Microstructural Evolution of Hyper-Eutectic Al-18% Si Alloy during Semi-Solid Isothermal Heat Treatment

Naglaa Fathy[1]

Abstract--- In this research the effect of semi-solid isothermal heat treatment on primary Si and α-Al grain of hyper-eutectic Al-18% Si is studied. At the early stages of heating time (up to 25 min), A significant refinement of primary Si particle is observed in Al-18% Si alloy when semi-solid isothermal heat treatment was applied at 585° C heating temperature. However, semi-solid isothermal heat treatment performed above heating time of 25 min might result in coarsening and agglomeration of primary Si. Hardness values for semi-solid heat treated Al-18% Si Alloy for all heating time range (10-40 min) are relatively higher compared with the as cast one. Hardness value of 72.5 HRB is achieved by heating Al-18% Si alloy at heating temperature of 585 °C for 20 min. The optimum semi-solid heating treatment condition was achieved at the temperature of 565°C for the range of 15 to 25 mins.

Keywords---Al-18% Si, Isothermal, heat treatment, microstructure, semi-solid.

I. INTRODUCTION

HYPEREUTECTIC Al–Si alloys such as A390 (Al–17% Si–4.5% Cu–0.5% Mg) are used in applications that require high resistance to wear and corrosion, good mechanical properties, low thermal expansion and reduced density. These properties are of particular interest to the automobile industry for the production of fuel-efficient vehicles using light-weight components produced from these alloys such as connecting rods, pistons, air conditioner compressors, cylinder liners and engine blocks [1]. Their good mechanical properties and high resistance to wear are essentially attributed to the presence of hard primary silicon particles distributed in the matrix. Therefore, the size and morphology of primary silicon in hypereutectic Al–Si alloys influence the mechanical properties of the alloys [2].

The presence of coarse primary Si particles (PSPs) in the microstructure of the Al–Si hypereutectic alloys has been identified as the main limitation for their industrial use. Even with the use of silicon modifiers and high cooling rates, the primary Si particles can only be reduced in size. Although the primary Si particles are very hard and certainly increase locally the wear resistance of the alloy, they are brittle and easy to crack exposing the soft Al matrix to extreme wear resulting in catastrophic failure automotive or aerospace components [3].

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The common microstructure of hypereutectic Al–Si alloys is composed of primary silicon particles (PSPs) and eutectic structure of α-Al and Si. The high strength and wear resistance of these alloys are attributed to the presence of hard silicon particles (both primary Si and eutectic Si). However, due to the formation of faceted and blocky primary Si during conventional processing, this group of alloys experience low ductility and poor machining properties, which greatly restrict their application in potential fields. Refinement of primary silicon particles is an effective way to overcome these disadvantages [4]-[6]**.** Primary silicon in hypereutectic Aluminum-silicon alloys is very hard, imparting improved wear resistance but also decreasing tool life during machining. To minimize machining issues while fully utilizing outstanding wear properties, primary silicon crystals should be controlled to uniform small size and have uniform spatial distribution. This can be accomplished by adding phosphorus to the melt, thus creating an abundance of AlP_3 nuclei suitable for initiating primary silicon crystal growth, and by solidifying cast product as rapidly as feasible [7].

To improve the strength and the formability of lightweight aluminum alloys for further industrial applications, semi-solid forming (SSF) technique is used as an alternative to traditional casting and forging processes. SSF is a method that can produce complex shape products. The process has advantages of productions of high quality and performance, and low cost. SSF is now a commercially manufacturing route producing millions of near net-shape parts per annum for the automotive industry. As a key branch of semi-solid technology, thixoforming attracted much attention due to its technical and economic advantages in processing alloys, which comprises of preparation, partial remelting and thixoforming of semi-solid billets. The preparation of semi-solid billet is fundamental to thixoforming process. The near-liquidus semi-continuous casting (LSC) based upon pouring temperature control ling for the control of solid particle morphology is a semi-solid preparation technology with high efficiency, low investment and extensive alloy application scope. The partial remelting of semi-solid billet is a critical procedure in the thixoforming process. Its purpose is not only to obtain a desirable nominal liquid fraction, but also to ensure the transformation of the solid phase to a spheroidal morphology with fine grain size [8-9].

