Microstructure Investigation of Using Slope Plate Casting Hypereutectic Al-Si Alloy

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ABSTRACT

In this work, the effects of the overheating temperature and tilt angle on the microstructure and hardness of a hypereutectic Al-23%Si alloy were investigated. Al-23%Si melt was overheated to (760, 790, 820 and 850) ºC and poured onto slope plate continuously cooled with water circulation underneath, with various tilt angles (40, 50, 60)º using a constant cooling length (300 mm). After, the melt became a semi-solid; the slurry was then filled the mould and completely solidified. Slope plate samples were reheated to a semi-solid temperature (550)ºC for (10 min) and then quenched in water.

Microstructural images analysis showed that the grain size and the shape factor of (β-Si) phase were decreased with increasing of the overheating temperature and tilt angles, on other hand, the volume fraction of (β-Si) phase was increased. The results of the reheating route showed that the grain size of (β-Si) phase was slightly increased after reheating at all overheating temperatures and tilting angles. On other side, the shape factor was improved, and the volume fraction of (β-Si) phase was decreased, as compared with slope plate results.

Keywords: Slope platecasting, Hypereutectic Al-Si alloy,Reheating .

دراسة البنية المجهرية لسبيكة (Al–Si) فوق الايوتكتك باستخدام الصفيحة المائلة

الخلاصــة

تم دراسة تأثير كل من درجة حرارة الصب (الإفراط في التسخين) وزاوية ميلان الصفيحة (زاوية الصب) على البنية المجهرية لسبيكة فوق اليوتكتك (Al-23%Si)، إذ تم تسخين منصهر

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السبيكة إلى (٧٦٠، ٧٩٠، ٨٢٠، ٨٥٠) درجة مئوية وثم صبه على الصفيحة المائلة والمبردة بشكل مستمر باستخدام مجرى توزيع ماء باستخدام زوايا مختلفة هي (٤٠،٥٠،٦٠) درجة وبطول تبريد ثابت (٣٠٠ ملم)، وبعد أن يصبح المنصهر بشكل عجينة شبه صلبة عند نهاية الصفيحة المائلة يتم صبه في قالب معدني ليتجمد بشكل كامل ٠سخنت العينات المنتجة بطريقة السباكة بالصفيحة المائلة إلى درجة حرارة شبه الصلبة (٥٥٠) درجة مئوية لمدة (١٠) دقائق، ثم تبريدها بالماء.
أوضحت نتائج الفحص المجهري بأن كل من درجة حرارة الصب وزاوية الصب لها تأثير على الحجم الحبيبي والهيئة أو عامل الشكل لطور السليكون الأولي (β-Si) . كما أوضحت النتائج بأن قيم الحجم الحبيبي وعامل الشكل لطور السليكون الأولي (β-Si) تقل، وقيم الكسر الحجمي تزداد، مع زيادة درجة حرارة الإفراط بالتسخين وزاوية ميلان الصب. أوضحت نتائج الفحص المجهري بأن استخدام تقنية الصب باستخدام الصفيحة المائلة أدى إلى تقليل الحجم الحبيبي لطور السليكون الأولي مع زيادة درجة حرارة الصب وزاوية الميلان، بينما أظهرت نتائج إعادة تسخين العينات بأن الحجم الحبيبي لطور السليكون يتزايد قليلا بعد التسخين لجميع درجات الإفراط بالتسخين وزوايا الصب مع تحسن في شكل وتركيب هذا الطور.

INTRODUCTION

Hypereutectic Al–Si alloy are attractive for automotive industry and desirable for wear resistant applications, where high strength and low weight are required, also, due to attractive properties such as low density, high stiffness, good wear resistance, and low coefficient of thermal expansion. In conventional casting, the machinability and formability of hypereutectic Al–Si alloys is worse due to the presence of coarser primary silicon as various morphologies, i.e., it is detrimental to their strength and plasticity. The use of die cast hypereutectic Al–Si alloy has been restricted owing to its high latent heat and consequent long solidification time resulting in die wear, segregation and excessive growth of primary silicon particles, and unfavorable shrinkage behavior. Therefore, the finer primary silicon generally resulted in improved mechanical properties, such as toughness and ductility, consequently, increase the industrial applicability of hypereutectic Al–Si alloys **[1-3]**. Under normal cast condition, the primary silicon in hypereutectic Al–Si alloys exhibits a variety of morphologies, such as polygonal, star-like, coarser platelet, etc. Generally, the machinability of hypereutectic Al–Si alloys is worse due to the presence of coarser primary silicon i.e., coarse microstructures, inherent brittleness, and poor workability when conventional methods are applied to produce such alloys. The production of finer primary silicon is desirable in most castings of hypereutectic Al–Si alloys **[4]**.

Semi-solid metal processing presents a solution to the problems associated with both conventional casting and metalworking processes due to its capability to use temperatures lower than those used in casting and a less energy used in metalworking as conventional forging and extrusion processes. Therefore, the semi-solid metal processing has great advantages over than conventional techniques **[5, 6]**.

Cooling Slope technique is used by pouring the molten metal over an inclined plate or tube, so that the nucleation together with mixing occur during the flow of the liquid, thereby producing a fine and less dendritic primary microstructure **[7]**.

