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Optimization of Rotation Speed and Casting Temperature in the Centrifugal Casting of Aluminum Alloy ADC12 Using Response Surface Methodology (RSM)

Syaharuddin Rasyid, Pria Gautama, Muhammad Ruswandi Djalal, Uswatul Hasanah Mihdar

Abstract – *This study aims to determine the parameters of centrifugal casting (rotary speed and casting temperature) on the optimal mechanical properties and microstructure of ADC12 aluminum alloy. To achieve this objective, the parameters of mixing speed and mixing temperature are selected and two levels of these parameters are considered. Tests based on the Response Surface Methodology (RSM) were used to design experiments and analyze data. The three selected speed ranges are 200, 250 and 300 rpm. The casting temperature changes are 640 °C, 660 °C and 680 °C. To determine the average granule size, hardness, tensile strength, and microstructure tests were carried out. The experimental design employed the Central Composite Design (CCD), and the specimens were produced based on the experimental run. The analysis of variance (ANOVA) results indicated that the parameters significantly influenced the response, leading to the establishment of a reliable model for the examined characteristics. The interaction between the parameters revealed that an increase in the rotational speed of the mold resulted in an augmentation of the properties. Based on the results of the analysis of variance and the relationship between the independent variables (rotation speed and pouring temperature) and the dependent variables (Hardness, Tensile Strength, and Secondary Dendrite Arm Spacing), the rotation speed variable is more dominant in improving the mechanical properties of aluminum alloy ADC12 when compared with the variable pouring temperature. The recommended casting parameters to produce optimal mechanical properties and microstructure of ADC12 aluminum alloy (Hardness 87.0005 HB, tensile strength 254.794 N/mm^2, and Secondary Dendrite Arm Spacing 15.4691 µm) are 300 rpm and 640°C with a desire of 0.985. Further research can be carried out at casting temperatures approaching freezing point at high mold rotation speeds.*

Keywords: *RSM, CCD, Centrifugal Casting, ADC12, Microstructure, Mechanical Properties*

Nomenclature

A	Surface area
ADC12	Aluminum Die Casting 12
Al-Si	Aluminum Silicon
CCD	Central Composite Design
Cu	Copper
Fe	Iron
Mg	Magnesium
Mn	Manganese
MO	Microscopy Optical
Pb	Lead
RSM	Response Surface Method
SDAS	Secondary Dendrite Arm Spacing
SEM	Scanning Electron Microscopy
Sn	Tin
Zn	Zinc
β	Coefficient term
x	Independent factors
Y	Dependent factors

I. Introduction

Centrifugal casting is a process where liquid metal is poured into a mold that is spinning. The rotation of the mold and the centrifugal force it generates causes the liquid metal to solidify, moving from the center of the mold to its edges. This movement aids in compacting the metal and eliminating any gaps or inconsistencies that are typically seen in gravity casting [1]-[4]. The rate of pouring, the temperature of the pour and the mold, and the material of the mold can all be adjusted individually or together to create the desired thermal gradient in the molten metal, which in turn determines how quickly it cools. The cooling rate significantly influences the grain structure of the casting, which then dictates its mechanical properties and its suitability for specific applications [5].

Therefore, various processing factors contribute to the characteristics of the centrifugal casting [6]. Gravity Die Casting is one of the methods of metal casting. These methods that only rely on gravitational force cause frequent defects in castings. Disabilities that often arise