In this study, the optimization and the effect of isothermal semi-solid heat treatment on refinement of the PSPs and matrix structure for hypereutectic Al–18% Si alloys was investigated. Much attention was paid to the relation between heating time and size and globularity of the PSPs.

II. Experimental

The alloy was melted in 30 kg capacity medium frequency induction furnace. The chemical composition of alloy samples is shown in **Table 1**. After flux treated, the melt was held at 750 °C for 5 min and then poured into a permanent mould whose size of mould cavity is ø50 mm×200mm.

The differential scanning calorimetric analysis (DSC) for the studied Al-Si alloy was conducted showing that solidus temperature of 575.5 °C, as shown in **Fig.1(a)**. The under present study Al- 18% Si alloy show a relatively wide range of solidification as shown in **Fig.1 (b).** Specimens of approximate dimensions 15x15x15 mm were cut for isothermal heat treatment as well as microstructure examination and hardness measurements. All specimens were heated to 585 ^{0}C hold for 10, 20, 30 and 40 mins, respectively in an electrically heated resistance furnace with heating rate of 10 °C.min^{-1}. After the semi-solid heat treatment, the samples were taken out immediately for air cooling

Table I
Chemical analysis of Al-Si samples, wt.-%
[A] Liquidus temperature ,[B] Solidus temperature

Element	wt.-%	Element	wt.-%
Si	17.95	Mn	0.02
Cu	4.20	Sn	0.07
Mg	0.55	Ti	0.06
Fe	0.75	V	0.03
S	0.01	$T_L(^0C)^a$	690
Ni	0.33	$T_s(^0C)^b$	575.5

Specimens in either as cast or heat treated condition were grinded, polished, etched with a solution consist of 2% HF, 25% HNO_3 and 73% H_2O and examined metallographically using an optical microscope and photomicrographs were taken.

Primary silicon particle sphericity (S= 4π × (area of the grain/grain circumference^2)) and primary silicon particle size, were measured and analyzed with Scentis image analyzer software (with errors 5%). Rockwell hardness test were also performed using 1/16 inch diameter ball and 100 kg$_f$ load.

III. Results and Discussion

Fig. 2 shows the microstructure of Al-18% Si alloy for as cast and semi-solid isothermal heated samples at 585 °C for range of 10 to 40 min. The microstructure of as cast sample is characterized by a dispersion of coarse primary Si particles in a matrix of denderitic Al–Si eutectic and some intermetallic particles. The microstructure of semi-solid isothermal heat treated Al-18% Si alloy is characterized by a relatively fine primary Si particles in a matrix of α-Al, eutectic Si and some intermetallic particles.

Table 2 shows quantitative measurement of structural features of as cast Al-18% Si alloy. It is clear that both primary Si particle and α-Al gain are affected by semi-solid isothermal heating treatment at 585 °C for heating time range from 10 to 40 min. Primary Si particles

Table II
Quantitative measurement of structural features of as cast Al-18% Si alloy

4 α-Al grain size	155
4 α-Al grain sphericity	0.35
Primary Si particle size, μm	70
Primary Si particle sphericity	0.50
Hardness, HRB	62

size decreases and its sphericity increases with increasing the heating time up to 20 min.

