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Optimization of semi-solid metal processing of A356 aluminum alloy †

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Abstract

Semi-solid metal (SSM) processing has been recognized as an advanced process to produce high-quality and low-cost engineering components. The cooling slope method is a simple route that can develop non-dendritic slurry for various purposes with reduced equipment and processing costs. In this study, the cooling slope method was employed to produce the A356 feedstock in SSM processing. The dendritic primary phase in the conventionally cast A356 alloy has transformed into a non-dendritic one through the use of ingots cast over a cooling plate with a different pouring temperature. After pouring, the melt that becomes semi-solid at the end of the plate is consequently poured into cylindrical steel molds with different mold temperatures. Also, the process has been conducted in different cooling slopes and different cooling lengths. Then, a back-propagation neural network has been designed to correlate the process parameters to grain size. Finally, genetic algorithm (GA) has been used to optimize the process parameters. Results indicate that the pouring temperature, mold temperature, cooling slope, and cooling length have significant effects on size and morphology of α-Al phase. The GA can optimize the process as well.

Keywords: Optimization; Semi-solid; Solidification; A356; Aluminum

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1. Introduction

Semi-solid metal (SSM) processing is a new technology for metal forming. Different from conventional metal forming technologies that use either solid metals (solid state processing) or liquid metals (casting) as starting materials, SSM processing involves semi-solid slurries in which non-dendritic solid particles are dispersed in a liquid matrix [1]. Various routes have been introduced to produce non-dendritic microstructure, such as magnetohydrodynamic (MHD) stirring [2] and ultrasonic vibration [3].

Among all the techniques of semi-solid metal processing, the cooling slope (CS) process is a simple route that can develop non-dendritic slurry with reduced equipment and processing costs for various purposes. In this method, the molten alloy with a suitable amount of superheat is poured on a cooling slope. Solid nuclei is subsequently formed because of the contact between the melt and the cooling slope, and is then broken into a refined microstructure as a result of the applied shear stress of gravity force and melt flow [4-6].

In the CS method, various parameters can affect the final microstructure. Numerous investigations have been conducted to produce a more refined and globular microstructure as a feedstock using this method. Taghavi and Ghasemi [4] reported that the length and angle of cooling slope had a prominent effect on the microstructure of A356 ingots produced by SSM. Birol [5] reported that the pouring temperature and cooling slope length have a prominent effect on the as-cast and reheated microstructure of A357 ingots. Legoretta et al. [6] conducted a parametric study to produce a thixotropic ingot of an A356 aluminum alloy via cooling slope.

Success of this process largely depends on selecting parameter values. Some investigations have been performed to optimize the SSM process. Li et al. [7] applied the genetic algorithm (GA) to optimize the design of parameters in a semi-solid extrusion process. Jiang et al. [8] found an optimal heating/cooling strategy to achieve a uniform temperature distribution along the radius of a cylinder in a relatively short time in the semi-solid forming of a A356 aluminum alloy. Park et al. [9] derived an optimum processing condition to minimize the grain size and solid fraction, as well as to maximize the average specimen temperature in the A356. Berrado and Rassili [10] determined the suitable operating conditions of the thixoforming process.

In this study, the effects of pouring and mold temperature, cooling slope, and length on the microstructure of the A356 aluminum alloy is investigated and the best parameters are selected to minimize the grain size. The A356 aluminum alloy is chosen because it has numerous benefits such as excellent cast ability, wear and corrosion resistance, and good weldability.

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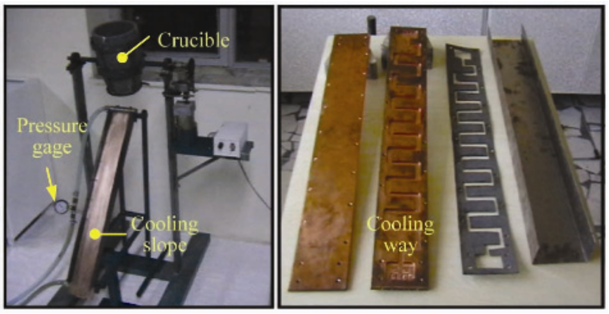
Table 1. Chemical composition of A356 aluminum alloy.

Al	Si	Mg	Fe	Ti	Cu	Mn	Other
92.14	7.10	0.33	0.17	0.10	0.06	0.03	< 0.08

Table 2. Range of input parameters of SSM process.

