Research Article

The Influence of Vertical Centrifugal Casting on Nickel Aluminum Bronze Alloy for Using in the Royal Thai Navy

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Received: 5 February 2020; Revised: 30 March 2020; Accepted: 1 April 2020; Published online: 23 April 2020

Abstract
This research presents a guideline for forming nickel aluminum bronze or NAB workpieces in better mechanical properties for use in the Royal Thai Navy. In the past, NAB workpieces were formed by static casting and then were used in seawater condition, and it was found that the deterioration and low lifespan was a result of cavitation corrosion. Therefore, the analysis can be made that the mechanical properties are inappropriate for use in seawater conditions. This research discusses the advantages of the vertical centrifugal casting method on the static casting regarding the specimen's hardness value. Therefore, the objective of this research is to study the influence of vertical centrifugal casting on hardness of NAB specimens using experimental design to determine appropriate conditions for NAB specimen's hardness. The appropriate level of the mould speed is 483.8384 rounds per minute and the radius from centre of rotation is the 100 mm, and the result of the appropriate factors is 177.3542 VH as a maximum hardness. The regression equation from this research can also be used to form other appropriate mould speeds for other size of workpieces.

Keywords: Design of experiment, Centrifugal easting, Nickel aluminum bronze, Hardness value

1 Introduction

The Royal Thai Navy has maritime sovereignty obligations that have the largest operating area in the sea, and therefore at present there is equipment that can withstand most sea conditions. However, it can only use the equipment for a certain period according to its lifespan. Therefore, it must be procured in order to change or repair the damaged part. The Royal Thai Naval Dockyard has the duty of obtaining the workpieces that must be changed to be suitable for use. In the past, the furnace used manganese bronze as the material for forming workpieces. Later it was found that nickel aluminum bronze (NAB) was better in term of both mechanical properties and resistance ability regarding corrosion and cavitation [1]. Therefore, this material is extensively used for workpieces formation for sea conditions [2]. Then the static casting method with green sand was used in NAB formation and it found that the obtained product's hardness was less than the standard and was unsuitable for use and may cause loss of confident in equipment use as well. A sample of NAB workpieces from own production is presented in Figure 1.

In general, the mission of the Royal Thai Navy included both open-sea operations and support for technical landings. Therefore, the equipment that works directly on seawater must be exposed to sand particles and electro-chemistry from natural conditions.

The equipment with lower specifications will have a shorter lifetime, and this may interface with missions. The condition of the equipment, impellers for seawater pumps after usage, is shown in Figure 2.

Please cite this article as: A. Kengpol and C. Chanchittakarn, "The influence of vertical centrifugal casting on nickel aluminum bronze alloy for using in the Royal Thai Navy," *Applied Science and Engineering Progress*, vol. 14, no. 3, pp. 503–510, Jul.–Sep. 2021, doi: 10.14416/j.asep.2020.04.005.

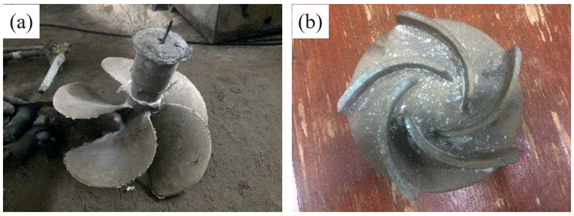

Figure 1: Sample of NAB workpieces from own production; (a) propeller, (b) impeller.

Figure 2: Impellers for seawater pumps after usage.

This research studies nickel aluminum bronze (NAB) workpieces such as seawater propellers for seawater pumps and related forming technical. These propellers receive mechanical energy from motors or shaft driving and transform this into seawater pressure [3] for use in cooling systems in the ships, such as hydraulic oil in the propeller system, main engines heat exchangers, the air conditioning system, etc. It is also used in the ship damage control system and ammunition storage room. Therefore, they are very important equipment within the ship. Then the workpieces are imported from outside companies instead of own production, which has a relatively high price per weight.This research focuses on improving the nickel aluminum bronze workpieces' mechanical properties in order to reach the standard by using vertical centrifugal casting technical, in order to be produce by oneself for use. This can be guide to reducing the cost of external-imported workpieces.

