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ORIGINAL ARTICLE

Modeling and analysis of the effects of processing parameters on the performance characteristics in the high pressure die casting process of Al–SI alloys

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Abstract The high pressure die casting (HPDC) process has achieved remarkable success in the manufacture of aluminum–silicon (Al–SI) alloy components for the modern metal industry. Mathematical models are proposed for the modeling and analysis of the effects of machining parameters on the performance characteristics in the HPDC process of Al–SI alloys which are developed using the response surface methodology (RSM) to explain the influences of three processing parameters (die temperature, injection pressure and cooling time) on the performance characteristics of the mean particle size (MPS) of primary silicon and material hardness (HBN) value. The experiment plan adopts the centered central composite design (CCD). The separable influence of individual machining parameters and the interaction between these parameters are also investigated by using analysis of variance (ANOVA). With the experimental values up to a 95% confidence interval, it is fairly well for the experimental results to present the mathematical models of both the mean particle size of primary silicon and its hardness value. Two main significant factors involved in the mean particle size of primary silicon are the die temperature and the cooling time. The injection pressure and die temperature also have statistically significant effect on microstructure and hardness.

Keywords High pressure die casting (HPDC) · Mean particle size of primary silicon · Hardness · Response surface methodology

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1 Introduction

Aluminum-silicon (Al–SI) alloys are widely used in the engineering industries because of their superior properties, such as light weight, good thermal conductivity, excellent castability, good weldability, excellent corrosion resistance and wear resistance properties [1, 2]. As far as Al–SI alloys are concerned, the characteristics of their microstructures have two phases: one is always soft and highly ductile, and the other considerably hard. The high volume fractions of hard silicon particles embedded in the aluminum α phase have the advantages to promote mechanical properties such as hardness, wear resistance and tensile strength. The microstructure of Al–SI alloys is subjected to the contents of silicon particles which exhibit the hypoeutectic, eutectic and hypereutectic properties. Therefore, for meeting the needs of good mechanical properties, it is important that the particles of hard phase, silicon particles, must be very fine and uniformly distributed within the soft phase, α aluminum matrix [3]. It has been proved that the increase of size and the change of morphology of the silicon grains will influence the machined characteristics such as the cutting force and the roughness of machined surface [4, 5]. Hence, the manufacturing technology of Al–SI alloys for dispersing silicon particle finely in the α aluminum matrix must be investigated in order to acquire the optimal mechanical properties.

The high pressure die casting (HPDC) process, by means of which the molten metal is injected at high pressure into a metallic die of required size and shape, is the most suitable for the manufacturing of Al–SI alloy components. The effects of process parameters on the microstructure and mechanical properties of Al–SI alloys in die casting process are relatively complex and need more extensive investigations [6, 7]. In the recent decade, research has been extensively conducted for commercial Al–SI alloys such as B390 alloy [8], hypoeutectic Al–SI alloy [9], LM6 alloy [10], LM13 alloy [11] and A356 alloy [12] on the microstructure and mechanical property using the die casting process or the squeeze casting process. The effects of process parameters, including the injection pressure, the melt temperature, the die temperature and the cooling rate, were deeply investigated from the size of the soft phase in the microstructure of Al–SI alloys.

The technology of the HPDC process in practical application is very complicated, and it is crucial to set up the processing parameters of HPDC process in order to obtain the good mechanical properties [13] and the desired performance for the manufacturing of Al–SI alloys components. In this paper, a statistical model is proposed to model the effects on the HPDC processing parameters about the performance characteristics of the mean particle size (MPS) of primary silicon and material hardness (HBN) value. The mean particle size (MPS) of primary silicon was chosen as the performance evaluation of Al–SI alloys microstructure. The mathematical model exploits the response surface methodology (RSM) to express the influences of processing parameters. The RSM is a statistical modeling approach for determining the relationship between various process parameters and responses with the various desired criteria, and further searching the significance of these process parameters on the coupled responses. It employs the sequential experimentation strategy for building the empirical model. Therefore, RSM is a collection of mathematical and statistical procedures that are useful for the modeling and analysis of problems; the response is affected by several variables and the main objective is to optimize this response [14]. Using the experimental design and applying the regression analysis, one can gain the modeling of the desired response with several independent input variables.. Consequently, the RSM is utilized to describe and identify, with a great accuracy, the influence of the interactions between different variables on the response when they are varied simultaneously. In addition, it is one of the most widely used methods to solve the optimization problem in manufacturing environments such as the optimal heat treatment conditions of different Ni-Co-Mo surfaced layers [15], the determination of effecting dimensional parameters on warpage of thin shell plastic parts [16, 17], the modeling and analysis of white layer depth in a wire-cut EDM process [18], and the parametric optimization of powder mixed electrical discharge machining [19], cutting conditions for surface roughness [20] and plasma spraying coatings [21]. In the present paper, the most important HPDC process machining parameters that affect the quality of castings are the die temperature, injection pressure and cooling time. Effects of these three machining parameters on the microstructure and hardness of Al–SI alloy are investigated by using the mathematical models developed in this study.

