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Microstructure and Mechanical Properties of Solution Treatment and Sr-Modification of Al-12%Si-1.5%Cu Alloy

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Abstract

The purpose of this paper was to investigate the effects of solution treatment time and Sr-modification on the microstructure and property of the Al-Si piston alloy. It was found that as-cast microstructures of unmodified and Sr-modified Al-Si alloys consisted of a coarse acicular plate of eutectic Si, Cu_3NiAl6 and Mg_2Si phases in the α-Al matrix but different in size and morphology. Both size and inter-particle spacing of Si particles were significantly changed by increasing of the solution treatment time. After a short solution treatment, the coarse acicular plate of the eutectic Si appears to be fragmented. Fully modified microstructure of Sr-modified alloy can reduce the solution treatment time to shorter compared to unmodified alloy. The maximum of a peak hardness value is found in the very short solution treatment of both Al-Si piston alloys. Compared to 10 h solution treatment, the solution treatment of 2-4 h is sufficient to achieve appropriate microstructures and hardness. The short solution treatment is very useful to increase the productivity and to reduce the manufacturing cost of the Al-Si piston alloys.

Keywords*: Al-Si based alloy, Solution treatment, Sr-modification*

1. INTRODUCTION

Al-Si based alloys both eutectic and near-eutectic alloys have an excellent castability, high corrosion resistance, high wear resistance and low thermal expansion at elevate temperature [1]. The Al-12Si-1.5Cu-Ni-Mg alloy (the AC8A or 336 alloy; JIS and ASTM standards, respectively) is one of the famous alloys in this group. These alloys are widely used for many types of the pistons and some elevated temperature applications in the automotive industry. Normally, the Al-Si piston is produced by the conventional permanent mold or low pressure die casting processes. After casting, T4, T5 and T6 heat treatments are selected to enhance the fracture toughness of as-cast Al-Si piston alloy. It has been well known that the strengthening of hardenable Al-Si based alloys, such as Al-Si-Cu and Al-Si-Mg alloys is base on the formation of intermetallic phase during decomposition of a metastable phase in the supersaturated solid

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solution state of α-Al in an age-hardening process [2]. In recent years, the precipitation hardening process of Al-Si based alloys has been investigated by addition of Cu or Mg to produce the strengthening phases [3]. Therefore, the mechanical property of the heat-treated alloys is extremely influenced by presences of the θ (Al_2Cu) and β (Mg_2Si) phases in the α -Al matrix. In high Si containing Al-Si alloy, size and distribution of the eutectic Si are also considered as the strong effect on the fracture toughness [4]. It is will accepted that two precipitation sequences are mainly responsible for the precipitation strengthening of Cu and/or Mg containing Al-Si based alloys, namely:

$$\text{Cu-contained alloy} = \alpha\text{SSS} \rightarrow \text{GP zones} \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta \tag{1}$$

$$\text{Mg-contained alloy} = \alpha\text{SSS} \rightarrow \text{GP zones} \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta \tag{2}$$

Where; αSSS is the supersaturated solid solution. GP zones are the Cu/Mg Guinier-Preston zones. θ″/β″ and θ′/β′ are the metastable phases. θ and β are the equilibrium phase [2].

According to the permanent mold casting process of the Al-Si piston, it has been well known that the as-cast alloy has poor mechanical properties because a lot of micro-segregation and a coarse acicular eutectic Si are contained. Therefore, it is essentially that the as-cast Al-Si piston alloy must follows by the homogenization or solution treatment processes to eliminate those problems. Thus, the control of solution treatment temperature and holding time is an important factor to optimize between the microstructure and mechanical property. However, the manufacturing cost should be considered one. Zhang et al. [5] reported that the short solution treatment time has great benefits on mechanical properties of Al-7Si-0.3Mg casting alloy. However, there are a few numbers of publications on the Al-Si piston alloy. Therefore, in this paper the effects of the solution heat treatment and Sr-modification on the microstructure and hardness of Al-Si piston alloy are presented.