Parameter	Values
Pouring temperature (°C)	615, 625, 650, 680
Cooling length (mm)	300, 400, 500, 600, 700
Cooling slope (degree)	30, 40, 50, 60
Mold temperature (°C)	25, 200, 400



(a) (b)

Fig. 1. (a) Cooling slope casting apparatus used in this study; (b) coil water way devised between two copper plates.

2. Experimental procedure

The chemical composition of A356 aluminum alloy used in this study is presented in Table 1. To conduct experiments, 2.5 kg of A356 alloy was melted in a silicon carbide crucible located at a resistance furnace. Then, the molten alloy was allowed to cool down to the pouring temperature, and was then poured on to the surface of a cooling plate 100 mm wide and with a maximum length of 700 mm (Fig. 1).

The cooling plate was adjusted at the different cooling lengths and cooling slopes (with respect to the horizontal plane) as listed in Table 2. Also, various molds and pouring temperatures were employed in the experiments (Table 2). The range of pouring temperatures have been selected based on the fact that temperatures lower than 615°C present a possibility of uncontrollable solidification of the flowing melt on the cooling slope and also temperatures higher than 680°C produce an insufficient fraction of solid phase. Also, a maximum mold temperature of 400°C has been selected based on experimental limitations.

The cooling system included a water tank, a water pump, a pressure indicator, and a coil water way devised between two copper plates in which the volume of water is 40 liters and the primary temperature is 18°C, which was set in the water tank, was pumped, and circulated with the fixed pressure of 1 bar in the coil way (Fig. 1(b)). The surface of the cooling slope was then coated with a thin layer of zirconium oxide to prevent sticking of the molten alloy. The melt, which has become semi-solid by the end of the cooling slope, filled the mold and was cooled down in an atmospheric condition.

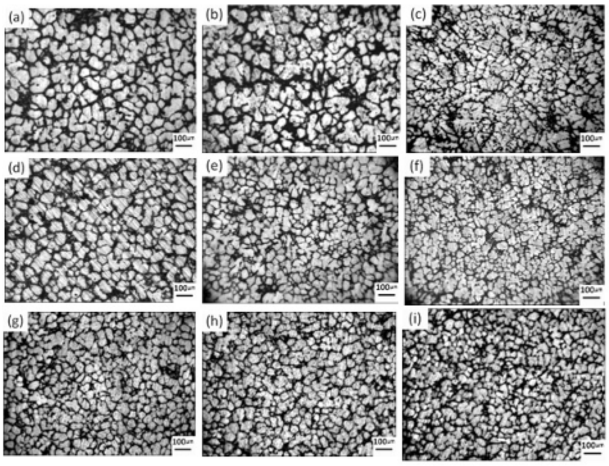


Fig. 2. Microstructures of ingots cast over the cooling slope with mold temperature of 25°C and the following pouring temperature values: (a) 650°C in the center zone; (b) 650°C in the middle zone; (c) 650°C in the wall zone; (d) 625°C in the center zone; (e) 625°C in the middle zone; (f) 625°C in the wall zone; (g) 615°C in the center zone; (h) 615°C in the middle zone; (i) 615°C in the wall zone.

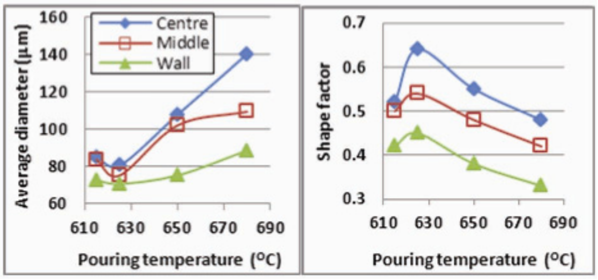
After finishing, the ingots obtained are sectioned transversely from the top, middle, and bottom sections of the solidified ingots. Then, the locations of the images are described as the center, the middle, and wall zones. These samples were etched with a 0.5% HF solution before they were examined with an optical microscope. To calculate the size and sphericity of the primary solid phase, the average diameter and shape factor was measured for a minimum of 400 grains for a sample by using Material Plus 4.1 image analyzer software.

3. Results and discussion

3.1 Effect of pouring temperature

Fig. 2 shows the microstructure of samples cast over the cooling slope with pouring temperatures of 650, 625, and 615°C, and a mold temperature of 25°C. Except for a rather thin wall zone, the change in the microstructural features of the parent alloy upon CS casting is highly evident. The primary phase morphology has transformed completely into a non-dendritic at the center of the ingots (Figs. 2(a), (d), and (g)). This outstanding change in the primary phase morphology is the consequence of a lower pouring temperature of the melt that leads to a higher number of solid particles and a fraction of the solid phase formed in the flowing melt over the surface.