2 Experimental procedure

2.1 Preparation of materials

For studying the influences of processing parameters in the die casting process, the Al-25Si alloy is manufactured as the basis of preliminary experiment. The experimental specimen, Al-25Si alloy, is a two-phase hypereutectic alloy manufactured by the procedure of melting pure aluminum and pure silicon in a high-frequency induction furnace. The chemical composition of Al-25Si in mass% is as follows: 25.4 Si, 0.14 Fe and Bal. Al. This Al-25Si alloy is a two-phase hypereutectic alloy, and reveals acicular eutectic silicon particles and the rod-like primary silicon phase in the microstructure. The experimental specimens were fabricated by using a CF-150DC cold chamber fully automatic die casting machine (Cheng Feng Machinery Works Co., Ltd). The die casting machine was shown in Fig. 1(a). The tie bar diameter is 90 mm, the die plunger stroke is 350 mm and the maximal locking force is 150 tons. The molten metals were maintained at 50°C above the liquid phase line (571°C). After 20 min. of argon degassing, the molten metals were poured into the slot sleeve and then injected into a rectangular die of dimensions mm^3 as shown in Fig. 1(b). The experimental die is made of tool steel SKD-61. SKD-61 is extensively used in the production of dies, plastic injection molding dies, spindle, jigs and fixtures, etc. The surface hardness of this material is over 55 HRC. Rectangular blocks of sizes mm^3 were cut off from the middle of the rectangular plate (mm^3) of each experimental casting.

2.2 Experiment design

The appearances of microstructure for Al–SI alloys are not only controlled by the contents of silicon particles, but also influenced by the die casting process parameters. Especially, the cooling rate is an outstanding factor for the phase performance of silicon particle in the microstructure of Al–SI alloys. In the die casting process, the processing parameters includes four categories, including die casting machine parameters, shot sleeve parameters, die parameters and cast metal parameters [6, 7]. Among them, the most significant parameters are die temperature (M_T), injection pressure (P_I) and cooling time (C_t). The die temperature (M_T) is the initial temperature of the die before the filling phase. The injection pressure (P_I) is the intensification pressure applied after the die is filled, and cooling time (C_t) is the time spent in the third phase (intensification). These three processing

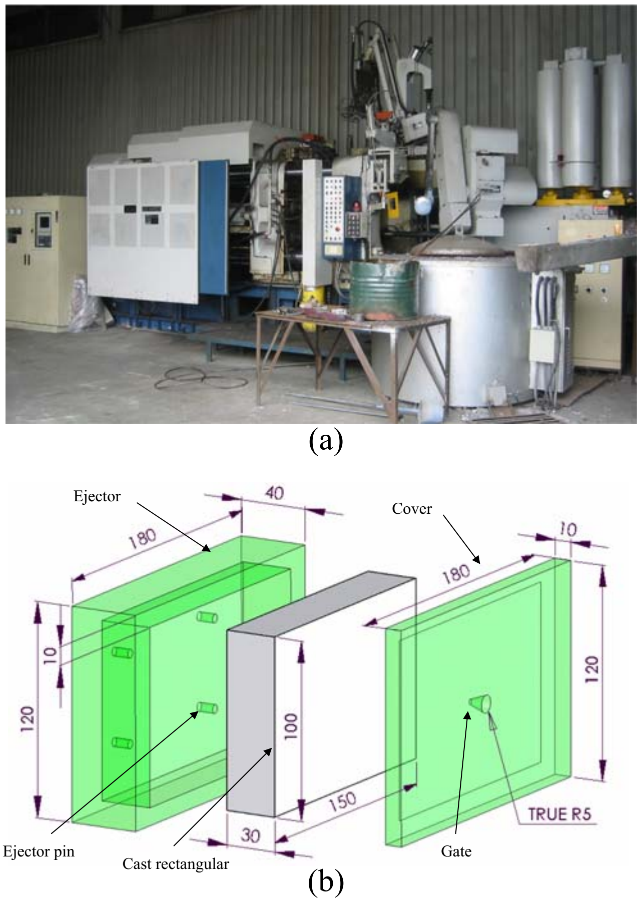

Fig. 1 (**a**) The die casting machine and (**b**) the rectangular type die

parameters relate to the cooling rate of die casting process, and chosen as the independent input variables in the analysis of RSM as well.