2. EXPERIMENTAL PROCEDURE

The alloy used in this paper was an Al-12Si based alloy with containing of Cu, Mg and Ni, the chemical composition was shown in Table 1. Two Al-Si based alloys were melted in a graphite crucible by an electric resistance furnace and then poured into a piston mold (steel mold). Fig. 1 shows the casting and solution heat treating processes of the experimental procedure. The pouring temperature was carried out at 680^{o}C. The piston 1 is unmodified casting condition; the melt was directly poured into a piston mold. The piston 2 is Sr-modified, after fluxing and degassing the melt was treated by addition of Sr about 0.03 wt. % in order to modify the microstructure. The solution treatment temperature was carried out at 520^{o}C with various solution treatments time for 0.5, 1, 1.5, 2, 4, 6, 8 and 10 h, followed by water quenching to room temperature. Subsequent aging treatment was carried out at 175oC for 15 h. The hardness measurement was tested by Brinell hardness tester. The aged sample was polished and etched by the dilute Tucker’s reagent for the microstructure examination. The age-hardening behaviour of the quenched sample was performed by using the differential scanning calorimetry (DSC).

Table 1. Chemical composition of the Al-Si based alloys (wt. %).

Alloy	Si	Cu	Ni	Mg	Fe	Mn
Al-Si alloy	11.84	1.36	1.14	1.11	0.52	0.63

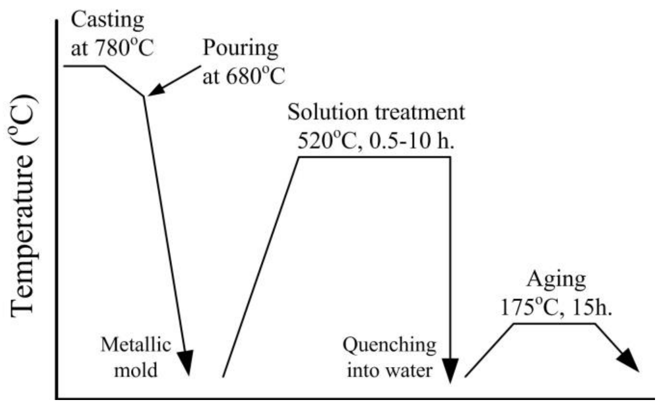

Figure 1. Schematic illustration of experimental procedure.

3. RESULTS AND DISCUSSION

3.1 Microstructure changes during solution treatment.

Fig. 2 and Fig. 3 show the optical microstructure of as-cast and heat-treated of the Al-Si piston alloys. The as-cast microstructure consisted of mainly primary α-Al dendrite, eutectic Si, Cu_3NiAl_6 (light-gray script), Mg_2Si (black script) and a few numbers of Fe-rich intermetallic phases in the interdendritic region as shown in Fig 2(a). The eutectic Si morphology of the unmodified Al-Si alloys (Piston 1) presents the coarse acicular plates. This morphology is very harmful for the fracture toughness of the Al-Si piston alloys. After 0.5 h solution treatment, it is found that the coarse acicular plate appears to be fragmented into fine and needle-like particles as shown in Fig. 2(b). After 2 h solution treatment, the eutectic Si becomes clearly fragmented and more spherical shape, as shown in Fig. 2(c). With a short solution treatment (less than 2 h.), the eutectic Si is fully modified into the less deleterious morphology. However, the distribution of Si particle is widely in size between the rod-like and fine-spherical particles. It is found that the Cu_3NiAl_6 and Mg_2Si phases are mostly dissolved into the α-Al matrix after prolonged solution treatment. On the other hands, the amounts of the strengthening particles (Mg_2Si and Al_2Cu) will increase after the age-hardening stage. After 4 h solution treatment, fine Si particles become substantially coarser while the inter-particle spacing is increased as shown in Fig. 2(d). After 6 h solution treatment, the inter-particle spacing is become longer in distance while size of Si particle is slightly increased (Fig. 2(e)). Uniformly distributed of Si particles are found in the prolonged solution treatment of 10 h as shown in Fig. 3(f).

The as-cast and heat-treated microstructures of Sr-modified alloy (Piston 2) are shown in Fig 3(a-f). The small addition of Sr fully modified the acicular plate eutectic Si into the fibrous morphology. The secondary dendrite arm spacing (DAS) is also changed into smaller as shown in Fig. 3(a). The fibrous eutectic Si is located and agglomerated in the interdendritic regions of the α-Al dendrite. With a short solution treatment of 0.5 h, the Si particles appear to be fragmented into the very refined particles as shown in Fig. 3(b). At the same time, the fibrous morphology changes to favorable spherical particle. After 2 h solution treatment, Si particles become slightly coarser but more uniformly distributed as shown in Fig. 3(c). In the heat-treated piston 2, size and inter-particle spacing of Si particles are significantly increased by increasing of the solution treatment time. Compared with the heat-treated piston 1, smaller of Si particles and more uniform are obtained in the heat-treated piston 2.