Fig. 3 shows the effect of the pouring temperature on the average diameter and shape factors of primary solid particles, respectively. The change in the average diameter in the center and middle zones of the ingot is extremely obvious. With a change in the pouring temperature in the center zone, it varies from (~ 141 μm) for a pouring temperature of 680°C to (~ 81 μm) for a pouring temperature of 625°C. The shape factor in



(a) (b)

Fig. 3. Effect of pouring temperature on (a) average grain diameter; (b) shape factor (mould temperature = 25°C).

the center of the ingot varies between 0.48 for a pouring temperature of 680°C (i.e., predominantly dendritic) and 0.64 for 625°C.

The transformation from the rosette to nearly globular morphologies through the degeneration of the dendritic structure apparently does not advance when the pouring temperature is decreased to lower than 625°C. The primary phase morphology, which is nearly globular at the center zone, was observed at a pouring temperature of 625°C and replaced by larger primary α-Alparticles (~85 µm) with the lower shape factor (~0.52) at a pouring temperature of 615°C. On the surface of the ingot, low superheat gave a much finer microstructure compared to higher pouring temperatures (72 versus 91.7 µm). The shape factor is always low (between 0.33 and 0.42) at the wall zone of the ingots and the structure is dendritic.

The degeneration of the dendritic structure and refinement in the morphology of the primary α-Al phase in the CS-cast ingots is a result of the fractional solidification that occurs on the cooling slope. When the molten alloy with a suitable pouring temperature is poured on to a cooling plate, its temperature drops quickly below the liquidus temperature. Primary α-Alcrystals are subsequently nucleated and detached from the cooling plate as a result of the shear stress applied by gravity force and melt flow. It is suspended in the flowing melt and collected at the bottom of the mold, and then finer and globular microstructure is produced. For the pouring temperature of 650°C and 680°C, a fraction of the solid phase results from the insufficient number of crystals nucleated and detached from the surface of the cooling plate to produce fine and spheroidal primary crystals. Moreover, the amount of molten alloy that was cast with high temperatures into the mold increased the sufficient heat that may be provided for remelting the negligible amount of solid particles distributed in the mold. The obtained microstructure exhibits rosettes and is nearly semi-globular in the center zone, with rosettes in the middle zone, and a dendritic character toward the wall zone. A decrease in pouring temperature to 625°C leads to a higher fractional solidification that occurs on the cooling plate, so it helps to increase the rate of nucleation and detachment of α-Al crystals. Consequently, degeneration of the dendritic structure advances and the microstructure is replaced by finer and nearly globular primary α-Alparticles.

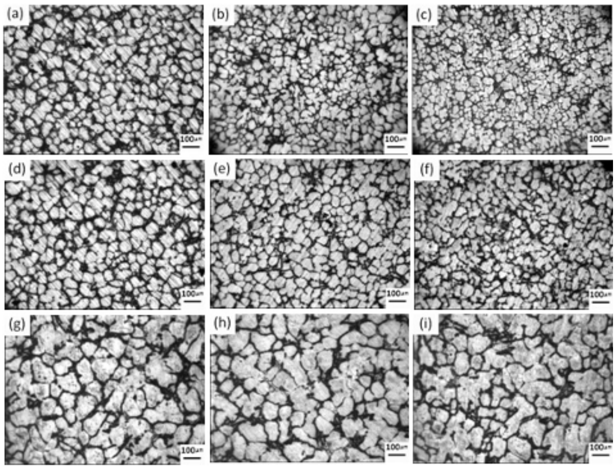
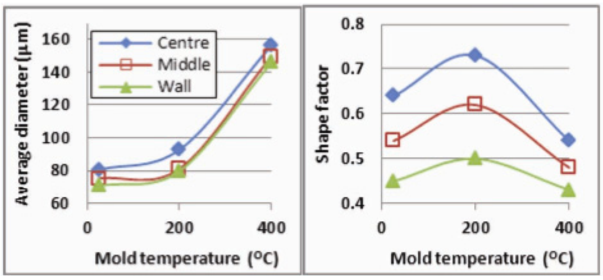


Fig. 4. Microstructures of ingots cast over the cooling slope with pouring temperature of 625°C and the following mold temperatures values: (a) 25°C in the center zone; (b) 25°C in the middle zone; (c) 25°C in the wall zone; (d) 200°C in the center zone; (e) 200°C in the middle zone; (f) 200°C in the wall zone; (g) 400°C in the center zone; (h) 400°C in the middle zone; (i) 400°C in the wall zone.