In this study, the experimental plans were designed on the basis of the central composite design (CCD) technique. The factorial portion of CCD is a full factorial design with all the combinations of the factors at two levels (high,+1 and low, −1) and composed of the eight star points, and six central points (coded level 0) which are the midpoint between the high and low levels. The star points are at the face of the cube portion on the design and this type of design is commonly called the face-centered CCD. In the present investigation, the experimental plans were conducted by using the stipulated conditions according to the face-centered CCD and involved in a total of 20 experimental observations in three independent variables. Each combination of experiments had been carried out two times under the same conditions at different time to acquire a more accurate result in the die casting process.

RSM is a sequential procedure and its procedure for modeling and analysis of the effects of processing parameters on the performance characteristics in the high pressure die casting process of Al–SI alloys including six steps which are focused on [13–17]:

(1) Defining the independent input variables and desired responses with the design constraints
(2) Adopting the face-centered CCD to plan the experimental design
(3) Performing the regression analysis with the quadratic model of RSM
(4) Calculating the statistical analysis of variance (ANOVA) for the independent input variables and to find which parameter significantly affects the desired response
(5) Determining the situation of the quadratic model of RSM and to decide whether the model of RSM needs screening variables
(6) Conducting confirmation experiment and verify the predicted performance characteristics

Table 1 shows both coded and actual values of three processing parameters and their possible ranges. These parameter levels, along with their respective ranges, are selected within the intervals recommended by the processing guides of Al-25Si alloy and by the operating parameters of mechanical equipment. The experimental matrix in the coded form adopted in this study is shown in Table 2. The coded values $X_{i,i=1,2,3}$ of the processing parameter used in Tables 1 and 2 are obtained from the following transformation equations:

$$X_1 = \frac{M_T - M_{T0}}{\Delta M_T} \quad (1)$$

$$X_2 = \frac{P_I - P_{I0}}{\Delta P_I} \quad (2)$$

$$X_3 = \frac{C_t - C_{t0}}{\Delta C_t} \quad (3)$$

where X_1, X_2 and X_3 are the coded values of parameters M_T, P_I and C_t, respectively. M_{T0}, P_{I0} and C_{t0} are the values of M_T, P_I, and C_t, at zero level. ΔM_T, ΔP_I and ΔC_t are the intervals of variation in M_T, P_I, and C_t, respectively.

2.3 Performance evaluation

In order to identify the influence of processing parameters on the microstructure property of Al–SI alloy in the die casting process, the performance of silicon particle in the microstructure was adopted as the performance evaluation.

Table 1 Design scheme of processing parameters and their levels

Parameters	Unit	Ranges	Levels		
			−1	0	+1
Die temperature (M_T)	°C	220–260	200	230	260
Injection pressure (P_I)	MPa	50–100	50	75	100
Cooling time(C_t)	s	10–20	10	15	20

The experimental specimens, after being machined, were washed and cleaned with a 3% dilute phosphoric acid solutions. Grinding and polishing were performed to have mirror finish on the transverse section and subsequently these faces were etched with 5% nital solution from 20 to 25 s. The microstructures of silicon particle were observed by using an image analyzer and a scanning electron microscope (SEM). The mean particle size (MPS) of primary silicon was chosen as the performance evaluation of microstructure for this study. The other performance evaluations adopted was the Brinell hardness (HBN) of the specimens. The measurements for Brinell hardness (HBN) were carried out on specimens with 187.5 kg load and a ball of 2.5 mm diameter, and made at least ten indentations. Therefore, the mean particle size (MPS) of primary silicon and the average value of material hardness (HBN) were adopted as the desired responses in this analysis, and it is assumed that they are affected by three HPDC processing parameters mentioned above.

3 Response surface modeling

In the RSM, the quantitative form of relationship between desired response and independent input variables can be represented as follows.

$$Y = f(M_T, P_I, C_t) \tag{4}$$

where Y is the desired response and f is the response function (or response surface). In the procedure of analysis, the approximation of Y was proposed by using the fitted second-order polynomial regression model, which is called the quadratic model. The quadratic model of can be written as follows:

$$Y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ii} X_i^2 + \sum_{i<j}^{3} a_{ij} X_i X_j \tag{5}$$

where a_0 is constant, a_{i}, a_{ii} and, a_{ij} represent the coefficients of linear, quadratic and cross product terms, respectively. X_i