2 Literature Review

In this section, we present 3 main ideas, which consist of the nickel aluminum bronze detail, the process of centrifugal casting, and factorial design based on the relevant theories in order to identify the relationship between the factors on the results.

2.1 *Nickel aluminum bronze*

Nickel aluminum bronze is a copper-based alloy that is developed from aluminum bronze alloys by adding elements such as nickel (Ni), aluminum (Al), iron (Fe) [2].

This research uses NAB no.C95800. It is one of the best corrosion-resistant materials for use in seawater [2] and it is wildly used all over the world. The NAB has the typical composition of Ni 4.5%, Fe 4.0%, Al 9.0%, Mn 1.2% and Cu 81.3% by %weight according to ASTM B148-97 [4]. The mechanical properties are presented in Table 1.

Table 1: Mechanical properties of NAB no. C95800 [4]

Mechanical Properties (As-cast)	Metric
Density	7.64 g/cc
Hardness Rockwell B	84–89
Hardness, Brinell	159
Ultimate Tensile Strength	585 MPa
Yield	240 MPa
Elongation at Break	15%
Modulus of Elasticity	110 GPa

There has been a great deal of research on NAB behavior regarding different types of heat treatment, such as normalizing, annealing, quenching and aging, along with research of NAB microstructure. It was found that the rapid cooling rate from some heat treatment methods are made more retain-beta phase on microstructure, which increases the strength [5]. On the other hand, it has more retain-beta phase on microstructure which cause the workpieces to be corroded easily in seawater conditions [2]. Therefore, NAB workpieces commonly anneal in 675 Celsius degrees for eliminating retain-beta phase before use. Some of the NAB as-cast workpieces can be used without heat treatment because they have a lower retain-beta phase.

2.2 *Centrifugal casting*

Centrifugal casting is a process of pouring the melt into the rotating mould [6], which is used for producing symmetrical shape casting.

Figure 3 presents a vertical centrifugal machine. This machine can be used to form the short symmetric workpieces such as flywheels, gears, bush-bearings

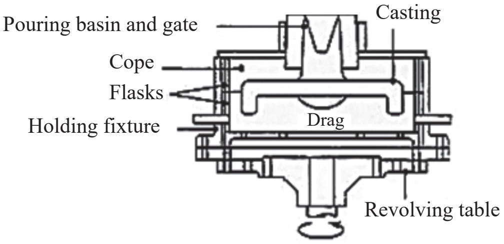

Figure 3: Vertical centrifugal casting.

and impellers [6]. There is revolving table for rotating the flaks in the holding fixture and other components, including pouring basin and gate, and the cope and casting are in the same position as the static casting.

The advantages of centrifugal casting over static casting are reducing the pits and holes from shrinkage, making finer grain in the microstructure, and having better mechanical properties [6]. On the other hand, these advantages can occur only with certain metals, depending on the phase diagram of each metals.

2.3 *Factorial design*

Factorial designs are widely used in experiments involving several factors, where it is necessary to study the joint effect of the factors on a response [7].

The 2^k factorial design is particularly useful in early stages of experimental work when many factors are likely to be investigated. Because there are only two levels for each factor, we assume that the response is approximately linear over the range of the factors chosen [7].

The 3^k factorial design consists of k factors and the level for experimental divides into 3 levels in each factor [8]. This design can lead to determining the appropriate level of factors. The results analysis can be presented in a contour plot and surface plot with a statistical program, and it can determine the appropriate level by using response optimizer tool.

3 Research Methodology

The research designed the analysis of experiment in order to screen the influence factors with 2^k factorial design technique in order to increase the hardness of the NAB specimens and to be able to find other proper conditions later using a 3^k factorial design.

The experiments began with the problem analysis in order to ascertain the dependent variables. The critical thing was that the objectives of the experiment had to be set correctly [9]. Experience and knowledge of casting theories were used to set up factors and factors' levels in order to apply them to the experiment [7]. Later on, the data were analysed using the analysis of variance (ANOVA) method in order to exclude insignificant factors [10].