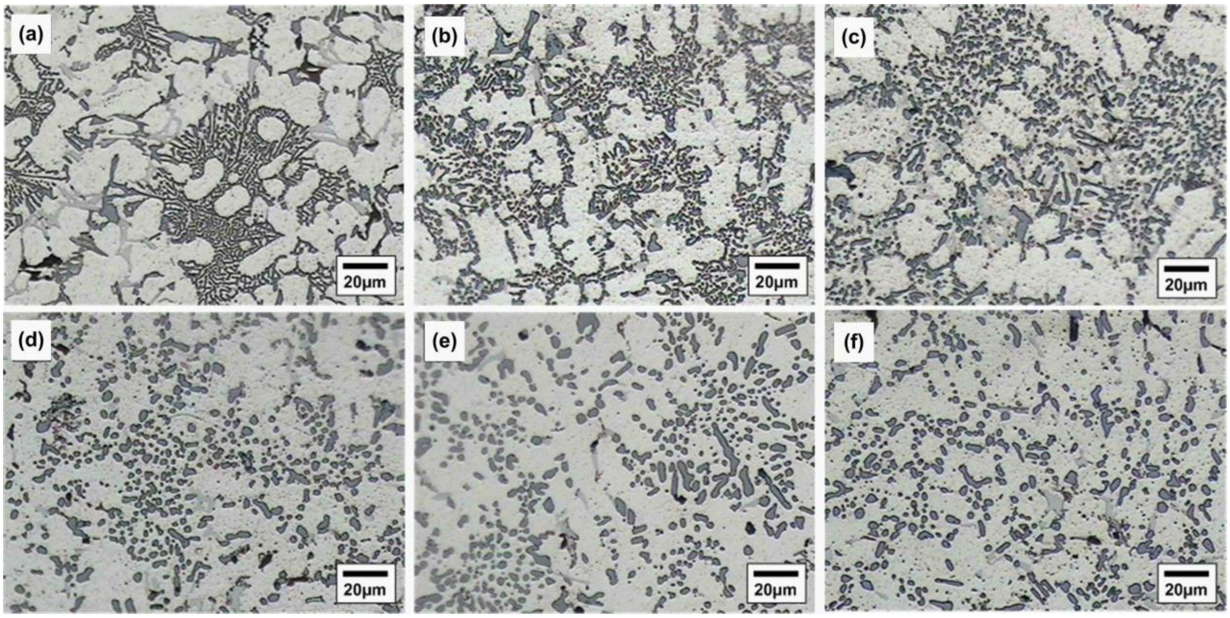

Figure 2. Microstructure of the piston 1 with various conditions;
(a) as-cast, (b) 0.5 h (c) 2 h, (d) 4 h, (e) 6 h and (f) 10 h solution treatments, respectively.