Table 2 Design layout and experimental results

Run	Coded factors			Actual factors			Response variables	
	X_1	X_2	X_3	M_T	P_I	C_t	Y_I(MPS, μm)	Y_2(HBN)
1	0	0	−1	230	75	10	95.3	105.3
2	0	0	+1	230	75	20	102.7	113.4
3	0	0	0	230	75	15	94.2	110.2
4	−1	+1	−1	200	100	10	82.5	132.4
5	0	−1	0	230	50	15	101.1	126.3
6	+1	−1	−1	260	50	10	112.3	105.2
7	0	0	0	230	75	15	94.1	110.6
8	0	+1	0	230	100	15	91.1	135.2
9	+1	+1	−1	260	100	10	103.7	132.2
10	−1	−1	−1	200	50	10	88.2	103.4
11	0	0	0	230	75	15	95.2	110.8
12	−1	0	0	200	75	15	84.8	125.6
13	+1	+1	+1	260	100	20	111.1	120.3
14	+1	0	0	260	75	15	108.5	119.3
15	+1	−1	+1	260	50	20	107.3	118.4
16	0	0	0	230	75	15	93.7	112.4
17	0	0	0	230	75	15	95.3	111.7
18	−1	−1	+1	200	50	20	92.9	128.4
19	−1	+1	+1	200	100	20	98.4	128.7
20	0	0	0	230	75	15	95.1	111.6

shows the coded variables corresponding to the studied machining parameters. The mean particle size (MPS) of primary silicon and the value of material hardness (HBN), indicated as Y_1 and Y_2, respectively, were analyzed as responses. This model using the quadratic model of *f* in this study aims to not only investigate the response over the entire factor space, but also locate region of desired target where the response approaches to its optimum.

4 Results and discussion

4.1 Mathematical model for the mean particle size (MPS) of primary silicon and the material hardness (HBN)

The average values of the mean particle size (MPS) of primary silicon and the material hardness (HBN) along with the 20 experimental runs are also listed in Table 2. The statistical significances of the fitted quadratic model, shown in Table 3, were evaluated by the *F*-test of ANOVA [13]. It is statistically significant for the fitted quadratic model to analyze the values of Y_1 and Y_2. The values of "Prob. > F" in Table 3 for the term of models are less than 0.05 (i.e. α= 0.05, or 95% confidence). This shows that the obtained models are considered to be statistically significant. It is desirable that the terms in the model have a significant effect on the response. In the resulting ANOVA table, the other important coefficient R^2, called determination coefficients, is defined as the ratio of the explained variation to the total variation and is a measure by the degree of fit. When R^2 approaches to a unity, the better the response model fits the actual data. That presents the less difference between the predicted and actual values. Furthermore, the value of adequate precision (AP) in this model, which compares the range of the predicted value at the design point to the average prediction error, is well above 4. When the value of ratio is greater than 4, it presents the adequate discrimination of the model. These obtained results present higher values of the determination coefficients (R^2) and adequate precision (AP) at the same time. These values were as follows: R^2=0.960785 and AP=20.522168 for MPS; R^2=0.942714 and AP=15.594099 for HBN. Consequently, the obtained models of MPS and HBN can be considered as significant effect for fitting and predicting the experimental results. In the same manner, the test of lack-of-fit also displays to be insignificant. Using the results obtained in Table 3, we present the final quadratic models of response equation in terms of coded factors as follows:

– The mean particle size of primary silicon (MPS, μm)

$$\begin{aligned} Y_1 = {} & 95.036 + 9.610\, X_1 - 1.500\, X_2 + 3.040\, X_3 \\ & + 0.959\, X_1^2 + 0.409\, X_2^2 + 3.309\, X_3^2 \\ & - 0.575\, X_1X_2 - 2.275\, X_1X_3 + 2.950\, X_2X_3 \end{aligned} \quad (6)$$

Table 3 The ANOVA table for the fitted models

Source	Sum of squares	Degrees of freedom	Mean square	*f*–Value	Prob. > F	
(a) For MPS						
Model	1241.812227	9	137.979136	27.222727	< 0.0001	Significant
Residual	50.685272	10	5.068527			
Lack of fit	48.365272	5	9.673054	20.84710	0.6732	Not significant
Pure error	2.32	5	0.464			
Cor. total	1292.4975	19				
Standard deviation=2.251338			R^2=0.960785			
Mean=97.375			R^2 Adjusted=0.925491			
Coefficient of variation=2.312029			Predicted R^2=0.715945			
Predicted residual error of sum of squares (PRESS)=367.140061			Adequate precision (AP)=20.522168			
(b) For BHN						
Model	1225.426727	9	136.158525	18.284835	<0.0001	Significant
Residual	74.465272	10	7.446527			
Lack of fit	72.145272	5	14.429054	31.097100	0.873262	Not significant
Pure error	2.32	5	0.464			
Cor. total	1299.892	19				
Standard deviation=2.728832			R^2=0.942714			
Mean=57.38			R^2 Adjusted=0.891157			
Coefficient of variation=4.755720			Predicted R^2=0.575919			
Predicted residual error of sum of squares (PRESS)=551.258703			Adequate precision (AP)=15.594099			

