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Optimization of the Casting Parameters of a Squeeze Cast Aluminum Alloy Composite using Taguchi Method

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ABSTRACT

A lot of attention has been on aluminum and its alloy due to its wide range of industrial applications and qualities likes low density, good formability, high conductivity, high specific rigidity, excellent corrosion resistance, high castability and attractive tensile strength. The most common problems associated with casting are some forms of imperfections which are voids, cracks, and inclusions with varying degree of relative stiffness. Optimizing squeeze casting parameters will eliminate these forms of imperfection which forms the basis of this study. An optimization technique for squeeze casting process parameters based on Taguchi method is reported in this project. Squeezed casts were prepared using three different parameters at three different levels. The settings of these parameters were determined using the Taguchi L9 orthogonal array giving nine runs and squeezed cast specimens were tested to obtain their hardness and tensile strength. The optimum parameter combination was obtained using the analysis of signal-to-noise (S/N) ratio. The optimized process parameter obtained for hardness was A2 – 38.79, B3 – 38.88, C2 – 38.80 corresponding to pouring temperature at 650^{0}C, mould temperature at 700^{0}C and squeeze pressure at 2000Pa. While that of tensile strength was A1 – 40.15, B2 – 40.89, C1 – 40.89 corresponding to pouring temperature at 650^{0}C, mould temperature at 700^{0}C and squeeze pressure at 3000Pa. Finally based on the tensile strength and hardness test carried out the optimum level process parameters was found to be 40.89N/mm^2 and 38.88HB.

1. Introduction

Recently, great attention has been focused on aluminum and its alloy due to their high technological value, wide range of industrial applications, and various advantages such as lower density, good formability, high conductivity, high specific rigidity, excellent corrosion resistance, high castability and attractive tensile strength [1 and 2]. Aluminum alloys has widespread use especially as the most important industrial material of foundry. They offer important opportunities for applications in a diversity of areas particularly in the mechanical, automotive and aerospace industry [3]. In recent years, a new casting technology called squeeze casting has been developed to make better use of aluminum alloys [4]. Squeeze casting (as liquid metal forging) is a casting process which solidifies the molten metal under pressure within a closed die positioned between the plates of a hydraulic press [5, 6 and 7]. Most problems associated with casting engineering materials results from isolated imperfections. The most common forms of these imperfections are voids, cracks, and inclusions with varying degree of relative stiffness. Compared with conventional casting methods, squeeze casting possesses have many pronounced advantages, such as free shrinkages and gas porosity, provide components with high integrity with improved mechanical properties. Reference [11] found that the squeeze casting process was an ideal process to produce high quality light metal components with near net shape.

Taguchi's method has been widely used in engineering design to optimize squeeze casting process parameters. The Taguchi's method contains system design, parameters design, and tolerance design procedures to achieve a robust process and result for the best product quality [8]. The main trust of Taguchi's techniques is the use of parameter design, for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristics (performances measure) with minimum variation (Ealey, 1994). Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally over a variety of conditions. To determine the best design, it requires the use of a strategically designed experiment, which exposes the process to various levels of design parameters [12].

[10] explained composite material as a material made from two or more constituent materials having different physical or chemical properties such that when combined, they produce a material with different characteristics from the individual components whereby individual components remain separate and distinct within the finished structure. A composite can be defined as a combination of a matrix and a reinforcement, which when combined gives properties superior to the properties of the individual components. The matrix, normally a form of resin, keeps the reinforcement in the desired orientation. It protects the reinforcement from chemical and environmental attack, and it bonds the reinforcement so that applied loads can be effectively transferred [13].

The need for improved engineering material with flexible design, fabrications and improved mechanical properties brought about the development of squeeze cast metal matrix composites. Over the years, there has been different squeeze casting parameters used in the development of metal matrix composites. This study focused on optimizing squeeze cast parameters of an aluminum alloy composite namely; squeeze pressure, melting temperature and the pouring temperature.