Semi-solid processing of Al-Si alloys using cooling plate method was reported in the literature **[8-10]**. Also, this method was stated as a suitable technique for high melting metals, such as gray cast iron and ductile iron **[11,12]**, where an improved structure of fine globular primary particles with a high degree of sphericity and phases clearly distinct from adjacent one was obtained.

The aim of this work is to study effect of Slope plate casting (SPC) on the microstructure of a hypereutectic Al-23%Si alloy (i.e., on refining and modification of primary Si phase).

EXPERIMENTAL WORK

Materials

The chemical composition of the hypereutectic Al-23%Si alloy used in this study is given in Table (1).

Procedure

The slope plate casting unit is shown in Figure (1). Figure (2) shows the schematic illustration casting procedure. It consists of three main components; flat slope plate continuous cooled with circulation underneath, steel crucible and steel permanent mould.

Cooling slope plate represents the essential component of slope plate casting unit, where the molten alloy was poured over a (40 mm wide and 550 mm long) flat plate. The plate is made from mild steel. The inclination of plate was set by using an angle scale fixed at the side of the slope plate.

The crucible is made from steel with dimensions, (height 13 cm × diameter 11.5 cm). The casting *mould* is made of AISI 1045 Steel to produce billets with dimensions, (length 100 mm × diameter 30 mm).

In this work, about 250 gram of the Al-23%Si alloy was charged in the steel crucible. It was then melted in an electric furnace. The melt was superheated at (100-150 ºC) over the liquids temperature (TL ≈ 740 ºC), which was estimated by the silicon weight percentage on the equilibrium phase diagram of binary Al-Si alloy **[13]**. The pouring temperatures were selected so as to limit the superheat of the melt, i.e., the melt was superheated at different pouring temperatures (760ºC, 790ºC, 820ºC and 850ºC), and they were investigated in this work. When the melt reached to this desired temperature the crucible was withdrawn from the furnace and fixed in a ring holder. A calibrated thermocouple type k (1200ºC) was inserted inside the crucible to determine the melt temperature, at which the pouring carried out. The molten alloy was poured onto (40 mm wide and 550 mm long) smooth flat cooling slope plate "chilled slope". The active cooling slope plate length was set at (300 mm). The process was done at different pouring angles (40, 50, 60)° with respect to the horizontal plane and cooled by water circulation underneath. The melt was then allowed to cool to the pouring temperature by water circulation underneath. The melt was poured sequentially at different pouring temperatures (760, 790, 820, and 850) °C with an inclination angle of plate.

After the melt was continuously cooled on the slope plate, it became semi-solid slurry at the end of cooling slope plate, prior to arriving in the mould. The slurry was then filled the permanent mould and completely solidified.

Partial Re Melting And Quenching

The slope plate casting specimens were reheated to a semi-solid temperature (550°C) **[13]**. These specimens were then soaked for (10 min) to allow spheroidization of the grains and then quenched in water.

Test and measurements

The slope plate produced and reheated specimens were provided for both of microscopic examination. This test is as follows:

The samples were cut and mounted. These samples were prepared using metallographic procedures. Eching was achieved by immersing each surface of the polished specimens for 20 seconds in (1% HF+2%HCl+97% Ethanol) as an etching solution.

The microstructures of the specimens were examined by an optical microscope. The image analysis of the specimens was employed by using computerized optical microscopy and J-Image software to calculate the grain size and shape factor of silicon particles. The grain size of Si particles and shape factor (R) were calculated according to following equations **[14]**:

$$d_{eq} = \sqrt{\frac{4A}{\pi}} \qquad \dots (1)$$

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

Where:

d_{eq} : The grain size of silicon particle.

A: the area of a silicon particle.

P: the perimeter of silicon particle.

Equation (2) describes the form of the particle and will be (1) for a circle, it increases with more complex geometries [14]. The volume fraction (Vf) of all samples was calculated to characterize the variation of microstructure with process parameters, volume fraction of the particles was calculated by dividing summation of the particles areas on the total area of an image.

Scanning Electron Microscope (model JSM-6460) equipped with an energy dispersive x-ray spectrometry (EDX), and (FESEM of model Hitachi-S-4160) were used to characterize some of the samples.

RESULT AND DISCUSSION

Microstructural Observations

Figure (3) shows the microstructure of as-cast sample 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 (α-Al+β-Si). The primary silicon has an average grain size approximately (123μm) and a complex shape factor equal to (2.73).

EFFECT OF SPC PROCESS PARAMETERS

Effect of superheat on the size & morphology of (β-Si) phase

Figure (4) shows the microstructure across the transverse section of hypereutectic Al-23%Si samples cast over the slope plate at different pouring temperatures, (760, 790, 820 and 850) ºC, (i.e. overheating 20, 50, 80 and 110) ºC, for tilt pouring angles (40, 50 and 60)º, using (300 mm) cooling slope length.

A comparison of Figure (3) with Figure (4) shows that applying inclined plate with melt overheating (20, 50, 80 and 110) ºC and tilt angles of (40, 50 and 60)º leads to the change in the microstructure. The change in the microstructure includes both of the grain size and the morphology of primary Si. The calculated grain size of primary Si, shape factor, and volume fraction obtained by the image analyzer software of cast samples as a function of pouring temperature are shown in Figures (4), (5) and (6), respectively.