– The material hardness (HBN)

$$
\begin{aligned}
Y_2 = 113.979 - 2.311\,X_1 + 6.712\,X_2 + 3.071\,X_3 \\
+ 4.327\,X_1^2 + 12.627\,X_2^2 - 8.772\,X_3^2 \\
- 0.050\,X_1X_2 - 2.500\,X_1X_3 - 6.725\,X_2X_3
\end{aligned} \quad (7)
$$

In terms of actual factors, the final quadratic models of response equation are as follows:

– The mean particle size of primary silicon (MPS, μm)

$$
\begin{aligned}
\mathrm{MPS} = 67.577 + 0.115\,M_T - 0.335 P_I - 1.644\,C_t \\
+ 1.065 \times 10^{-3}\,M_T^2 + 6.545 \times 10^{-4}\,P_I^2 \\
- 0.132\,C_t^2 - 7.666 \times 10^{-4}\,M_T P_I \\
- 0.015\,M_T\,C_t + 0.024\,P_I\,C_t
\end{aligned} \quad (8)
$$

– The material hardness (HBN)

$$
\begin{aligned}
\mathrm{HBN} = 272.212 - 2.033\,M_T - 1.939\,P_I \\
+ 19.009\,C_t + 4.808 \times 10^{-3}\,M_T^2 \\
+ 0.020\,P_I^2 - 0.351\,C_t^2 - 6.661 \\
\times 10^{-5}\,M_T\,P_I - 0.017\,M_T\,C_t \\
- 0.054\,P_I\,C_t
\end{aligned} \quad (9)
$$

The above mathematical model can be used to predict the values of MPS and HBN within the limits of the factors studied. The differences between measured and predicted response are illustrated in Figs. 2 and 3. The results of comparison for two responses prove that the predicted value of MPS and HBN are close to those readings recorded in the experiment with a 95% confident interval.

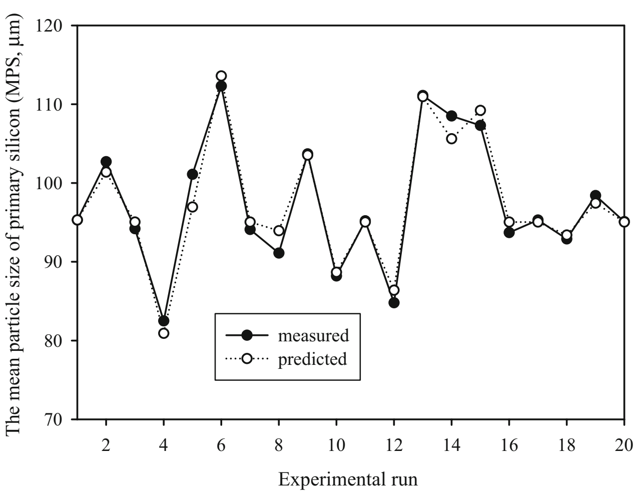

Fig. 2 The comparisons between measured and predicted value for the mean particle size of primary silicon (MPS, μm)

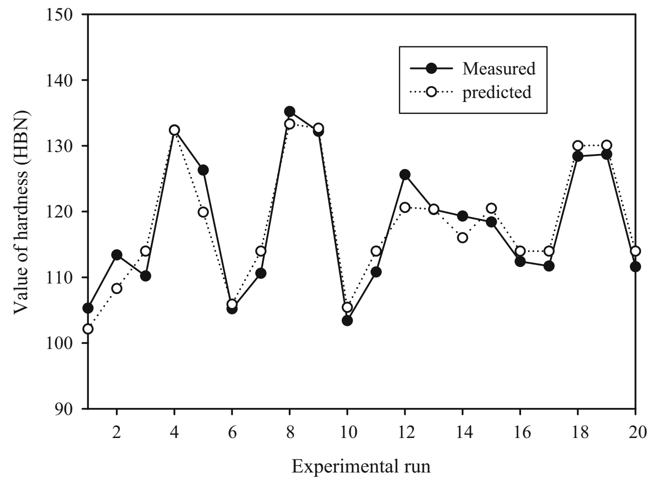

Fig. 3 The comparisons between measured and predicted value for the material hardness (HBN)

According to the results in ANOVA, a sensitivity analysis for the processing parameters on the values of MPS and HBN is performed and shown in Fig. 4. From the results of percent contribution for each processing parameter, the first two significant factors on the value of MPS are the die temperature (M_T) and the cooling time (C_t) with the contribution of 49% and 28%, respectively. It demonstrates that these two process parameters play major roles for the growing status of primary silicon particles in the microstructure. The sensitivity analysis shown in Fig. 4 also presents that the injecting pressure (P_I) and die temperature (M_T) with the contribution of 36% and 18% are the most statistically significant on the material hardness (HBN).

