REPONSE SURFACE METHODOLOGICAL APPROACH IN JEWELRY-BODIED CASTING

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ABSTRACT

Jewelry-bodied casting is the most important upstream process causing defects in jewelry industries. Three process parameters , that are, Ingate Angle , Mold Temperature and Pouring Temperature which influence to the density of products were studied using response surface methodological approach. Casting materials were three types of silver alloy. A 2^3 full factorial central composite design (CCD) and a small composite design (SCD)were employed . The relationships of Ingate Angle, Mold Temperature and Pouring Temperature and density of products were determined by using regression analysis. Two models of expected function were used , that are , quadratic model and exponential model of linear equation . The appropriate models were determined and the comparisons of different designs were conducted. The results indicated that small composite design was more efficient than central composite design , quadratic models were more appropriate than exponential models of linear equation in all types of silver alloy using CCD and exponential models of linear equation were more appropriate than quadratic models in all types of silver alloy using SCD.

KEYWORDS : response surface methodology , central composite design , small composite design , jewelry-bodied casting

1. INTRODUCTION

Jewelry-bodied casting is the most important upstream process causing defects in jewelry industries. The casting conditions have affected the occurrence of defects and quality requirement. There are many controllable factors that affect to the quality , such as , Types of Alloy , Ingate Angle , Mold Temperature and Pouring Temperature.[6] These controllable factors have to be varied regarding of product appearance. The jewelry casting operators sometimes work by using their skills with trial and error in controllable factors setting , and causes problems in product quality .

The application of statistical experimental design [4] in jewelry-bodied casting can result in improving product quality , reducing process variability , i.e. , closer confirmation of the output response to nominal and target requirements and reducing development time and overall costs. Conventional practice of classical method of maintaining other factor involved at an unspecified constant level does not depict the combined effect of all the factors involved. This method is also a time consuming process and requires a number of experiments to determine optimum levels , which are unreliable. These limitation of a classical method process can be eliminated by optimizing all the affecting parameters collectively by statistical experimental design using response surface methodology (RSM). Response surface methodology [5] is the statistical and mathematical techniques useful for developing , improving and optimizing processes. It also has important applications in the design , development , and formulation of new products , as well as in the improvement of existing product designs. This approach can help the jewelry casting operators in Quality Control area work better and can control the consistency of product quality with less effort. Moreover , it can help them in new

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product development in case of they do not know the exact appropriate casting conditions used in the process. In this work , the response of process is density of products. There are three controllable factors interested in jewelry-bodied casting process affecting to the density of products , that are , Ingate Angle , Mold Temperature and Pouring Temperature. Three types of silver alloys that used in product casting called Alloy 1 , Alloy 2 and Alloy 3 are investigated whether they result in the casting quality. Shape of casting product are pendant , square and 5 grams weight. We measure the quality characteristics of casting product in form of density. When there are the defects[7] , especially the porosity which the most normally occur in process , the density of products will decrease. The pure silver has specific density of 10.5 grams per cubic centimeter. This is the target of quality requirement.

In previous work , the Central Composite Design (CCD) in jewelry-bodied casting indicated that three controllable factors influenced to yield of product , that are , Ingate Angle , Mold Temperature and Pouring Temperature , and using three types of alloys as above mention. The regression analysis and process optimization were performed by using Microsoft Excel Solver. Mostly defects were gas porosity called pinhole and shrinkage porosity. Ingate Angle , Mold Temperature and Pouring Temperature influenced to yield of product in the relationships of quadratic functions. This present work , the Central Composite Design and Small Composite Design (SCD) in jewelry-bodied casting are considered as tools for the analysis and the results will be compared. The response variable in the present study is the density of product. In Regression Analysis , the estimated functions are in forms of quadratic functions and exponential of linear equation. The performance measures are the coefficient of Determination (R^2) and Mean Square Error (MSE).

2. MATERIALS AND METHODS

2.1 Materials

There are three types of silver alloy used in jewelry-bodied casting as follows.

