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**Submission date:** 18-Jul-2021 04:48PM (UTC+0700)

**Submission ID:** 1620954805

**File name:** Rasyid\_2019\_IOP\_Conf.\_Ser.\_Mater.\_Sci.\_Eng.\_619\_012028.pdf (511.22K)

**Word count:** 4285

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To cite this article: Syaharuddin Rasyid *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **619** 012028

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## Optimization of stirring parameters on the rheocast microstructure and mechanical properties of aluminum alloy ADC12

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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 stirring time parameter 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 (straight plate stirrer models) at 610°C with a variation of speed 250, 300, 350 rpm for 20, 40, 60 seconds. Furthermore, the aluminum slurry of ADC12 is poured on a metal mold with temperature 600°C. The microstructure characteristics were examined by direct observation using optical microscopy, secondary  $\alpha$ -Al phase dendrite arm spacing and shape factor were identified. The mechanical properties were investigated by the hardness test and tensile test. The microstructure and mechanical properties of aluminum alloys ADC12 made with semi-solid rheocasting casting technology using several parameters stirring have been studied, and the results obtained can be synergized as follows. The highest mechanical properties (Hardness 122,5 HB, Tensile strength 238.2 N / mm<sup>2</sup>) occur at 300 rpm stirring speed and 20 seconds stirring time. Secondary Dendrite Arm Spacing (SDAS) lowest occurred at 25 rpm stirring speed and 20 seconds stirring time of 13.93  $\mu$ m. The highest shape factor occurs at 300 rpm stirrer spin and 20 seconds stirring time of 0.47. The optimal stirring parameters recommended for producing a hardness response of 122,071 HRC, tensile strength 236,271 N / mm<sup>2</sup>, Shape Factor (SF) 0.38994, and Secondary Dendrite Arm Spacing (SDAS) are 317 rpm (stirring speed) and 20 seconds (stirring time).

**Keywords:** Optimization, DOE, ADC12.

### 1. Introduction

The semi-solid metal forming technology has evolved since the early 1970s, and leader in the metal processing technology in the 21<sup>st</sup> century [1-3]. Conventional casting, dendrites micro-structure formed naturally may have disabilities, such as depreciation and gas shocks that weaken the mechanical properties [4]. In the process of semi-solid, micro-globular structures formed by shear rate applied to the molten metal which is in the range of compaction [5]. The solid fraction with a high percent ( $\pm$  60%), solids still has good mobility and can be formed by conventional forming processes [6].



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Some researchers have explained the dendrites transformation into spheroidal morphology with a stirring mechanism. The shear rate causes the dendrite to bend and break so that it decreases surface energy [7, 8]. Dendrite melting results at the root locally due to the stirring process [9-10]. Changes in the dendritic transformation into spheroidal morphology due to solute convection stirring at [11]. In recent years, many methods have been introduced for the production of the semisolid slurry as scientifically sound and viable industry with the preferred microstructure is called a thixotropic microstructure as a raw material. One of them is mechanical stirring. A number of researchers have investigated the formation of semi-solid metal with mechanical stirring. Rashid et al. [12] have improved the mechanical properties of aluminum alloy ADC12 with mechanical stirring molten alloy. Fan et al. [13] by using a mechanical stirrer can produce thin shielding parts that cannot be produced by the conventional die-casting process. Barabazon et al. [14] have investigated the effects of mechanical stirring on microstructure and mechanical properties of Aluminum Alloys. Niroumand et al. [15-17] to evaluate the microstructure rheocast by creating new mechanisms. They studied Al-7.1% Si alloys that are engineered under different stirring speeds and solid fractions. they show that the newly proposed mechanism for the formation and evolution of micro rheocast can explain and justify experimental results.

Some researchers have used DOE to optimize various types of manufacturing processes [18-22]. In this study, efforts have been made to develop models to predict optimal stirring parameters in the ADC12 aluminum alloy semi-solid casting process.

In this work by using a mechanical stirrer slurry maker constructed by the authors, several experiments have been conducted on the effects of stirring parameters such as stirring time and stirring speed. For all these experiments, investigated on the microstructure and mechanical properties of aluminum alloys ADC12 in the semi-solid foundry.