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include faulty flow, air cavity, and shrinkage cavity. These defects will give a bad influence on the quality of castings products. The quality improvement of castings can be done by giving a thrust to the molten metal during the filling process of the print cavity. Push force in the casting process will be obtained if using the casting method with rotating molds. This method produces a product with a better microstructure because the gases contained in the molten metal can come out with the influence of centrifugal force [7]-[9]. By creating a robust design matrix that is intended to deliver properly structured experimental trials within predetermined ranges of variables, flexible statistical software, such as Response Surface Methodology (RSM), decreases the time required for proper analysis. Additionally, the RSM-based empirical models fully take into account the linear, quadratic, polynomial, and interaction impacts of the various process parameters, producing precise and realistic forecasts for the values of the near-optimal process factors in the designated operability zone [10]-[15], [22]-[24]. The maximum tensile strength, withstanding stress and percentage of elongation obtained by fabricated hypoeutectic Al-Si alloy hollow cylindrical workpieces when using a centrifugal casting process have increased when compared to using a conventional gravity casting process [10]. The increased wt.% of reinforcement, die speed, and particle size results in decreased wear loss. The effect of melting temperature on wear and CoF was the least, and an increase in melting temperature increases the wear loss, while particle size was the second most influential factor found after reinforcement wt.% on CoF [16]. The objective of this research was to create models that could anticipate the best rotation speed variation and casting temperature fluctuation in the aluminum alloy (ADC12) while using the rotating mold casting technique.

The centrifugal casting process parameters for the aluminum alloy ADC12 are optimized in this work using a mathematical model built using the Response Surface Method (RSM) and Central Composite Design (CCD).

This paper consists of several parts. Section II provides an overview of material composition, material preparation, microstructural analysis and mechanical testing, experiment design and statistical analysis. Section III explains the design scheme and findings from experiments, Experiment Design and Statistical Analysis (Hardness, Tensile Strength, and Secondary Dendrite Arm Spacing), and optimization, and Section IV presents the research conclusions.

II. Research Method

The aluminum alloy (ADC12) was used in this investigation. Table I displays this alloy's chemical make-up.

II.1. Materials Preparation

A 300 °C temperature is reached after preparing and heating metal molds. ADC12, an aluminum alloy substance, is ready (280 grams).

In the melting furnace, the alloy material for aluminum ADC12 must be melted until it reaches the desired temperature. The temperature parameters used are 640 °C, 660 °C, and 680 °C. thermocouple gauge readings of the temperature of the aluminum fluid and infrared temperature gauge readings of the temperature of the metal mold. If the aluminum is melted and the mold has reached the temperature according to the parameters specified, then the process of casting aluminum liquid into the mold with the rotating system. The rotational speeds that are employed include 200, 250, and 300 rpm. The metal must be removed from the mold as the last stage.

The specimens of casting results are composed of tensile specimens, hardness, and microstructure.

II.2. Analysis of the Microstructure and Mechanical Testing

Experimental research is done on the foundry's mechanical characteristics, including the type of hardness and tensile characteristics. A Brinell hardness tester is utilized to measure hardness, and a steel ball indenter is employed with a 613 N load for 5 s. Using a 100 kN capacity universal testing machine, the tensile characteristics are examined at room temperature. As a reference, ASTM B557 was used to generate the test specimens. Optical microscopy is used to evaluate the characteristics of microstructures (MO). Image analysis was used to determine the size of the secondary dendritic arm spacing

II.3. Designing an Experiment and Statistical Analysis

To find out how operational factors affected the response in the area under investigation, a DOE at two levels was conducted. Changes in casting temperature (min, B) and rotation speed (rpm, A) were selected as independent variables. The factor's range of values and coded levels are listed in Table II. A polynomial equation was used to predict the reaction as a function of the individual components and their interactions (Eq. (1)).

Interaction is when one element is unable to have the same impact on a reaction to a different degree of a different factor [17]. Due to the four independent elements in this study, the answers for the linear and quadratic polynomials are as follows [18]:

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_i x_i^2 + \sum\sum \beta_{ii} x_i x_j \qquad (1)$$

where x_i and x_j are the independent factors, and β_0, β_i, β_{ii}, and β_{ij} are the coefficient terms for the linear, square, and interaction regressions, respectively (*A* and *B*).

The multiple regression analysis, analysis of variance (ANOVA), and analysis of the data's ridge maximum phases of the response surface regression (RSREG) technique were all performed using software called Design-Expert 6.0.5 [19].

