EFFECT OF SQUEEZE CASTING PROCESS PARAMETERS ON SURFACE ROUGHNESS OF A413 ALLOY AND A413-B₄C COMPOSITES

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ABSTRACT

Aluminum alloy and their composites gather more interest in research field due to its wide applications in aerospace and automobile industries. Squeeze casting technique has potential to meet the existing demand for making the uniform, smooth surface, refined pore-free and near net shape components. In this work, a three-level full factorial design is employed to produce A413 alloy and A413-B₄C composites. A surface finish of both alloy and composite varies with their process parameters and their scientific theories are discussed. Variance analysis is performed on the response using ANOVA to determine the contribution of parameters and significance of the model. The observed results indicate that A413 alloy shows smooth surface finish (0.31 μ m) over the A413-B₄C composites (0.48 μ m) and the optimal parameters are 140 MPa squeeze pressure, 225°C die temperature, 725°C melt temperature, 4 Wt.% of B₄C particles.

KEYWORDS: A413 Alloy and A413-B₄C composites, Squeeze Casting & Surface Roughness

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INTRODUCTION

Aluminum alloys have been widely used in many applications over the past twenty years. The demands made by the transportation industries for lightweight components have led to an increased use of aluminum alloys in the production of a wide variety of castings, including critical automobile components such as engine blocks, cylinder heads, piston etc., [1-2]. Aluminum alloys are generally processed through sand casting, investment casting, continuous casting, centrifugal casting, gravity die casting, pressure die casting, etc. Die casting techniques are widely employed for producing intricately shaped castings with a good surface finish in aluminum die casting industries [3]. Generally, gravity and pressure die casting process exhibit several casting defects such as gas porosities, shrinkage porosities, segregations, hot tears, etc., especially for short freezing range aluminum silicon alloys, the casting parameters should also be controlled very closely to achieve a sound casting [4]

New casting techniques have been developed to compensate these shortcomings. Of the many such techniques available, squeeze casting has greater potential to create high-quality cast components [5]. Squeeze casting is a generic term to specify a fabrication technology where the solidification process is promoted under high pressure, which combines the advantages of gravity die casting and hot forging into a single operation where molten metal is solidified under applied hydrostatic pressure [6]. This enables the production of components with high integrity, close tolerance, good surface finish and fine mechanical properties [7]. In this process, the pressure is applied to solidifying liquid metal. Due to the intimate contact between the liquid metal and the mold and hence a higher rate of heat transfer across the metal mold interface, premium quality castings are obtained [8].

The squeeze casting process parameters that affect the quality of castings are the intensity of applied pressure, melt temperature and die preheating temperature. The die was coated with a graphite suspension before each experiment. It is postulated that pressures more than about 100 MPa are able to fully eliminate gas and shrinkage porosities [9]. In squeeze casting the die, temperature is usually held at between 200°C -300°C for aluminum and magnesium alloys, while the applied pressure varies between 50-150 MPa [10]. The lower die temperature (<150°C) cause inadequate fluidity, thermal fatigue failures in the dies and cold laps on the surfaces of the casting whereas higher die temperature (>400°C) leads to hot spots and shrinkage pores in the casting. In order to eliminate shrinkage and gas porosity, this pressure is usually in the range of 70 to 105 MPa (10 to 15 ksi) for simple shapes and 140 to 210 MPa (20 to 30 ksi) for thin sections and complex shapes [11]. Among various process parameters, the influenced parameters such as pouring temperature (700-740°C), is determines in terms of heat transfer and surface roughness of LM6 alloy. Surface roughness is primarily dependent on the production process, mold material, melt treatment and cooling condition or heat transfer. Heat transfer of molten materials is an important factor to the conversion of the microstructure and mechanical properties. The results show that increasing pouring temperature resulted in decreasing heat flow and surface. However, other parameters do not exhibit a significant influence on those features [12]. The Optimal level of process parameters to obtained better surface finish of squeeze cast components with LM6 aluminium alloy are squeeze pressure of 140 N/mm², die preheating temperature of 250°C and copper material were considered [13]. The optimal level of process parameters to obtained better surface finish of squeeze cast components with LM24 aluminum alloy are squeeze pressure of 105 N/mm², die preheating temperature of 350°C and Mild steel material were considered [14]. Previously, Soundararajan et al., have investigated the mechanical properties of A413 and A413-B4C composites processed through squeeze casting route using full factorial design. Results showed for symmetric castings, the optimal parameters were applied pressure (140 MPa), melt temperature (725°C), die preheating temperature (225°C) and 12 wt. % of B4C [15,16].

