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RESEARCH ARTICLE - MECHANICAL ENGINEERING

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Effects of Low-Frequency Mechanical Vibration and Casting Temperatures on Microstructure of Semisolid $AlSi_8Cu_3Fe$ Alloy

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Abstract This paper is concerned with the influence of vibration on the cooling slope casting and gravity casting. Mechanical vibration during cooling slope casting is a new technique. Also isothermal holding period of hypoeutectic Al–Si alloy to prepare semisolid slurry has been studied. The convection caused by the vibration during solidification had remarkable effects on the formation of spherical α-Al particles. The main vibration effects include evolution and increase of nucleation and thus reducing as-cast grain size; globularization of particles and production of a more homogenous metal structure. In this work, mechanical mould vibration and mechanical-inclined plate vibration was applied to an $AlSi_8Cu_3Fe$ alloy at fixed frequency. Metallographic examinations and grain analysis were done on specimens obtained with different pouring temperatures and casting methods. The α-Al particles were spherical in cooling slope casting under vibration, as compared with cooling slope casting without vibration and gravity casting with vibration. A grain analysis along with different casting techniques was performed in order to understand the vibration effect. A heat-transfer mechanism seems responsible for the vibration effect in grain formation.

Keywords Semisolid processing · Non-dendritic structure · Vibration

الخلاصة

تُعنى هذه الورقة العلمية بتأثير الاهتزاز على منحدر تبريد الصب وجاذبية الصب. إن الاهتزاز الميكانيكي في أثناء منحدر تبريد الصب هو أسلوب جديد. وقد درست أيضا فترة المسك المتحاور لسبيكة ألمنيوم-سيليكون ذات قصور في سهولة الانصهار لإعداد طين شبه صلب. وكان للحمل الحراري الناجم عن الاهتزاز خلال الترسيخ آثار ملحوظة على تشكيل جسيمات ألمنيوم α. وتتضمن تأثيرات الاهتزاز الرئيسي تطور وزيادة التنوي، وبالتالي الحد من حجم الحبوب المصبوبة وتكوير الجزيئات وإنتاج هيكل معدني أكثر تجانسا. وفي هذا العمل تم تطبيق قالب الاهتزازات الميكانيكية و اهتزاز اللوح المائل الميكانيكي على سبيكة AlSi8Cu3Fe في تردد ثابت. وقد أجريت فحوص جغرافية المعدن وتحليل الحبوب للعينات التي تم الحصول عليها عند درجات حرارة صب مختلفة وطرق الصب. وكانت جسيمات ألمنيوم α كروية في منحدر تبريد الصب تحت الاهتزاز بالمقارنة مع منحدر تبريد صب من دون اهتزاز الصب وجاذبية صب مع اهتزاز. وقد أجري تحليل الحبوب جنبا إلى جنب مع تقنيات الصب المختلفة من أجل فهم تأثير الإهتزاز. وتبدو آلية نقل الحرارة مسؤولة عن تأثير الاهتزاز في تكوين الحبوب.

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1 Introduction

Semisolid metal processing, compared with conventional casting methods in the near-net shape is believed to be a promising technology. The semisolid metal processing composes solid–liquid slurries. These solid–liquid slurries have been formed under axial forces between dies. The process is called thixoforming. Semisolid slurries exhibit a rheological behaviors and this is thixotropy. Size and morphology of solid particles in semisolid slurries have the strongest effects on rheological behavior of semisolid slurries [1–3]. According to semisolid metal forming, resistance to flow in semisolid slurries containing solid particles with dendrite morphology, when it is sheared during forming into die, is higher than semisolid slurries containing solid particles with rosette or spherical morphology in a constant solid fraction. On the contrary, semisolid slurries containing globular particles easily flow during thixoforming [3,4]. These semisolid slurries with fine and globular solid particles have been assigned as thixotropic microstructures.

The cooling slope casting is used to produce ingots for thixoforming. Cooling slope casting is a very simple process. The primary crystal of the ingots obtained from the cooling slope has been reported to become spherical after being maintained in the semisolid state [5].

$AlSi_8Cu_3Fe$ alloy was studied in this paper. $AlSi_8Cu_3Fe$ alloy has close eutectic composition including relatively higher Si from A356 and A357 alloys. It has good fluidity, pressure strength, hot cracking resistance, good mechanical properties and is used to produce various automotive components such as airbrake castings, gear boxes and air cooled cylinder heads. Thixoforming of the alloy in semisolid state can highly remove existent problems in die casting process and thus offers many advantages such as low-pouring temperature, long mould life, low porosity etc.

The cooling slope casting process under vibration offers various advantages compared to the stationary cooling slope casting. It is a suitable and low-cost process to prepare ingots with high quality. Microstructures of ingots prepared in the process are quite fine. When the casting is performed on the stationary-inclined plate some remnant material on the surface can occur in spite of coated to the surface. However, this remnant material can efficiently be avoided when the casting is performed under vibration. Finally, this process includes dynamical solidification behaviors and microstructure formation mechanisms [6]. For the thixoforming process, the ingot must be reheated into the semisolid range. The microstructure of ingot and the reheating process is very important in forming process of an ingot. In this work, the globularization of $AlSi_8Cu_3Fe$ alloy microstructure obtained from cooling slope casting and cooling slope casting under vibration, the effects of the reheating temperature were investigated. This method was compared with gravity casting. The vibration has an effect on the solidification of the casting fragmentation of the growing grains. Therefore, it has been used successively for pure metals and alloys [7]. Dendrite arms are detached by the effects of vibration during casting [8]. In this study, low frequency was tested to the cooling plate. The effect of high frequency will be investigated in the future.

2 Experimental Methods

In this work, semisolid thixoformability of $AlSi_8Cu_3Fe$ aluminum alloys was investigated. The chemical composition of $AlSi_8Cu_3Fe$ alloy is shown in Table 1.

The melting range and solid fraction against temperature of $AlSi_8Cu_3Fe$ alloy was determined by differential scanning calorimetry (DSC) technique. DSC tests were used to determine amplitude of phase transformation during heating. All of DSC works were carried out on Seteram DTA–DSC device in Tubitak-Mam. Temperature and heat flow (exothermic effect) diagram during solidification obtained from DSC works is shown in Fig. 1. Solid fraction (%)–temperature (°C) diagram of $AlSi_8Cu_3Fe$ alloy was evaluated from DSC diagram and shown in Fig. 2. With reference to, the liquidus temperature is estimated from the DSC data to be 582 °C (Fig. 2).

