Application of Taguchi Method Using Computer Software to Determine Nodularisation Effect of Ductile Iron Castings

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Abstract - Ductile iron was well manufactured and used around the world. Among its advantages are easy to cast as cast iron but with mechanical properties as similar as stainless steel. There was various processing method developed to enhance the efficiency of nodularisation effect during production of ductile iron. In mould treatment is one of the process that offered higher magnesium recovery than other process. The purpose of this paper is to analyze the nodularisation effect on the parameter of ductile iron castings. An attempt has been made to obtain optimal settings of the casting parameters, in order to yield the optimum condition for in mould treatment of ductile iron castings. Two different stages of experiment were conducted to investigate the effects. The objective of first stage experiment also known as preliminary experiment is to determine a fixed parameter that was identified earlier as not affected main objectives directly. The main purpose is to obtain sound casting. Then, actual experiment to determine the control factors that affected the nodularisation parameters of in mould casting was conducted. The control factors considered were; size of castings cavity, distance effective from reaction chamber, percentage of MgFeSi used and the size of MgFeSi particles. The effects of the selected process parameters on the nodularisation and the subsequent optimal setting of the parameters have been accomplished using Taguchi Method. Four different sets of result were studied. It was tensile strength, magnesium concentration, nodule count and hardness of casting. The result indicates that the selected parameters significantly affect the nodularisation of ductile iron castings.

INTRODUCTION

Application of ductile iron continues to increase over the years. It is due to its ease of recycling, relatively low cost production and producing capability with a wide range of microstructure and mechanical properties [1].

Ductile iron is born from continuous research done towards cast iron. The characteristic for both of iron is differing much. While cast iron is simply known as brittle with graphite flake microstructure, ductile iron is ductile and held the advantages of uniform distribution of nodule graphite microstructure. It offers a combination of strength, fatigue resistance, toughness and ductility in addition of famously advantages of cast iron – machinability, castability and economic of production [2].

The production of ductile iron means for adding magnesium to molten metal. There is four common techniques classified; transfer method (open ladle addition, sandwich, trigger process), plunging method, injection method and pressure ladle or pressurized chambers method. Because of fading problem, in mould method was developed in which metal is inoculated as it poured into the casting or within the actual running system of the casting itself.

In mould method is classified as late inoculation technique offers advantages of virtually elimination of fading problem, lower increasing of silicon content in molten metal, effectively preventing the formation of carbide and greater consistency of structure uniformity.

Inoculation mechanism for in mould differs to great extent from other techniques. For example, during addition of nodularizing alloy to the iron inside the mould, the resulting high pressure of magnesium vapor may damage the mould itself. Otherwise, the vapor entrapped in the mould cavity may lead to the formation of incomplete castings.

The injurious effect of nodularization can be screening by using nodularizing alloys with relatively low magnesium content. But, the decrease of magnesium content in alloying agent may contribute of higher percentages alloy used which leading to yield decreasing. To make matter worse, the probability of partially undissolved alloy after filling the mould may occurs. Therefore the percentage and size of nodularizing alloy should be carefully applied in conjunction with the temperature and pouring rate of the molten metal, in order to successfully complete the inoculating process inside the mould [3].

With it, confirmation of parameters influence such percentage of nodularization agent used towards casting mechanical properties is worth to study for. Other than that, control factors such the particle size of nodularization agent, distance reactive from reaction chamber, and influence of casting cavity for effect of nodularization was also investigated. Hence, with the right combination of control factors, microstructure of the casting cavity as well as the mechanical properties of selected range can be predicted [4].

METHODOLOGY

The experiment was conducted into two separate stages. The first stage was preliminary trial to determine fixed parameter namely pattern and mould design suitability, pouring and melting process parameters. The second stage of the experiment was conducted to establish the controlling factors with the relevant level range of value. The design of the experiment was based on Taguchi Method approach.

The objective of the preliminary experiment is to determine a fixed parameter that was identified earlier as not affected objectives directly. The main purpose of preliminary experiment is to obtain sound casting. A defective part due to castings defect will considered unsuccessful. The parameters studied is the suitability of pattern and reaction chamber volume, mould and sand mix selection, material to be cast, MgFeSi to be inoculated and pouring process parameter suitability.

After the preliminary experiment done, the actual experiment to determine the control factor that affected the nodularization parameters of in mould casting was conducted. Taguchi method was used as medium to identify main effects, interactions, significance contribution of factors and its expected optimum value in range selected.

Controllable factors with significance impact to inoculation effect were studied. Adjustable parameters and it range was determined using data from preliminary experiment, literature review and direct study of the system. The list of factors are effective distance from reaction chamber (m), percentage of FeSiMg used during inoculation (%), size of FeSiMg used during inoculation (mm) and size of casting cavity (kg). The range of factors was between two levels of design parameter.