A significant refinement of primary Si particle size of 35 μm and its sphericity of 0.69 are observed in Al-18% Si alloy when semi-solid isothermal heat treatment was applied at 585 ^{0}C heating temperature for 20 min heating time (see Fig.3). By increasing heating time up to 20 min, the percent of liquid in the mixture of liquid- solid increases until its maximum value at 585 °C. The liquid phase starts in the eutectic region that has minimum meting temperature. The amount of Si solved in liquid increases by increasing the percent of liquid in the mixture resulting in increasing the Si diffusion from higher concentration value (primary Si particle) to lower concentration one (eutectic melted region) through solid eutectic region. Si diffusion

rate from the surface of primary Si particle will affected by its morphology, while the rate of diffusion will be higher for thin

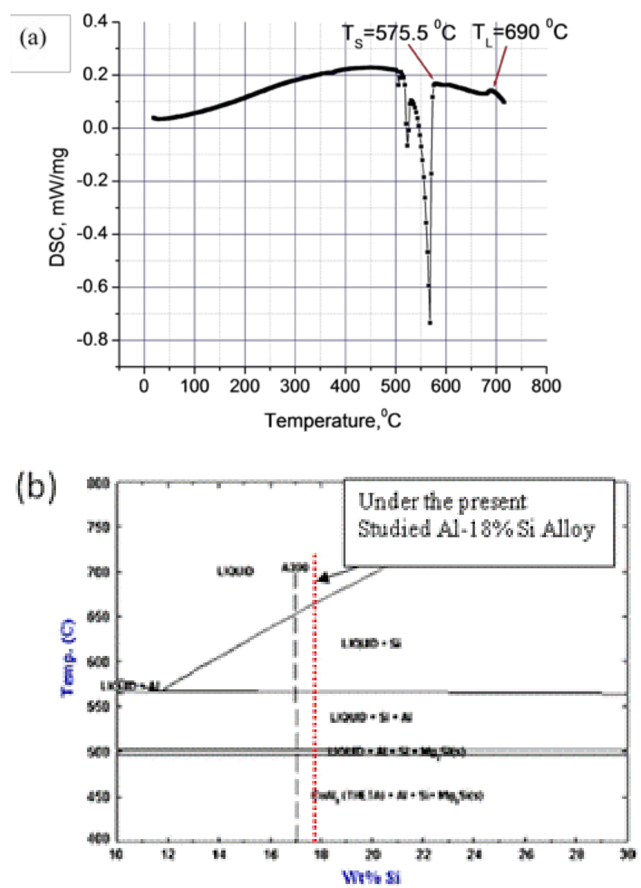

Fig.1 (a) DSC curve and (b) schematic phase of Al-Si alloy according to previous work [2].

section rather than thick one causing the refining(decreasing the size and increasing sphericity) of primary Si particle and α-Al grain (see Fig.4). After heating the Al-18%Si alloy samples for heating time of 30 min, both of primary Si particles and α-Al show increasing in their grain they reach to the maximum liquid percent in the mixture and its saturation is the reason of coalescence and particles agglomerations that appear in both 30 and 40 min heating time. Pervious study [10] indicate that The isothermal holding at the temperature near the eutectic point enhances the separation of *α* (Al) and Si eutectic phases, and therefore, the Al in the solution can easily precipitate on the existing *α* (Al). After the short holding time, low