Metal matrix composites are most promising materials in achieving superior mechanical properties over monolithic alloys due to the presence of micro-sized particles in the matrix [17]. Addition of ceramic particles in the metal affects the eutectic solidification time and cooling rate of MMCs. The Surface finish of the casting depends on the solidification rate and distribution of the ceramic particles. A further section modulus of the castings has a significant effect on solidification behavior [18]. The development of 2024 aluminium alloy metal matrix composites reinforced with Al₂O₃ particles of 10,20,30 vol.% in size of 16,32,66 micron [19]. In the development of 2024 aluminum matrix composite, matrix alloy was reinforced with varying B₄C 3,5,7 and 10 vol.% in two different sizes of 29 and 71 micron. Both of them observed that the density of the composites decreased with increasing volume fraction and decreasing particle size, whereas the porosity and hardness of the composites increased with increasing particle content and decreasing particle size. The larger particles (<80 micron) were uniformly distributed in the matrix where the smaller particles (< 20 microns) lead to

agglomeration. The better results were obtained when the matrix is reinforced with 10 vol.% in both the cases[20].

Several studies investigate the mechanical and surface properties of aluminum alloy castings having symmetric/asymmetric shapes processed by squeeze casting technique. Still, there is a lack of investigation on the surface roughness of squeeze cast A413 alloy and A413-B₄C composite using full factorial design. The main intent of this work is to investigate the effect of influencing process parameters like applied pressure, melt temperature and die preheating temperature on the surface roughness of A413 alloy and A413-B₄C composites. While other parameters like die material, die coating material, the surface roughness of the die (0.3 microns), time of applying pressure, stirring speed and time were kept constant throughout the experimentation.

EXPERIMENTAL TECHNIQUE

MATERIALS

Aluminum silicon-based A413 is a eutectic alloy, which is having a major composition of 85.95% of aluminum and 11% to 13% of silicon and associated with the density of 2.66 g/cm³. The silicon widely used in aluminum alloys might be due to the salient features such as low density, helps in improving fluidity, reducing the melting temperature, abrasion resistance, low cost and easy availability. In general Al-Si alloys are associated with excellent pressure tightness, good hot tear resistance, good castability, good machinability, high specific strength and high corrosion resistance. The 98.8 % purity reinforcement B₄C particles having 44 microns was chosen for our work since it is one of the most promising ceramic materials due to its attractive properties, including high strength, low density, extremely high hardness, good chemical stability and neutron absorption capability

Table 1: Chemical Composition of a 413 Aluminium Alloy

Elements	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
Tested %	0.1	0.1	11.81	0.56	0.5	0.1	0.1	0.1	0.05	0.1	Reminder

Table 2: Chemical Composition of Boron Carbide (B₄C)

Elements	B	C	Ca	Fe	Si	F	Cl
Standard %	80.0	18.1	0.3	1.0	0.5	0.025	0.075

Experimental Setup

The setup comprises of an electric furnace capable of attaining 1000^oC with EN8 crucible employed to melt the ingot metal up to 2 Kg. The furnace also consists of a leak- proof bottom pouring arrangement with a preheated pathway for uniform pouring temperature of melt into the die. Thermocouples with digital indicator were used to control the melt temperature, pathway temperature and the die temperature. A stirrer assembly with up/down movement is provided to stir the melt at a variable speed (100 -1500 rpm). The reinforcement particle pre-heating furnace of 1000^oC is mounted on top of the crucible with a suitable controller for heating and adding particles directly to the melt while stirring. A motorized hydraulic power press of 50 Ton capacity with pressure indicator is used for applying desired pressure over the melt, and an H13 split die is clamped over the base of hydraulic power press setup as shown in figure 1

