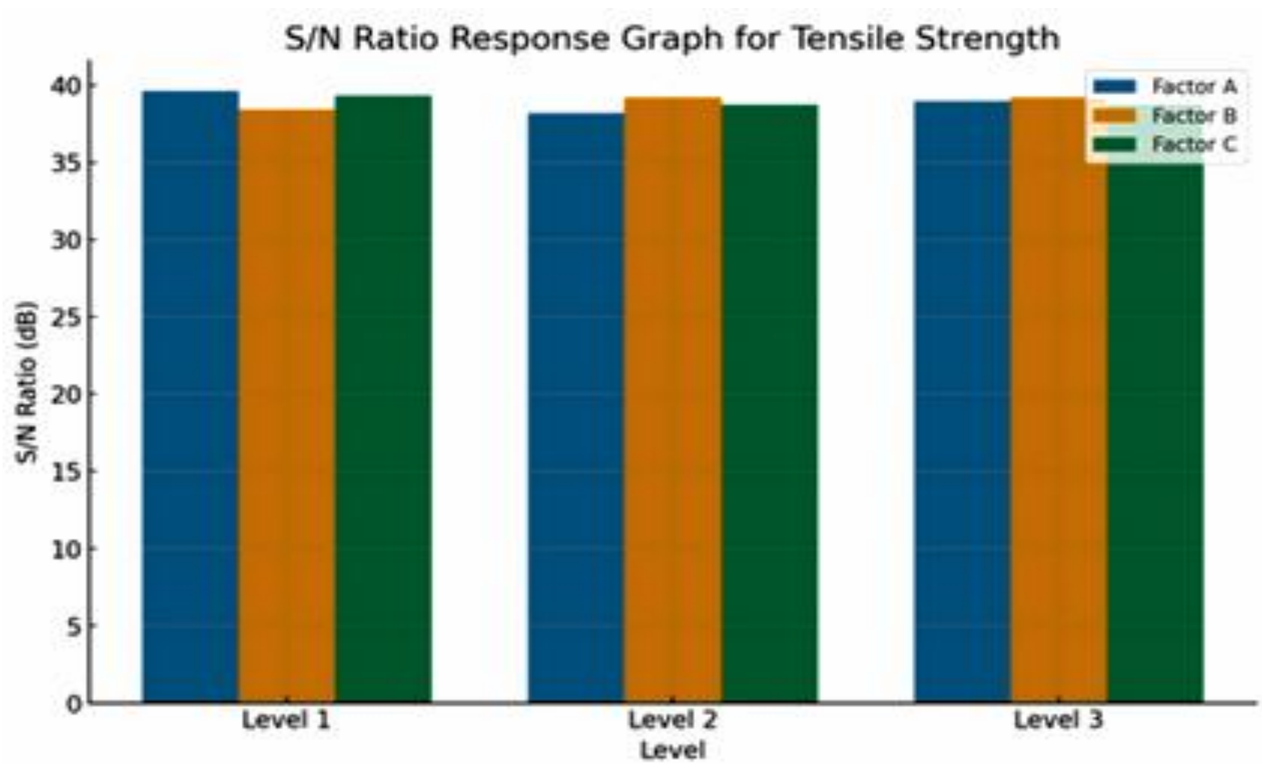

Figure 4: Response graph for signal to noise (S/N) ratio for tensile strength test

