Optimization of Pouring Temperatures and Stirrer Speed Parameters on a Semi-Solid Slurry of ADC12 Al Alloy Prepared by Mechanical Stirring

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Abstract. This paper presents an experimental design approach for the optimization process parameters for the aluminum solid alloy casting of ADC12 alloys. To achieve this goal, the pouring temperatures and stirring speed are selected and two levels of this parameter are considered. Design of expert (DOE) of tests was used for experimental design and analysis of results. The aluminum ADC12 slurry is stirred by a mechanical stirrer (round rods stirrer models) with a variation of speed 250, 300, 350 rpm for 20 seconds. Furthermore, the aluminum slurry of ADC12 is poured on a metal mold with a temperature of 620 °C, 600 °C, and 580 °C. The microstructure characteristics were examined by direct observation using optical microscopy, secondary α-Al phase dendrite arm spacing and shape factor were identified. The mechanical properties were investigated by the hardness test and tensile test. The mechanical properties and microstructure of aluminum alloys ADC12 made with semi-solid rheocasting casting technology using several parameters pouring temperature and stirring speed have been studied, and the results obtained can be synergized as follows. ADC12 aluminum alloy slurry preparation using a round rod mechanical stirrer on semi-solid casting can improve mechanical properties. Low pouring temperature and high stirring speed are reliable techniques for producing the right mechanical and microstructure properties for a semi-solid casting process (Rheo casting). The pouring temperature and stirring speed are recommended to produce optimal mechanical properties and the round microstructure is 580 °C and 350 rpm.

1. Introduction
One of the methods for fabricating a near net shaped castings is semi-solid metal processing (SSM). It takes advantage of the flow behavior of raw materials prepared in the mushy zone. Bilateral combinations like this show solid and slurry-like behavior. This means that as solid, the material maintains structural integrity and stand-alone characteristics in the form of temporary billets by applying shear strength, the material flows easily as a slurry and fills the mold cavity progressively. The advantages of this process are lower porosity and shrinkage voids, lower processing temperatures, less mold erosion, and higher mold life [1-4].
The final microstructure is very sensitive to superheat the melting and casting temperatures low in promoting spheroidal morphology of a phase-Al in the aluminum alloy prepared by the new processing rheocasting [5]. To get the semi-solid slurry in the formation of rheo, pouring temperature, and cooling rate of the molten alloy [6-8] are strictly controlled. The liquefaction is carried out in the solid-liquid phase area [9] to ensure the primary phase morphology is in the solid-liquid phase [10].

Aluminum alloy is one of the most popular alloys for the SSM process. This alloy has a wide solidification range, a relatively low melting point, superior formability, and better mechanical properties. The desired structure in all SSM processes is defined as a structure free of dendrites, spherical, minimum eutectic particles or without being trapped. Therefore, globular morphology is the most noteworthy problem [11].

Dendritic transformation into spheroidal morphology with a stirring mechanism has been explained by several previous researchers. The decrease in surface energy due to shear velocity causes dendrites to bend and break [12, 13]. The change in dendritic transformation becomes spheroidal morphology because of the stirring of dissolved convection [14]. A number of researchers have investigated the formation of semi-solid metals with mechanical stirring. The effects of pouring temperature on the slurry manufactured by weak electromagnetic stirring were researched. The results indicate that it is feasible to manufacture the slurry with particle-like primary phases by low superheat pouring and weak electromagnetic stirring, and there is an important effect of the pouring temperature (superheat temperature) on the morphology and the size of primary 0-A1 in A356 Al alloy [15].

Rasyid et al. [16] have investigated the effects of pouring temperature on microstructure and mechanical properties of ADC12 Aluminum Alloys. The aluminum ADC12 slurry is stirred by a mechanical stirrer at 300 rpm for 60 seconds. Furthermore, the aluminum slurry of ADC12 is poured on a metal mold with a starting temperature of 580-680 °C. The pouring temperature had an effect on the change of mechanical properties and microstructure of aluminum alloy of ADC12. Furthermore, Rasyid et.al. [17] have investigated the effects of stirring parameters on the rheocast microstructure and mechanical properties of Aluminum Alloy ADC12. A short period of stirring below the liquidus temperature to form a non-dendritic structure. The final morphology of the primary particles after a short period of stirring time has little impact as the stirring time increases. The optimal mechanical properties (hardness and tensile strength) were obtained at 20 seconds of stirring time and 300 rpm of stirring rate.