Figure 1: Squeeze Casting Setup

Figure 2: Cast Samples

Experimental Procedure

Experiments were planned in the first stage for A413 alloy by varying Squeeze Pressure(70,105and140MPa), Die preheating temperature (150°C, 225°C and 300°C) and Melt temperature (650°C, 725°C and 800°C). In the second stage for A413-B4C composites, Squeeze Pressure(70,105and140MPa), die preheating temperature (150°C, 225°C and 300°C) and B4C particles (4, 8 and 12 wt.%) are chosen as process parameters where melt temperature 725°C is taken as the fixed parameter. In our first stage of work, 1kg of A413aluminiumalloy ingot was melted in the furnace by varying temperature until a homogeneous liquid phase is obtained. During this phase, a cover flux of 8g is added to clean the melt and hexachloroethane (C_2Cl_6) of 12g is used as a degasser to remove the entrapped gases from the molten metal. Then the molten metal is transferred into the preheated pathway through bottom pouring arrangement. Preheated pathway helps in smooth pouring of the melt, also it avoids the temperature loss and turbulence flow of the melt into the preheated die. The compression loads were applied at a delay time of about five seconds after pouring molten metal and retained on the solidifying molten metal for a periodof60seconds to produce sound castings. By varying the process parameters casting samples were made. In the second stage of experimental work, after impurities are removed from the melt, the mechanical stirrer rotating at 300 rpm agitates the melt. Agitation would break the oxide layer formed on the surface of the melt so that the reinforcement particles can be easily incorporated into the melt. While stirring fine vortex is created and the preheated B₄Cparticles with same weight % of K₂TiF₆ is gradually added in order to increase the wettability. Then by aforesaid process the molten metal is carefully poured into the preheated die. Finally, the cast samples are separated from the die cavity and to measure the surface roughness of the casted samples by using a Mitutoyo surface roughness tester. Surface roughness data values are collected from each specimen at three location readings for all the specimens were noted for each set. The average values are taken for further processing

Table 3: Assigned full Factorial Design with the Acquired Data

Sl. No	A413 Alloy			Roughness Ra (μm)	A413 – B ₄ C Composite			Roughness Ra (μm)
	Squeeze Pressure (MPa)	Die Preheating Temp (°C)	Melt Temperature (°C)		Squeeze Pressure (MPa)	Die Preheating Temp (°C)	B ₄ C wt. %	
1	70	150	650	0.79	70	150	4	0.71
2	70	225	650	0.67	70	225	4	0.64
3	70	300	650	0.73	70	300	4	0.75
4	70	150	725	0.62	70	150	8	0.84
5	70	225	725	0.52	70	225	8	0.74
6	70	300	725	0.62	70	300	8	0.78
7	70	150	800	0.76	70	150	12	0.87
8	70	225	800	0.67	70	225	12	0.79
9	70	300	800	0.78	70	300	12	0.89
10	105	150	650	0.61	105	150	4	0.57
11	105	225	650	0.55	105	225	4	0.56
12	105	300	650	0.57	105	300	4	0.57
13	105	150	725	0.48	105	150	8	0.62
14	105	225	725	0.45	105	225	8	0.63
15	105	300	725	0.51	105	300	8	0.67
16	105	150	800	0.58	105	150	12	0.78
17	105	225	800	0.47	105	225	12	0.75
18	105	300	800	0.61	105	300	12	0.76
19	140	150	650	0.45	140	150	4	0.51
20	140	225	650	0.38	140	225	4	0.48
21	140	300	650	0.41	140	300	4	0.55
22	140	150	725	0.36	140	150	8	0.65
23	140	225	725	0.31	140	225	8	0.53
24	140	300	725	0.35	140	300	8	0.61
25	140	150	800	0.52	140	150	12	0.71
26	140	225	800	0.37	140	225	12	0.68
27	140	300	800	0.42	140	300	12	0.73