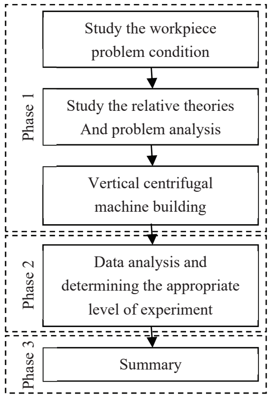

Figure 4: Research procedure.

The result of the ANOVA revealed the main factors influencing the hardness of the NAB specimens significantly when p-value < 0.05. The results of response were presented in contour plot and surface plot, which aimed to determining the appropriate level of factors. Then the statistical program and the tool response optimizer were used for analysing the experiment, leading to a reliable response.

The research proceeded according to Figure 4, and it consisted of 3 phases of research procedures, as seen in the details below:

3.1 *Phase 1: Data collection*

The experiment results are from the NAB specimen for analysing if they accorded with the hypothesis or not. In this phase, there were three steps: 1) Reviewing the cause of the problem and studying the casting theory for predicting an initial solution; 2) Making an experiment plan and creating a support machine; 3) conducting a causal analysis in order to specify the factors for consideration. The propose was to increase the hardness value from the several factors that may occur with NAB specimens. As for the case analysis, the team brainstormed in order to review the cause, using statistic tools, and a cause and effect diagram to summarize the related causes of problems.

3.2 *Phase 2: Factorial design and determining the appropriate level for the experiment*

An appropriate design for experiment was created from reviewing the initial cause with related factors and summarizing for analysis.

- Step 1, to screen the influence factors and to design the 2^k factorial design.
- Step 2, to search the appropriate conditions for the experiment and to create a regression equation for explaining the influence of factors regarding the results and designing the 3^k factorial design.

3.3 *Phase 3: Summary*

The experimental results determined the appropriate level of influential factors in term of the result.

4 Results and Discussion

4.1 *Phase 1: Data collection*

After studying the theory and advantage of vertical centrifugal casting in terms of static casting to search for the true cause of the NAB specimen hardness in each form of vertical centrifugal casting, the data were revealed, as can be seen below.

Table 2: Factors and levels of factors during control the process in the 2^k factorial design

Factor	Level of Factor		Unit
	Low (–)	High (+)	
Mould speed	100	600	RPM
Well depth	0	25	mm
Radius from the centre of rotation	40	100	mm

A vertical centrifugal machine was designed and built according to Table 2 for the experiment. The machine and specimen pattern were created successfully and they are presented in Figures 5 and 6 respectively.

The control factors are also important in terms of their effect to the experiment accuracy [11]. The NAB alloy has a melting temperature at 1,045 to 1,060°C [1].

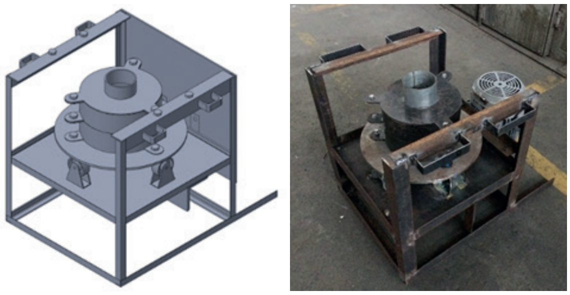

Figure 5: Vertical centrifugal casting machine.

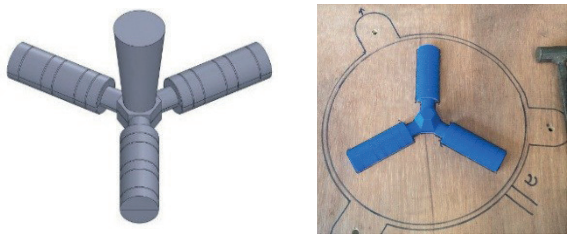

Figure 6: Specimen pattern and jig of flask.