Cooling slope casting under vibration method was developed by applying vibration to the inclined plate in cooling slope casting. In this method, the castings were realized by integrated vibration unit to cooling slope casting (Fig. 3). The frequency of vibration applied in the inclined plate is 5.75 Hz. The melt pouring from

Table 1 Chemical composition of $AlSi_8Cu_3Fe$ alloy using in this work (%)

Si	Fe	Cu	Mn	Mo	Zn	Cr	Ni
8.163	0.972	2.987	0.170	0.144	0.737	0.0181	0.196

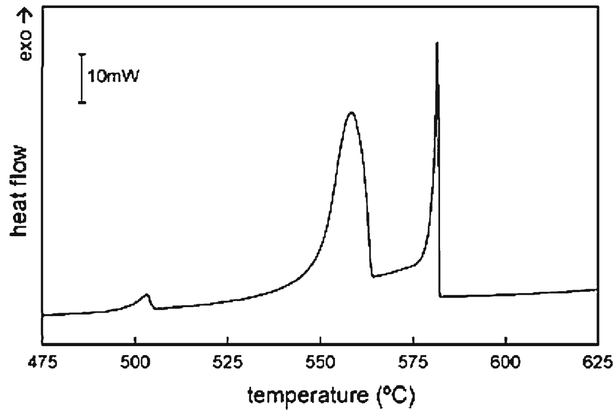

Fig. 1 DSC curve of $AlSi_8Cu_3Fe$ alloy during solidification

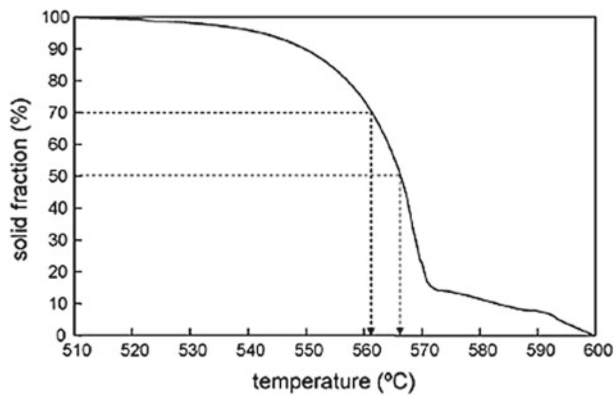

Fig. 2 Temperature curve of $AlSi_8Cu_3Fe$ alloy

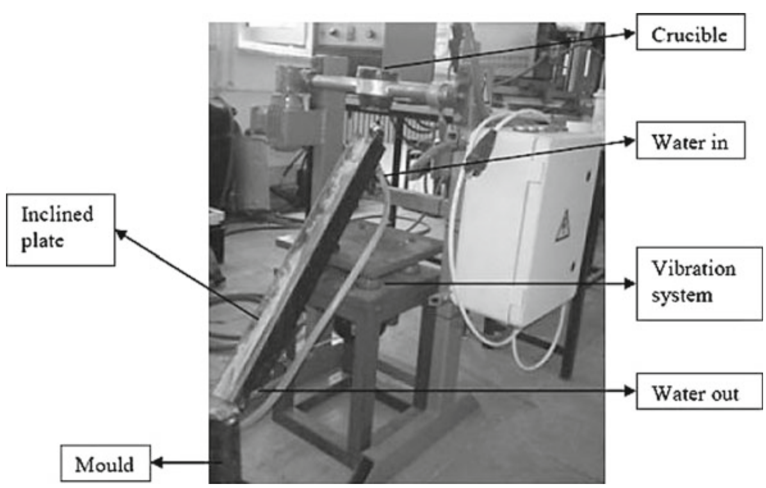

Fig. 3 Setup of the cooling slope casting under vibration

cooling slope under vibration was filled into the mold and the ingot cooled to room temperature. The frequency of vibration applying the mold during gravity casting is 5.75 Hz. The frequency of 5.75 Hz determined by an accelerometer was same for all experiments.

The parameters of cooling slope casting are shown in Table 2. The castings are carried out at three different pouring temperatures of 615, 630, 650 °C as low-, middle- and high-pouring temperature to determine optimum pouring temperature. The castings were performed cooling slope with angle of 60° and contact length

Table 2 Parameters of cooling slope casting

Specimen	$AlSi_8Cu_3Fe$ (A380)
Pouring temperature (°C)	615, 630, 650
Inclined plate	
Material	Mild steel
Coating	BN
Angle (°)	60
Length (mm)	500
Mold	AISI 4340 ($41CrNiMo_6$)
Vibration frequency (Hz)	5.75