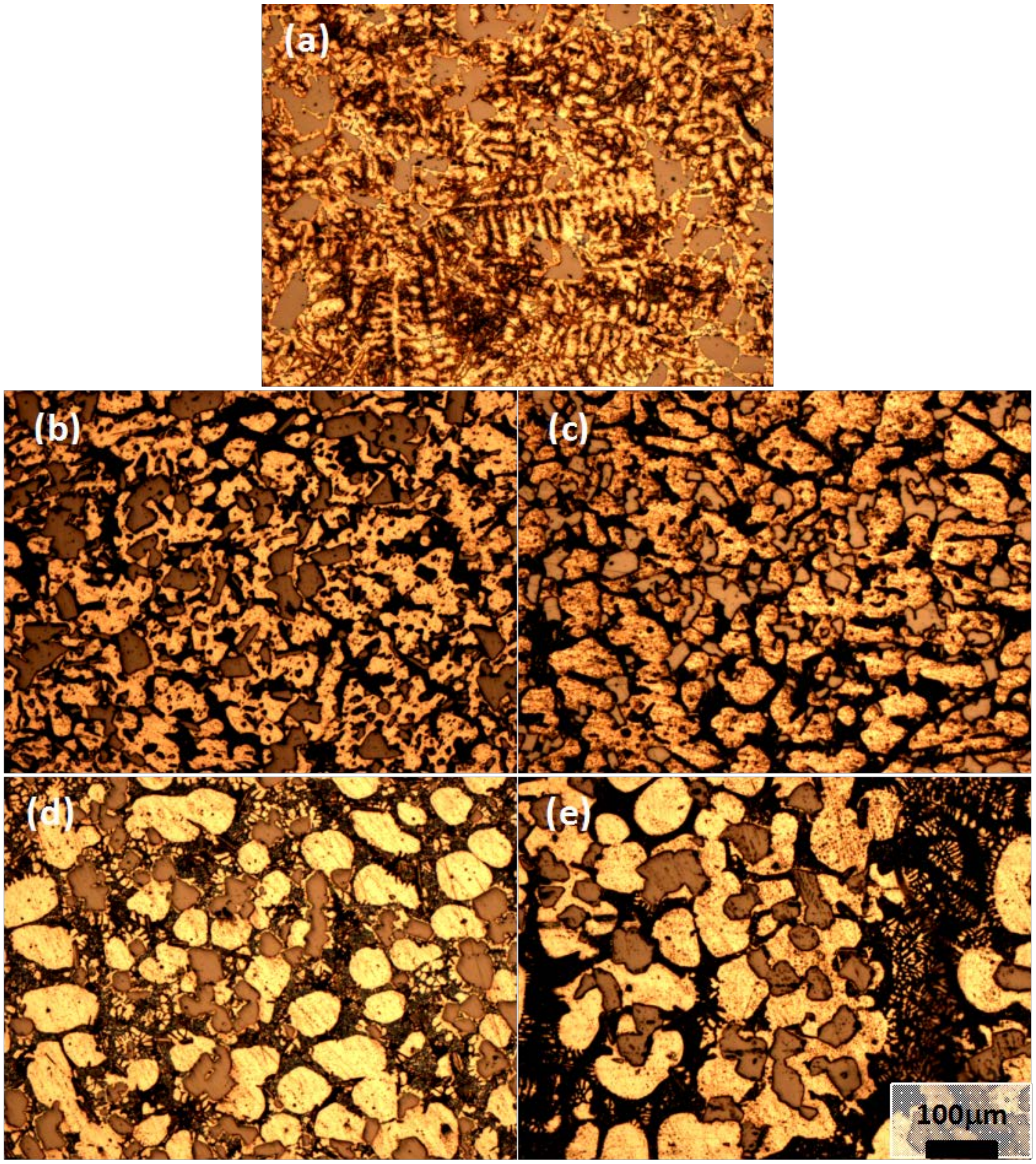

Fig. 2 Microstructure of Al- 18% Si alloy for as cast and isothermal heat treated at 585 ^{0}C; a) As cast b) heating time of 10 min; c) heating time of 20 min; d) heating time of 30 min; e) heating time of 40 min

melting point phase melts which distributes in the recrystallization grain boundaries or within grain as a result of the holding temperature that is higher than the solidus. With increasing holding time, many small liquid droplets within grain combine and form several big liquid drops in order to reduce the interfacial energy. After full recrystallization and then increasing the holding time, Ostwald ripening and coalescence play an important role to make the average size of the solid particles increase. Ostwald ripening involves the growth of large particles at the expense of small particles, and it is governed by the Gibbs–Thompson effect which alters the chemical potential of solutes at the particle/liquid interface, depending on the curvature of the interface [**11**].The reduction of interfacial energy between the solid phase and liquid phase provides the driving force for grain coarsening. Note that there are still a small number of irregular-shaped grains, which probably result from the coalescence of two spheroidal grains.