Therefore, the pouring temperature had to be higher than 1,060°C and enough not to solidify during the pouring process. Then, the pouring temperature was fixed at 1,150°C and mould temperature was fixed at 28°C at room temperature.

For controlling the error from the solidification of each specimen, the rotation table was rotated until the specimen's temperature is below 675°C as the microstructure of specimens has fixed characteristics.

4.2 *Phase 2: Two-level factorial design and determining an appropriate level for the experiment*

Table 2 presents 3 factors during the control process in the 2^k factorial design.

Hypothesis Setting.

1. Hypothesis 1: Influence of mould speed.
   $H_0{:}\tau_1 = \tau_2 = 0$ $\quad i = 1,2,\ldots,a$
   $H_1{:}\tau_1$ or $\tau_2 \neq 0$ $\quad$ At least one τ_i
2. Hypothesis 2: Influence of well depth.
   $H_0{:}\beta_1 = \beta_2 = 0$ $\quad j = 1,2,\ldots,a$
   $H_1{:}\beta_1$ or $\beta_2 \neq 0$ $\quad$ At least one β_j
3. Hypothesis 3: Influence of radius from the centre of rotation.
   $H_0{:}\gamma_1 = \gamma_2 = 0$ $\quad k = 1,2,\ldots,a$
   $H_1{:}\gamma_1$ or $\gamma_2 \neq 0$ $\quad$ At least one γ_k

4. Hypothesis 4: Treatment interactions, mould speed and well depth.
   $H_0:(\tau\beta)_{ij} = 0$ for all i and j
   $H_1:(\tau\beta)_{ij} \neq 0$ At least one $(\tau\beta)_{ij}$
5. Hypothesis 5: Treatment interactions, mould speed and radius from the centre of rotation.
   $H_0:(\tau\gamma)_{ik} = 0$ for all i and k
   $H_1:(\tau\gamma)_{ik} \neq 0$ At least one $(\tau\gamma)_{ik}$
6. Hypothesis 6: Treatment interactions, well depth and radius from the centre of rotation.
   $H_0:(\beta\gamma)_{jk} = 0$ for all j and k
   $H_1:(\beta\gamma)_{jk} \neq 0$ At least one $(\beta\gamma)_{jk}$
7. Hypothesis 7: Treatment interactions, mould speed, well depth and radius from the centre of rotation.
   $H_0:(\tau\beta\gamma)_{ijk} = 0$ for all i,j and k
   $H_1:(\tau\beta\gamma)_{ijk} \neq 0$ At least one $(\tau\beta\gamma)_{ijk}$

Where τ is the influence of the mould speed, β is the influence of the well depth, and γ is the influence of radius from the centre of rotation.

The research repeated this experiment 3 times. The total number of experiments was $2 \times 2 \times 2 \times 3 = 24$. The α was set at 0.05, using a statistical program to analyze the experiment as follows:

1. Normal distribution: according to the data. The residual distribution was investigated using a normality plot and it was found that the distribution was normal with a p-value = 0.588.

2. Independent examination of the residual: According to the data. The distribution of residual was investigated using the scatter plot function in the residual versus observation order and it was found that the plots were independent with no fix form.

3. Variance Stability: According to the data. The diagram of residual distribution can be compared with the fitted value. The output from 2^k factorial design is presented in Figure 7 and Table 3.

According to Table 3, the p-value in the ANOVA table was used to determine the influential factors on the hardness of the NAB specimens. The influential factors were mould speed and the radius from the centre of rotation with p-value < 0.05. On the other hand, the well depth factor and every interaction had no influence on the hardness of the NAB specimens with a p-value > 0.05.

For power and sample size testing we used a statistical program for checking the adequacy of the replicate. This 2^k factorial design fixes the parameter, which consisted of a replicate at 3, a standard deviation at 1.64570, and effects at 5.083. The result was a power value at 1.000 which was sufficient power for finding the mean different in the investigated factors.