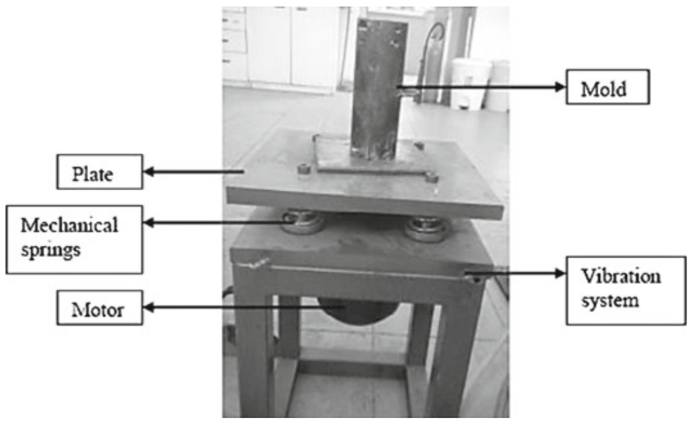

Fig. 4 Gravity casting under vibration

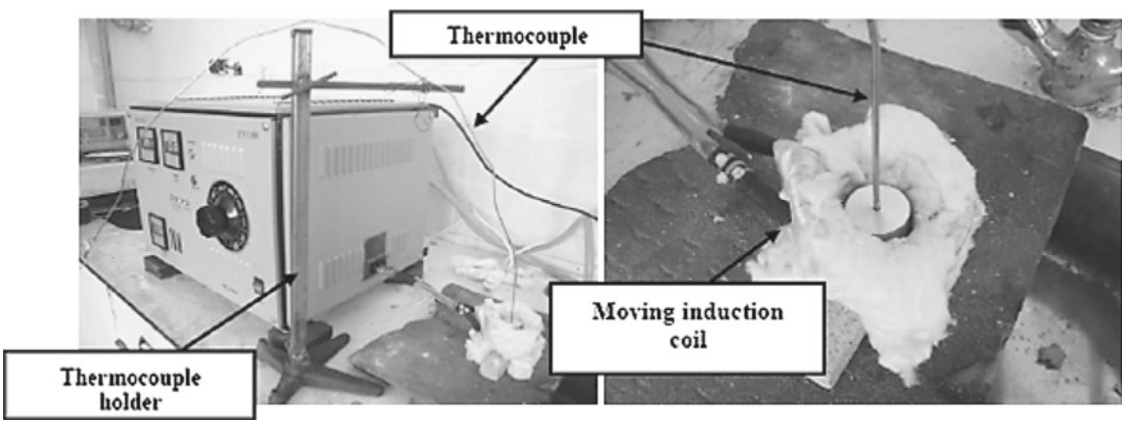

Fig. 5 Induction heating unit during

of 500 mm. The aluminum alloy was melted in a graphite crucible in a resistance furnace. 0.2 g of strontium is added as grain thinner within the alloy during melting. Because, it is well known that modification of commercial aluminum alloy by adding certain elements, such as calcium, sodium, strontium, and antimony, to hypoeutectic aluminum–silicon alloys results in a finer lamellar or fibrous eutectic network. Shabestari et al. noted that strontium addition not only refines silicon particles, but also changes the morphology of some intermetallic particles. Therefore, aluminum–silicon alloys are cast usually in the modified condition [9,10]. Immediately before casting, the flux is added into the melt. The flux removes the gas in the melt and allows cleaning of the impurities, and melt to the surface. The crucible is placed in the cooling slope experimental apparatus and the temperature control was provided with a K-type thermocouple. Melt in the crucible is poured to the plate-coated BN, turning of 90° in its own axis driven by the motor, when the casting temperature is reached to desired temperature. The melt was filled into the mould which was preheated to 200 °C by flowing along 500 mm from inclined plate of 60°.

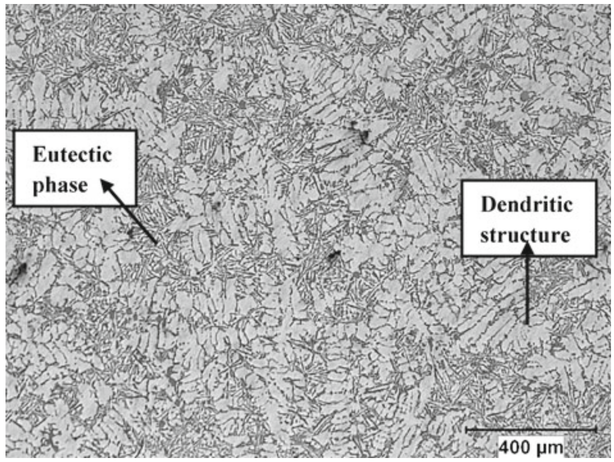

Fig. 6 The microstructure of $AlSi_8Cu_3Fe$ alloy obtained from gravity casting

The vibration was also applied in two different times of 5 and 10 min to the mold during gravity casting (Fig. 4). Gravity casting was carried out at 700 °C, so that $AlSi_8Cu_3Fe$ alloy reaches the casting temperature, used in casting industry.

The ingot of $AlSi_8Cu_3Fe$ alloy obtained from casting was machined to diameter of 30 mm and length of 40 mm. Thus, the ingot was adapted to induction heating coil. The ingot temperature was controlled during heating process. A hole in diameter of 3 mm to the center of ingot was machined and K-type thermocouple was placed in the hole to measure and exactly control the temperature of the slurry (Fig. 5).

Heating power to provide uniform liquid/solid fraction must be fully controlled. It was found that liquid/solid fraction of 40–50 % determined from DSC diagram can be obtained at 565 and 567 °C and the heating experiments was performed to optimize the values. Thermocouple was removed from the ingot and then the sample was left in water by lifting the moving coil.

Samples obtained from the experiments were prepared as metallographic. Polished samples were etched in 5 % HF solution. Microstructures were photographed with NIKON Ecilipse optical microscope supported by NIKON digital camera. The grain analyses were realized to microstructures with CLEMEX professional edition analysis program.

3 Results and Discussion

Figure 6 is shown the microstructure of specimen directly poured into the cylindrical mold without cooling slope: gravity casting. The microstructure contained coarse dendrites of α-Al phase.

The microstructure at constant cooling slope is shown in Fig. 7. As shown in Fig. 7, it is clearly seen that the dendrites are more broken at low temperature and rosette structure is completely consisted, moreover, the grains are very close to globular form, because nucleation will be more at the lower pouring temperature on water-cooled plate surface during cooling slope casting. It is also seen that the dendrite structure is almost broken at pouring temperature of 630 °C. However, when the pouring temperature is increased, both the grains are coarse and the dendrite structure is not properly broken. At the temperature of 650 °C, it was observed that the eutectic structure is more distinct and that grain conglomeration takes place. According to Birol, the temperature of melt is easily dispersed and the temperature quickly drops below the liquidus temperature when the molten alloy flows over the inclined plate. α-Al crystals nucleated on the cooling slope and are detached from the inclined plate, trapped in the flowing melt and are collected in the mold at the bottom before they develop to the dendrite arms [11].

The microstructures of the castings obtained from the inclined plate under vibration at the pouring temperatures of 615, 630 and 650 °C were shown in Fig. 8. As shown in Fig. 8, when the stationary-inclined plate and inclined plate with vibration are compared, it can be observed that the vibration is increased the nucleation amount. This case can be explained by the vibration during flowing from inclined plate of melt causing a more homogeny cooling, faster heat transfer and fragmentation of the solids [12].