4.2 The effect of process parameters on the mean particle size of primary silicon

Figure 5 illustrates the microstructure of experimental specimen under an injecting pressure of 75 MPa, cooling time of 15 s and different die temperature of 200°C, 230°C and 260°C. From the figure, it is clear that the value of MPS increases with increase in die temperature. Increasing the die temperature will result in larger grain due to slower heat transfer and smaller cooling rate during solidification. The molten metals injected into die mould under higher die temperature, which results in slower rate of solidification, have more time for the growth of primary silicon particle in the microstructure [8, 11]. Therefore, the mutual primary silicon particles spread to form the rod-like and massive primary silicon phase [9, 10].

The influence of processing parameters such as the die temperature (M_T), injecting pressure (P_I) and cooling time (C_t) during the die casting process have been analyzed on the basis of the mathematical model developed in the Sect. 4.1. Figure 6 depicts the effects of die temperature

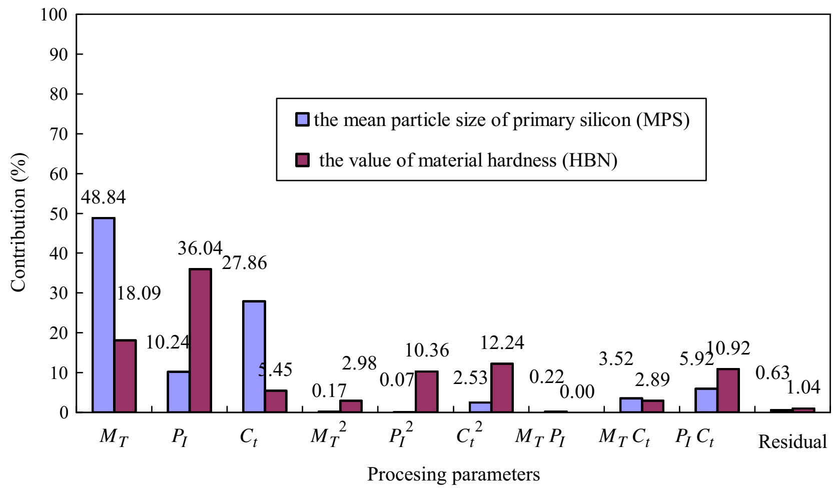

Fig. 4 The sensitivity analysis of processing parameters on the MPS and HBN

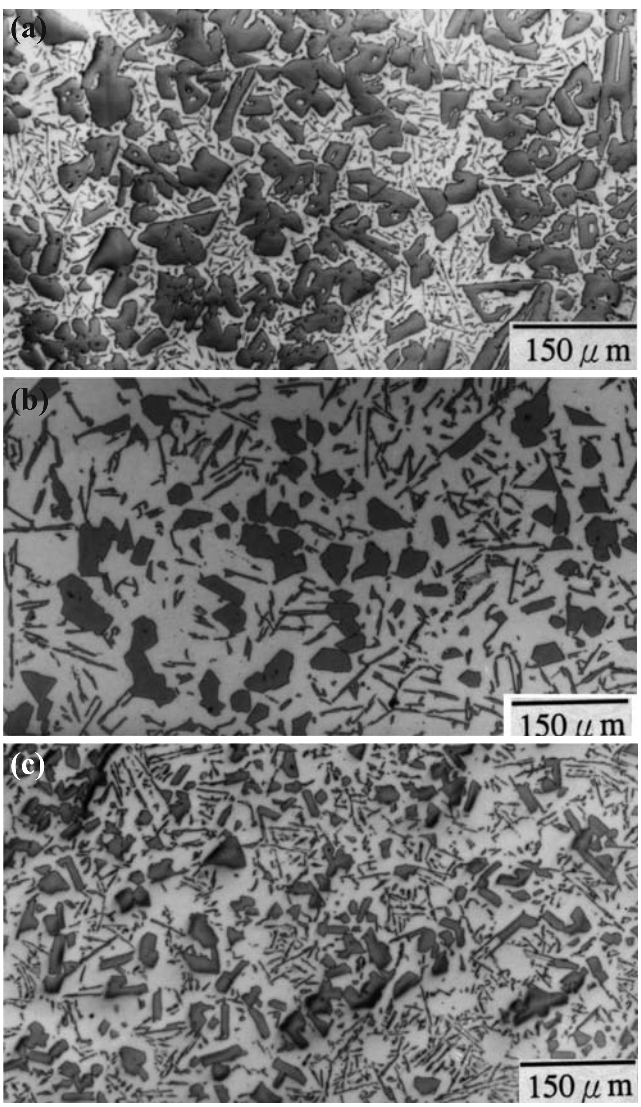

Fig. 5 Effect of die temperature on the microstructure of die cast Al-25Si: (**a**) 260°C, (**b**) 230°C and (**c**) 200°C under an injecting pressure of 75 Pa and cooling time of 15 s

(M_T) and cooling time (C_t) on the value of MPS of die cast Al-25Si alloy under the injection pressure of 75 MPa. It illustrates that the value of MPS goes on increasing with the die temperature. The value of MPS is found to increase with the increase of cooling time as well. Figure 7 shows the effect of injection pressure (P_I) on the value of MPS at the different die temperature (M_T) of 200°C, 230°C and 260°C. The figure shows that the value of MPS is not affected significantly by the pressure of injection. In general, the pressure of injection has the advantage of increasing the density and suppressing the shrinkage during the solidification of metals [9–11].

