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Taguchi Design of Manufacturing Condition for Semi-Solid Al-Si Alloy fabricated by Cooling Slope Plate method

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ABSTRACT

In this paper, we used Taguchi design to find an optimum condition for semi-solid Al-Si aluminum alloy fabricated by cooling slope plate method. In CS method, molten alloy was poured over an inclined cooling plate in order to make the semisolid slurry. The semisolid slurry flowed and solidified into a mold placed at the bottom end of the slope. In Taguchi's design, it is well-known that high value of S/N ratio (Signal vs. Noise) is better. Consequently, manufacturing conditions were arranged as table of orthogonal array L9(3^4), and then pouring temperature and tilt angle of cooling plate factors were determined. From microstructural observations, grain size and shape factor were measured by image analyzer. The results of S/N ratios showed that the pouring temperature has the main effect on grain size and morphology of silicon phase of an Al-23%Si alloy cast by cooling slope plate method, since S/N ratio which is sensibility on surround environment was the highest. The optimum conditions were also identified.

Introduction

In recent years, many semisolid processing techniques have been developed to produce semisolid slurries with such discrete microstructures named thixotropic non-dendritic globular microstructures as feedstock materials for subsequent thixoforming [1]. One such process is the Cooling slope plate which acts as appropriate process of slurry preparation with high efficiency, low equipment and running costs, accordingly, it is developed rapidly [2]. In the Cooling slope plate process, the alloy melt is poured onto inclined cooling plate, and the semisolid slurry can be prepared under the process conditions of water cooling and melt flow. Birol has successfully prepared a semisolid slurries of A357 and A390 aluminum-silicon alloys by this process [3,4]. Also, this process was stated as a suitable technique to prepare slurries of high melting temperature metals, such as gray cast iron and ductile iron[5, 6]. Hypereutectic Al–Si alloy is an excellent choice for automotive industry and desirable for wear resistant applications, where wear resistance, cooling characteristics and reduced density are required [7].

Taguchi Design method have been employed to improve products and manufacturing processes. Essentially, it has been used quite successfully in several industrial applications to optimize the manufacturing processes, and to solve quality problems [8, 9].

The resultant cast microstructures via Cooling slope plate method are controlled by many factors such as pouring temperature, cooling length and tilted angle of cooling plate, a flow behaviour on cooling plate. Besides, there are further noise factors which impact negatively microstructures of semi-solid Al-Si alloy, for instance, atmosphere condition including temperature and humidity, skill of workers etc. However, considering them as experimental factor is necessary to many experimental times. Optimization the main factors in Cooling slope plate method by Taguchi design will be very suitable to reduce effect of noise factors. The aim of this paper is to optimize an experimental conditions for producing semisolid billet via Cooling slope plate in accordance with orthogonal array table by Taguchi design.

Experimental Procedure

Hypereutectic Al-23%Si alloy was used for experimental materials. The chemical composition of hypereutectic Al-23%Si alloy is achieved by apparatus Thermo ARL 3460, Optical Emission Spectrometer, it was 23.25%Si-0.219%Fe-0.01%Mn-0.009%Mg-0.003%Zn 0.001%Cu-0.001%Ni. The slope plate and permanent mould were made from the structural steel and AISI 1045 Steel, respectively.

Cooling slope plate was employed for producing semisolid billets with the diameter of 30mm and the height of 100mm. Firstly, a series of the Al-23%Si alloys were melted. Then, the melt was superheated at different pouring temperatures. At that time, the melt alloy was poured into a cylindrical mould via slanted cooling plate. The dimensions of slanted cooling plate were 40mm wide, 550 mm long and 6mm thickness. The cooling length was set at 300mm. And, the process was done at pouring angles 40, 50, 60° with respect to the horizontal plane and cooled by water circulation underneath. Subsequently, the melt was continuously cooled on the slanted plate, it became a semisolid slurry at the end of slanted cooling plate, prior to arriving in the mould. The slurry was then filled the mould, and entirely solidified. Cooling slope plate process in this study is shown in Fig.1.

Samples used for microstructural examination were prepared by using the standard metallographic procedures, grinding, polishing and followed by etching in solution of 1% HF, 97% Ethanol and 2%HCL.The microstructure of the alloy was observed by using computerized optical microscopy Nikon ECLIPSE ME600, equipped with a digital camera Nikon DIGITAL DXM 1200F. The average particle size and shape factor of solid phases were measured using a digital image analysis system. Average particle size and shape factor of solid phases are calculated in each case by applying Eqs. (1) and (2) [**10**]:

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$$D_{eq} = \sqrt{\frac{4A}{\pi}} \quad (1)$$

$$F = \frac{P^2}{4\pi A} \quad \in [1, \infty] \quad (2)$$

where Deq, F, A and P are the average particle size, shape factor, area, and perimeter of solid particles. Equation (2) describes the roundness of the particle and will be (1) for a circle, it increases with more complex geometries [10].