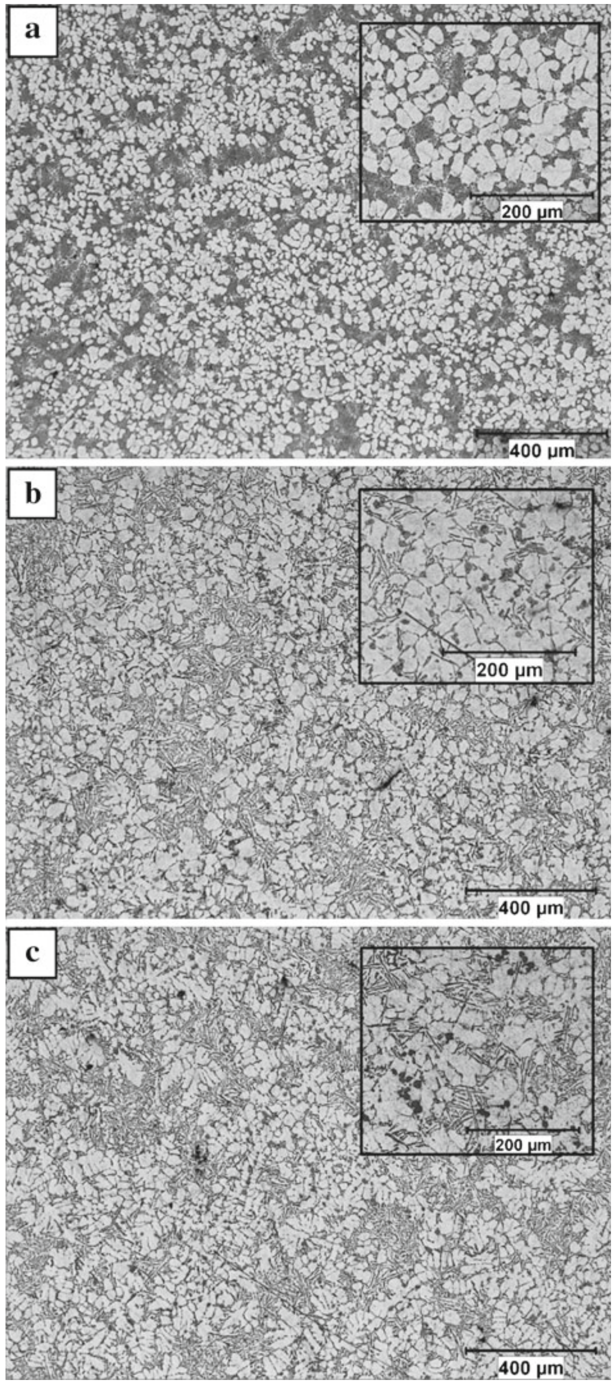

Fig. 7 The microstructures obtained from different pouring temperatures on the stationary cooling slope casting of $AlSi_8Cu_3Fe$ alloy; **a** 615 °C; **b** 630 °C; **c** 650 °C

Kocatepe et al. investigated the effects of vibration application in range of 15–41.7 Hz frequency to mold for Al–Si alloy. They found that the vibration decreased the solidification time of the casting. Solidification time had very important role on the microstructure of cast aluminum alloys. Solidification time reduction means an increase in cooling rate. This may be based on an increase of convection in the melt during nucleation. Primary Silicon particles nucleate on the surface of the plate and mold. According to Kocatepe [7], vibration brings about turbulence which causes waves on the surface. These waves may cause the particles to separate from the inclined plate surface the particles. Thus, a collision happens between the nucleus and this brings a

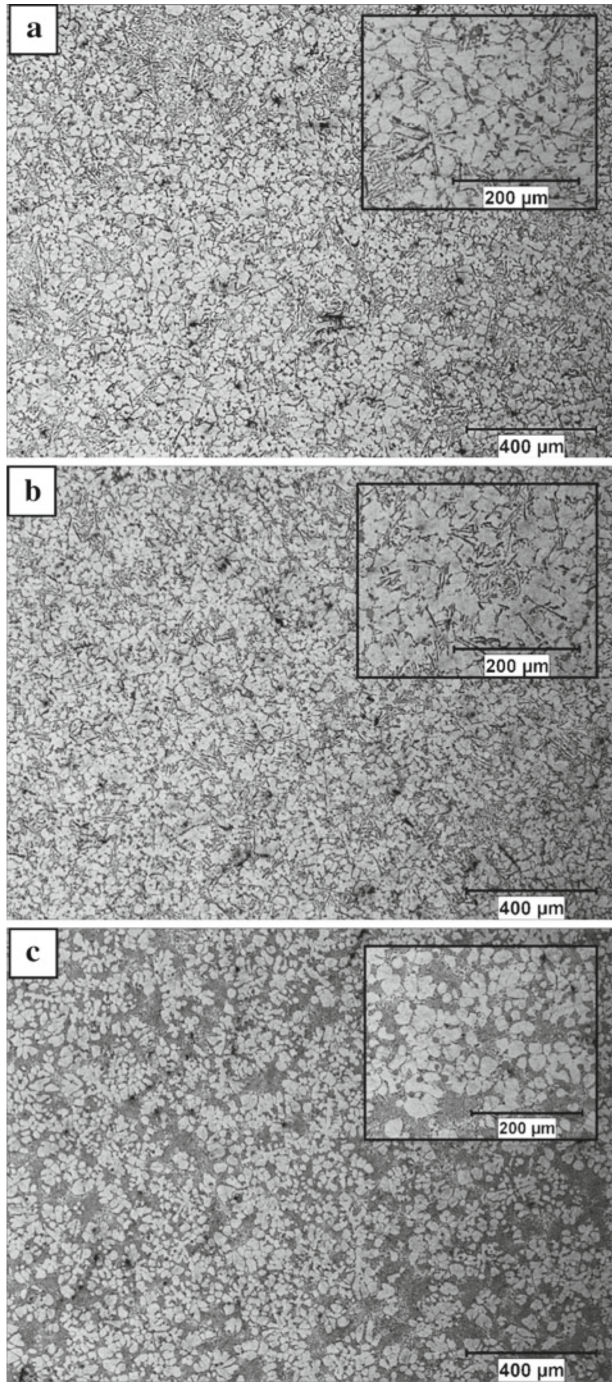

Fig. 8 The microstructures obtained from different pouring temperatures on the cooling slope casting under vibration of $AlSi_8Cu_3Fe$ alloy; **a** 615 °C; **b** 630 °C; **c** 650 °C

uniform heat transfer mechanism on the cooling slope between dynamic nucleuses. This process can increase to nucleation rate and give homogeny cooling. Finally, the combined effect of the shear stress during flow and the vibration caused more nucleation, thus the grain size reduced. Besides, to remove from solidification shell composed during stationary cooling slope casting was effectively possible owing to cooling slope casting under vibration. Taghavi et al. applied the mechanical vibrations to the direct mold in a range of 10–50 Hz. They determined that the effect of vibration is not significant at 10 Hz frequency. It can be concluded that