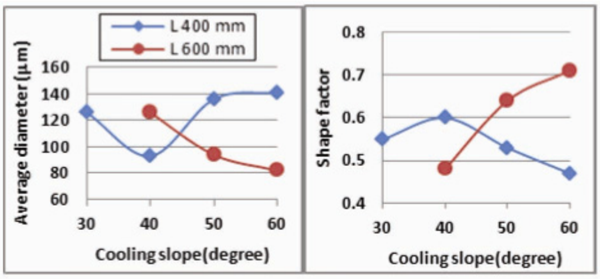
(a) (b)

Fig. 5. Effect of mold temperature on (a) average grain diameter; (b) shape factor (pouring temperature = 625°C).

3.2 Effect of mold temperature

Fig. 4 illustrates the microstructure obtained at different mold temperatures of 25, 200, and 400°C with the pouring temperature of 625°C. For the mold temperature of 25°C, a high cooling rate gave a small primary α-Al particle size in the center zone (~81 µm), middle zone (~75 µm), and wall zone (~71 µm) of the ingot (Figs. 4(a)-4(c)). Increasing the mold temperature up to 200°C results in larger primary α-Alparticles in the center zone (~88 µm), the middle zone (~80 µm), and the wall zone (~76 µm) of the ingot (Figs. 6(d)-6(f)). The shape factor has also improved the whole microstructure. Further increase in the mold temperature from 200 to 400°C cannot create better refined and globular microstructures, because the size of α-Al particles increases and the shape factor decreases again. Fig. 5 shows the effect of mold temperature on average diameter and shape factor of primary α-Alparticles.

The cooling rate is considered as a key parameter in the so-



(a) (b)

Fig. 6. Effect of cooling slope on (a) average grain diameter; (b) shape factor (pouring temperature = 625°C).

lidification of casting parts. Various rates of solidification can lead to change in the microstructure, grain size, morphology of eutectic phases, distance between dendrite arms, and intermetallic phases. At the mold temperature of 25°C, the time for appropriate displacement and configuration of primary solid particles was insufficient because of the high heat gradient and fast solidification of melt. Therefore, the morphologies obtained were not homogeneous.

Through the increase in the mold temperature up to 200°C, solidification rate was reduced at the lower heat gradient compared with the previous one. Therefore, the diffusion ripening and possibility of displacement advanced further and with a lower segregation rate of the eutectic phase. Thus, the globular and larger α-Al particles with the appropriate distribution were obtained. Further increase in the mold temperature of up to 400°C decreased the solidification speed of the eutectic phase but increased its ripening. Moreover, the appropriate opportunity was provided for the diffusion and transformation of primary α-Al phase, which led to an increasing grain size and decreasing shape factor. Therefore, in this paper, the mold temperature of 200°C is considered as the optimum value.

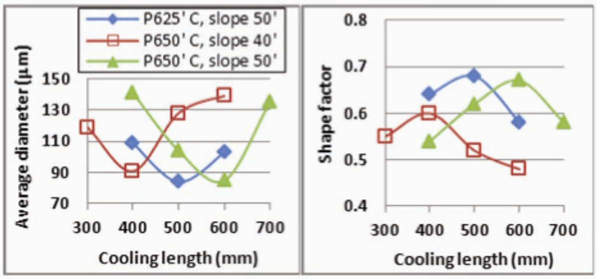
3.3 Effect of cooling slope

Fig. 6 shows the effect of cooling slope on average grain diameter and shape factors. When the cooling length is 400 mm, and by increasing its temperature from 30° to 40°, the shear stress and melt flow rate increases and causes it to crash the dendrite arms and clash more to each other. Therefore, grain size and shape factor is modified by approximately 10%.

More increase in cooling slope temperature from 40° to 60° reduces the time of the shear stress applied; thus, grain size increases and shape factor decreases.

When the cooling length is 600 mm and the cooling slope temperature is 40°, the contact time of melt and cooling surface is high, solid fraction increases, and agglomeration occurs. Therefore, the average grain size is high and the shape factor is low. By increasing the cooling slope, the shear stress and melt flow rate increases and improves the microstructure.