2. Methodology

Genichi Taguchi introduced several statistical tools and concepts for quality improvement. According to him, the key element for achieving high quality and low cost product is parameter design. Through parameter design, optimal levels of process parameters (or control factor) are selected such that the influence of uncontrollable (or noise) factors causes minimum variation of system performances or response. These parameters should be controlled to improve the quality of both casting process and product. This session detailed the methods and materials used in achieving the set objective of this research.

2.1 Composite Preparations

Aluminum scraps used for window frames were sourced from a local workshop in Edo state. The Aluminum scrap was characterized using the energy dispersive X-ray fluorescence spectrometer. The X-ray fluorescence (XRF) is a powerful analytical technique used in a wide variety of industries to determine the elemental composition of various materials. XRF analyzers are widely recognized as a means for accurate, rapid, and non-destructive testing. To determine the elemental composition of the aluminum scarp used, the Skyray EDX3600B high-end energy dispersive XRF spectrometer (EDXRF) was used. This system comes with a large sample chamber which supports most sample sizes. It comes with a vacuum pump for light element detection and a helium injection system for liquid analysis. The Skyray EDX3600B is a multifunctional rapid analyzer applicable to a variety of applications. It has easy-to-operate software suitable for all users. The software highlights the information a user may require on one screen including elemental spectrum, measurement time, sample image and the real-time test result, critical instrument data and more. Furthermore, this system provides a color camera system for simple sample alignment and viewing. In only 10 minutes, the operator can see the main elements contained in a sample.

2.2 Experimental procedure

The fabrication of the metal matrix composite was done using the direct squeeze-casting method. In this method, because of the high pressure applied during the solidification of the molten metal in the mold, porosities caused by both gas and shrinkage are eliminated. The contact between the molten metal and the mold is improved by pressurization, which results in a pore-free, finer, grain-size with improved mechanical properties. The procedure involved in this process is highlighted:

i. The mold which has the cavity of the desired shape was produced.
ii. The furnace (open hearth furnace) was powered with the aid of 30 liters of diesel.
iii. 2kg of aluminum scrap was measured and placed in a crucible that fit the inner diameter of the furnace to melt.
iv. The aluminum scrap was heated to a temperature above 600˚C.
v. All dirt and unwanted materials were removed from the molten metal.
vi. Sawdust Ash at room temperature was added in 5%, 10% and 15% by wt. respectively into the molten Al alloy in steps and was mixed thoroughly to get the uniform distribution of the residue in the metal matrix.
vii. The reinforced molten aluminum was placed back into the furnace and was left for about 60 minutes.
viii. The slurry was poured into the pre-heated mold, to get a near net shape according to the ASTM standards for testing tensile, hardness and impact strength and pressure was immediately applied and allowed to cool to room temperature.
ix. After solidification, the reinforced matrix was allowed to cool.

In this research a three level L9 orthogonal array with nine experimental runs was selected (Table 1 and 2), and the specimens (Figures 1, 2 and 3) were machined and tested for hardness and tensile test. The hardness of each specimen is measured by using hardness apparatus while the tensile tests were done using the tensor meter. The total degree of freedom (DoF) is calculated using Equations (1) and (2)

$$\text{Total DoF} = \text{no. of experiments} - 1 \quad (1)$$

$$\text{Total DoF} = 9 - 1 = 8 \quad (2)$$

Table 1: Control factors and levels

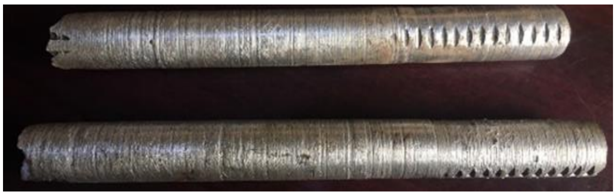
Control factors	**Code**	**Level 1**	**Level 2**	**Level 3**
Pouring Temperature (^{0}C)	A	600	650	750
Mold Temperature (^{0}C)	B	600	650	700
Squeeze Pressure (Pa)	C	2000	2500	3000