## 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 Aluminum 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  $\pm 250^{\circ}\text{C}$ . Aluminum alloy material ADC12 is prepared ( $\pm 280$  gram). The alloy material of aluminum ADC12 is melted to  $650^{\circ}\text{C}$  temperature using gas furnace. Metal mold temperature measurements using infrared temperature gauges and aluminum fluid measurements using a thermocouple gauge. In a temperature of  $605^{\circ}\text{C}$ , the aluminum alloy liquid or slurry of ADC12 is stirred with a mechanical stirrer straight plate stirrer models of stirring speed of 250, 300, and 350 rpm. Time stirring 20, 40, and 60 seconds. 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 time of stirring and stirring speed on size, the main feature of ADC12 rheocast, and recognizing stirring requirements for significant changes in dendritic microstructure was examined.

### 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 Brinell 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. Characteristics of microstructures are examined by optical

microscopy (MO). The secondary dendritic arm spacing of the  $\alpha$ -al (SDAS) phase and the size of the eutectic base phase Si were measured using image analysis.

Image analysis techniques were used to investigate the microstructure of rheocast samples following standard metallographic procedures and. average particle size and average dendritic arm spacing (DAS) dendrite were measured using a linear intercept method. The equation used to calculate the particle form factor (SF) of the particle is [23]:

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

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. Stirring speed (rpm, A) and stirring time (min, 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. An interaction is the failure of the one factor to produce the same effect on the response at different levels of another factor [24]. In this work, there were four independent factors; therefore, the response for the quadratic polynomials becomes:

**Table 2.** Independent Factors and their Levels for DOE of semi solid casting process.

Independent Factors	Unit	Level		
		-1	0	1
Stirring Speed (A)	(rpm)	250	300	350
Stirring Time (B)	(second)	20	40	60

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_i x_i^2 + \sum \sum \beta_{ij} x_i x_j \quad (2)$$

where  $b_0, b_1, b_{ii}, b_{ij}$  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 stirring speed and stirring time for the optimization of the semi solid casting route. The design is used to obtain 9 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 DOE.

**Table 3.** Design layout and experimental results.

Std	Stirring Speed (rpm)	Stirring Time (second)	Coded		Hardness (HBN)	Tensile Strength (N/mm <sup>2</sup> )	SDAS ( $\mu$ m)	SF
			A	B				
1	250	20	-1	-1	120.6	227.4	14.99	0.47
2	300	20	0	-1	122.5	235.1	13.93	0.43
3	350	20	1	-1	121.8	231.8	16.99	0.38
4	250	40	-1	0	120.7	225.7	21.63	0.38
5	300	40	0	0	122.2	231.8	16.77	0.30

6	350	40	1	0	121.9	229.9	17.62	0.36
7	250	60	-1	1	120.3	220.5	24.43	0.36
8	300	60	0	1	121.7	226.7	17.89	0.26
9	350	60	1	1	121.4	225.0	20.67	0.32

3.1. Hardness

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

**Table 4.** ANOVA with CI = 95% for model and factors of the hardness.

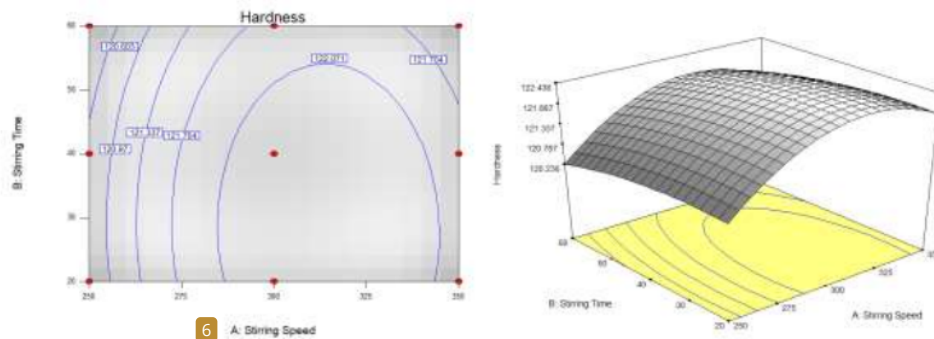
Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	4.58	5	0.92	33.54	0.0078	significant
A	2.04	1	2.04	74.75	0.0033	
B	0.37	1	0.37	13.73	0.0342	
A <sup>2</sup>	2.07	1	2.07	75.68	0.0032	
B <sup>2</sup>	0.094	1	0.094	3.44	0.1608	
AB	2.500E-003	1	2.500E-003	0.092	0.7820	
Residual	0.082	3	0.027			
Cor Total	4.66	8				

The obtained empirical equation of the hardness in the form of an actual factor is as stated in equation (1),

$$Hardness = 122.28 + 0.58A - 0.25B - 1.02A^2 - 0.22B^2 - 0.025AB \tag{1}$$

Where A is stirring speed (rpm) and B is stirring time (s).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 1.