As shown in Fig. 6, optimum values should be selected for the cooling slope and length to optimize the SSM process.



(a) (b)

Fig. 7. Effect of cooling length on (a) average grain diameter; (b) shape factor.

3.4 Effect of cooling length

Fig. 7 illustrates the effect of cooling length on average grain size and shape factor. Pouring length affects the microstructure by changing the flow time of the slurry on the cooling plate. These changes the shear rate exerted to the slurry and the temperature of the slurry at the end of the cooling slope. As shown in Fig. 7, the best microstructure is achieved with a pouring length of 400 mm. By increasing the pouring length from 300 mm to 400 mm, the number of solid particles detached from the surface of the plate increases. Thus, more primary solid particles are formed, which makes the particle diameter decrease from 118 μm to 91 μm and the shape factor increase from 0.55 to 0.6. Further increase in the pouring length up to 600 mm increases the particle diameter to 138 μm and makes the shape factor decrease to 0.48 because of high flow time of slurry on the plate; thus, the solidification rate on the cold plate increases so that the flow of slurry cannot detach the solid particles. Therefore, solid particles of the slurry adhere to the plate and the molten metal does not have contact with the cold plate and formation of new nucleuses does not occur. Increase in the duration time of flow may lead to an increase in the contact and agglomeration of solid particles. To observe the interactions of pouring length and tilt angle, we repeated these experiments with the same parameters but with a tilt angle of 50°. Increasing the tilt angle from 40° to 50° is the best morphology achieved with the pouring length of 600 mm. This result shows that the aforementioned theory is probably true because increasing the tilt angle increases the velocity of slurry on the plate, thereby causing the solid particles to adhere to the plate.

By increasing the cooling length to a special minimum value (such as 400, 500, or 600 mm), we can decrease the average grain size and the shape of the grains can be more spherical because of the increase in the shear stress applied.

The special value mentioned moves from 400 mm to 600 mm in different conditions because of the selection of slope or pouring temperatures, which increases the shear stress applied.

3.5 Neural network design

Modeling of the SSM process with a back-propagation neural network (BPNN) is composed of three stages: training, validation, and testing.

The data consist of values for the parameters of pouring temperature (pt), cooling slope (cs), and cooling length (cl), as well as the corresponding grain size in the center zone. In this study, the mold temperature is constant (200°C) as mentioned in section 3.2. A total of 37 data sets (approximately 70% of all data) were selected randomly and used for the training process, 8 data sets (approximately 15% of all data) were used to validate the network and to stop training before overfitting, and the remaining 8 data sets were used to test the predictive accuracy of the trained and verified model. To correlate the process parameters to the grain size, a BPNN model was used with three inputs (pouring temperature, mold temperature, and cooling slope) and one output (grain size). To determine the number of the hidden nodes in the network, several BP networks with various hidden nodes (max to 8 nodes) are considered and the corresponding mean square errors (MSE) are calculated by

$$MSE = \frac{1}{M}\sum_{i=1}^{M}(t_k - a_k)^2 \qquad (1)$$

where M is the total number of training patterns, t_k is the target value, and a_k is the network output value.

Training of the different architectures was conducted using the Matlab R2011 software. The results indicated that a single hidden layer BPNN with six neurons and Levenberg-Marquardt training algorithm can provide an MSE of 0.00025, 0.00079, and 0.00076 for training, validation, and test, respectively.

This network also provides R > 99% in training, R > 98% in validation, and R > 99% in the test process. The training, validation, and test results are presented in Fig. 8. This figure shows that the model provides good results and the best prediction, which is reflected by an extremely high value of 0.99 of the correlation coefficient and the low value of MSE. Therefore, the network of (3-6-1) has the best result.