Table 2: Experimental design table using L9 Orthogonal array

Trial No	A (^{0}C)	B (^{0}C)	C (Pa)
1	600	600	2000
2	600	650	2500
3	600	700	3000
4	650	600	2500
5	650	650	3000
6	650	700	2000
7	750	600	3000
8	750	650	2000
9	750	700	2500

Where; A - Pouring Temperature; B - Mold Temperature; C - Squeeze Pressure

Figures 1: Samples after squeeze casting



Figures 2: Samples after tensile testing

Figures 3: Samples after hardness testing

2.3 Taguchi contributions are the signal to noise ratio it was developed as a proactive equivalent to the reactive loss function. The tensile and hardness test were considered the quality characteristic of interest with the concept of "the larger the better". The S/N ratio used for this type response is given by equation (3)

$$(S/N)_{dB} = -10\log\frac{1}{n}\sum_{i=1}^{n}\left[\frac{1}{{Y_i}^2}\right] \quad (3)$$

Where dB is decibel and Y_i is the response value for a trial condition repeated n times.

The parameters: pouring temperature (A), mold temperature (B), and squeeze pressure (C) were assigned to the 2nd, 3rd and 4th columns of L9 array respectively. The S/N ratios were computed for tensile strength and hardness test in each of the nine trial conditions (Table 3, 4 and 5).

Table 3: S/N ratio for tensile strength and hardness test

Trial	Pouring Temperature (^{0}C)	Mold Temperature (^{0}C)	Squeeze Pressure (Pa)	S/N Ratio Tensile Strength	S/N Ratio Hardness
1	600	600	2000	38.0160	38.8183
2	600	650	2500	36.8559	38.4846
3	600	700	3000	41.1677	38.8669
4	650	600	2000	40.3773	38.7704

5	650	650	2500	38.5422	38.5792
6	650	700	3000	41.5371	39.0122
7	750	600	2000	37.4547	38.3899
8	750	650	2500	40.3773	38.5792
9	750	700	3000	39.9538	38.7704

Table 4: Response table for signal to noise ratio of tensile strength test

Level	Pouring Temperature (^0C)	Mold Temeperature (^0C)	Squeeze Pressure (Pa)
1	38.67	38.62	38.62
2	40.15	38.59	38.59
3	39.36	40.89	40.89
Delta	1.48	2.3	2.3
Rank	2	1	1
Optimal Level	A1	B2	C1

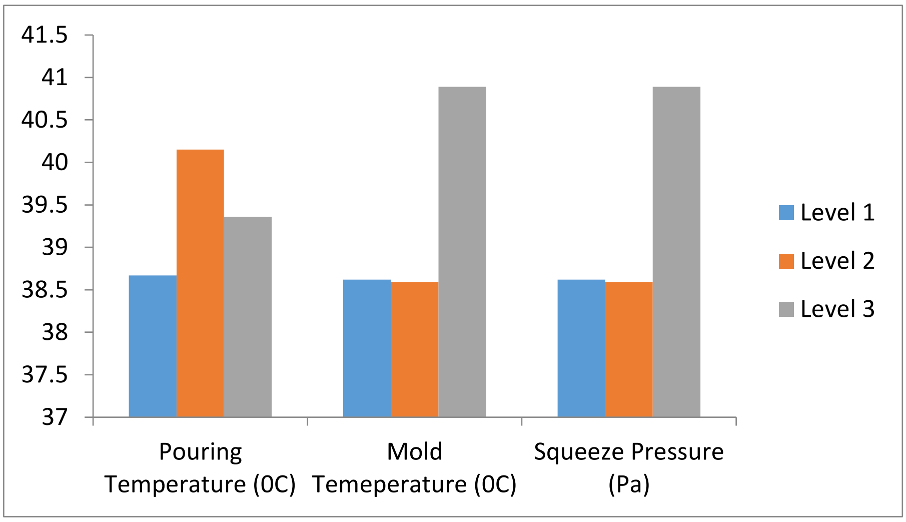


Figure 4: Response graph for signal to noise ratio of tensile strength test

Table 5 Response Table for S/N Ratio of the hardness test result

Level	Pouring Temperature (^0C)	Mould Temeperature (^0C)	Squeeze Pressure (Pa)
1	38.72	38.66	38.80
2	38.79	38.55	38.68
3	38.58	38.88	38.61
Delta	0.21	0.34	0.19
Rank	2	1	3
Optimal level	A2	B3	C2