TABLE I
THE COMPOSITION OF THE ALUMINUM ALLOY ADC12

	Weight %					
Aluminum	Si	Cu	Fe	Mn	Mg	Zn
Alloy	9.55	2.01	0.91	0.16	0.22	1.31
(ADC12)	Ti	Cr	Ni	Pb	Sn	Al
	0.03	0.02	0.14	0.11	0.02	85.49

TABLE II
INDEPENDENT FACTORS AND LEVELS FOR THE DOE OF ROTATION MOLD CASTING

Independent Factors	Unit	Level -1	Level 0	Level 1
Rotation speed	(rpm)	200	250	300
Casting Temperature	°C	640	660	680

The R2 coefficient of determination was used to assess the model's quality, and the F-test was used to determine its statistical significance [20].

III. Result and Discussion

Contribution percentage for each experimental input parameters determined by analysis of variance [10]. To optimize process performance, Full Factorial Design (FFD), quadratic power model Response Surface Methodology (RSM) transformation and Strong statistical Design Expert (DX6) computer program is used for Design Experiment (DOE), namely to establish the effects of centrifugal casting mold rotation speed and casting temperature, on the mechanical properties and microstructure of aluminum ADC12 alloy. This study illustrates how changing the rotation speed and casting temperature can improve the use of rotating molds. Nine design points are obtained using the design for trials using a total of two components. Table III lists the designs and the feedback. Following the experiments, DOE is used to approximation the response surface.

III.1. Experiment Design and Statistical Analysis of Hardness

The Linear Model fits the results for hardness at rotational speed and casting temperature. Table IV contains the results of the ANOVA for the hardness data.

The linear model is viable because its Prob>F value is substantially lower than 0.0001. Regarding the coefficients, rotational speed and pure temperature were thought to be important variables.

TABLE III
DESIGN SCHEME AND FINDINGS FROM EXPERIMENTS

Std	Rotation speed (rpm)	Casting temperature (°C)	Coded A	Coded A	Hardness (HBN)	Tensile Strength (N/mm^2)	SDAS (µm)
1	200	640	-1	-1	83.85	245.67	19.39
2	250	640	0	-1	85.07	247.77	17.11
3	300	640	1	-1	87.42	253.52	15.54
4	200	660	-1	0	81.20	237.92	20.27
5	250	660	0	0	82.33	239.51	18.16
6	300	660	1	0	83.77	242.84	16.34
7	200	680	-1	1	77.9	216.63	21.86
8	250	680	0	1	78.98	221.17	19.83
9	300	680	1	1	80.98	230.17	18.51

TABLE IV
ANOVA FOR THE MODEL AND COMPONENTS AFFECTING HARDNESS WITH A 95% CONFIDENCE INTERVAL

Source	Sum of Squares	dF	Mean Square	F-value	Prob>F	
Model	71.09	2	35.54	339.14	<0.0001	significant
A	14.17	1	14.17	135.19	<0.0001	
B	56.92	1	56.92	543.10	<0.0001	
Residual	0.63	6	0.10			
Cor Total	71.72	8				

The model's F-value of 339.14 indicates that it is significant, as seen in Table IV.

This large of a "Model F-Value" might occur due to noise only 0.01 percent of the time. Model terms are regarded as significant when "Prob > F" is less than 0.0500. In this case, key model terms include *A* and *B*. If the value is more than 0.1000, model terms are not significant. Equation is the empirical hardness equation that was obtained as a real factor (2):

$$\text{Hardness} = 82.39 + 1{,}54\,A - 3{,}08\,B \tag{2}$$

where *A* is rotating speed and *B* is casting temperature variation. Equation (2) represents the mathematical model obtained to predict the value of hardness (the dependent variable) based on two independent variables, namely rotation speed and casting temperature. Equation (2) is based on the assumption that the relationship between rotation speed, casting temperature, and hardness is linear.