**Figure 1.** Response surface graph of (a) contours and (b) 3D Surface for hardness.

(Figure 1 shows the hardness of casting results with variations of stirrer rotation (250, 300, and 350 rpm) and stirring time 20, 40, and 60 seconds. The graph shows the hardness of the ADC12 material of semisolid casting. The longer the stirring time the hardness value decreases, but on the increase of

stirrer rotation, the hardness value increases until 300 rpm rotation and the hardness value decreases at 350 rpm rotation.)

3.2. Tensile Strength

Results for tensile strength at various stirring speeds and stirring time 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 stirring speeds and stirring time was considered a significant factor. Tensile strength was insensitive to the change in stirring speeds and stirring time.

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	154.03	5	30.81	87.58	0.0019	significant
A	28.60	1	28.60	81.31	0.0029	
B	81.40	1	81.40	231.41	0.0006	
A <sup>2</sup>	40.20	1	40.20	114.28	0.0017	
B <sup>2</sup>	3.83	1	3.83	10.88	0.0458	
AB	2.500E-003	1	2.500E-003	7.107E-003	0.9381	
Residual	1.06	3	0.35			
Cor Total	155.09	8				

The obtained empirical equation of tensile strength in the form of an actual factor is as stated in equation (2),

$$Tensile\ Strength = 232.12 + 2.18A - 3.68B - 4.48A^2 - 1.38B^2 + 0.025AB \tag{2}$$

here A is stirring speed (rpm) and B is stirring time (s).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 2.

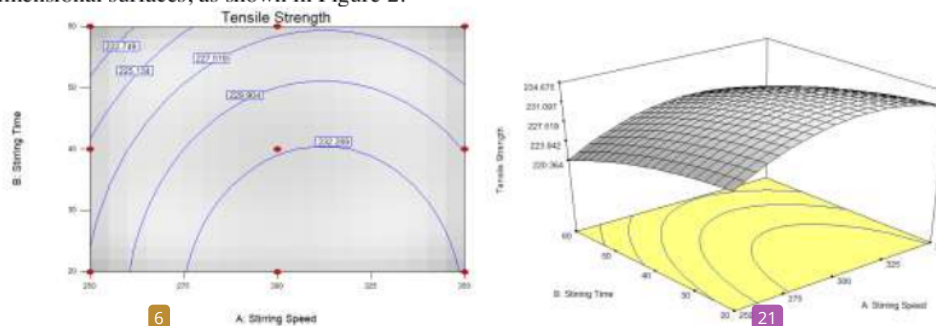


Figure 2. Response surface graph of (a) contours and (b) 3D Surface for tensile strength.

Figure 2 shows the tensile stress values of casting results with variations of stirrer rotation (250, 300, and 350 rpm) and stirring time (20, 40, and 60 sec.) The graph shows the tensile stress values of the semisolid-coated ADC12 material. then the value of tensile stress decreases, but at the increase of stirrer rotation, tensile stress value increases up to 300 rpm rotation and tensile stress value decreases at 350 rpm rotation.

3.3. Secondary Dendrite Arm Spacing (SDAS)

Results for secondary dendrite arm spacing at various stirring speeds and stirring time show that it fits the quadratic model. The ANOVA for the secondary dendrite arm spacing data is given in Table 6. Having its Prob>F of much more 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. Secondary arm spacing was insensitive to the change in stirring speeds and stirring time.

Table 6. ANOVA with CI = 95% for model and factors of secondary dendrite arm spacing.