Taguchi Design

Depending on objectives, the Taguchi method describes three different formulas of mean square deviations (i.e., signal–to– noise ratios) comprising the nominal–the–better, the larger the–better and the smaller–the–better. The signal–to–noise ratios can be considered as an average performance characteristic value for each experiment. These three different signal–to–noise ratios, corresponding to n experiments, are presented as follows [9]:

Nominal – the – better cases:

$$\text{Signal - to - noise ratio} = -10 \log\left[\frac{1}{n}\sum_{i=1}^{n}(yi - m)^2\right]$$

$$\text{Signal - to - noise ratio} = -10 \log[(\bar{y} - m)^2 + \bar{s}^2] \quad (3)$$

Larger – the – better cases:

$$\text{Signal - to - noise ratio} = -10 \log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (4)$$

Smaller – the – better cases:

$$\text{Signal - to - noise ratio} = -10 \log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right]$$

$$\text{Signal - to - noise ratio} = -10 \log\,(\bar{y}^2) \quad (5)$$

where *m* is a target value for nominal–the–better cases; *y* is the mean value of the collected data; *s* denotes the standard deviation; y_i is the collected data through experiments and n represents the number of experimental runs.

In this paper, to optimize the production of semisolid Al-23%Si alloy by Taguchi design, two factors were chosen as controlling variables for grain size and shape factor, which are pouring temperature of melt (Factor X), tilt angle of cooling plate (Factor Y). Each one has three levels. These factors and their levels are shown in Table (1). An orthogonal array of L9(3^4) shown in Table (2) was applied to plan the studied experiments. It can be seen that there are in overall 9 experiments needed for this work. Both of the aforementioned grain size and shape factor are a selected quality objectives. By applying signal-to-noise ratio analysis, based on the Taguchi method an optimal parameter setting was identified.

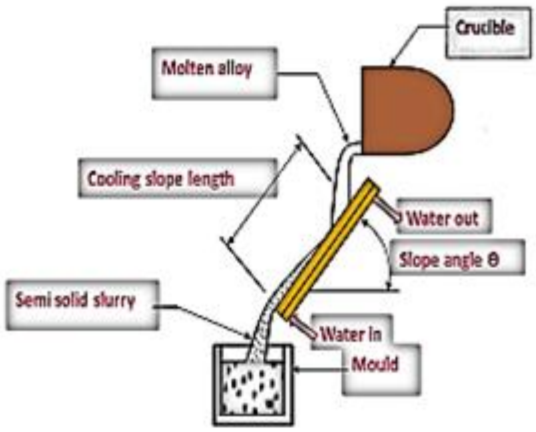

Figure 1. Schematic of Cooling slope plate process

Results and Discussion

Figure (2a) manifests the microstructure of as-cast of a hypereutectic Al-23%Si alloy which was directly cast into the metallic mould. It can be seen that the microstructure contains bulk primary silicon (β-Si) in the network of the eutectic phase. Otherwise, in the case of using cooling slope plate, both of the grain size and the morphology of primary Si have been changed in accordance of cooling and the melt flow. The microstructural changes were obvious at the end of cooling plate, where the remaining layer of molten alloy was also examined, as shown in Fig. (2b).

Figure (3) shows the microstructures of an alloy at different conditions using cooling slope plate. The measured grain sizes and shape factor under designed experimental conditions are shown in Table (2). Consequently, the experimental conditions those presented the smallest grain size in this study was 820°C for pouring temperature and 60° for tilt angle of cooling plate.

The changing in microstructures resulted via cooling slope plate can be attribute to two conditions; high heat transfer as result from contact between the melt and cooling plate, and exerted shear stress on the layers of the melt as a result of gravity force [1]. From the microstructural observations and the measured data, it can be seen that the melt pouring temperature has a significant effect on the size and morphologies of primary silicon in an alloy.