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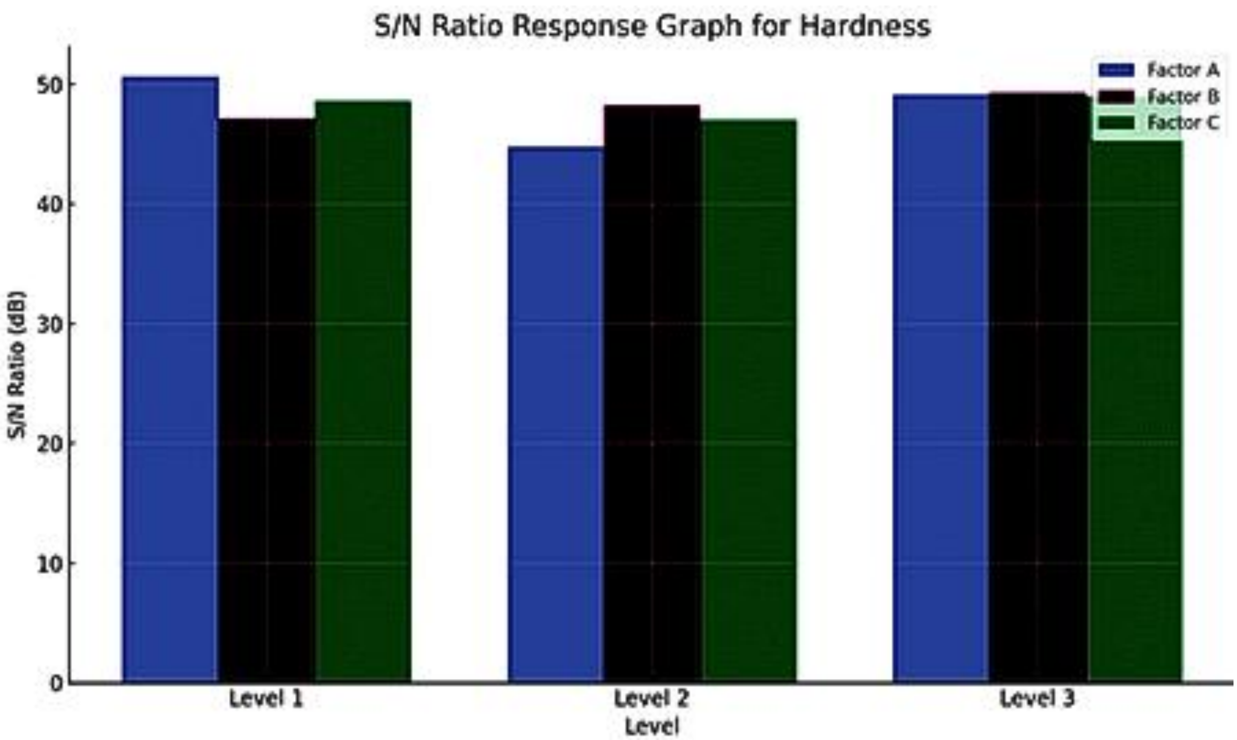

Figure 5: Response graph for signal to noise (S/N) ratio for hardness test

4.0. CONCLUSION

From the tensile strength and hardness test results, it is clear that squeeze casting parameters have a big impact on aluminum cast parts. Of the three variables (mould temperature, pouring temperature and squeeze pressure) squeeze pressure had the biggest positive effect. Samples cast under high squeeze pressure (Category C) had the highest tensile strength 96.58 MPa and Brinell hardness 407.18 BHN, indicating higher material density and less porosity due to effective pressure application during solidification. Mould temperature (Category A) had the least effect. Samples from this group had the lowest average tensile strength 74.01 MPa and hardness 129.54 BHN, meaning insufficient die preheating can cause poor flow and structural defects. Pouring temperature (Category B) had moderate effect, better results at higher temperature but not as big as squeeze pressure. The signal-to-noise (S/N) ratio analysis gave the optimal parameter combination for tensile strength as A1B2C1 while that of hardness is A1B3C3. Practical observation reaffirms squeeze pressure is the key to mechanical improvement. So squeeze pressure and proper pouring and mould temperature is the key to produce good quality aluminum cast parts.

Conflict of Interest

The authors declare that there is no conflict of interest.

Authors' Contribution

Kingsley Imanze was responsible for the experimental design, specimen preparation, and mechanical testing. Samuel Ayodeji Omotehinse supervised the research, carried out data analysis, and led the manuscript writing and editing. Both authors read and approved the final manuscript.

Authors' Declaration

The authors affirm that the content of this manuscript is original, has not been published elsewhere, and is not under consideration for publication in any other journal. The authors accept full responsibility for the integrity and accuracy of all data and interpretations presented herein

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