From the microstructural observations and the calculated results, it can be seen that the melt pouring temperature has a significant effect on the size and morphologies of primary silicon in hypereutectic Al-23%Si alloy. The size of primary silicon is decreased with increasing of the melt overheating at a constant tilt angle. In addition, primary silicon at a pouring temperature of 760ºC exhibits a variety of morphologies, such as coarser polygonal, and other regular shape, with a shape factor (approximately 2.3) and the grain size of (β-Si) phase (approximately 50.4 µm) at tilt angle 40º, Figure (4a). When pouring temperatures are (790 and 820) ºC, primary silicon becomes smaller (approximately 29.7 and 23.6 µm), with a shape factor (1.88 and 1.81), respectively, Figure (4b&c). On the other hand, increase of the pouring temperature from (760 to 850) ºC leads to a decrease in the (β-Si) grain size from (approximately 50.4 to 21.6 µm), and the shape factor changes from (2.3 to 1.5) at a constant tilt angle 40º, Figure (4d).When increasing the melt pouring temperature from (760 to 850) ºC for 50º tilt angle leads to a decrease in the (β-Si) grain size from (48.8 to 18.5 µm), and the shape factor changed from (2.1 to 1.38), respectively, Figure (4e-h). Figure (7) shows the relationship of the volume fraction of Si as a function of pouring temperature, the graphs show that the volume fraction of Si is increased with increasing of pouring temperature and tilt pouring angles.

Figure (4i-l) depicts that more refined (β-Si) grains are obtained when the pouring temperature is increased to 850ºC for tilt angle 60º. As compared with above conditions, the grain size of (β-Si) phase is smaller (approximately 16µm) than those (34, 23.7 and 19.3 µm) at (760, 790 and 820)ºC, respectively. Also, the morphology of (β-Si) phase is fairly improved, and the shape factor changed from (1.97 to 1.36), respectively.

It can be observed that the elevation of temperature to 850ºC contributed to more refinement of primary (β-Si) phase, where the size of silicon grains is decreased to lower values at a constant tilt angle. As compared with the other overheating temperatures, the grain size of primary (β-Si) phase at 850ºC and tilt angles (40, 50 and 60)º is decreased to (approximately 21.6, 18.5 and 16 µm) with a shape factor (approx. 1.5, 1.4, 1.36), respectively.

The refinement of the primary silicon may be explained as follows:

During the initial stages of solidification, primary silicon grains nucleate on the surface of the plate due to low solubility of silicon and the difference of densities between Si grains ($2.33g/cm^3$) and liquid matrix ($2.62g/cm^3$) [15]. Size and number of nuclei depend upon cooling rate [16]. At higher pouring temperature (higher overheating), a faster cooling rate is obtained, and the latter leads to the higher under cooling during solidification [17]. Higher undercooling levels are responsible for increasing of the nucleation rate of primary (β-Si) phase which cause a high grain density. A high grain density, i.e., large number of grain "nuclei" during the initial stages of solidification of an alloy melt, results in increasing of the volume fraction of Si [18].

The morphology of the primary silicon on the slope plate is changed due to the movement of the melt over the slope plate, resulting in breaking of the edges of Si grains in the same fashion of dendrite arm fragmentation in stirring [19**]**. On the other hand, the shear stress which is produced by the liquid forced flow may cause the solid grains to separate from the slope plate wall **[20]**.

The proposed mechanism for the transformation of the primary silicon phase concluded that the elevation of melt overheating temperature is advantageous to obtain finer octahedral "polygonal" primary silicon. The silicon tetrahedral in the melt of Al-Si alloys, and h liquid structure should be beneficial for the formation and growth of the nuclei of primary silicon. With increasing melt overheating temperature, some Si-Si bonds in the Si-Si clusters are destroyed, and Si atoms diffuse from Si-Si cluster into the Aluminum bulk melt[4]. Therefore, the higher the melt overheating temperature, the smaller the size of Si–Si cluster due to the destruction of Si–Si bonds. Thus, from the above discussion, the primary silicon in the melt at 850ºC should be octahedral (polygonal) and finer than that at the other pouring temperatures.

With increasing under cooling levels, i.e., increasing overheating temperatures, the growth velocity of Si crystals accelerates so that the growth velocity of less favorable direction, which is very slow at low under cooling levels, becomes gradually equal to that of preferred 112 direction. Consequently, it is expected that the change of growth kinetics of Si crystals from layer growth to radial growth results in morphology changes of Si crystals, the changed mechanism of Si growth may change the eutectic morphology from acicular to fibrous in addition to change the shape of primary Si phase[21].

Effect of Tilting Angle on the Size and the Morphology of (B-Si)

The hypereutectic Al–23%Si alloy was poured over slope plate at different tilting angles, (40, 50 and 60)º. Figures (4a,e&i), (4b,f&j), (4c,g&k) and (4d,h&l) show the effect of tilting angles on the microstructure of the hypereutectic Al–23%Si samples cast over the slope plate, at pouring temperatures (760, 790, 820 and 850) ºC, respectively.

Figure (4a) reveals that the size of primary (β-Si) phase is decreased from (approximately 123 to 50 µm) as compared with as-cast microstructure with improvement in morphology, and the shape factor changed from (2.73 to 2.3). In addition, with increasing the tilt angle to 50º at the same pouring temperature, the size of silicon grains is decreased from (approximately 50.4 to 48.8 µm), and the shape factor is changed from (approximately 2.3 to 2.1), as shown in Figure (4e).