Output of control factors experimented were tensile strength (MPa), magnesium concentration (%), material hardness (BHN) and nodule count (unit/mm^2).

Appropriate orthogonal array (OA) was based on standard selection of orthogonal array. Since there was four set of factor and two level of maximum and minimum range was selected, the suitable orthogonal array is L_8. Experimental performance was evaluated with 8 sets of experiment reading taken. The experiment is conducted with two repetitions.

S/N ratio and Analysis of Variance (ANOVA) are used to analyze the experimental data. The term ‘signal’ represents the desirable value (mean) while the term ‘noise’ represents the undesirable value (S.D.) for the characteristic output. Therefore, the signal to noise (*S/N)* ratio is the ratio of the mean to the S.D. Taguchi used the *S/N* ratio to measure the quality characteristic deviating from the desired value.

Analysis of Variance (ANOVA) is a table of information that displays the contribution of each factor. The purpose of the analysis of variance is to investigate which design parameters significantly affect the quality characteristic. This is to accomplish by separating the total of the variability of the *S/N* ratios, which is measured by the sum of the squared deviations from the total mean *S/N* ratio, into contributions by each of the design parameters and error.

The performance at the optimum condition is estimated only from the significant factors. By using Qualitek-4 software, the results can be transforming into graph. From the graph, the interaction can be identifying either linear or non-linear interaction. These both type of interactions may occur when the level more than two. If there were only two levels, only linear interaction will occurred.

For verification of the optimal design parameters through the confirmation experiment, the levels set at optimum condition obtained from analysis. The confirmation experiments were conducted after the possible optimal settings were identified. Then, the expected result from the analysis was compare to the results obtained from conformation experiments.

Result from the confirmation test should agree with the optimum performance (Y_{opt}) estimated by the analysis.

The experimental setup was utilized the orthogonal array designed to determined the control factors. The experiment preparation for green sand mould, ladle preparation, charging material (pig iron) and induction furnace was almost the same as preliminary experiment.

For pattern design, control factor contribute directly since it located two parameters studied, distance reactive from reaction chamber and size of casting cavity.

FeSiMg inoculant percentage used also reflected directly as the parameters studied needed two level range of percentage. Minimum level inoculated was 0.3 % and maximum level inoculated was 0.7 %. While a mesh was used to differentiate particles at minimum level (0.5 mm) and maximum level (3.0 mm) as Table 1.

Table 1: Control factors

Random order	**No of trial**	**Factors**			
		A	**C**	**B**	**D**
		FeSiMg %	Distance from reaction chamber (m)	FeSiMg size (mm)	Casting size (kg)
1	1	0.3	0.1	0.5	0.75
4	2	0.3	0.1	3.0	2.0
2	3	0.3	0.3	0.5	0.75
3	4	0.3	0.3	3.0	2.0
7	5	0.7	0.1	0.5	2.0
5	6	0.7	0.1	3.0	0.75
8	7	0.7	0.3	0.5	2.0
6	8	0.7	0.3	3.0	0.75

Light return scrap in the amount of 10 % of the total charge was charged in the induction furnace after being pre-heated for 1 hour. When the return was melted, grey iron ingot was charged. The total charge for each melting was 50 kg.

To ensure clean molten metal and ladle/ furnace walls, slag was removed by adding ferrogen based flux. As the melting proceeds, extra scrap was added, till the required metal temperature is reached. Once the temperature rose to 1500 $\pm$ 20 ^{0}C, the furnace was shutdown. Slag was skimmed and pouring was conducted when the melt reached the temperature 1400 $\pm$ 50 ^{0}C. The furnace was tilted at convenience degree to allow molten metal poured into ladle as figure 1.

Figure 1: Pouring of molten metal

Casting cavity was fettled to remove gates and risers, surface cleaning and chipping of any unnecessary projections on surfaces. Then, the casting was checked to determine any defect. The casting was sent to machining for specimen shaping as tensile strength specimen, spectrometer specimen and microstructure specimen according to required standard testing specimen.

The rough casting was machine using manual milling and lathe machine until 19 mm diameter size. After that, the sample was further machine using CNC machine for detailed specification. The specimen was machine according to American Society for Testing and Materials (ASTM) A370 standard size with 12.5$\pm$ mm round tension test, 50 mm gage length, 10mm radius of fillet and 60 mm length of reduce section.

The tensile strength test was conducted using universal tensile test machine with automatic data processing system. The ends of the specimen are enlarged where they fit in the grips so that failure will not occur near the grip itself. Failure at the ends would not produce the desired information about the specimen, because the stress distribution near the grips is not uniform and is affected by the stress concentrations.