1. Alloy 1 consists of silver 94.22 % and copper 5.78 % by weight.
2. Alloy 2 consists of silver 94.22 % , copper , zinc and silicon 5.78 % by weight.
3. Alloy 3 consists of silver 94.22 % , copper , zinc , silicon and indium 5.78 % by weight.

Pure silver[6] is a precious metal. It is white color , ductile , and easy to processability. It is harder than gold but less ductile than copper. It is the most inductility. Its melting point is 961 degree celcius. Copper mixing in sterling silver [6]will increase hardness and strength of alloy. It will increase wareness ability but decrease elongation. While alloy is melted , copper will interact to oxygen in atmosphere and occurs copper oxide film coating over surface of product. It seems dull on surface of product and is not beautiful. Zinc mixing in sterling silver [6] will be as deoxidizer. Zinc will interact to oxygen and occurs zinc oxide to prevent copper oxide film coating over surface of product. Silicon mixing in sterling silver [6] will increase the smoothness of surface but the excessive silicon also makes the product crack easily , and creates hard spots inside product. Indium mixing in sterling silver [6] will increase tarnish resistance but decrease hardness and strength.

2.2 Jewelry-bodied casting process [6]

Jewelry-bodied casting is the process of investment casting process. It helps to smoothen the surface of products and more precise appearance. The casting process is called lost wax casting which uses vulcanized rubber mould producing wax products and lost wax by heating plaster mould of wax trees. After lost wax , it will make product appearance hole inside alike to wax product appearance. This plaster mould is heated in oven in order to strengthen the mould itself. Then products will be cast in vacuum induction furnace.

There are three controllable factors affecting to the density of products. Ingate Angle is a melting metal angle used as ingate in gating system. It varies corresponding to product appearance. Mold Temperature is the final temperature of heated plaster mold using for pouring melted metal. It affects to the microstructure of products. It should differ appropriately from pouring temperature in order to make complete solidification. Pouring Temperature is the final temperature of melted metal using for pouring melted metal into the heated plaster mould. Melting Temperature of pure silver is 961 degree celcius. Pouring temperature should be over melting temperature of metal 50-100 degree celcius so that it is certain that the solid metal becomes in whole liquid metal. Low pouring temperature makes microstructure be equiaxial grain. High pouring temperature makes microstructure be columnar grain.

Casting products used as specimens in this work were pendant , square shape , and 5 grams weight. Casting specimens were polished and inspected by vision. The defects were detected and recorded. Then the density of specimens was measured and recorded. After that the microstructure of specimens was analyzed.

Density of specimens was measured by using four-digits digital reading electronic balance. We measured weight of specimens in air and in water. When the specimen was submerged in water, buoyant force occurred equal to weight of liquid which substituted by volume of specimen. Density of specimen was calculated by mass of specimen in air divided by volume of specimen.

2.3 Experimental design

Two types of design for RSM will be conducted, i.e. Central Composite Design (CCD) and Small Composite Design (SCD). The Central Composite Design was proposed by Box and Wilson [1]. It consists of 2^k full factorial points or 2^{k-q} resolution V fraction factorial points called cubic points, $2k$ axial or star points and $n_0 \geq 2$ runs in the design center (where k is number of controllable factors, q is number of fraction, and n_o is number of design center runs). The cubic points are used for detecting of first-order parameters in the model. The star points are used for detecting of second-order parameters in the model. They are located at a common distance, α, from the design center. The design center runs are used for guarantee that the predicted values will have constant variance[2]. CCD with the rotatability property conducts by choosing an appropriate axial distance [5], $\alpha = \sqrt[4]{F}$ (F= number of 2^k factorial points). Rotatability property is important for a second-order design to possess a reasonably stable distribution of scaled prediction variance throughout the experimental design region. The reasonably stable scaled prediction variance provides insurance that the quality of the predicted response values is roughly the same throughout the region of interest.

The Small Composite Design was proposed by Hartley [3]. It garners its name from the ideas of the central composite design, but the factorial portion is neither complete 2^k nor a resolution V fraction, but, rather, a special resolution III fraction in which no four-letter word is among the defining relations. As a result, the total run size is reduced from that of CCD.