Increasing the tilt angle to 60º will decrease the grain size of primary (β-Si) phase to (34 µm) with a shape factor of (approximately 1.9), Figure (4i).

Figures (4b,f&j) show the effect of the tilt angles at 790ºC. It is observed that the size of silicon grains is decreased from (29.7, 28.8 to 23.7 µm), the shape factor is varied from (1.88 , 1.85 to 1.73) for tilt angles (40, 50, and 60)º, respectively. At 820ºC, it is observed that the size of silicon grains is decreased from (23.6, 22.6 to 19.3 µm), the shape factor is altered from (1.8, 1.7 to 1.6) for tilt angles (40, 50, and 60)º, respectively, as shown in Figures (4c,g&k)

At 850ºC and different tilt angles, as shown in Figures (4d,h&l), the grain size of the primary silicon is decreased from (21.6, 18.5 to 16 µm), and the shape factor is varied from (1.5, 1.38 to1.36), using (40, 50 ,60)º tilt angles, respectively. Figure (7) illustrates the effect of pouring temperature and tilt angles on the volume fraction of (β-Si) of SPC samples. It can be seen that the volume fraction of (β-Si) is increased with increasing of tilting angle at constant pouring temperature. In addition, the volume fraction of (β-Si) seems to be increased with decreasing of grain size of (β-Si).

From the above discussion, it can say that more refinement and improvement in microstr- ucture is obtained when the plate is inclined at 60º tilt angle. This may be due to increase the cooling rate with increasing of tilting angle.

Birol [22] concluded that the pouring temperature and high cooling rates (large tilt angle) are responsible for the small size of the primary Si particles. Other researchers [19] reported that the inclination of the slope plate governs the flow rate and contact time between the molten alloy and the cooling slope plate, if large angle is employed, the alloy flows faster, and fewer crystals are produced.

On other hand, rapid cooling of the liquid melt most likely resulted in a higher number of nucleation sites for primary Si crystals and restricted their growth by reducing the time necessary for the diffusion process.

Generally, primary silicon grows by the attachment of Si atoms to the surfaces of primary silicon particles. Therefore, the diffusion of Si atoms will play an important role during the growth of primary silicon. The diffusion of Si atoms will become much difficult with increasing cooling rate (tilt angle), which suppresses the growth of primary silicon to a great extent. Therefore, the primary silicon size is significantly decreased with increasing tilt angle [4].

Effect of Reheating on Microstructure

Figure (8) shows the microstructure of hypereutectic Al-23%Si slope plate samples after reheated to semi-solid temperature (550ºC) for (10 min) and then quenched in water. Figure (9) manifests the relationship between grain size of primary (Si) of reheated samples and pouring temperature at different tilting angles. This Figure shows that there is no major effect of reheating on the size of primary Si. The size of (β-Si) phase is slightly increased after reheating at all overheating temperatures and tilting angles. On the other hand, the shape factor of (β-Si) phase is changed, and the volume fraction of (β-Si) phase is slightly decreased after reheating, as shown in Figures (9) and **(**10**)**, respectively.

The results of reheated samples indicate that with increasing of pouring temperature from (760, 790, 820 to 850) ºC at constant tilt angle 40º, the grain size of (β-Si) phase is decreased from (51.8, 33.7, 29.8 to 23.5 µm) as compared with (50.4, 29.7, 23.6 to 21.6 µm), respectively for slope plate samples, and the shape factor is changed from (1.85, 1.76, 1.66 to 1.4) as compared with (2.3, 1.88, 1.81 to 1.5), respectively for slope plate samples. Also, the volume fraction of Si is increased from (2, 5.3, 11.4 to 15.2 %) as compared with (5.2, 5.7, 7.3 to 20), respectively for slope plate samples.

At 50º tilt angle and (760, 790, 820, 850) ºC pouring temperatures, the grain size of (β-Si) phase is decreased from (51.3, 31.3, 23.2 to 20 μm) as compared with (48.8, 28.8, 22.6 to 18.5 μm), respectively for slope plate samples, and the shape factor is changed from (1.73, 1.5, 1.44 to 1.37) as compared with (2.1, 1.85, 1.7 to 1.38) for slope plate samples. Besides, the volume fraction of Si is increased from (5.4, 7.3, 14 to 16 %) as compared with (5.6, 6.7, 8.7 to 20%), respectively for slope plate samples.

Using 60º tilt angle and (760, 790, 820, 850) ºC pouring temperatures, the grain size of (β-Si) phase is decreased from (38.9, 23.8, 22 to 19.5 μm) as compared with (34, 23.7, 19.3 to 16 μm), respectively for slope plate samples, and the shape factor is changed from (1.5, 1.47, 1.44 to 1.3) as compared with (1.97, 1.73, 1.6, 1.36) for slope plate samples. In addition, the volume fraction of Si is increased from (7.5, 12, 15 to 19.3 %) as compared with (7.7, 12.5, 15.6 to 22.7), respectively for slope plate samples. The comparison of the grain size values of (β-Si) phase before and after reheating is illustrated in Figure (12**)**. The increasing of the size of (β-Si) after reheating may be resulted from dissolving the eutectic structure and depositing on the primary phase. Previous work discussed the coarsening phenomena as follow: When Al-Si eutectic has been re melted, the molten eutectic is arranged during holding, and the fraction of the dissolved Si particles is believed to have deposited on the primary Si grains, contributing to the coarsening process during holding in the semi-solid state [22].