As the specimen is pulled, the load is measured and recorded. The elongation over the gage length is measured simultaneously by mechanical gage and electrical resistance strain gage. For material does not have an obvious yield point and ductile such ductile iron, it may not be easy to determine the exact location on the stress-strain curve at which yielding occurs, because the slope of the straight (elastic) portion of the curve begin to decease slowly. So, a stress-strain curve is offset by a strain of 0.002, or 0.2 % elongation. A line is drawn on the stress-strain diagram parallel to the initial linear of the curve. The intersection of the offset line and stress-strain curve will define the yield stress

The same tensile strength specimen was machined to 1 cm^2 size each using abrasive cutoff for microstructure sample and spectrometer sample. Then, a magnesium concentration was determined using GDS spectrometer. The result will show how much magnesium recovery to determine the processing efficiency. The variations in magnesium yield are established as;

$$= \frac{\%Mg\ from\ spectrometer*100*100}{\%Added\ FeSiMg*\%Mg\ in\ the\ alloy} \qquad (1)$$

In an optimum process the yield should be >65 % and the variations less than +/- 5 %.

After the specimen was cutoff to 0.5 cm^2 sizes, mounting and grinding process was done according to standard microstructure requirement. Then, the specimen was polish until reflective view occurs before it was etched with 3 % nital (3% nitric acid and 97 % alcohol). The microstructure was determined by 100 xs, 200x and 400x magnification using Nikon attached camera.

Once the microstructure picture captured (Figure 2), the calculation of nodule count utilized the manual point count [8]. Among the steps applied such as;

The approximation of sphericity is accounted as

$$= \frac{4x\pi xarea}{perimeter^2} \qquad (2)$$

The nodularity by count is counted as

$$= \frac{no.of.acceptable}{no.of.acceptable + no.of.unacceptable} \qquad (3)$$

The sphericity > 0.5 considered accepted.

RESULT

16 samples was tested for nodule count. The maximum value achieving 99 nodule/mm^2 (trial 6, sample 1) and the lowest was 67 nodule/mm^2 (trial 4, sample 2) as indicated in Table 2. During trial 1 to 4, the value ranged between 67 nodule/mm^2 to 82 nodule/mm^2. While during trial 5 to 8, the value ranged between 85 nodule/mm^2 to 99 nodule/mm^2.

Table 2: Nodule count

Trial	Sample 1 (nodule/mm^2)	Sample 2 (nodule/mm^2)
1	82	81
2	72	73
3	78	77
4	68	67
5	89	88
6	99	98
7	85	86
8	96	95

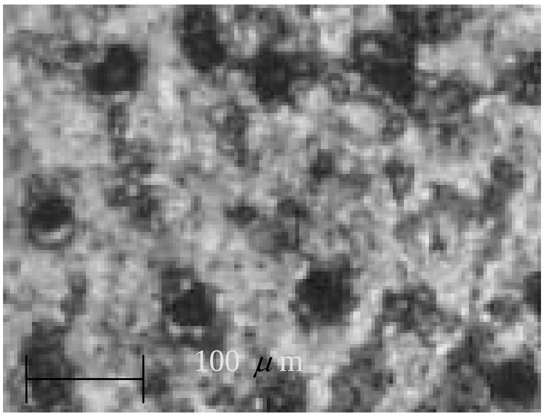

Figure 2: microstructure of nodule in iron matrix

Based on Qualitek-4 software, calculation was done to determine the S/N ratio; main effect existed between parameters, analysis of variance (ANOVA), optimum condition and its contribution.

Table 3: S/N ratio of experimental trial results

Trial	S/N ratio
1	38.222
2	37.206
3	37.785
4	36.585
5	38.938
6	39.868
7	38.638
8	39.599

Table 4: Main effects for nodule count

	Factors	Level 1	Level 2	L2 – L1
1	MgFeSi %	37.449	39.261	1.812
2	Distance from r.c(m)	38.558	38.152	-0.406
4	MgFeSi size(mm)	38.396	38.314	-0.083
5	Casting size(kg)	38.869	37.842	-1.028
6	INTERACT 2 X 4	38.336	38.374	0.038

It was analyzed that there is two types of interaction existed to determine nodule count. Firstly, interaction between MgFeSi size and casting cavity size when level of MgFeSi size control factor changes. (Figure 3). Secondly, interaction between MgFeSi % and MgFeSi size when level of MgFeSi percentage control factor changes (Figure 4).

While, after the improvement of analysis of variance (ANOVA) for these sets of trial, it was found the optimum condition and performance to determine the significance factors that affect nodule count is as Table 4.