Moreover, these irregular-shaped grains possibly originating from the extruded grains have not yet been completely broken up. When the holding time is long enough, which makes the solid volume fraction lower down, the Ostwald ripening mechanism also begins

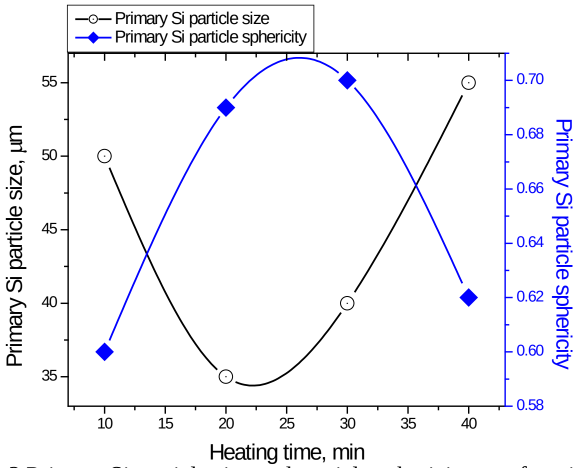

Fig.3 Primary Si particle size and particle sphericity as a function of heating time.

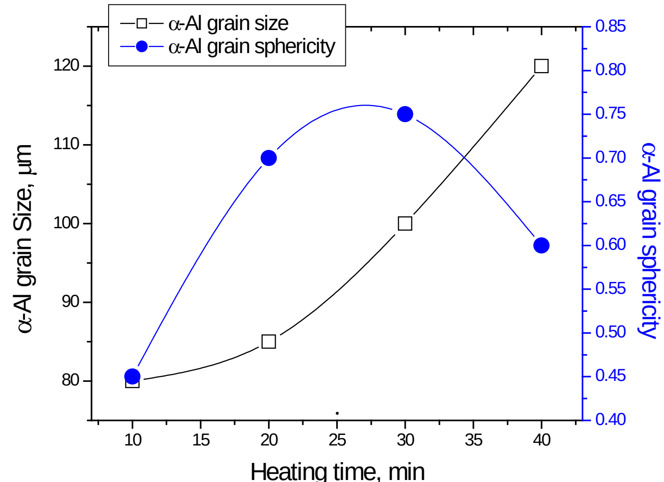

Fig. 4 α-Al grain size and particle sphericity as a function of heating time.