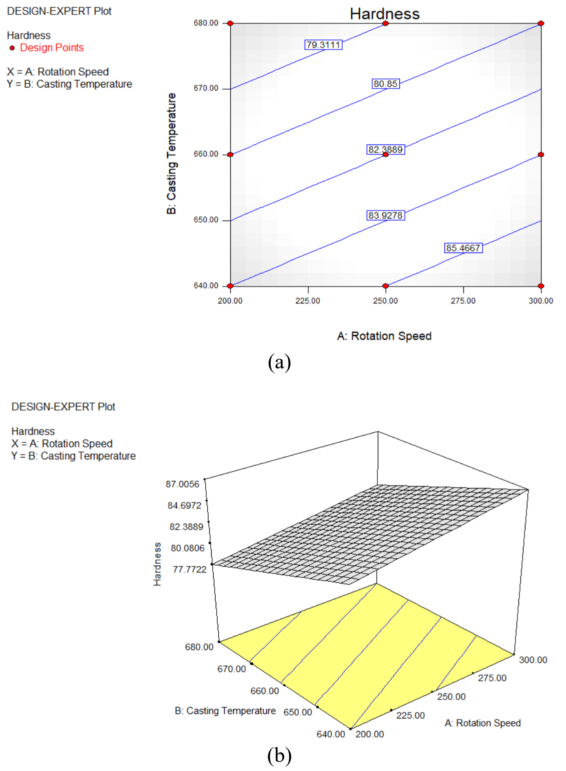
In this case, an increase of one unit in rotation speed or casting temperature will result in an increase in the corresponding regression coefficient. Positive regression coefficients indicate a positive relationship between the independent variables and the dependent variable.

In the equation, 82.39 is the intercept value when all the independent variables are zero. In this context, when the spin speed and pour temperature are both zero, the "Hardness" value is expected to be 82.39. The coefficient for spin speed (1.54) describes the average change in “Hardness” for each one-unit increase in spin speed, assuming the pouring temperature remains constant. In this case, if the rotational speed were increased by one unit, a 1.54 increase in "Hardness" would be expected.

The Coefficient for Pour Temperature (-3.08) describes the average change in “Hardness” for each one-unit increase in pour temperature, assuming the rotational speed remains constant. In this case, if the pouring temperature were increased by one unit, a 3.08 decrease in "Hardness" value would be expected. Figures 1 demonstrate how, in addition to three-dimensional surfaces, the equation can be readily illustrated as a response surface contour.

Figures 1 show the results of casting hardness at different rotational speeds (200, 250, and 300 rpm) and casting temperatures (640, 660, and 680 °C). The graph illustrates the degree of hardness achieved when rotating dies are used to cast aluminum alloy (ADC12). The higher the pouring temperature, the lower the hardness value. The pouring temperature can affect the hardness of aluminum.

Aluminum that is cast at a higher temperature tends to have a lower hardness.



Figs. 1. Response surface graph for hardness showing (a) contours and (b) 3D surface

The cooling process at a lower temperature can produce a denser microcrystal structure and result in an increase in hardness. If the rotational speed in the centrifugal casting process is higher, the hardness value is also higher. This is caused by the influence of centrifugal force, which increases the compaction process and increases the hardness value.

III.2. Experiment Design and Statistical Analysis of Tensile Strength

It fits the linear model according to results for tensile strength at rotating speed and pour temperature change. Table V contains the results of the tensile strength data's ANOVA. The linear model is valid because its p-value is considerably lower than 0.01. Both the variation in rotation speed and the variation in casting temperature were regarded as significant factors in the coefficients.

The modification in pour temperature and rotating speed had no effect on tensile strength. Design scheme and findings from experiments Table V demonstrates that the model is implied to be significant by the Model F-value of 56.18. The probability of noise producing a "Model F-Value" this large is only 0.01 percent. When "Prob > F" is less than 0.0500, model terms are considered significant.

The derived empirical tensile strength equation is given in equation as an actual factor (3):

$$\text{Tensile Strength} = 237{,}24 + 4{,}39\,A - 13{,}16\,B \quad (3)$$

where A represents rotational speed and B represents pour temperature.