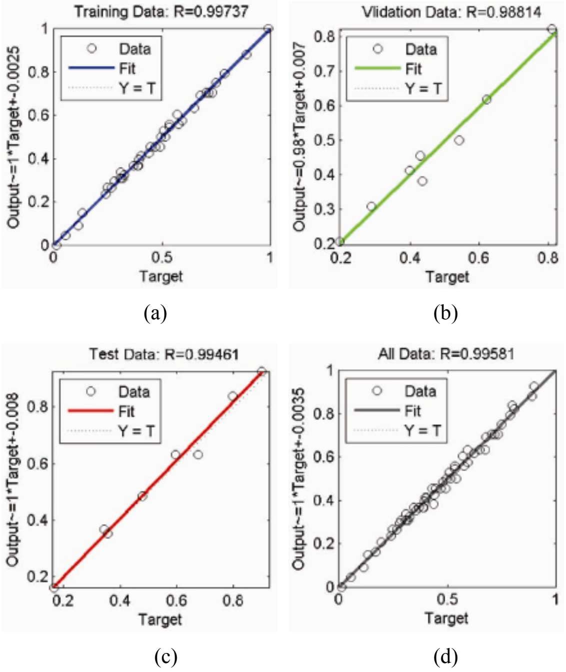
3.6 Optimization of the SSM process

Now, the BPNN model is used to determine a set of optimal SSM process parameters. In the current case of optimization of the SSM process, the cost function to be minimized is the BPNN, which predicts the grain size. The required constraints are 615 < pt < 680, 30 < cs < 60, and 300 < cl < 700.

The GA [11] starts with an initial point in the input space. To find global optimum solutions, the optimization process should be repeated several times with different starting points to fully assure that the obtained point is globally optimal. Among all of the possibly obtained candidates of optimal input parameters, the setting that provides the lowest grain size and meets the constraint requirements is selected as the global optimum point in the SSM process. To optimize the present problem and to obtain optimal solutions with less computational effort, the GA parameters are listed in Table 3. Fig. 9 shows the objective function (grain size) versus iteration number. In the figure, the minimum value of 78.0734 has been achieved for grain size at an iteration number of 44. Total time of the optimization process for 50 iterations was 1.5 minutes. The optimal inputs corresponding to the minimum value of the grain size are reported in Table 4.

Table 3. Parameters of GA that led to the best result.

Parameter	Value	Elaboration
Population size	100	100 random starting point (pt, cs, cl) as binary values which 615 < pt < 680, 30 < cs < 60 and 300 < cl < 700
Crossover fraction	0.85	New input parameter will contain 85% of old inputs.
Mutation rate	0.01	1% of bits in each input parameter are inverted randomly to prevent the algorithm from being trapped in a local minimum.
Migration fraction	0.2	20% of individuals are migrated (migration sent the best individuals in each population to each neighbor, replacing the worst individuals).
Migration interval	20	Migration occurs after 20 iterations.
Generations	50	50 iterations
Function tolerance	1.00E-06	Stop criteria



(a) (b)

(c) (d)

Fig. 8. BPNN predicted versus measured values.

Also, Fig. 10 indicates the center zone of the microstructure of A365 in optimal conditions (and mold temperature 200°C), which has an average grain size of 78 micron.

Table 4. Optimal results generated by GA.

Inputs			Output
Pouring temperature (°C)	Cooling slope (degree)	Cooling length (mm)	Grain size (micron)
630.0044	59.99529	494.602	78.0734

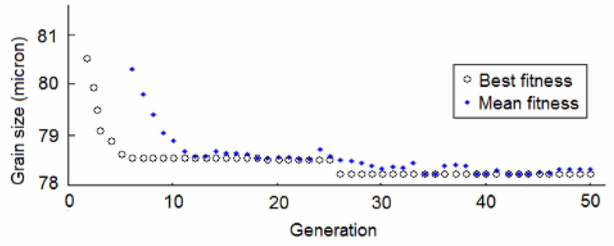


Fig. 9. Fitness value (grain size) versus iteration number.

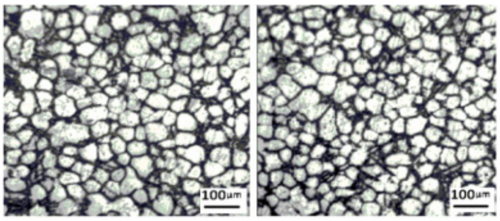


Fig. 10. Optimal microstructure of A356 in two different point of center zone.

4. Conclusions

The dendritic primary phase in the microstructure of conventionally cast alloy readily changes to a fine and non-dendritic structure by applying copper-made cooling slope. The microstructure produced by the cooling slope depends on the pouring and mold temperatures. An optimum pouring temperature was observed in which minimum grain size and maximum sphericity were created at a constant angle and length. Increasing the mold temperature up to 200°C causes globularity and appropriate distribution of α-Alparticles. When the mold temperature increases up to 400°C, the globules of the α-Al phase become extremely large compared with the microstructures of ingots produced with the mold temperature of 25°C and 200°C. These particles are not globular and the shape factor also decreases. The proposed neural network can predict the average grain size as well. A verification test has shown that the optimal values provide the best microstructure.

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