4.3 The effect of process parameters on the material hardness

With further increase at the pressure of injection, the gas and shrinkage porosities of die cast parts decrease toward

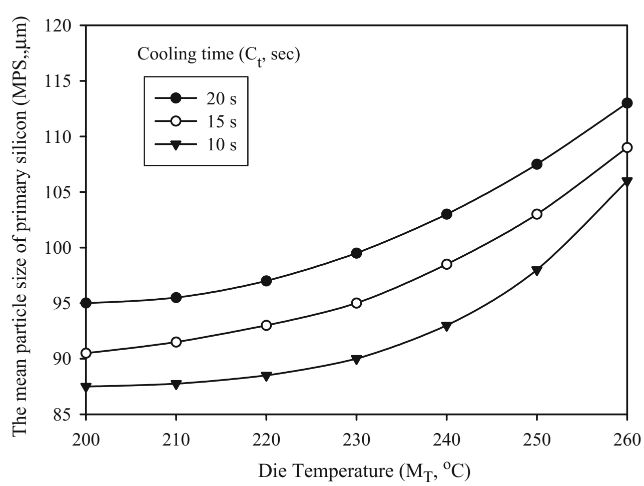

Fig. 6 Effects of die temperature (M_T) and cooling time (C_t) on the mean particle size of primary silicon of die cast Al-25Si alloy under the injection pressure (P_I) of 75 MPa

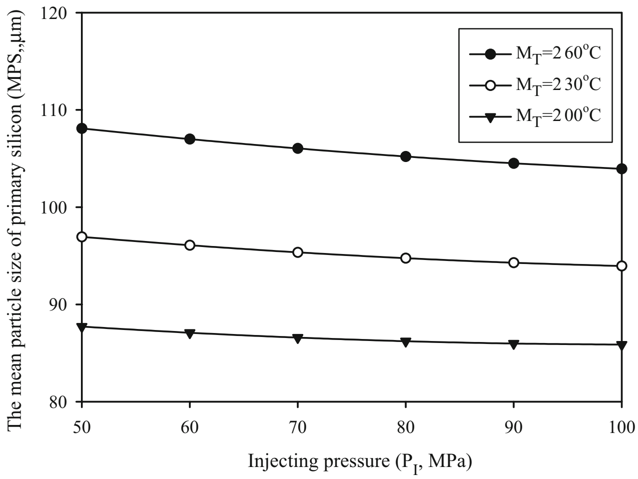

Fig. 7 Effects of die temperature (M_T) and injecting pressure (P_I) on the mean particle size of primary silicon of die cast Al-25Si alloy under cooling time (C_t) of 15 s

disappearance. The density approaches to its theoretical value simultaneously. Besides, applying larger injection pressure resulted in massive finer primary silicon phase grown from the surface of die cast parts. This is caused by the compression and compaction of the casting into the die; when injection pressure is larger, it will promote a higher heat transfer. Therefore, the values of hardness are improved by the refinement of massive finer primary silicon phase on the surface of die cast parts [6, 7]. Figure 8 shows the effect of injecting pressure (P_I) on the value of HBN at the different die temperature (M_T) of 200°C, 230°C and 260°C. From the figure, it is evident that the value of HBN increases steadily when the injection pressure increases. The slope of the curve is steeper at lower die temperature and becomes less steep at higher die temperature. This has been attributed to the sudden increase of cooling rate which leads to the increase of massive primary silicon phases, hence the value of HBN was improved. From the Fig. 8, the values of HBN decrease with the increase of die temperature due to the smaller cooling rate during solidification.