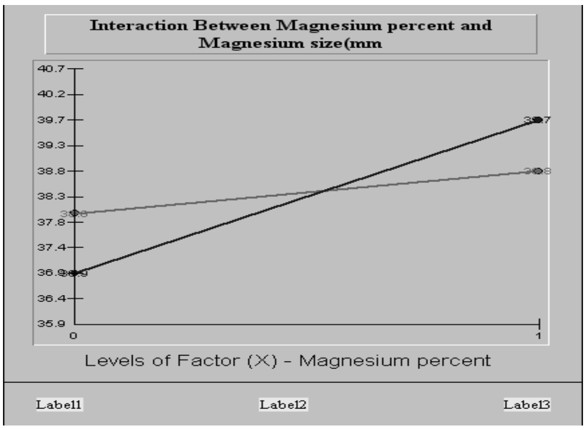

Figure 3: interaction between MgFeSi size and casting cavity size when level of MgFeSi size control factor changes.

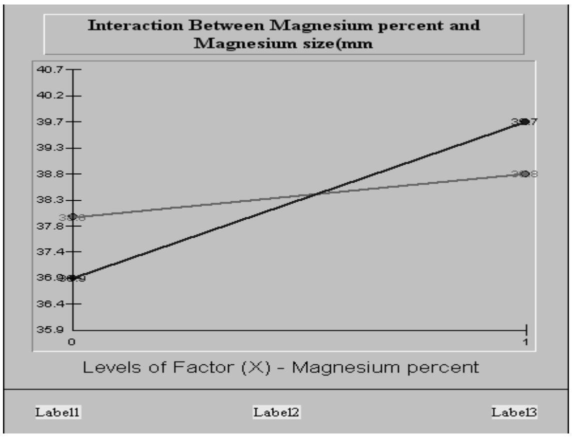

Figure 4: Interaction between MgFeSi % and MgFeSi size when level of MgFeSi percentage control factor changes.

The estimation of expected result from optimum condition can be done by S/N ratio (THE BIGGER THE BETTER) as manipulation of mean standard deviation (MSD);

$$MSD = [\left(\frac{1}{y_1^{\ 2}}\right) + \left(\frac{1}{y_2^{\ 2}}\right) + \ldots + \left(\frac{1}{y_n^{\ 2}}\right)]/n$$

$$MSD = 10^{[-\left(\frac{S}{N}\right)/10]}$$

$$MSD = 10^{[-(39.976)/10]}$$

MSD = 0.00001005

Expected performance in QC units (or overall evaluation criteria) is;

Y_{exp} = SQR (1/MSD)

Y_{exp} = 99.7 nodule/mm^2

The significance factor and interaction influence graph is as Figure 5. MgFeSi percentage was the most significant factor influenced nodule count (achieving 70%). It was followed by size of casting cavity (25%).More nodule count is expected whenever more MgFeSi was used. Less cavity size will raise more nodule count compared to bigger size of cavity.

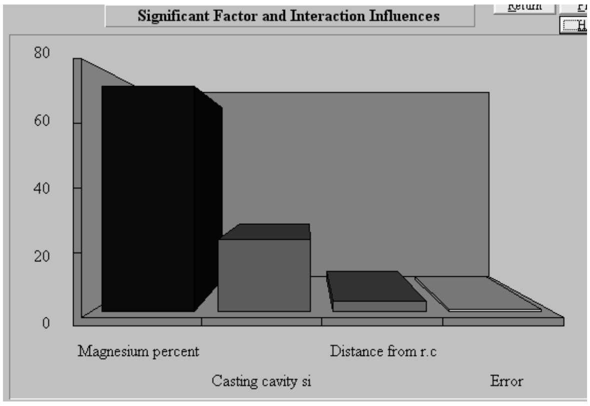

Figure 5: Significance factor and Interaction influences of nodule count (pooled)

Confirmation casting trial was done to ensure the estimated result at optimum condition is reliable. The error percentage is calculated by using the following equation:

$$\% \text{ Error} = \frac{Predicted - Actual}{Actual} \text{ x } 100 \quad (4)$$

Table 5: Comparison of predicted and validation result

Trial	Theoretical value	Control factors Predicted result	Validation result (Actual)	Error (%)
Nodule no	-	99.7	88	12.00%

SUMMARY

Further analysis using ANOVA revealed that the most significance factor influenced nodule count number is the percentage of MgFeSi used during inoculant (Figure 5). It contributes 70% of overall factors and followed by casting cavity size factor that contributes 20%. The rest is considered do not significance. Validation experiment (88 nodule/mm^2) was -12.00% error compared to predicted control factors experiment (99.7 nodule/mm^2).

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