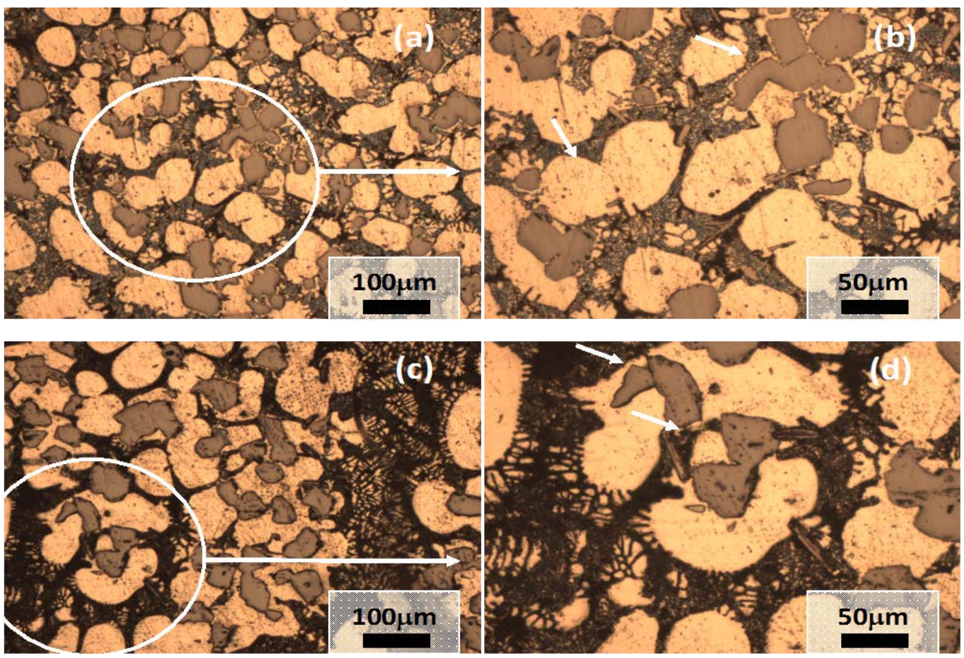

Fig.5 Effect of isothermal semi-solid heat treatment at 585 ^{0}C on the structure of Al- 18% Si alloy, a) 30 min. heating time, b) higher magnification of a, C) 40 min heating time, d) higher magnification of c, the arrows indicate for coalescence

after the structural coarsening. The larger grain gradually becomes spheroidal to lower the solid/liquid interfacial energy. It is clear that the high semisolid It is clear that the high semisolid isothermal temperature reduces the volume fraction of solid and accelerates the spherical evolution of the solid particles, long isothermal time makes the semisolid particles more globular, but the size of the particles would grow larger [10].

Fig. 6 shows generally that hardness values for semi-solid heat treated Al-18% Si Alloy for all heating time range (10-40 min) are relatively higher compared with the as cast one. Hardness value of 72.5 HRB is achieved by heating Al-18% Si alloy at heating temperature of 585 ^{0}C for 20 min. Hardness value increases with heating time up to 20 min due to the grain refining of primary Si particle and α-Al grain, meanwhile, hardness value decreases with heating time above 20 min due to coalescence and particles agglomerations.

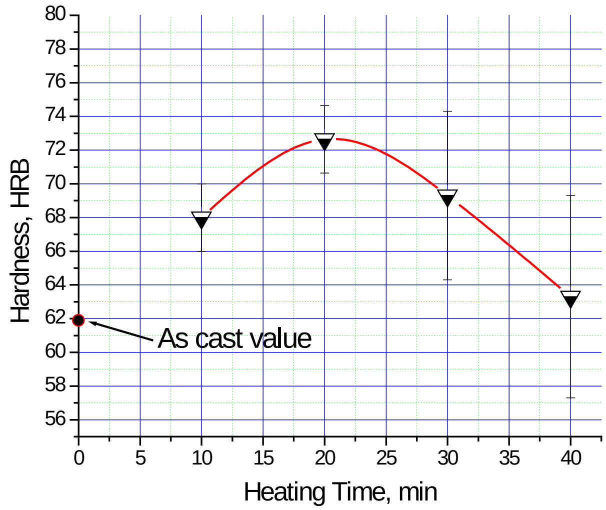

Fig. 6 Hardness of as cast and isothermal heat treated Al-18% Si alloy at 585 ^{0}C as a function of heating time.

The current study indicates that reasonable heating time should be selected in order to get the optimum combination of hardness and structure property for semi-solid isothermal heat treatment of Al-18% Si alloy. The optimum semi-solid heating treatment condition was achieved at the temperature of 565 ◦C for the range of 15 to 25 mins.

IV. Conclusion

The effect of the semi-solid isothermal heat treatment on microstructure and hardness of hyper-eutectic Al-18% Si alloy was investigated, which led to the following conclusions:

1. Primary Si particle and α-Al gain are affected by semi-solid isothermal heating treatment at 585 ^{0}C for heating time range from 10 to 40 min.

2. At the early stages of heating time (up to 25 min), A significant refinement of primary Si particle is observed in Al-18% Si alloy when semi-solid isothermal heat treatment was applied at 585 ^{0}C heating temperature. However, semi-solid isothermal heat treatment performed above heating time of 25 min might result in coarsening and agglomeration of primary Si.

3. Hardness value of 72.5 HRB is achieved by heating Al-18% Si alloy at heating temperature of 585 ^{0}C for 20 min.

4. The optimum semi-solid heating treatment condition was achieved at the temperature of 565 ◦C for the range of 15 to 25 mins.

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