Design of Expert (DOE) has been used by several researchers to optimize various types of manufacturing processes [18-21]. In this study, a model has been developed to predict the optimization of cast temperature and stirring speed in the ADC12 aluminum alloy semi-solid casting process. In this work by using a mechanical stirrer (round rods model) slurry maker constructed by the authors, several experiments have been conducted on the effects of pouring temperatures (580-620 °C) and stirring speed (250-350 rpm) with stirring times 20 second. For all these experiments, investigated the microstructure and mechanical properties of aluminum alloys ADC12 in the semi-solid casting.

2. Experimental Procedures
In this study, the secondary ADC12 alloy was used. The chemical composition of this alloy is shown in Table 1. The liquidus temperature of this alloy is 582 °C. The chemical composition of the aluminum alloy ADC12 is seen in Table 1.

Table 1. The composition of ADC12 aluminum alloys

| ADC12 Alloys | Weight % |
|--------------|----------|
| Si | Cu | Fe | Mn | Mg | Zn | Ti | Cr | Ni | Pb | Sn | Al |
| 9.55 | 2.01 | 0.91 | 0.16 | 0.22 | 1.31 | 0.03 | 0.02 | 0.14 | 0.11 | 0.02 | 85.49 |
2.1. Preparation of SSR slurry

Metal molds are prepared and heated to a temperature of ±300°C. Aluminum alloy material ADC12 is prepared (±300 gram). The alloy material of aluminum ADC12 is melted to 650 °C temperature using a gas furnace. Metal mold temperature measurements using infrared temperature gauges and aluminum molten measurements using a thermocouple gauge. In a temperature of 630 °C, 610 °C, and 590 °C, the aluminum alloy molten or slurry of ADC12 is stirred with a mechanical stirrer round rod stirrer models (Fig.1) of stirring speed of 250, 300, and 350 rpm. The liquid or aluminum alloy of ADC12 aluminum is poured into the metal mold. The specimens of casting result are made of the tensile specimen, hardness, and microstructure. In this study, the effect of pouring temperature and stirring speed on size, the main feature of ADC12 rheocast, and recognizing stirring requirements for significant changes in dendritic microstructure was examined.

![Figure 1. Mechanical stirrer round rod model](image1)

2.2. Mechanical testing and microstructure analysis

The mechanical properties of the foundry are investigated experimentally, including the nature of hardness and tensile properties. Hardness is evaluated by a Brinnel hardness tester, where steel ball indenter is used at 613 N load for 5 s. Tensile properties are checked at room temperature using a universal screw driven type screw machine with a capacity of 100 kN. The test specimens were designed based on ASTM B557 (Fig 2). Characteristics of microstructures are examined by optical microscopy (MO). The grain size of the α-al phase and the size of the eutectic base phase Si were measured using image analysis.

![Figure 2. Tensile specimens (ASTM B557)](image2)

Figure 3 shows the surface microstructure of aluminum alloy products ADC12 stirred slurry aluminum by mechanical stirrer round rod model. Optical micrographs showing the effect of stirring speed rate on the microstructure in semi solid casting at pouring temperature 580 ºC.
Figure 3. Optical micrographs showing the effect of stirring speed rate on the microstructure in semi solid casting at pouring temperature 580 °C (a, b, and c), 600 °C (d, e, and f), 620 °C (g, h, and i)

Image analysis techniques were used to investigate the microstructure of rheocast samples following standard metallographic procedures and average grain size was measured using a linear intercept method. The equation used to calculate the particle shape factor (SF) of the particle is [22]:

$$SF = \frac{4\pi A}{P^2}$$  (1)

Where P and A are the perimeter and area of individual particles respectively. A perfectly spherical particle would have a shape factor value of unity, and an infinitely long needle-like particle would have a shape factor equal to zero.
2.3. Experimental design and statistical analysis

To explore the effect of the operational factors on the response in the region of investigation, a DOE at two levels was performed. Pouring temperatures (C, A) and Stirring speed (rpm, B) were selected as independent factors. The range of values and coded levels of the factors are given in Table 2.