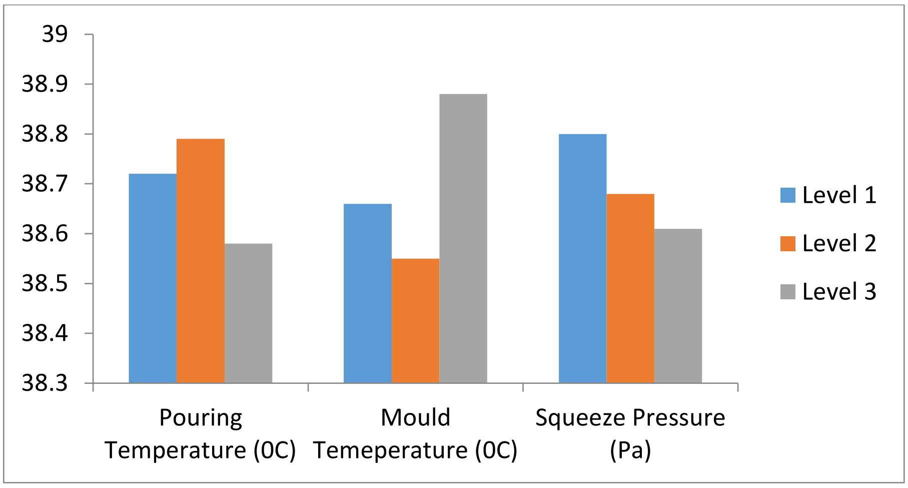


Figure 5: Response graph for S/N Ratio of the hardness test result

3. Results and Discussion

The result from the characterization of the Aluminum scrap showed that there exists a complex chemical composition of 91% aluminum content with Fe 0.4%, Mg 8.1%, Zi 0.2%, etc.

Results shown in Table 3, indicates that, the S/N ratio which yielded the optimal tensile strength is 41.5371 and it corresponds to Trial 6 while the least S/N ratio of the tensile strength 36.8599 was obtained from Trial 2. Results shown in Table 4 and Figure 4 indicates the optimal S/N ratio values for pouring temperature, mould temperature, and squeeze pressure as 40.15, 40.89, 40.89 which corresponds to level A1, B2 and C1 respectively. The optimal result for tensile strength was therefore the combination, A1, B2 and C1, which represents a pouring temperature of 650^{0}C, mould temperature of 700^{0}C and squeeze pressure of 3000Pa.

Results shown in Table 3, indicates that, the S/N ratio which yielded the optimal hardness test is 39.0122 corresponding to Trial 6 while, trial 7 produced the least S/N ratio result as 38.3899. Results shown in Table 5 and Figure 5 indicates the optimal S/N ratio values for pouring temperature, mold temperature, and squeeze pressure as 38.79, 38.88 and 38.80 corresponding to level A2, B3 and C1 respectively. The optimal result for hardness was therefore the combination A2, B3 and C1, which represents a pouring temperature of 650^{0}C, mould temperature of 700^{0}C and squeeze pressure of 2000Pa.

4. Conclusion

Squeeze casting parameters (squeeze pressure, mold temperature and pouring temperature) of a certain aluminum alloy was optimized using L9 Taguchi method of nine (9) experimental runs. Taguchi's method has been widely used in engineering design to optimize squeeze casting process parameters. The optimal result for tensile strength obtained are pouring temperature of 650^{0}C, mould temperature of 700^{0}C and squeeze pressure of 3000Pa. The optimal result for hardness obatined are pouring temperature of 650^{0}C, mould temperature of 700^{0}C and squeeze pressure of 2000Pa. The tensile strength and hardness test carried out on the optimal sample showed the tensile strength and hardness as 40.89N/mm^2 and 38.88BHN respectively.

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