TABLE V
ANOVA FOR THE MODEL AND TENSILE STRENGTH-RELATED PARAMETERS WITH A 95% CONFIDENCE INTERVAL

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	1155.27	2	577.64	56.18	0.0001	significant
A	115.37	1	115.37	11.22	0.0154	
B	1039.920	1	1039,9	101.14	<0.001	
Residual	61.69	6	10.28			
Cor Total	1216.96	8				

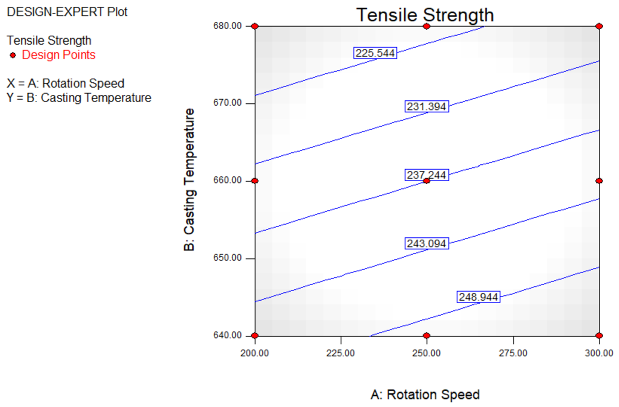
The linear model regression Equation (3) above is a mathematical model used to predict the value of Tensile Strength based on two independent variables, namely Rotation Speed and Casting Temperature. In the equation, there are two terms that describe the relationship between the independent and dependent variables:

- *Constant or intercept (237,24):* This value indicates the expected Tensile Strength when the Rotation Speed and Casting Temperature values are zero. In this context, the constant represents a fixed contribution to Tensile Strength that is not dependent on the independent variables.
- *Regression coefficient for Rotation Speed (4,39):* This coefficient indicates the magnitude of the influence of Rotation Speed on Tensile Strength. In this case, each one-unit increase in Rotation Speed will result in a Tensile Strength increase of 4,39.
- *Regression coefficient for Casting Temperature (-13,16):* This coefficient indicates the magnitude of the influence of Casting Temperature on Tensile Strength. In this case, each one-unit increase in Casting Temperature will result in a decrease in Tensile Strength of 13,16.

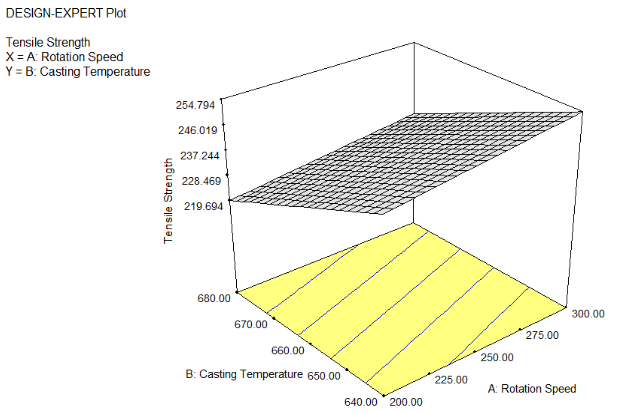
According to Equation (3), the parameter determining the growth in the tensile strength value of the ADC12 aluminum alloy is more strongly influenced by the centrifugal die rotational speed. This is consistent with the findings of other research, which indicated that the rotational speed of the die is a key factor in controlling particle gradation and distribution [10], [11]. His notion of the centrifugal method states that the mold must have a rotational speed that is within an acceptable range for safety considerations as well as for centrifugal casting [5], [21]. As demonstrated in Figures 2, the equation can be conveniently shown as a response surface contour as well as three-dimensional surfaces. Figures 2 show the tensile stress values of castings at different rotational speeds (200, 250 and 300 rpm) and casting temperatures (640 °C, 660 °C and 680 °C). In Figures 2, it can be seen that the tensile strength increases with increasing rotational speed and decreasing casting temperature.

III.3. Experiment Design and Statistical Analysis of Secondary Dendrite Arm Spacing (SDAS)

It fits the quadratic model, as shown by results for secondary dendrite arm spacing at various pour temperatures and rotating speeds. Results of the ANOVA for the secondary dendrite arm spacing data are shown in Table VI.