A 2^3 full factorial central composite design with five coded levels leading to 19 runs of experiments was performed. There were 8 cubic points, 6 axial points and 5 center points in design. The design was rotatable CCD, using an axial distance $\alpha = \sqrt[4]{8}. = 1.682$. And a small composite design with five coded levels leading to 15 runs of experiments was performed. There were 4 cubic points, 6 axial points and 5 center points. The design was rotatable SCD, using axial distance $\alpha = 1.682$. Response was measured as density of products. There were three controllable factors influencing to response, that are, Ingate Angle, Mold Temperature and Pouring Temperature. For statistical calculation, the variables were coded according to equation (1)

$$x_i = (\xi_i - \xi_i^*) / d_i \qquad (1)$$

where x_i is independent variable coded value, ξ_i is natural independent variable real value, ξ_i^* is natural independent variable real value on the center point and d_i is step change value. The range and levels of variables investigated in this research are given in Table 1, Table 2 and Table 3. This initial setting of levels of variables is selected corresponding to the phase diagrams of casting alloy mixture. Such phase diagrams can indicate the approximate range of Pouring Temperature using in casting process.

Table 1 Coded variable levels and natural variable levels used in Alloy1

Factor	Coded variable levels and natural variable levels				
	-1.682	-1	0	1	1.682
Ingate Angle (°)	34.77	45	60	75	85.23
Mold Temperature (°C)	463.18	470	480	490	496.82
Pouring Temperature (°C)	933.18	940	950	960	966.82

Table 2 Coded variable levels and natural variable levels used in Alloy2

Factor	Coded variable levels and natural variable levels				
	-1.682	-1	0	1	1.682
Ingate Angle(°)	34.77	45	60	75	85.23
Mold Temperature (°C)	513.18	520	530	540	546.82
Pouring Temperature (°C)	973.18	980	990	1000	1006.82

Table 3 Coded variable levels and natural variable levels used in Alloy3

Factor	Coded variable levels and natural variable levels				
	-1.682	-1	0	1	1.682
Ingate Angle(°)	34.77	45	60	75	85.23
Mold Temperature (°C)	513.18	520	530	540	546.82
Pouring Temperature (°C)	1033.18	1040	1050	1060	1066.82

In this research , we used quadratic model and exponential model of linear equation for predicting the relationships of response (y) and three controllable factors. The quadratic model for predicting the relationships of response and three controllable factors was expressed according to equation (2).

$$y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} x_i x_j \qquad (2)$$

where β_0 was intercept on y-axis , β_i were linear coefficients , β_{ii} were quadratic coefficients , β_{ij} were cross-product coefficients ,and x_i , x_j were coded independent variables.

The exponential model of linear equation for predicting the relations of response and three controllable factors was expressed according to equation (3).

$$y = \exp^{(\beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} x_i x_j)} \qquad (3)$$

where β_0 was intercept , β_i were linear coefficients , β_{ij} were cross-product coefficients , and x_i , x_j were coded independent variables.

The Minitab (version 13.0) software was used for regression analyses of the data obtained. The statistical significance of the regression coefficients were determined by Student ' s t test. The model equations were determined by Fisher 's test. The appropriate adequate models were determined by lack of fit test and the proportion of variance explained by the models obtained were given by the coefficients of determination (R^2) and R^2 (adjusted). Comparison of prediction models were determined and the efficiency of CCD and SCD were compared using R^2 (adjusted) and mean square error (MSE). Note that the optimal setting will not be the issue of the work at present. It will be conducted in near future.