Figure 1: Comparison of Surface Roughness for A413 and A413-B₄C Composite

RESULTS AND DISCUSSIONS

Statistical Analysis

In order to determine the significance of each parameter involved in the process, analysis of variance (ANOVA) was performed based on values of response (Roughness). The determination coefficient (R^2) value indicates the integrity of fits of the model. The value of the mean adjusted determination coefficient for A413 alloy $R\text{-Sq} = 96.11\%$ and adjusted $R^2 = 96.11\%$ and for A413-B₄C composite $R\text{-Sq} = 94.22\%$ and adjusted $R^2 = 92.48\%$ indicates the higher significance of the model. From the table 4-5 it is evident that for pure A413 alloy, Squeeze pressure has a strong influence on surface roughness contributing 74.4% ,followed by die preheating temperature about 14% and melt temperature has the least contribution of 7.8%. For a composite, Squeeze pressure and B₄C Wt.% have a strong influence on surface roughness contributing 42.72%, 40.92% respectively and die preheating temperature contributes about 10.5 %. For both pure alloy

and composite P-values of the response were lower than 0.005, which shows that all three parameters including Squeeze Pressure, Die Preheating temperature and the weight percentage of B₄C are effective for controlling the surface roughness.

Table 4: Analysis of Variance for Surface Roughness of A413 Alloy, Using Adjusted SS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Squeeze pressure	2	0.364274	0.364274	0.182137	190.98	0.000
Die preheating temperature	2	0.069119	0.069119	0.034559	36.24	0.000
Melt temperature	2	0.038430	0.038430	0.019215	20.15	0.000
Error	20	0.019074	0.019074	0.000954		
Total	26	0.490896				

S = 0.0308821 R-Sq = 96.11% R-Sq(adj) = 94.95%

Table 5: Analysis of Variance for Surface Roughness A413-B₄C Composite, using Adjusted SS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Squeeze pressure	2	0.162452	0.162452	0.081226	73.89	0.000
Die preheating temperature	2	0.040185	0.040185	0.020093	18.28	0.000
B ₄ C Wt.% percentage	2	0.155607	0.155607	0.077804	70.78	0.000
Error	20	0.021985	0.021985	0.001099		
Total	26	0.380230				

S = 0.0331551 R-Sq = 94.22% R-Sq(adj) = 92.48%

Effect of Squeeze Pressure

Based on main effect plot figures 3 and figure 4, scientific theories for obtaining better surface finishes for A413 alloy and A413-B₄C Composite at various squeeze pressures are elucidated. As the molten metal solidifies an air gap is formed at the metal–mold interface, which is found to have a major influence on the surface roughness and the properties of the conventional castings. Air gap reduces the heat transfer coefficients at the interface, thus prolonged solidification occurs resulting in a poor surface finish. For prepared casting/composites squeeze pressure levels less than 140MPa are not sufficient to eliminate air gaps completely at the metal mold interface. Also, the air entrapment results in the formation of microporosity, which would have a deleterious effect on the surface finish. Whilst 140 MPa squeeze pressure breaks the air gap completely, tightly bonded with the metal-matrix and pushes molten metal closer to the die cavity, resulting in a higher solidification rate, further it replicates the surface roughness of the die (average 0.3micron) on the prepared castings. Also, High solidification rate hinders the formation of inclusions in the casting. These inclusions deteriorate the surface quality of castings. Squeeze pressure of 140 MPa accelerates the solidification rate of prepared casting/composites and it is sufficient for producing quality castings with a superior surface finish.