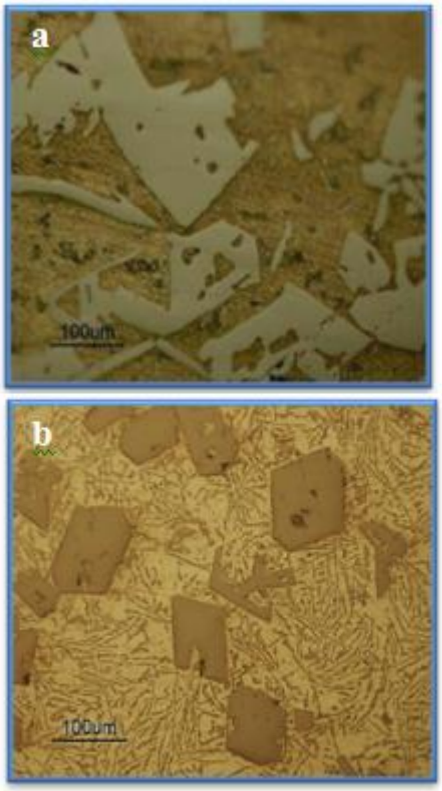

Figure 2. Microstructure of an alloy directly poured into the mold a) Microstructure of remaining molten alloy at the end of plate b)

In Taguchi design, the optimum condition was determined by high S/N ratio which influence by control factor. In this work, grain size was specified as smaller–the–better because mechanical properties of an alloy are improved with finer grain. Thus, S/N ratio can be calculated by the aforementioned equation (5).

Mean effects of S/N ratios for grain size is shown in Fig. (4). The S/N ratio was -26.75 at 820°C pouring temperature (X3), and -27.96 at 60o tilt angle of cooling plate (Y3).

Table 1. Control factors and their levels

		Levels		
Control factor	**unit**	**1**	**2**	**3**
X: Pouring Temp.	°C	760	790	820
Y: Tilt angle	degree	40	50	60

Table 2. Orthogonal Array Table of experimental runs and results

No.	Pouring Temp.	Tilt angle of Cooling plate	Grain size	Shape factor
1	760	40	50.41	2.3
2	790	40	29.71	1.88
3	820	40	23.57	1.81
4	760	50	48.83	2.1
5	790	50	28.80	1.85
6	820	50	22.58	1.72
7	760	60	34	1.97
8	790	60	23.76	1.73
9	820	60	19.33	1.59

Figure 3. Microstructure of Al-23%Si alloy produced by Cooling slope plate at different conditions