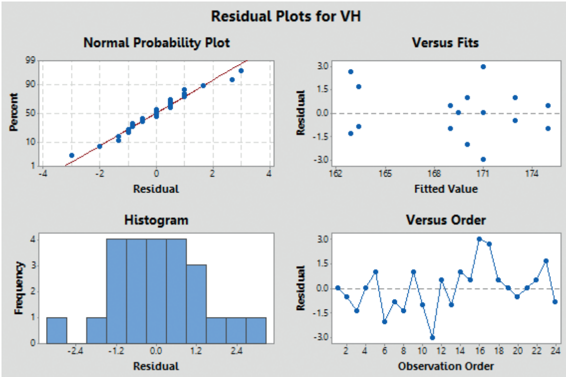

Figure 7: Residual plot for 2^k factorial design.

Figure 7 presents graphs of the residual plots for Vicker hardness. The graph shows the residual on a vertical axis and the independent variable on a horizontal axis. The graphs were distributed evenly and without trend, so a linear regression model was appropriate for the data.

Table 3: The results of the ANOVA are presented in an ANOVA table for the 2^k factorial design for the hardness value of the NAB specimens

Factorial Regression: Response Versus M-Speed, Well, Radius					
Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-value**	***p*-value**
Model	7	381.153	54.446	20.10	0.000
Linear	3	360.708	120.236	44.39	0.000
M-Speed	1	204.167	204.167	75.38	0.000
Well	1	1.500	1.500	0.55	0.468
Radius	1	155.042	155.042	57.25	0.000
2-Way Interaction	3	17.042	5.681	2.10	0.141
M-Speed*Well	1	0.375	0.375	0.14	0.715
M-Speed*Radius	1	10.667	10.667	3.94	0.065
Well*Radius	1	6.000	6.000	2.22	0.156
3-Way Interaction	1	3.375	3.375	1.25	0.281
M-Speed*Well*Radius	1	3.375	3.375	1.25	0.281
Error	16	43.333	2.708		
Total	23	424.458			
Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	1.6457	89.79%	85.32%	77.03%	

After that, the influential factors were selected in order to be analysed with the 3^k factorial design by adding the middle level of each factor to investigate the relationship of the influential factors on the response, which may not be linear, and to find the appropriate factor levels. In this case the problem could be solved using a central composite design where 3^k factorial design is more accurate method. The data for the 3^k factorial design are presented in Table 4.

Table 4: Factors and levels of factors during the control process in the 3^k factorial design

Factor	Level of Factor			Unit
	Low (–)	Mid (0)	High (+)	
Mould speed	100	350	600	RPM
Radius from centre of rotation	40	70	100	mm.

The research repeated the experiment 3 times according to previous experimental. The total number of experiments was 3 × 3 × 3 = 27. The α was set at 0.05, using a statistical program to analyze the experiment in full quadratic as follow:

1. Normal distribution: according to the data. The residuals distribution was investigated with a normality plot and it was found that the distribution was normal with a p-value = 0.244.

2. Independent examination of the residual: according to the data. The distribution of residual was investigated using the scatter plot function in residual versus observation order and it was found that the plots were independent and therefore the model was considered to be appropriate.

3. Variance Stability: according to the data. The diagram of the residual distribution can be compared with the fitted value. The output from the 3^k factorial design is presented in Figures 8–10 and Table 5.

According to Figure 8, the graphs are not distributed evenly and without trend, and therefore a linear regression model was not appropriate for the data. Therefore, the appropriate regression model was investigated by lack of fit testing, it found that full quadratic is appropriate method for data analysis according to Table 5 the lack of fit has p-value = 0.198. Therefore the regression equation was considered to be appropriate for use.

Figure 11 shows the relation between 2 factors: The mould speed and the radius from the centre of rotation. The appropriate level of factors was identified by using the 3^k factorial design with the response optimizer in the statistical program. The appropriate level of the factors for reaching the best hardness value

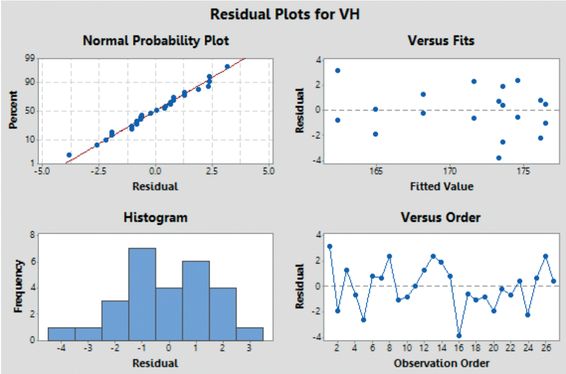

Figure 8: Residual plot for 3^k factorial design.