(a)



(b)

Figs. 2. Tensile strength response surface graph showing (a) contours and (b) 3D surface

TABLE VI
ANOVA SHOWS A 95% CONFIDENCE INTERVAL FOR THE MODEL AND THE SECONDARY DENDRITE ARM SPACING COMPONENTS

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	32.37	5	6.47	347.48	0.0002	Significant
A	20.65	1	20.65	1108.02	<0.0001	
B	11.10	1	11.10	595.58	0.0002	
A^2	0.16	1	0.16	8.72	0.0599	
B^2	0.40	1	0.40	21.74	0.0186	
AB	0.063	1	0.063	3.35	0.1644	
Residual	0.056	3	0.019			
Cor Total	32.43	8				

Since the quadratic model's p-value is significantly higher than 0.01, it is valid. Both the stirring speeds and the stirring times were seen as important coefficients. The variation in pour temperature and rotating speed had no effect on secondary arm spacing. Equation represents the empirical relationship between secondary dendrite arm spacing and a real factor (4):

$$\mathrm{SDAS} = 18.07 - 1{,}85\,A + 1.36\,B + 0.28\,A^2 + \\ +0.45\,B^2 + 0.12\,AB \tag{4}$$

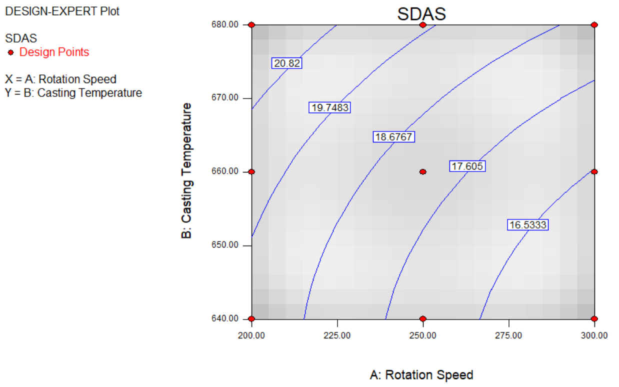
where A is the rotational speed and B is the change in pour temperature. The quadratic equation above is a mathematical model used to predict the value of Secondary Dendrite Arm Spacing based on two independent variables, Rotation Speed and Casting Temperature. In the equation, there are six terms that describe the relationship between the independent and dependent variables:

- *Constant (18.07):* This value represents the constant or intercept, indicating the expected value of Secondary Dendrite Arm Spacing when the Rotation Speed and Casting Temperature are zero. Regression coefficient for Rotation Speed (-.1,85): This coefficient indicates the magnitude of the influence of Rotation Speed on Secondary Dendrite Arm Spacing. In this case, each one-unit increase in Rotation Speed will in a decrease in Secondary Dendrite Arm Spacing by 1.85;
- *Regression coefficient for Casting Temperature (1.36):* This coefficient indicates the magnitude of the influence of Casting Temperature on Secondary Dendrite Arm Spacing. In this case, each one-unit increase in Casting Temperature will result increase in Secondary Dendrite Arm Spacing by 17.06;
- *Regression coefficient for the interaction between Rotation Speed and Casting Temperature (0.12):* This coefficient indicates the influence of the interaction between Rotation Speed and Casting Temperature on Secondary Dendrite Arm Spacing. If there is an increase in both Rotation Speed and Casting Temperature simultaneously, the Secondary Dendrite Arm Spacing will increase by 0.12;
- *Regression coefficient for Rotation Speed squared (0.28):* This coefficient indicates the quadratic influence of Rotation Speed on Secondary Dendrite Arm Spacing. It means that the quadratic increase in Rotation Speed will affect the change in Secondary Dendrite Arm Spacing;
- *Regression coefficient for Casting Temperature squared (0.45):* This coefficient indicates the quadratic influence of Casting Temperature on Secondary Dendrite Arm Spacing. It means that the quadratic increase in Casting Temperature will affect the change in Secondary Dendrite Arm Spacing.