Effect Of Die Preheating Temperature

The scientific theories for obtaining better surface finish for A413 alloy and A413-B₄C Composite at various preheating temperature figure 3and figure 4 are as follows. Initially, die preheating helps to evaporate the entrapped air/gases from the die cavity. During solidification of melt, preheating temperature affects heat transfer rate at the surface of the die cavity. Thus die temperature has influence over the surface finish. However, lower die preheating temperature less than 225⁰C results in cold laps on the surface of casting/composites due to rapid solidification. Also, Lower die temperature causes thermal fatigue in the die due to hightemperature gradient. If die temperature is increased beyond 225⁰C hot spots and shrinkage pores will be formed in the casted sample due to solidification delay. Further, high die temperature cause localized welding of castings/composites with the die cavity. These problems will have a negative

impact over the surface of the castings/composites. For prepared casting/composites die preheating temperature of 225°C should be maintained to obtain a better surface finish and defect free sound casting/composites.

Effect of Melt Temperature

From the main effect plot figure 3, for 413 alloy scientific theory for obtaining better surface finish at melt temperature, of 725°C are discussed below. Melt temperature has a significant influence on the surface finish of the castings. Smooth surface was obtained with increasing melt temperature. The main intent of higher melt temperature is to increase fluidity. As the melt temperature increases the viscosity of the melt decreases and it will have intimate contact quickly with the die surface. Thus it promotes the solidification rate and results in a uniform surface finish for the entire surface of the casting. While melting temperature higher than 725°C increases the surface finish of the castings as it reduces the solidification rate and dies life. Whereas lower melt temperature less than 725°C leads to inadequate fluidity in a liquid melt, incomplete die filling, cold laps, premature solidification in castings/composites. A suitable melt temperature depends on several factors, such as a size of the casting, liquidus temperature, freezing range of the metal and die complexity. For these A413 cast samples, melt temperature should be 725°C for producing a better surface finish. Similar value of 725°C melt temperature is taken as a constant for all the prepared A413-B₄C Composite.

Effect of B₄C Weight Percentage

From the figure 4, Addition of ceramic reinforcement particles in A413 aluminum alloy reduces total solidification time of the castings. Hence reinforcement particle size and weight percentage have influence over the surface roughness of castings. As the weight percentage of B₄C particles increased beyond 4 wt.% moderate surface finish is obtained. Squeeze pressure increases the solidification rate, but this trend may attribute to the fact that the rate of heat transfer reduced, as the presence of B₄C particles more than 4 wt.% reduce the thermal conductivity and thermal diffusivity resulting in prolonged solidification. At 8 wt.% and 12 wt.% large amount of B₄C particles with 44micron were uniformly distributed on the surface of the castings which diminish the surface finish of the castings with high strength. Agglomeration due to increased above 12wt% reinforcement contents may be the reason for the decrease in strength values due to stress concentration in the prepared samples. Also, more than 44micron grain size of the particles shows higher surface roughness value. For A413 alloy B₄C particles should be within 4 wt.% for producing a precise quality composite with the better surface finish.

Figure 2: Main Effect Plot on Ra for A413 Alloy

Figure 3: Main effect plot on Ra for A413-B₄C composite

CONCLUSIONS

- A413 alloy and A413-B₄C composite were successfully fabricated through squeeze casting route using full factorial design with a cylindrical cavity of (average 0.30 microns) surface roughness.
- Surface finish of A413-B₄C composite deteriorates due to the addition of B₄C particle (44- micron size) compares with A413 alloy.
- From ANOVA that the most significant factor for surface roughness are squeeze pressure (74.4%) followed by die preheating temperature (14%) and melt temperature (7.8%) has a minimum contribution for A413 alloy. In case of A413-B₄C composite, most potent process parameters is identified as squeeze pressure (42.72%) and B₄C weight (40.92%) followed by die temperature (10.5%).
- The statistical results reveal that the model is significant with R²96.11% and 92.48% for A413 alloy and A413-B₄C composite. An Optimum level of parameters for obtaining better surface finish for both pure alloys (0.31µm) and composite (0.48µm) are found to be,

Squeeze Pressure: 140 MPa

Melt temperature: 725°C B₄C weight %: 4 Wt.%

Die Preheating Temp: 225°C Die Preheating Temperature: 225°C

- Applied squeeze pressure plays a major role in closely replicates the surface roughness of the die for both casted A413 alloy and A413-B₄C composite.

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