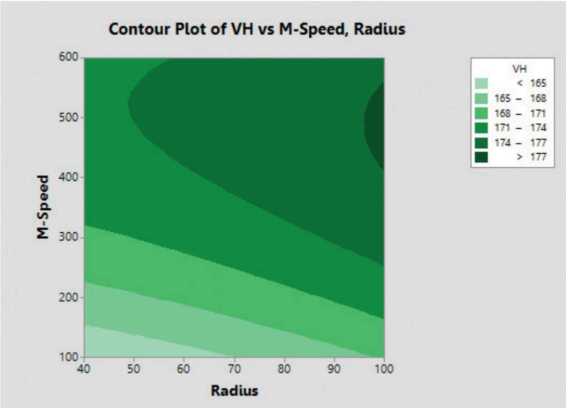

Figure 9: Structure between the factors of the mould speed and the radius from the centre of rotation.

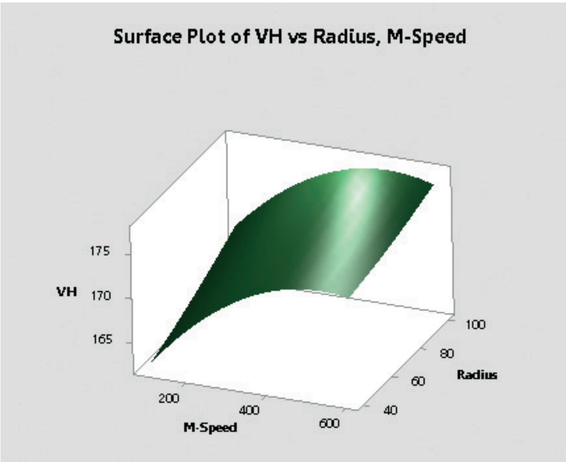

Figure 10: Response surface between the factors of the mould speed and the radius from the centre of rotation.

Table 5: The results of the ANOVA are presented in an ANOVA table for the 3^k factorial design for the hardness value of the NAB specimens

Factorial Regression: Response Versus M-Speed, Well, Radius					
Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-value**	***p*-value**
Model	5	608.056	121.611	34.00	0.000
Linear	2	513.889	256.944	71.84	0.000
M-Speed	1	420.500	420.500	117.57	0.000
Radius	1	93.389	93.389	26.11	0.000
Square	2	88.833	44.417	12.42	0.000
M-Speed*M-Speed	1	88.167	88.167	24.65	0.000
Radius*Radius	1	0.667	0.667	0.19	0.670
2-Way Interaction	1	5.333	5.333	1.49	0.236
M-Speed*Radius	1	5.333	5.333	1.49	0.236
Error	21	75.111	3.577		
Lack-of-Fit	3	16.778	5.593	1.73	0.198
Pure Error	18	58.333	3.241		
Total	26	683.167			
Model Summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	1.8912	89.01%	86.39%	81.70%	

was a mould speed of 483.8384 rounds per minute and a radius from the centre of the rotation at 100.00 mm.

However, in reality the workpieces usually used in the Royal Thai Navy have different shapes and sizes for each application and they usually have corrosion or cracks on their tips after usage. For this reason, the radius from the centre of rotation must be set according to the size of workpiece. The relationship of the influential factors in term of the result of the NAB specimen's hardness can be explained by using regression Equation (1) below:

$$\begin{aligned}\hat{y} \;=\; & 153.65 + 0.0685x_1 + 0.055x_2 \\ & -0.000061x_1^2 + 0.000370x_2^2 \\ & -0.000089x_1 x_2 \qquad (1)\end{aligned}$$

Where $\hat{y}$ is the fitted result (hardness of the NAB specimen), $0685x_1$ is the rotation speed in rounds per minute, and x_2 is the radius from the centre of rotation in millimetres.