A polynomial equation (Eq. 2) was used to predict the response as a function of independent factors and their interactions. Interaction is the failure of the one factor to produce the same effect on the response at different levels of another factor [23]. In this work, there were four independent factors; therefore, the response for the quadratic polynomials becomes:

\[ Y = \beta_0 + \sum \beta_i x_i + \sum \beta_i x_i^2 + \sum \sum \beta_{ij} x_i x_j \]  

where \( \beta_0, \beta_i, \beta_{ii}, \beta_{ij} \) are the constant, linear, square and interaction regression coefficient terms, respectively, and \( x_i \) and \( x_j \) are the independent factors (A and B). Design-Expert 6 software was used for multiple regression analysis, analysis of variance (ANOVA), and analysis of ridge maximum of data in the response surface regression (RSREG) procedure. The goodness of the model was evaluated by the coefficient of determination \( R^2 \) and its statistical significance was checked by the F-test.

3. Result and Discussion

This study demonstrates the effect of pouring temperature and stirring speed for the optimization of the semi solid casting route. The design is used to obtain 13 design points within the whole range of two factors for experiments. The designs and the response are given in Table 3. Following the experiments, the response surface is approximated by the DOE.

Table 2. Independent factors and their levels for DOE of semi solid casting process

| Independent Factors       | Unit      | Level |
|--------------------------|-----------|-------|
| Pouring temperatures (A) | (°C)      | 580   |
|                          |           | 600   |
|                          |           | 620   |
| Speed stirrer (B)        | (rpm)     | 250   |
|                          |           | 300   |
|                          |           | 350   |

\[ (2) \]

Table 3. Design layout and experimental results

| Std | Pouring temperatures (rpm) | Stirring speed (rpm) | Coded A | Coded B | Hardness (HBN) | Tensile Strength (N/mm²) | Grain Size (µm) | SF |
|-----|----------------------------|----------------------|---------|---------|----------------|-------------------------|-----------------|----|
| 1   | 580                        | 250                  | -1      | -1      | 80.4           | 237.8                   | 31              | 0.61|
| 2   | 600                        | 250                  | 0       | -1      | 81.0           | 213.6                   | 33              | 0.50|
| 3   | 620                        | 250                  | 1       | -1      | 80.8           | 205.5                   | 45              | 0.59|
| 4   | 580                        | 300                  | -1      | 0       | 81.3           | 234.1                   | 29              | 0.64|
| 5   | 600                        | 300                  | 0       | 0       | 81.0           | 224.4                   | 30              | 0.49|
| 6   | 600                        | 300                  | 0       | 0       | 80.8           | 222.2                   | 29              | 0.50|
| 7   | 600                        | 300                  | 0       | 0       | 81.2           | 222.6                   | 31              | 0.48|
| 8   | 600                        | 300                  | 0       | 0       | 80.8           | 222.6                   | 30              | 0.50|
| 9   | 600                        | 300                  | 0       | 0       | 81.2           | 222.4                   | 29              | 0.48|
| 10  | 620                        | 300                  | 1       | 0       | 79.3           | 213.8                   | 35              | 0.62|
| 11  | 580                        | 350                  | -1      | 1       | 82.4           | 220.5                   | 22              | 0.72|
| 12  | 600                        | 350                  | 0       | 1       | 81.5           | 226.7                   | 24              | 0.66|
| 13  | 620                        | 350                  | 1       | 1       | 80.8           | 225.0                   | 31              | 0.67|
3.1. Hardness

Results for hardness at pouring temperature and stirring speeds show that it fits the linear model. The ANOVA for the hardness data is given in Table 4. Having its Prob>F of much less than 0.01, the linear model is valid. As for the coefficients, the pouring temperature and stirring speeds were considered as a significant factor.

| Source    | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|-----------|----------------|----|-------------|---------|----------|
| Model     | 11.38          | 2  | 5.69        | 32.86   | <0.0001  | significant |
| A         | 4.34           | 1  | 4.34        | 25.04   | 0.0005   |
| B         | 7.04           | 1  | 7.04        | 40.68   | <0.0001  |
| Residual  | 1.73           | 10 | 0.17        |         |          |
| Cor Total | 13.10          | 12 |             |         |          |

The obtained empirical equation of the hardness in the form of an actual factor is as stated in equation (3).

$$\text{Hardness} = 80.67 - 0.85A + 1.08B$$  \hspace{1cm} (3)

where A is pouring temperature (°C) and B is speed stirrer (rpm).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 4.