Scanning Electron Microscope Observations

SEM images depict the role of SPC process in refinement of primary Si phase and the morphological change of Si after slope plate casting as shown in Figure (13). It is observed from the figure that primary silicon become smaller after slope plate casting. The large size of primary phase (β-Si) particle in as-cast sample Figure (13a), is transferred to blunted Si particles sit between eutectic structure, as shown in Figure (13b), then these Si particles were fractured into smaller size particles, as shown in Figure (13 c&d). Besides, smaller grain size of Si is resulted with increase of the pouring temperature and tilting angle.

CONCLUSIONS

(1) It can be deduced that the pouring temperature (superheat) and tilt pouring angle have the significant role in the evolution of primary silicon particles during slope plate casting.

(2) Increasing of superheat temperature and tilting angle led to decrease the grain size, shape factor and increase the volume fraction of (β-Si) phase.

(3) The size of (β-Si) phase was slightly increased after reheating at all superheat temperatures and tilting angles. On other hand, the shape factor was improved, and the volume fraction of (β-Si) phase was decreased after reheating.

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Table (1) Chemical composition of hypereutectic Al-23%Si alloy.

element	Si	Mg	Cu	Zn	Fe	Mn	Ni	Al
Wt%	23.25	0.009	0.001	0.003	0.219	0.01	0.001	balance

Figure (1) Photograph of the Slope Plate Casting unit Used in this work.

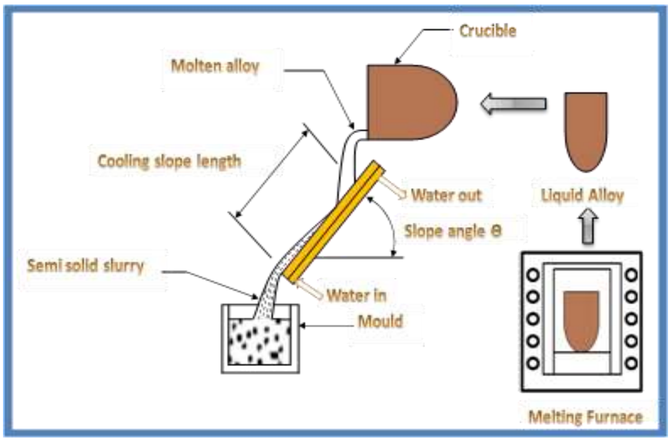

Figure (2) Schematic illustration of slope plate casting process.[23]

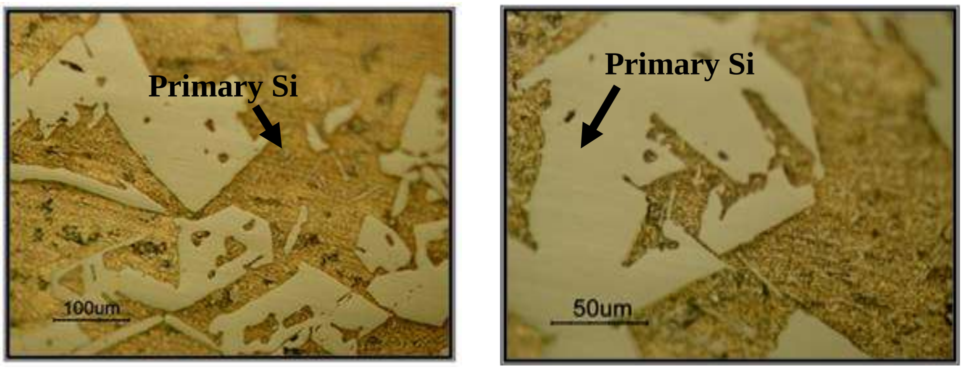

Figure (3) Microstructure of as-cast sample directly Poured into the steel mould.