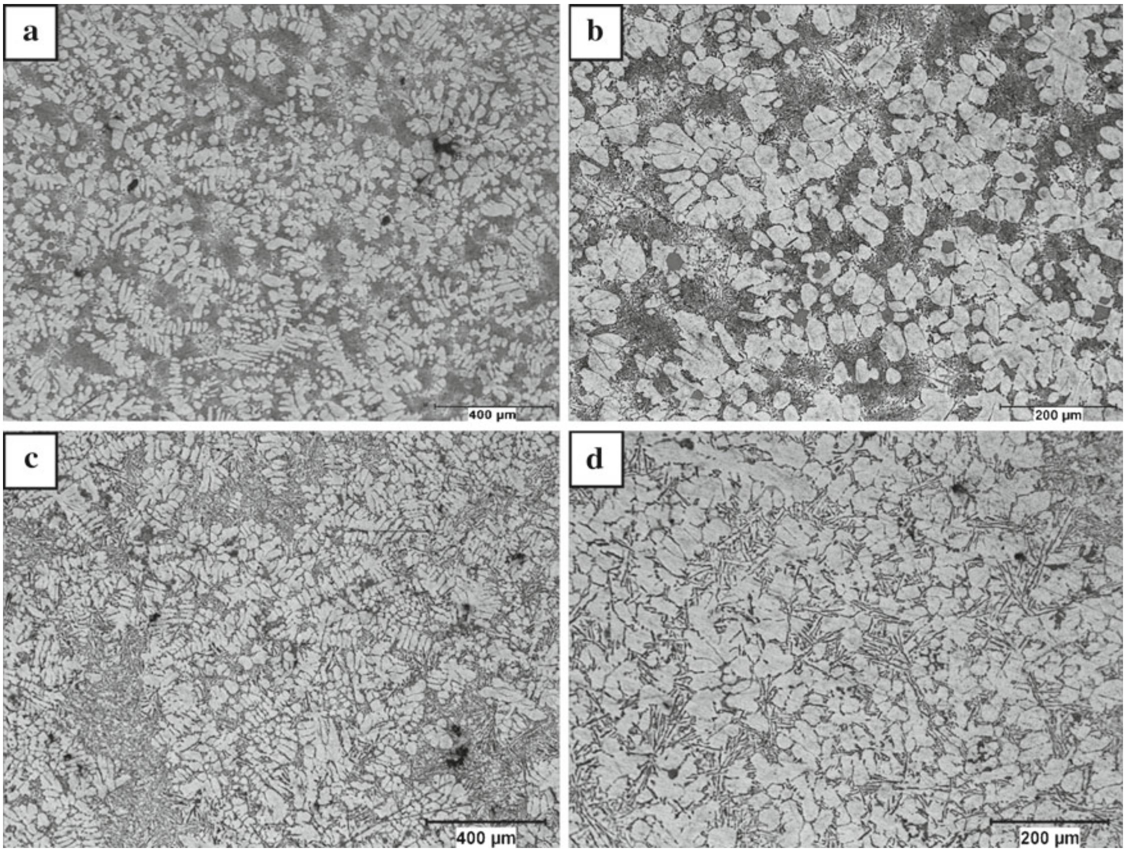

Fig. 9 The microstructures during gravity casting under vibration for **a**, **b** 5 min; **c**, **d** 10 min

low-frequency vibrations does not have enough effect for globularization, but it can improve the cooling slope effect [13].

Gravity casting was applied under vibration in two different times of 5 and 10 min to compare vibrations on cooling slope plate with direct mold (Fig. 9). When the vibration was applied to direct mold, it was examined that the dendrite arms were partially broken, however, they could not be left away from each other. The grain structure could not achieve an effective structure such as vibrated cooling slope casting. According to Fig. 9, when the vibration time increased, it is observed that the grains are agglomerated and not distributed uniformly. Moreover, when the vibration time increased, the eutectic structure of intergranular was more explicit. Taghavi et al. [13] noted that the viscous drag forces induced by vibration lead to detachment of dendrite arms. The dendrite arms detached during flow on the inclined plate are moved by the liquid and acted as the new sources for nucleus. When a dendrite arm is detached, detached arms encounter with the adjacent arms and lead to more detachment of dendrite arms.

The microstructure results obtained from cooled in water after holding at reheating temperature of 565 °C in the induction unit of the ingots are shown in Fig. 10. It was observed that the required liquid phase for thixoforming cannot be created enough at 565 °C. In Fig. 10, more grain has been formed owing to the effect of vibration; liquid phase cannot create a sufficient rate to fully surround the structure, even though, it can be understood that the grains are in a form closer to spherical particles with the effect of vibration.

While α-Al primary phase of $AlSi_8Cu_3Fe$ alloy existed as solid, almost the whole at 567 °C, eutectic structure melted. The specimens were held for 5 min isothermally at this temperature. The results of microstructure evolution are shown in Fig. 11. The rosette morphology of casting ingots is transformed to globular particles uniformly dispersed after reheating and holding isothermally.

According to Fig. 11, it can be observed that the grains in globular form and suitable liquid/solid fraction are obtained. However, more globular form was obtained especially at lower pouring temperatures with the vibration effect. It was determined that the grains exhibited tendency to aggregation at higher pouring temperature.