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	83.39	5	16.68	8.88	0.0510	Not significant
A	5.55	1	5.55	2.96	0.1841	
B	48.62	1	48.62	25.90	0.0147	
A <sup>2</sup>	20.37	1	20.37	10.85	0.0459	
B <sup>2</sup>	0.55	1	0.55	0.29	0.06266	
AB	8.29	1	8.29	4.42	0.01263	
Residual	5.63	3	1.88			
Cor Total	89.02	8				

The obtained empirical equation of secondary dendrite arm spacing in the form of an actual factor is as stated in equation (3),

$$SDAS = 16.55 - 0.96A + 2.85B + 3.19A^2 - 0.52B^2 - 1.44AB \quad (3)$$

here A is stirring speed (rpm) and B is stirring time (s).

For convenience, the equation can be displayed as response surface contour as well as three-dimensional surfaces, as shown in Figure 3.

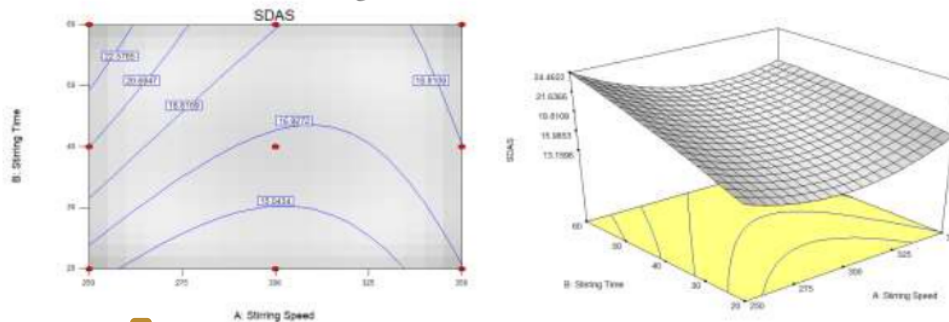


Figure 3. Response surface graph of (a) contours and (b) 3D Surface for secondary dendrite arm spacing.

Figure 3 shows the grade of secondary dendrite arm spacing with mixed rotation variations (250, 300, and 350 rpm) and stirring time (20, 40, and 60 sec.) The graph shows the secondary dendrite arm spacing of ADC12 semisolid foundry. The longer the agitation time the secondary dendrite arm spacing value is higher, but in the stirrer rotation increase, the secondary dendrite arm spacing value decreases to 300 rpm and the secondary dendrite arm spacing value increases at 350 rpm rotation.)

3.4. Shape Factor (SF)

Results for shape factor at various stirring speeds and stirring time 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 linear model is valid. As for the coefficients, both of the stirring speeds and stirring time was considered a significant factor. Shape factor was insensitive to the change in stirring speeds and stirring time.

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	0.023	2	0.012	6.95	0.0274	significant
A	3.750E-003	1	3.750E-003	2.26	0.1831	
B	0.019	1	0.019	11.63	0.0143	
Residual	9.939E-003	6	1.656E-003			
Cor Total	0.033	8				

The obtained empirical equation of secondary arm spacing in the form of an actual factor is as stated in equation (4),

$$SF = 0.36 - 0.025A - 0.057B \tag{4}$$

here A is stirring speed (rpm) and B is stirring time (s).