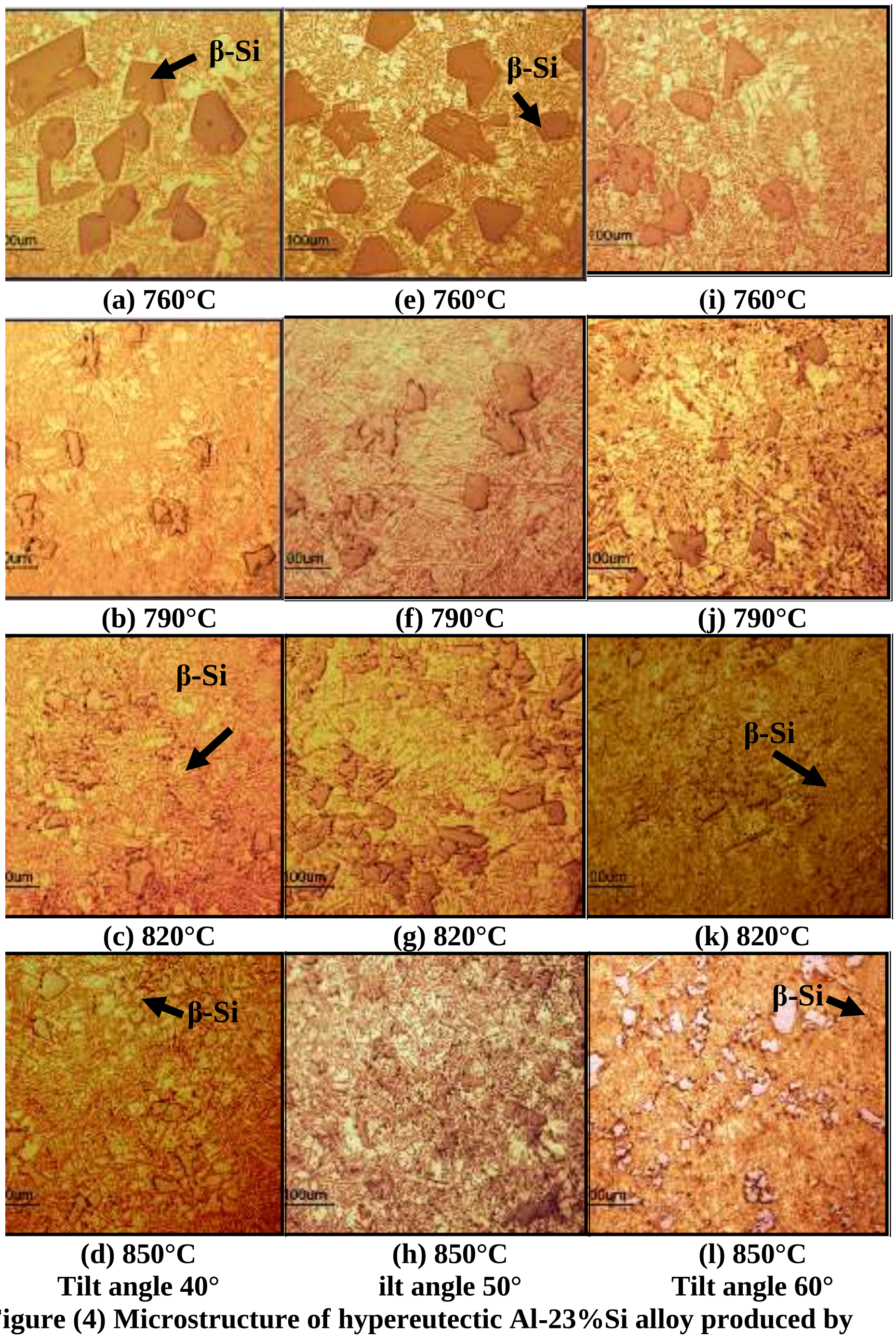

Figure (4) Microstructure of hypereutectic Al-23%Si alloy produced by SP casting at tilt angles 40°, 50° and 60° and different pouring temperatures

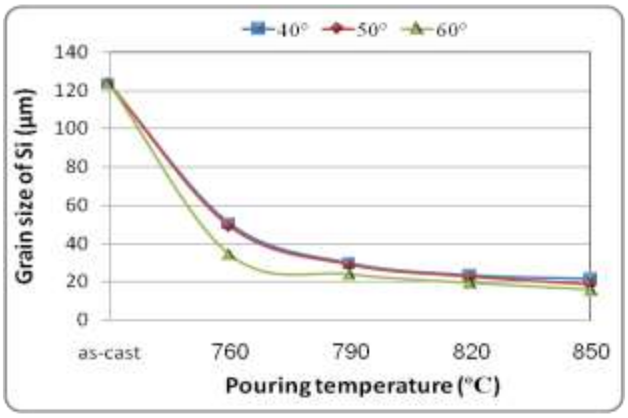

Figure (5) The relationship between grain size of primary (Si) of SPC samplesand pouring temperature at different tilting angles.

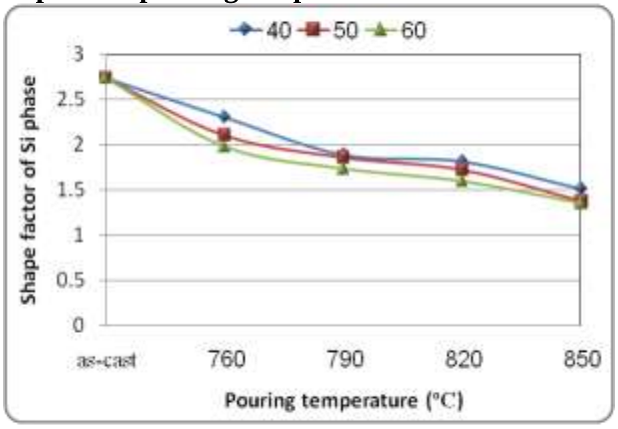

Figure (6) The relationship between shape factors of primary (Si) of SPC samples and pouring temperature at different tilting angles.