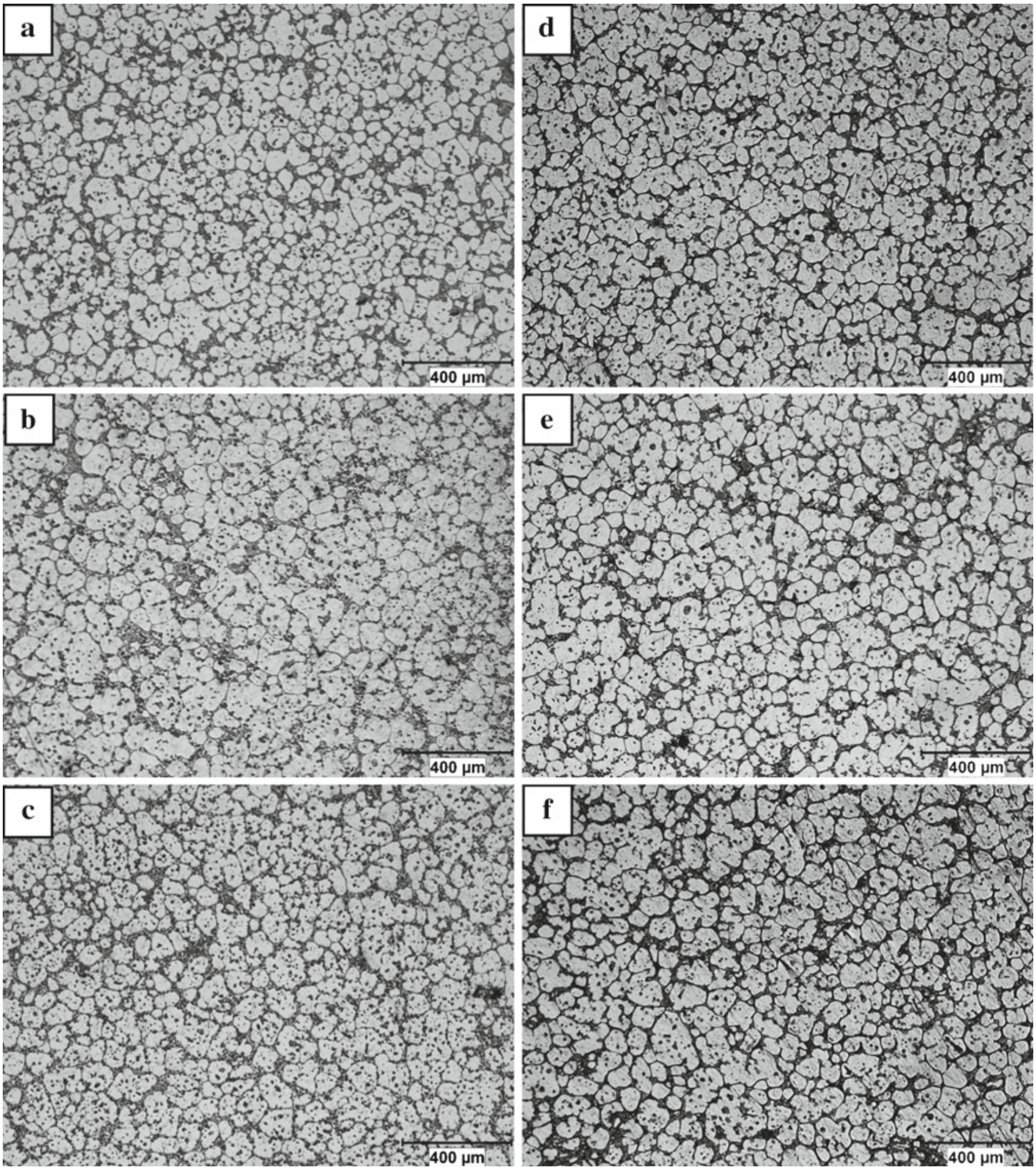

Fig. 10 The microstructures obtained from holding at 565 °C for 5 min of the ingots from stationary cooling slope casting: **a** 615 °C, **b** 630 °C, **c** 650 °C; the microstructures obtained from holding at 565 °C for 5 min of the ingots from cooling slope casting under vibration: **d** 615 °C, **e** 630 °C, **f** 650 °C

The grains obtained from gravity casting and gravity casting under vibration was also reheated to semisolid state. Thus, the importance of production of non-dendritic structure was understood before thixoforming. It appeared that the ingots produced by gravity casting were in semisolid state and there was no globularization at all (Fig. 12). Limmaneevichitr et al. [14] applied mold vibrations at 55 Hz frequency, they obtained globular microstructure after reheating, and thus they offered an alternative method for semisolid processing. In this study, the low-frequency vibration (5.75 Hz) to directly mold also did not produce globular microstructure.

The solid/liquid fractions in semisolid heating temperature and the sphericity of grains in globular form were acquired. Solid fraction diagram obtained from stationary cooling slope casting is shown in Fig. 13; solid fraction diagram obtained from cooling slope casting under vibration is shown in Fig. 14.