3. RESULTS AND DISCUSSION

3.1 Results

The comparison between CCD and SCD using quadratic models in the same alloy is illustrated as follows :

Types of Alloy	Criteria	CCD	SCD	Comparison
1	R^2 (adjusted)	51.00 %	40.20 %	SCD is more efficient
	MSE	0.00714	0.00176	than CCD in Alloy 1
2	R^2 (adjusted)	99.99 %	99.99 %	CCD is more efficient
	MSE	0.00170	0.00252	than SCD in Alloy 2
3	R^2 (adjusted)	45.00 %	52.80 %	SCD is more efficient
	MSE	0.00380	0.00088	than CCD in Alloy 3

The comparison between CCD and SCD using exponential models of linear equation in the same alloys was illustrated as follows:

Types of Alloy	Criteria	CCD	SCD	Comparison
1	R^2 (adjusted)	26.90 %	100 %	SCD is more efficient
	MSE	0.00007	Nearly 0	than CCD in Alloy 1
2	R^2 (adjusted)	1.0 %	100 %	SCD is more efficient
	MSE	0.00004	Nearly 0	than CCD in Alloy 2
3	R^2 (adjusted)	19.60 %	100 %	SCD is more efficient
	MSE	0.00005	Nearly 0	than CCD in Alloy 3

The comparison of appropriate models between quadratic models and exponential models in the same design were illustrated as follows:

CCD

Types of Alloy	Models	R^2 (adjusted)	MSE	Comparison
1	Quadratic	51.00 %	0.00714	Quadratic is more
	Exponential	26.90 %	0.00007	appropriate than
2	Quadratic	99.99 %	0.00170	Exponential in all types
	Exponential	1.00 %	0.00004	of silver alloy for CCD
3	Quadratic	45.00 %	0.00380	
	Exponential	19.60 %	0.00005	

SCD

Types of Alloy	Models	R^2 (adjusted)	MSE	Comparison
1	Quadratic	40.20 %	0.00176	Exponential is more
	Exponential	100 %	Nearly 0	appropriate than
2	Quadratic	99.99 %	0.00252	Quadratic in all types
	Exponential	100 %	Nearly 0	of silver alloy for SCD
3	Quadratic	52.80 %	0.00088	
	Exponential	100 %	Nearly 0	

3.2 Discussion

Three controllable factors , that are , Ingate Angle , Mold Temperature and Pouring Temperature affected to density of products and most defects are gas porosity which make the density of product be lower.

The response surface methodological approach in jewelry-bodied casting described by quadratic models are evaluated that small composite design is more efficient than central composite design. It had lower mean square error and higher the coefficient of determination (R^2 (adjusted)) , except for alloy type 1. For alloy type 1 , SCD is more efficient than CCD , the mean square error of SCD is about 25 % less than that of CCD although the coefficient of determination of CCD is about 26 % more than that of CCD. For alloy type 2 , the coefficient of determination are the same , but the mean square of CCD is about 67 % less than that of SCD. For alloy type 3 , SCD is more efficient than CCD , the mean square error of SCD is about 23 % less than that of CCD and the coefficient of determination of SCD is about 15 % more than that of CCD.

In addition , the response surface methodological approach in jewelry-bodied casting described by exponential models of linear equation is evaluated that small composite design is more efficient than central composite design. It had lower mean square error and higher the coefficient of determination (R^2 (adjusted)). For alloy type 1 , the coefficient of determination of SCD is about 73 % more than that of CCD and the mean square error of SCD is very negligible. For alloy type 2 , the coefficient of determination of SCD is about
99 % more than that of CCD and the mean square error of SCD is very negligible. For alloy type 3 , the coefficient of determination of SCD is about 90 % more than that of CCD and the
mean square error of SCD is very negligible.

However , regarding of design types , the comparison between quadratic models and exponential models of linear equation is illustrated that quadratic models are more appropriate than exponential models of linear equation in all types of alloy using CCD. Quadratic models have higher coefficient of determination (R^2 (adjusted)). In contrast , exponential models of linear equation are more appropriate than quadratic models in all types of alloy using SCD. Exponential models have higher coefficient of determination (R^2 (adjusted)).

4. CONCLUSION

This work gives the idea of quality engineering application based on experimentation to jewelry industry. It can apply this idea for experimental planning and use the experimental design for developing quality of products. The limitations of application are the high costs of casting materials and complication of experimental procedure.

The results indicated that for casting process , the CCD is preferred to SCD if the quadratic models will be employed to estimate the density of products. On the other hand , the SCD is preferred to CCD if the exponential models will be applied to estimate the density of products.

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