Moreover, this research formed the impeller for seawater pump by using vertical centrifugal casting method. The dimension of the impeller pattern was 170 mm. The pattern and mould of the impeller are presented in Figure 12. The response optimizer tool was also used in this formation, where the parameter fixed the hardness value at maximum and the radius from the centre of rotation at 85 mm, according to Figure 13.

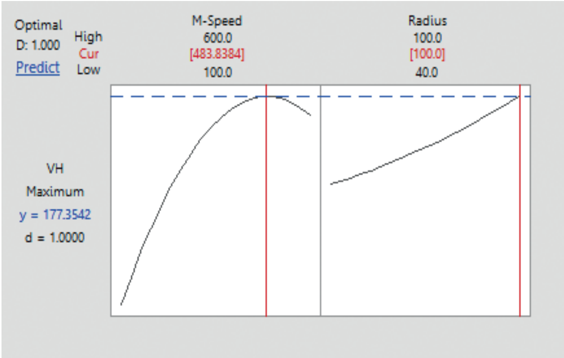

Figure 11: Response optimizer for maximum hardness of the NAB specimen.

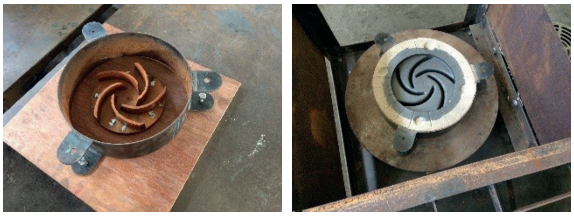

Figure 12: Impeller pattern and mould.

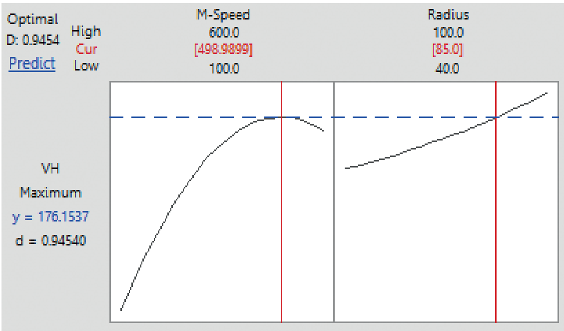

Figure 13: Response optimizer for the impeller of the seawater pump.

According to Figure 13, the results of the response optimizer show that the appropriate mould speed for reaching the best hardness value was 498.9899 rounds per minute. Therefore the impeller was casted according to the response optimizer results. The as-cast impeller is presented in Figure 14 and comparative analysis was used to confirm the results of the experiment.

Figure 14: The impeller from vertical centrifugal casting.

5 Conclusions

The hardness value of nickel aluminum bronze can be improved by using the vertical centrifugal casting method.

The factors regarding the vertical centrifugal casting method that influence the hardness value are mould speed and radius from the centre of rotation. The results of this research are analysed using the experiment method, which consisted of 2^k factorial design and 3^k factorial design. The influential factors were presented in regression equation, which can be used to predict the hardness of the NAB workpieces formed using the vertical centrifugal casting method. It was found that the appropriate level of the mould speed was 483.8348 rounds per minute and the radius from the centre of rotation was 100 mm, and the result of the appropriate factors is 177.3542 VH as a maximum hardness value. For each size of workpiece, the response optimizer can also be applied to determine the appropriate mould speed in order to reach the best hardness value.

Acknowledgments

The research was carried out in the Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok. The authors are deeply grateful to Dr. Swieng Thuanboon and Dr. Borpit Thossateppitak for their invaluable advice, and to the Royal Thai Naval Dockyard for the financial support of this research project. Additionally, special thanks go to the commanders of the Thonburi Naval Dockyard and the Workshop Department of Sattahip Naval Base until this study come to completion.

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