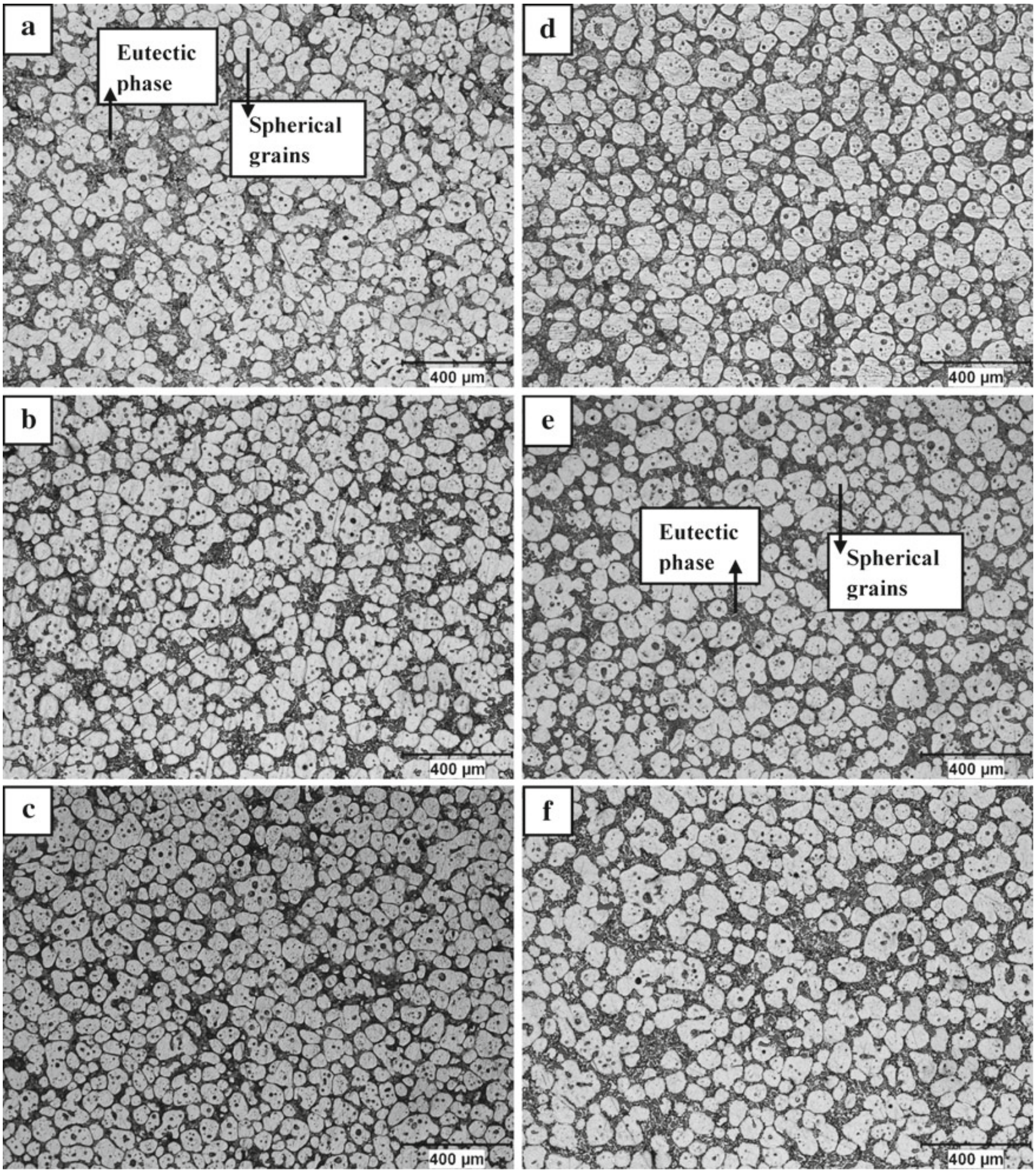

Fig. 11 The microstructures obtained from holding at 567 °C for 5 min of the ingots from stationary cooling slope casting: **a** 615 °C, **b** 630 °C, **c** 650 °C; the microstructures obtained from holding at 567 °C for 5 min of the ingots from cooling slope casting under vibration: **d** 615 °C, **e** 630 °C, **f** 650 °C

It is seen that more liquid fraction was obtained with isothermal holding in reheating temperature of 567 °C for 5 min (Fig. 13). The solid fraction was acquired about 0.4, 0.5 f_S value (solid fraction) which is suitable for thixoforming. The best value of solid fraction for thixoforming has reached with cooling slope casting under vibration in the pouring temperature of 615 °C and reheating temperature of 567 °C. As the casting temperature increased, more liquid phase occurred. Thus, less α-Al grains in the structure endured. However, this situation showed deviation in the isothermal heating of 567 °C in the ingot obtained from stationary cooling slope casting. Although the reduction of solid fraction is expected, it increased. This situation can be explained by microstructure. This parameter has occurred to keep the liquid inside grain. Therefore, formation of the liquid