![Response surface graph of hardness](image)

Figure 4. Response surface graph of (a) contours and (b) 3D surface for hardness

Figure 1 shows the hardness of casting results with variations of pouring temperature (580 °C, 600 °C, and 620 °C) and stirring speed (250 rpm, 300 rpm, and 350 rpm). The higher the pouring temperature the hardness value decreases, but on the increase of stirrer speed, the hardness value increases. The highest hardness is 82.4 HBN at a pouring temperature of 580 °C and a stirring speed of 350 rpm.

3.2. Tensile strength

Results for tensile strength at a various pouring temperature and stirring speeds show that it fits the quadratic model. The ANOVA for the tensile strength data is given in Table 5. Having its Prob>F of
much less than 0.01, the quadratic model is valid. As for the coefficients, both of the pouring temperature and stirring speeds was considered a significant factor. Tensile strength was insensitive to the change in pouring temperature and stirring speeds.

Table 5. ANOVA with CI = 95% for model and factors of the tensile strength

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|--------|----------------|----|-------------|---------|----------|
| Model  | 832.15         | 5  | 166.43      | 427.23  | <0.0001  |
| A      | 556.81         | 1  | 556.81      | 1430.04 | <0.0001  |
| B      | 244.48         | 1  | 244.48      | 627.90  | <0.0001  |
| A²     | 6.95           | 1  | 6.95        | 17.85   | 0.0039   |
| B²     | 27.65          | 1  | 27.65       | 71.00   | <0.0001  |
| AB     | 2.72           | 1  | 2.72        | 6.99    | 0.0332   |
| Residual | 2.73      | 7  | 0.39        |         |          |
| Cor Total | 834.85    | 12 |             |         |          |

The obtained empirical equation of tensile strength in the form of an actual factor is as stated in equation (4).

\[
\text{Tensile Strength} = 222.39 - 9.63A + 6.39B + 1.59A^2 - 3.16B^2 - 0.82AB
\] (4)

Where A is pouring temperature (°C) and B is speed stirrer (rpm).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 5.

![Figure 5. Response surface graph of (a) contours and (b) 3D surface for tensile strength](image)

Figure 5 shows the tensile stress values of casting results with pouring temperature (580 °C, 600 °C, and 620 °C) and stirring speed (250 rpm, 300 rpm, and 350 rpm). The tensile stress of aluminum alloy ADC12 increases with increasing stirrer speed. However, the tensile stress of aluminum alloy ADC12 decreases with increasing pouring temperature. The maximum tensile stress is 237.8 N / mm2 at a pouring temperature of 580 °C and a stirring speed of 350 rpm.

3.3. Grain size

Results for grain size at a various pouring temperature and stirring speeds show that it fits the quadratic model. The ANOVA for the grain size data is given in Table 6. Having its Prob>F of much
less than 0.01, the quadratic model is valid. As for the coefficients, both of the stirring speeds and stirring time was considered a significant factor. Grain sizes were insensitive to the change in pouring temperature and stirring speeds.

### Table 6. ANOVA with CI = 95% for model and factors of grain size

| Source  | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|---------|----------------|----|-------------|---------|----------|
| Model   | 347.16         | 5  | 69.43       | 29.40   | 0.0001   | significant |
| A       | 121.50         | 1  | 121.50      | 51.45   | 0.0002   |              |
| B       | 192.60         | 1  | 192.60      | 81.58   | <0.0001  |              |
| A²      | 28.10          | 1  | 28.10       | 11.90   | 0.0107   |              |
| B²      | 0.27           | 1  | 0.27        | 0.11    | 0.7470   |              |
| AB      | 2.25           | 1  | 2.25        | 0.95    | 0.3615   |              |
| Residual| 16.53          | 7  | 2.36        |         |          |              |
| Cor Total| 363.69        | 12 |             |         |          |              |

The obtained empirical equation of grain size in the form of an actual factor is as stated in equation (5).

\[
\text{Grand Size} = 29.52 - 4.5A - 5.67B + 3.19A^2 - 0.31B^2 - 0.75AB \tag{5}
\]

Where A is pouring temperature (°C) and B is speed stirrer (rpm).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 6.