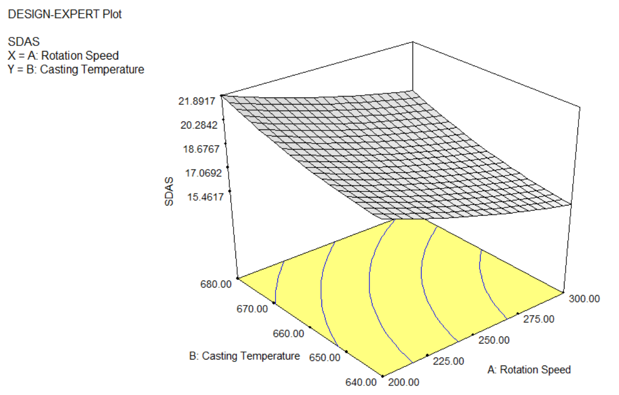
Figures 3 illustrate how the equation can be shown as a three-dimensional surface as well as a response surface contour for convenience. Figures 3 show the relationship between the distance between the secondary dendrite arms and the rotational speed (200, 250 and 300 rpm) and casting temperature (640, 660 and 680 °C). The distance between the secondary dendrite arms will increase as the casting temperature increases and the rotational speed decreases.

III.4. Optimization

Empirical models for all casting reactions as a function of rotational speed variations and casting temperature variations have been constructed, allowing the selection of the best casting parameter settings. To match expectations for all casting responses, the expected range of each casting response, the expected rotational speed variation range, and the expected casting temperature fluctuation range can all be changed.



(a)



(b)

Figs. 3. Response surface graph for secondary dendrite arm spacing with (a) contours and (b) 3D surface

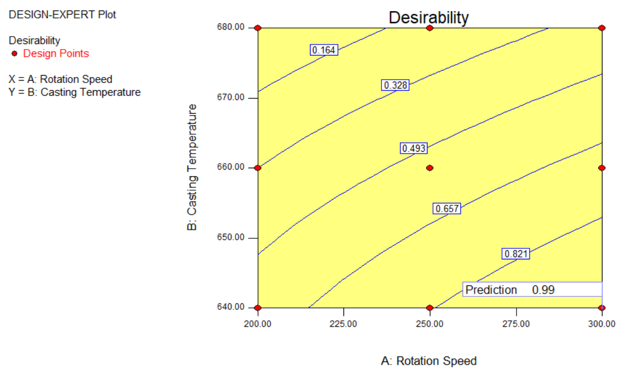


Fig. 4. Some desirability to casting temperature and rotating speed

To achieve the best mechanical properties and lowest SDAS, the recommended mixing parameters from the results of this research are at a rotational speed of 300 rpm and a casting temperature of 640 °C to produce optimal mechanical properties for ADC12 aluminum alloy (Hardness 87.005 HB, Tensile strength 254.794 MPa, and SDAS 15.4691) with a desire of 0.985. Figure 4 can be seen from several desirability effects on casting temperature and rotational speed. This requirement must be satisfied by the rotational speed variation and the casting temperature variation falling inside the yellow plot of the overlay of all casting reactions (Figure 5).

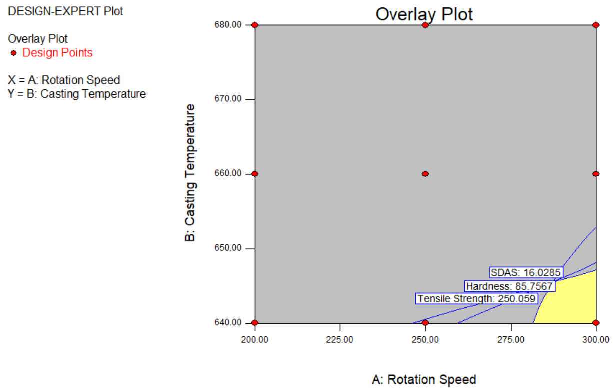


Fig. 5. Input factor overlay plot for the preset response criteria of a minimum of 85.7567 HBN hardness, 250.059 MPa tensile strength, and 16.0285 µm SDAS

In Figure 5 it can be seen the recommended casting parameters to obtain the optimal hardness, tensile strength, and secondary dendrite arm spacing criteria in the ADC12 aluminum alloy centrifugal casting process. The recommended casting parameters are a rotational speed of 280-300 rpm and a casting temperature of 640-645 °C.