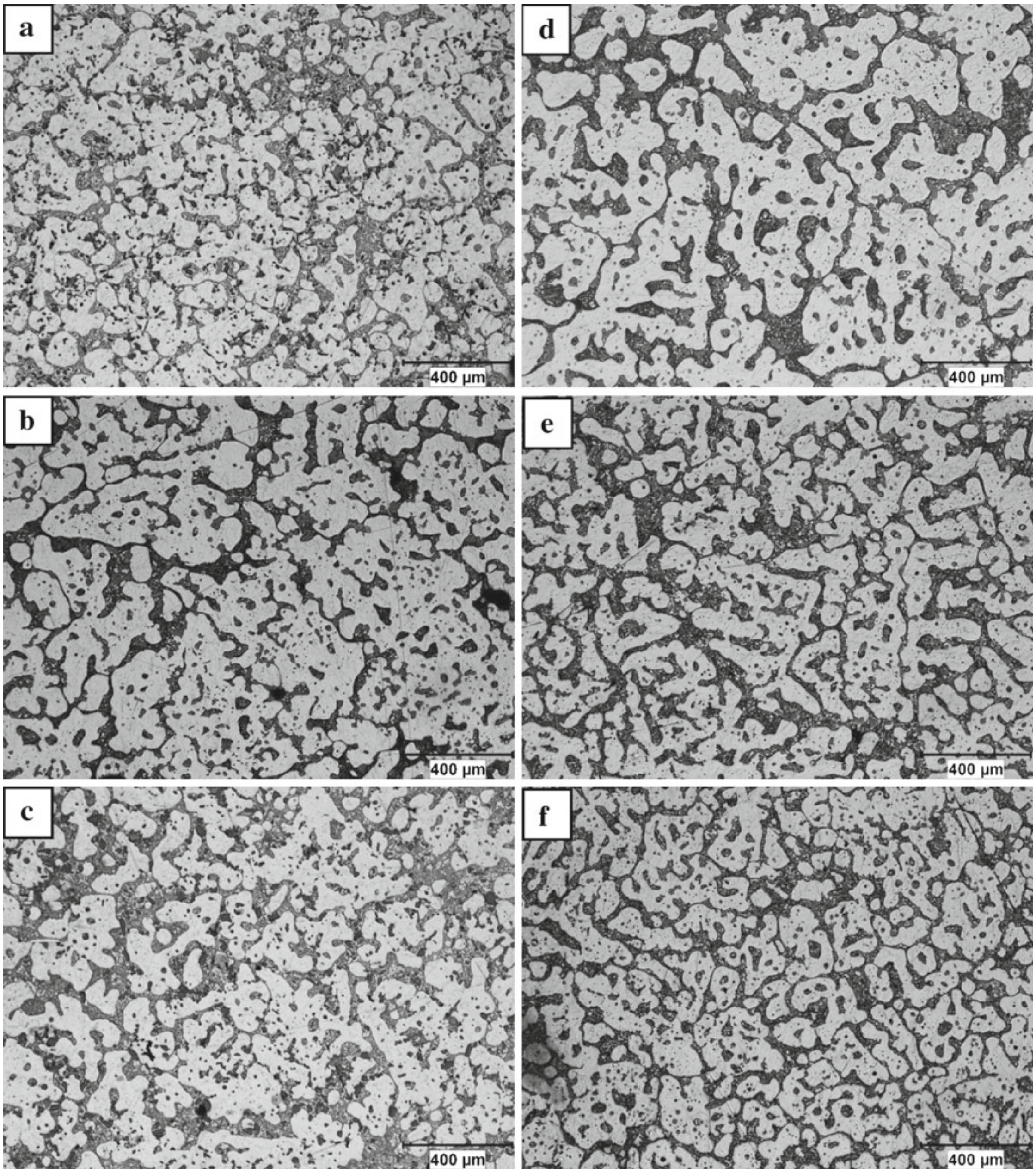

Fig. 12 The microstructures obtained from reheating of 565 °C (**a**), 567 °C (**b**) of gravity casting; the microstructures obtained from reheating of 565 °C (**c**), 567 °C (**d**) of gravity casting under vibration for 5 min; the microstructures obtained from reheating of 565 °C (**e**), 567 °C (**f**) of gravity casting for 10 min

phase is less in grain boundary, which is not required for thixoforming. This was not observed when vibration was applied because more uniform grain consisted with the effect of vibration.

Sphericity analysis was carried out for the determination of globularization during reheating. Accordingly, the diagram which shows the effect of isothermal process to sphericity of ingots obtained from different casting parameters is shown in Fig. 15. The best globular grain structure has been reached in reheating temperature of 567 °C on cooling slope casting under vibration in low-pouring temperature. It was clearly seen that much more globular grain structure is obtained from cooling slope casting under vibration. Globular grain form was attained by surrounding with liquid phase during semisolid heating; more uniform grains were separated in the structure and were exposed to more efficient shear stress during casting.

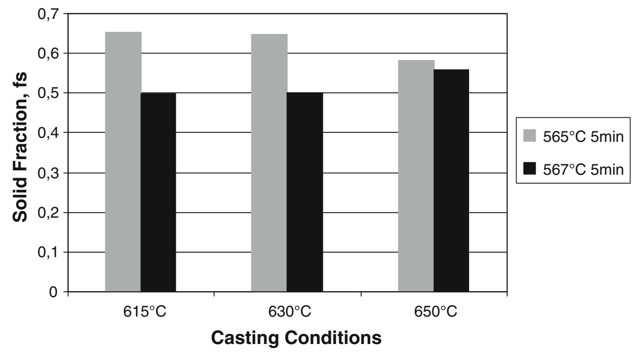

Fig. 13 The diagram of solid fraction obtained from reheating isothermally at semisolid temperatures against casting conditions on the stationary cooling slope casting

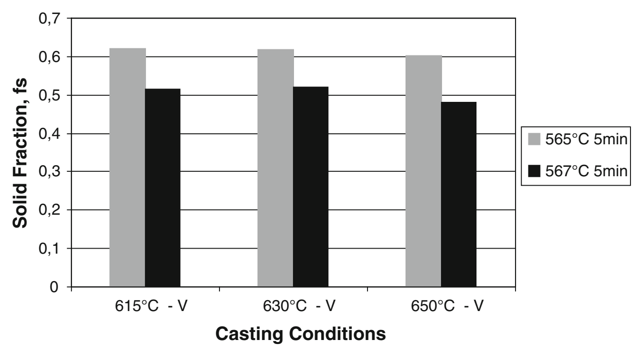

Fig. 14 The diagram of solid fraction obtained from reheating isothermally at semisolid temperatures against casting conditions on the cooling slope casting under vibration

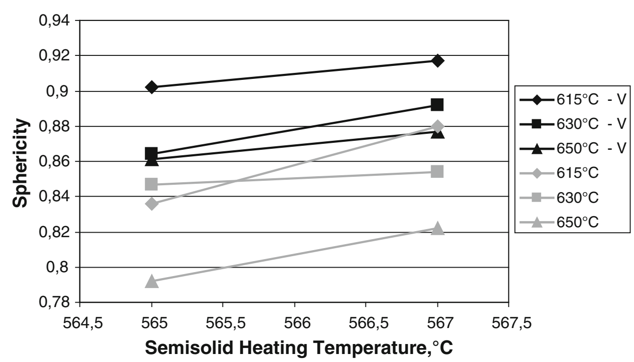

Fig. 15 The diagram of sphericity versus conditions of casting conditions when reheating of different temperatures

Table 3 Percentage of grains with ideal sphericity (in the range of 0.95–1)

Pouring temperature (°C)	Stationary-inclined plate Percentage of grains in the range of 0.95–1 sphericity	Vibrated-inclined plate Percentage of grains in the range of 0.95–1 sphericity
615	90.1	94.5
630	83.5	92.5
650	82.4	89

Also, it can be explained by more uniform grain structure occurring thanks to vibration by the grain analysis of sphericity. The results obtained from the analysis of sphericity are given in the Table 3. The percent of the grains in the range of the sphericity for 0.95 and 1 increased with the application of vibration. At the same time, the lower pouring temperature gives more sphericity.

4 Conclusions

The feedstock for thixoforming should have a non-dendritic microstructure that dispersed uniformly in liquid matrix of globular particles. Spherical grains constitute an extremely suitable microstructure for thixoforming because they do not show a high resistance against the shearing during thixoforming. The reduction of pouring temperature in specimens obtained from the cooling slope casting constituted the grains called rosette which are more non-denritic and equiaxed. The application of vibration to the inclined plate during cooling slope casting gave rise to more uniform grain formation. And this constitute a very important and efficient method for thixoforming process. The optimized pouring temperature, reheating and applied vibration were achieved on the inclined plate. The solid fraction and sphericity are functions of the reheating temperature, pouring temperature and casting method. The optimum conditions for thixoforming were achieved when the specimens were reheated at 567 °C and poured at 615 °C under vibration.

In this study, low-frequency mechanical vibrations were applied to the inclined plate. It was founded that mechanical vibrations at low frequency enhanced the globularization during cooling slope casting but it was not observed during gravity casting. It is well known that mechanical vibrations at high frequency can be proposed as an alternative method for formation of spherical grains. However, for the cooling slope casting, to achieve an ideal flow and temperature field in the melt on the inclined plate, the operating frequency has to be low.

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