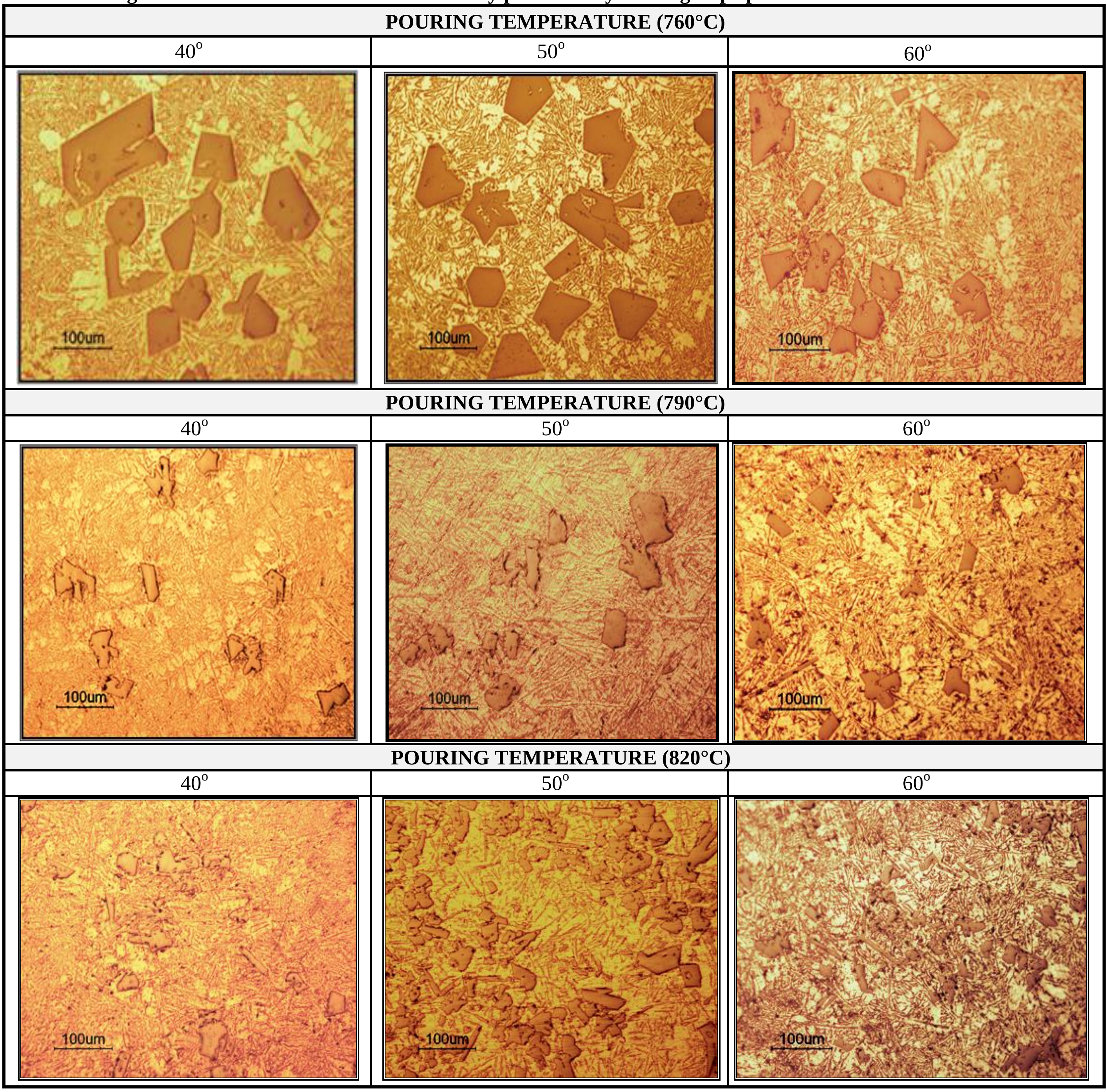

Figure (5) shows S/N ratios for shape factor with two factors, where S/N ratio is -4.66 for pouring temperature and -4.93 for cooling plate's angle. In this work, response of S/N ratio is more sensitive to variation of pouring temperature than tilt angle of cooling plate. This means that the influence of pouring temperature on grain size is larger than tilt angle of cooling plate. Therefore, pouring temperature has to considered as main factor to produce semi-solid billet of the studied alloy using cooling slope plate method.

As a result, the optimized conditions which are specified to produce semi-solid billet of Al-23%Si alloy; 820^{o}C as a pouring temperature and 60^o as a tilt angle of cooling plate. Other factors like cooling length, melt flow rate and mold material may also be considered as control factor to reduce effect of noise factor.

Conclusions

The semi-solid Al-23%Si alloy was fabricated by cooling slope plate method. The introductory results can be briefed as follows:

- The results of S/N ratios showed that the pouring temperature has the main effect on grain size and morphology of silicon phase of an Al-23%Si alloy cast by cooling slope plate method, since S/N ratio which is sensibility on surround environment was the highest.
- The optimum conditions for an Al-23%Si alloy was 60° of cooling plate, 820°C of pouring temperature with (19.33 µm) grain size, (1.59) roundness.

Acknowledgements

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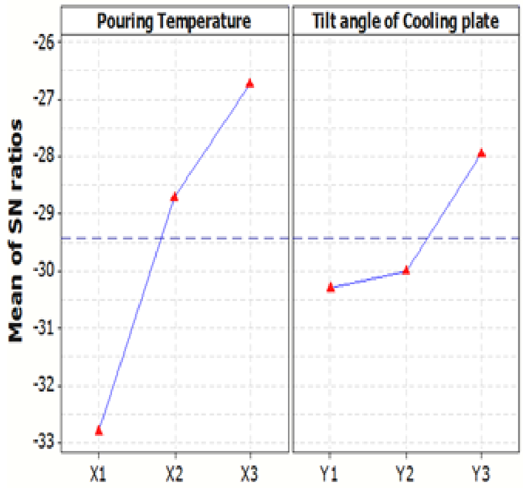

Figure 4. Mean of SN ratios for Grain Size of Two Factors showing an Optimized Condition X3Y3

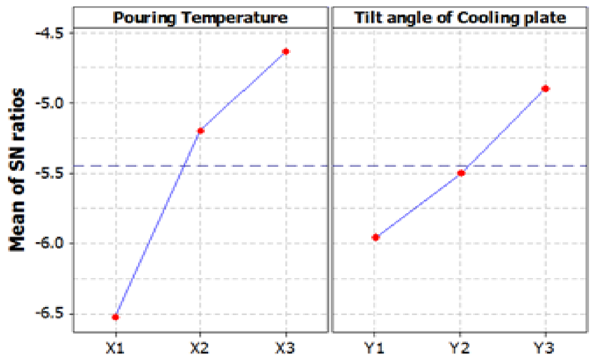

Figure 5. Mean of SN ratios for shape factor of Two Factors showing an Optimized Condition X3Y3

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