IV. Conclusion

The experimental design employed the Central Composite Design (CCD), and the specimens were produced based on the experimental run. The analysis of variance (ANOVA) results indicated that the parameters significantly influenced the response, leading to the establishment of a reliable model for the examined characteristics. The interaction between the parameters revealed that an increase in the rotational speed of the mold resulted in an augmentation of the properties. Based on the results of the analysis of variance and the relationship between the independent variables (rotation speed and pouring temperature) and the dependent variables (Hardness, Tensile Strength, and Secondary Dendrite Arm Spacing), the rotation speed variable is more dominant in improving the mechanical properties of aluminum alloy ADC12 when compared with the variable pouring temperature. The recommended casting parameters to produce optimal mechanical properties and microstructure of ADC12 aluminum alloy (Hardness 87.0005 HB, tensile strength 254.794 N/mm^2, and Secondary Dendrite Arm Spacing 15.4691 µm) are 300 rpm and 640 °C with a desire of 0.985. Further research can be carried out at casting temperatures approaching freezing point at high mold rotation speeds.

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Authors' information

Department of Mechanical Engineering, State Polytechnic of Ujung Pandang.

Syaharuddin Rasyid was born in Sungguminasa on January 5th. Completed his Bachelor's degree in 1994 at the Department of Mechanical Engineering, Hasanuddin University, Makassar, Indonesia. Masters Education (mechanical construction) at Hasanuddin University Postgraduate Program in Mechanical Engineering in 2004. Doctoral education (materials and metallurgy) at Hasanuddin University Mechanical Engineering Doctoral Study Program in 2019. Currently he is conducting research on the characteristics of aluminum alloys with semi-solid casting techniques and engineering design of appropriate technology. Previous research on the characteristics of steel materials with heat treatment techniques.
E-mail: syaharuddinrasyid@poliupg.ac.id

Pria Gautama was born in Ujung Pandang on September 22, 1979. He obtained his bachelor's degree in Mechanical Engineering from the Hasanuddin University (Makassar, Indonesia) in 2004. After completing his bachelor's degree, he pursued a master's degree in Mechanical Engineering from the Bandung Institute of Technology (Bandung, Indonesia) and graduated

in 2011. His research has primarily focused on Material Engineering. Currently working as a Lecturer in the Mechanical Engineering Study Program at the Department of Mechanical Engineering, State Polytechnic of Ujung Pandang (Makassar, Indonesia).
E-mail: pria_gautama@poliupg.ac.id

Muhammad Ruswandi Djalal was born on March 11, 1990, in Ujung Pandang. He graduated with a bachelor's degree in Energy Engineering from the State Polytechnic of Ujung Pandang (Makassar, Indonesia) in 2012. Following his bachelor's degree, he pursued a master's degree in Electrical Engineering at the Sepuluh Nopember Institute of Technology (Surabaya, Indonesia) and graduated in 2015. His studies have primarily focused on artificial intelligence, renewable energy, and power system stability. Currently, he is enrolled in the PhD program in the Department of Electrical Engineering at the Sepuluh Nopember Institute of Technology. Additionally, he serves as a lecturer in Energy Engineering in the Department of Mechanical Engineering at the State Polytechnic of Ujung Pandang (Makassar, Indonesia).
E-mail: wandi@poliupg.ac.id

Uswatul Hasanah Mihdar was born in Pangkep on January August 1st. Completed her Bachelor's degree in 2014 at the Department of Mechanical Engineering, State Polytechnic of Ujung Pandang, Makassar, Indonesia. Masters Education (Mechanical Engineering) at Institute Technology of Bandung in 2021. Currently he is conducting research on the characteristics of aluminum alloys with semi-solid casting techniques and engineering design of appropriate technology. Previous research on the manufacture of lathe casting component (tailstock) using parametric design.
E-mail: uswatulhasanahmihdar018@poliupg.ac.id