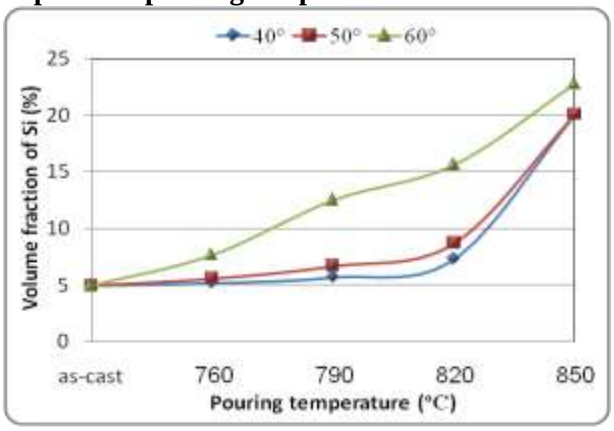

Figure (7) The relationship between volume fraction of primary (Si) of SPC samples and pouring temperature at different tilting angles.

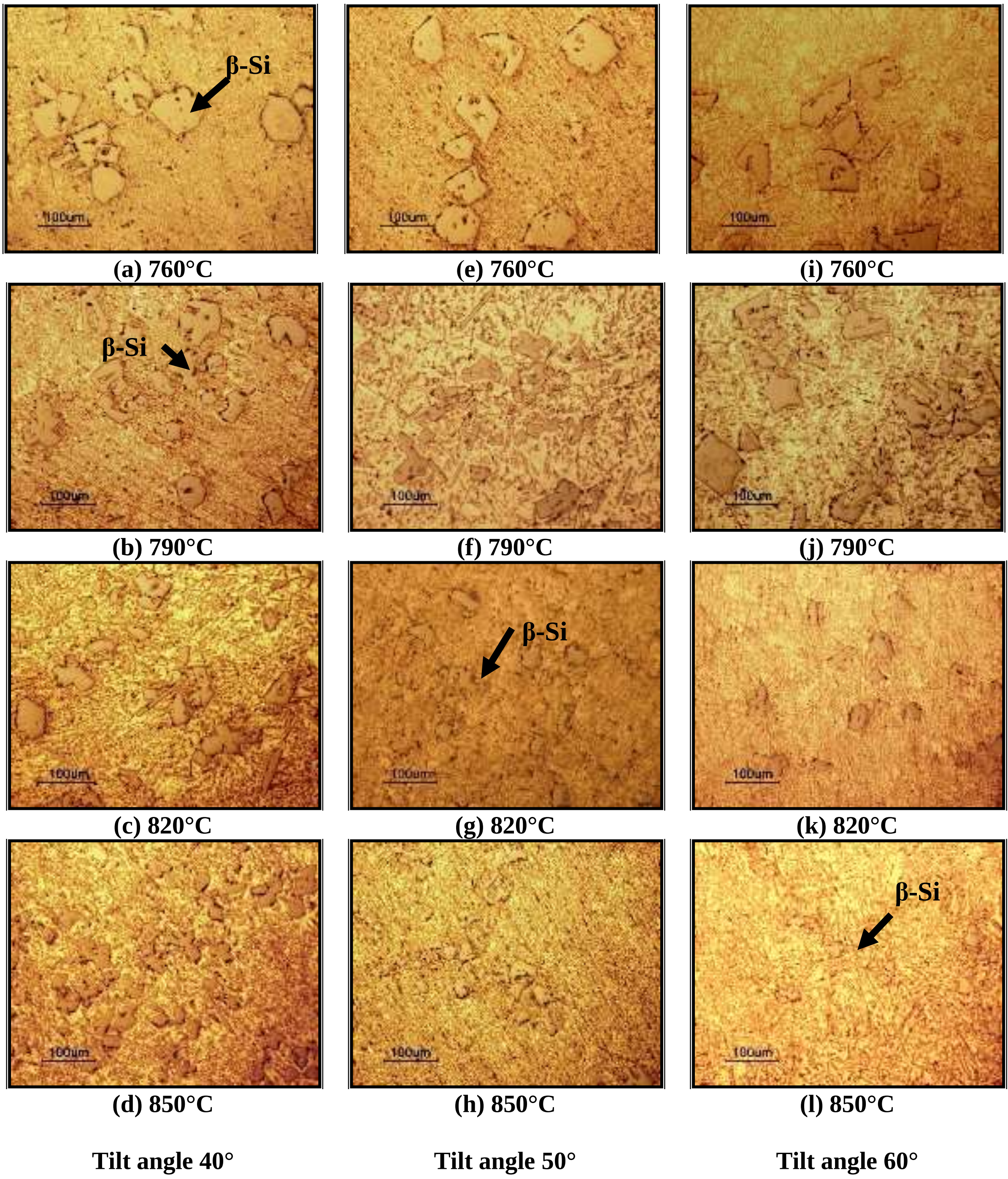

Figure (8) Microstructures of Reheated samples cast at the 40°,50° and 60° tilt angles and different pouring temperatures.

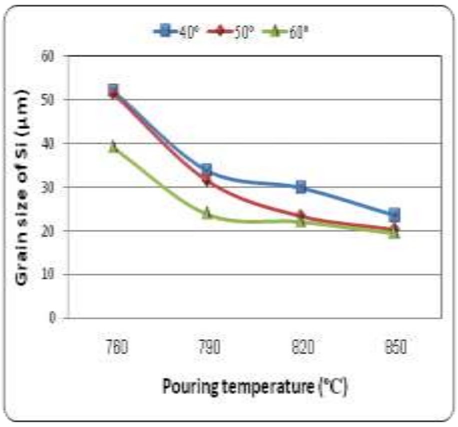

Figure (9) The relationship between grain size of primary phase (Si) of Reheated-cast samples and pouring temperature at different tilting angles.