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

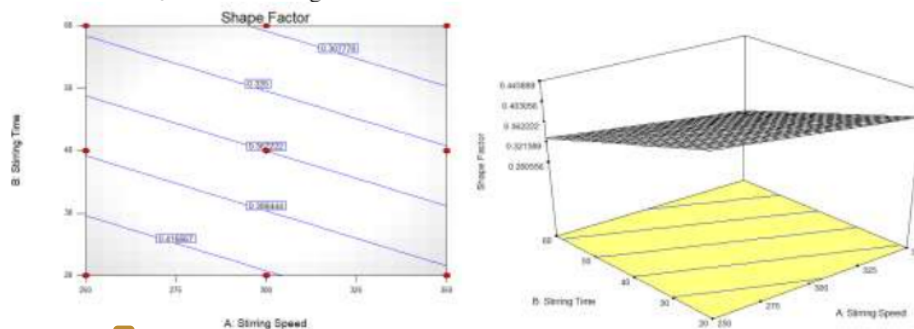


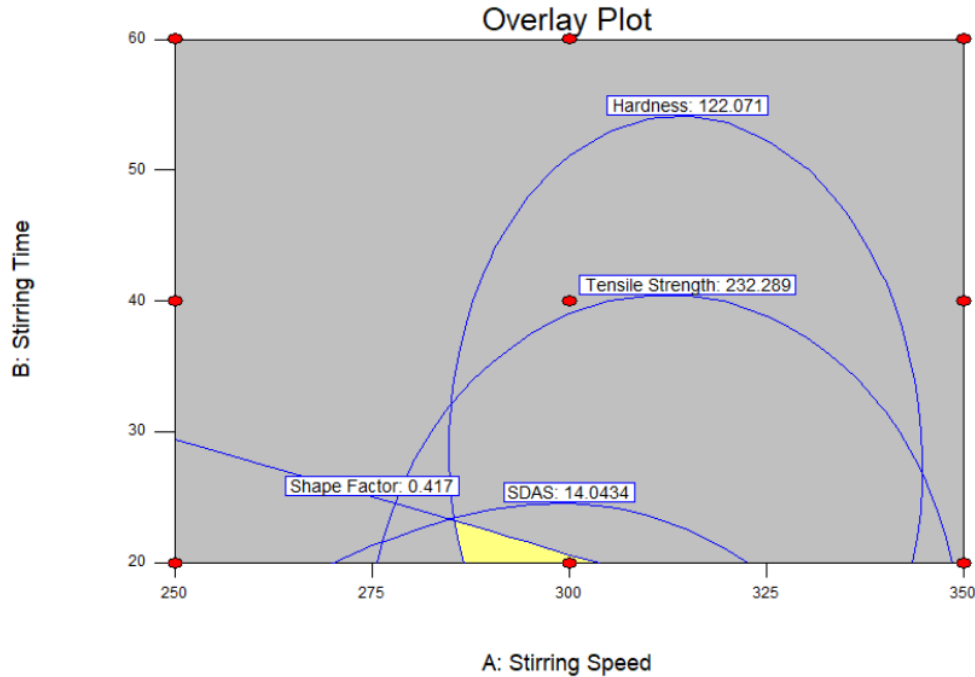
Figure 4. Response surface graph of (a) contours and (b) 3D surface for shape factor.

Figure 4 shows the shape factor values of casting results with variations of stirrer rotation (250, 300, and 350 rpm) and stirring time (20, 40, and 60 seconds). The graph shows the shape factor value of the ADC12 material of semisolid foundry. The longer the stirring time the shape factor value decreases, but in the stirrer rotation increase, shape factor value increases until 300 rpm rotation and shape factor value decreases at 350 rpm rotation.)

3.5. Optimization

Now that the empirical model for all casting responses as a function of stirring speed and stirring time 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 stirrer speed and stirring time in line with expectations for all foundry responses can be determined. For example, that in order to obtain optimal mechanical properties, minimum SDAS, and optimum shape factor, the stirring parameters should be carried out at 300-325 rpm rotation range and 20 seconds stirring time. To

achieve this criterion, the stirrer speed range and the timing of the sweep must be within the yellow plot of the overlay (Figure 5) of all casting responses.



**Figure 5.** Overlay plot of the input factors for the predetermined response criteria of a minimum of 122.071 HRC hardness, 232.289 N/mm<sup>2</sup> tensile strength, 0.417 shape factor, and 14.0434  $\mu$ m SDAS.

### 8 Conclusion

The microstructure and mechanical properties of aluminum alloys ADC12 made with semi-solid rheocasting casting technology using several parameters stirring have been studied, and the results obtained can be synergized as follows. The highest mechanical properties (Hardness 122,5 HB, Tensile strength 238.2 N/mm<sup>2</sup>) occur at 300 rpm stirring speed and 20 seconds stirring time. Secondary Dendrite Arm Spacing (SDAS) lowest occurred at 25 rpm stirring speed and 20 seconds stirring time of 13.93  $\mu$ m. The highest shape factor occurs at 300 rpm stirrer spin and 20 seconds stirring time of 0.47. The optimal stirring parameters recommended for producing a hardness response of 122,071 HRC, tensile strength 236,271 N/mm<sup>2</sup>, Shape Factor (SF) 0.38994, and Secondary Dendrite Arm Spacing (SDAS) is 317 rpm (stirring rate) and 20 seconds (stirring time).

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#### Acknowledgments

This article can be completed in cooperation between the lead author and lecturer of the Department of Mechanical Engineering, Hasanuddin University. Thanks to the Department of Mechanical Engineering, Ujung Pandang State Polytechnic, and Geology Department of Hasanuddin University for the provision of research facilities.

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