![Figure 6](image.png)

**Figure 6.** Response surface graph of (a) contours and (b) 3D surface for grain size

Figure 6 shows the grade of grain size with variations of pouring temperature (580 °C, 600 °C, and 620 °C) and stirring speeds (250 rpm, 300 rpm, and 350 rpm). The grain size of ADC12 aluminum alloy decreases with increasing stirrer speed, the grain size of aluminum alloy ADC12 increases with increasing pouring temperature. The minimum grain size is 20 μm at a pouring temperature of 580 °C and a stirring speed of 350 rpm. The grain size of ADC 12 aluminum alloy strengthens the results of mechanical properties testing. The mechanical properties of the material are inversely proportional to grain size.
3.4. Shape Factor (SF)

Results for shape factor at various pouring temperature and stirring speeds show that it fits the quadratic model. The ANOVA for the shape factor data is given in Table 7. Having its Prob>F of much less than 0.01, the quadratic model is valid. As for the coefficients, both of the temperature and stirring speeds was considered a significant factor. Shape factor was insensitive to the change in temperature pouring and stirring speeds.

Table 7. ANOVA with CI = 95% for model and factors of shape factor

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|--------|----------------|----|-------------|---------|----------|
| Model  | 0.083          | 5  | 0.017       | 21.20   | 0.0004   |
| A      | 1.350E-003     | 1  | 1.350E-003  | 1.72    | 0.2310   |
| B      | 0.022          | 1  | 0.022       | 27.53   | 0.0012   |
| A²     | 28.10          | 1  | 28.10       | 40.61   | 0.0004   |
| B²     | 7.588E-003     | 1  | 7.588E-003  | 9.67    | 0.0171   |
| AB     | 2.50E-004      | 1  | 2.50E-004   | 0.29    | 0.608    |
| Residual | 5.492E-003   | 7  | 7.846E-004  |         |          |
| Cor Total | 0.089          | 12 |             |         |          |

The obtained empirical equation of shape factor in the form of an actual factor is as stated in equation (6).

\[ SF = 0.50 - 0.015A - 0.060B + 0.11A^2 + 0.052B^2 - 7.500E - 003AB \]  

(6)

here A is pouring temperature (°C) and B is speed stirrer (rpm).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 7.

Figure 7. Response surface graph of (a) contours and (b) 3D surface for shape factor

Figure 7 shows the grade of grain size with variations of pouring temperature (580 °C, 600 °C, and 620 °C) and stirring speeds (250 rpm, 300 rpm, and 350 rpm). The shape factor aluminum alloy ADC12 increases with increasing stirrer speed, whereas Shape factor aluminum alloy ADC12 decreases with increasing pouring temperature. The maximum shape factor is 0.72 at a pouring temperature of 580 °C and a stirring speed of 350 rpm. Roundness or form factor is inversely
proportional to grain size. The smaller the grain size, the greater the form factor and the increasing mechanical properties.

3.5. Optimization
Now that the empirical model for all casting responses as a function of pouring temperature and stirring speed has been obtained, the selection of the optimal casting parameter setting can be performed. One can adjust the expected range of each casting response and the range of pouring temperature and stirring speed in line with expectations for all foundry responses can be determined. For example, that in order to obtain optimal mechanical properties, minimum grain size, and optimum shape factor, the stirring parameters should be carried out at 350-325 rpm rotation range and 580-590 °C pouring temperature. To achieve this criterion, the pouring temperature range and the speed stirring must be within the yellow plot of the overlay (Figure 8) of all casting responses.

![Overlay Plot](image)

**Figure 8.** Overlay plot of the input factors for the predetermined response criteria of a minimum of 82.0759 HBN hardness, 232.21 N/mm² tensile strength, 0.636 shape factor, and 23.119 μm grain size

4. Conclusion
The mechanical properties and microstructure of aluminum alloys ADC12 made with semi-solid rheocasting casting technology using several parameters pouring temperature and stirring speed have been studied, and the results obtained can be synergized as follows. ADC12 aluminum alloy slurry preparation using a round rod mechanical stirrer on semi-solid casting can improve mechanical properties. Low pouring temperature and high stirring speed are reliable techniques for producing the right mechanical and microstructure properties for a semi-solid casting process (Rheo casting). The pouring temperature and stirring speed are recommended to produce optimal mechanical properties and the round microstructure is 580 °C and 350 rpm.
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