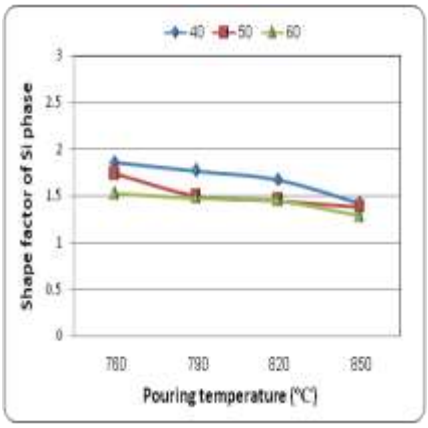

Figure (10) The relationship between shape factor of primary phase (Si) of Reheated-cast samples and pouring temperature at different tilting angles.

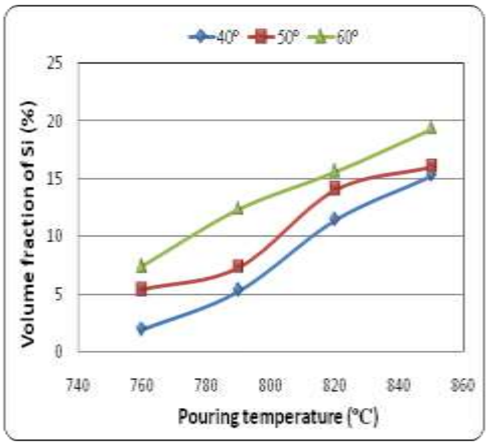

Figure (11) The relationship between volume fraction of primary phase (Si) of Reheated-cast samples and pouring temp. at different tilting angles.

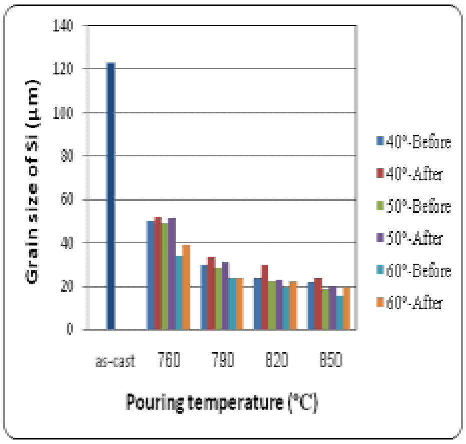

Figure (12) A comparison between grain size values of (β-Si) phase before & after reheating, as function of pouring temp. at different tilting angles.

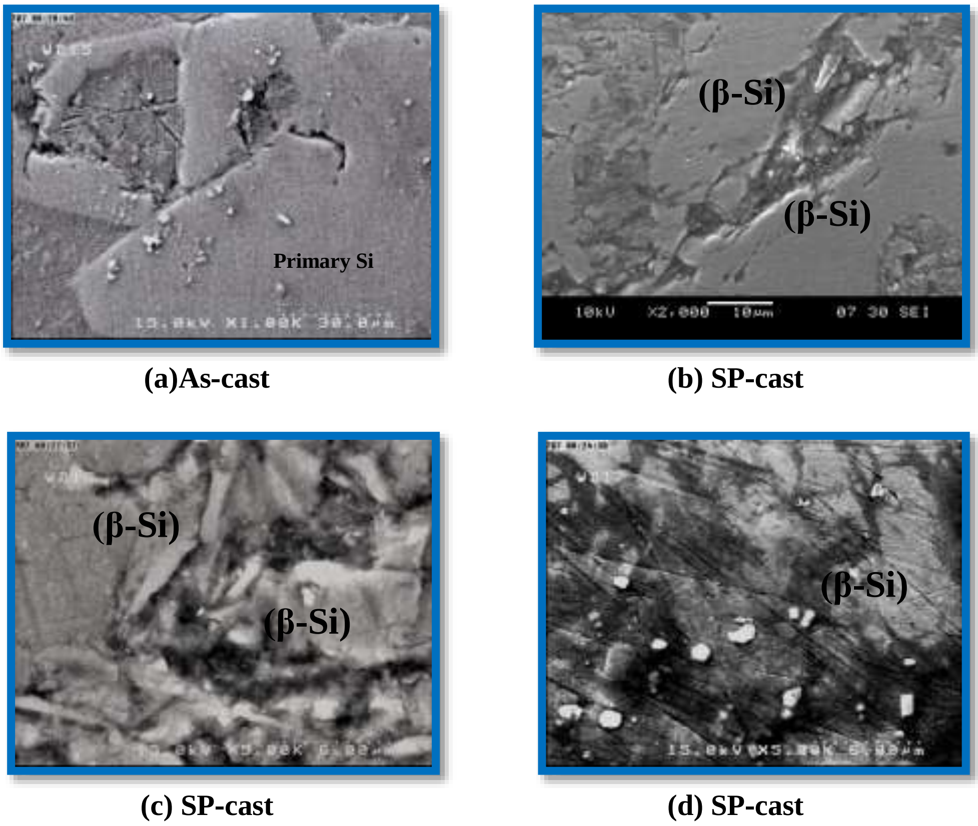

Figure (13) SEM images of SPC sample show the change of (β-Si).