Figure 9 presents the effect of cooling time (C_t) on the value of HBN at the different die temperature (M_T) of 200°C, 230°C and 260°C. From this figure, it shows that the increase in the cooling time leads to the increase of hardness while it is less than 16 s. The HBN decreases for longer cooling time. The reason for this result is that the increasing of cooling time leads to more sufficient time for the growth of primary silicon particles within the microstructure. When cooling time is more than 16 s, the ripening of the silicon particles resulted in the effect of cooling time on the size of silicon particles. Therefore, the surface of die cast parts possesses less massive and fine primary silicon phase and lower value of hardness as well. As shown in Fig. 9, it is obvious that the value of hardness decreases with the increase of the die temperature.

5 Conclusions

In the HPDC process of Al–SI alloys, the mathematical models of the mean particle size (MPS) of primary silicon and the material hardness (HBN) have been carried out to correlate the dominant machining parameters, including the die temperature, injection pressure and cooling time. The face-centered CCD technique plan based on the RSM has

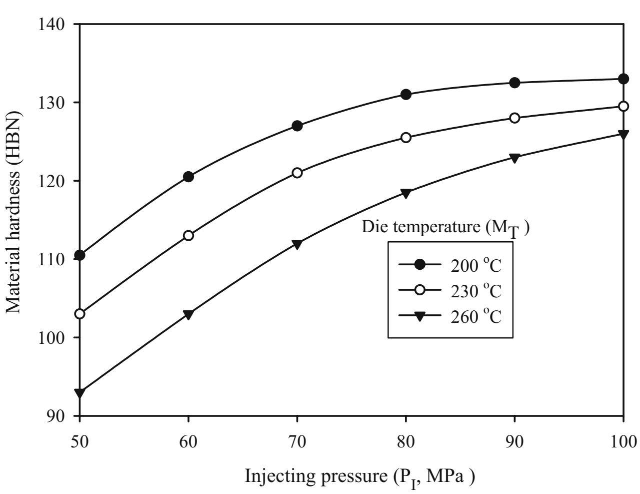

Fig. 8 Effects of die temperature (M_T) and injecting pressure (P_I) on the material hardness (HBN) of die cast Al-25Si alloy under cooling time (C_t) of 15 s

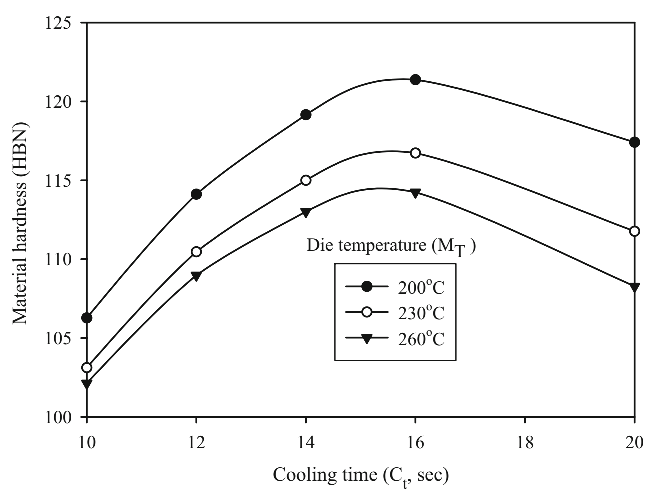

Fig. 9 Effects of die temperature (M_T) and cooling time (C_t) on the material hardness (HBN) of die cast Al-25Si alloy under the injection pressure (P_I) of 75 MPa

been employed to carry out the experimental study. The conclusions of research are as follows:

(1) The results of ANOVA and comparisons of experimental data show that the mathematical models of the value of MPS and HBN are fairly well fitted with the experimental values with a 95% confidence interval.
(2) The two main significant factors on the value of MPS are the die temperature and the cooling time with the contribution of 49% and 28%. Statistically, it is significant for the value of HBN that the pressure of injection and the die temperature have the contribution of 36% and 18%.
(3) The value of MPS generally increases with the increase of die temperature and cooling time. The value of MPS is not affected by the pressure of injection. The values of HBN increase with the increase of injecting pressure and decrease with increase of die temperature.
(4) Applying larger injecting pressure results in massive finer primary silicon phase grown from the surface of die cast parts. The increase in the cooling time leads to the increase of hardness.

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