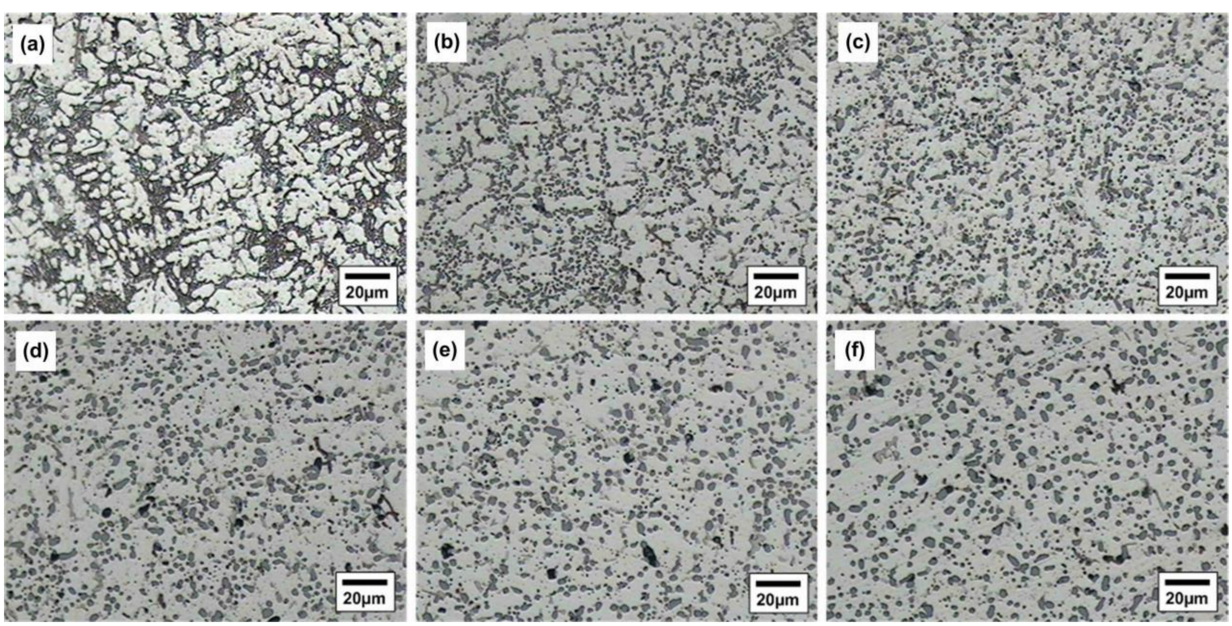

Figure 3. Microstructure of the piston 2 with various conditions;
(a) as-cast, (b) 0.5 h (c) 2 h, (d) 4 h, (e) 6 h and (f) 10 h solution treatments, respectively.

The microstructure changes can be explained by regards to the fragmentation, spheroidization and coarsening of Si particles. In as-cast alloy, the Mg and Si contents are distributed fairly homogeneously. Both elements become very homogeneous when the Al-Si piston alloy was heated to an elevate temperature within about 10 min [1]. At elevate temperature the coarse acicular plates of eutectic Si changed to a fine fragmented particle. The fragmentation and the spheroidization of Si particles can explain by the instability of the interface between two difference phases and is driven by a reduction in the total interfacial energy. After prolonged holding time the Si particle size is increased into coarser particle while very fine Si particle is dissolved. This stage is called the “coarsening”. The degree of fragmentation, spheroidization and coarsening of Si particle depends on the solution treatment temperature and isothermal holding time [5].

3.2 Age hardening curve.

Fig. 4 shows the evolution of Brinell hardness of the Al-Si piston alloys after age-hardening. Hardness value of the piston 1 is lower than the piston 2 as resulted from cast microstructure. The hardness values of the as-cast piston 1 and piston 2 are approximately 64 and 71 HB, respectively. The maximum of the peak hardness of both Al-Si pistons is found in the 0.5 h heat-treated alloys approximately 96 and 106 HB, respectively. Subsequently, the hardness is substantially decreased from 1 to 4 h solution treatments. This phenomenon is affected by the dissolution of very fine Si particle. After prolonged solution treatment, it is found that the hardness not significantly decreased due to the uniform distribution of Si particles.

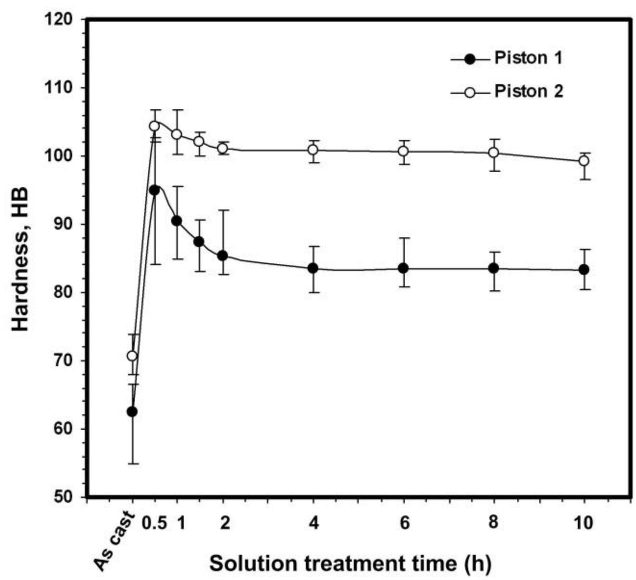

Figure 4. Evolution of hardness value as a function of the solution treatment times.

3.3 DSC analysis of quenched specimen.

The precipitation sequences of the heat-treated Al-Si piston can explain with regards to the formation of the Al_2Cu (equation 1), Mg_2Si (equation 2) and complex precipitate phases [2]. From the DSC curves in Fig 5, fifth importance peaks were detected. An exothermic Peak A in the temperature range of 60-175^oC is the formation of the GP-I zones in the early stage of aging which consists of clusters of Mg/Si/vacancy and Al/Cu/vacancy. Large endothermic peak B in the temperature range about 175-250^oC is the dissolution of the GP-I zones. High exothermic peak C is the formations of the Cu_2Al (β'') and Mg_2Si (θ'') which particularly forms in the temperature range of 250-280^oC. The overlapped exothermic peaks of D and E in the temperature range of 280-305^oC relate to the precipitation of β' and θ' [2]. The formations of stable and phases can be detected in temperature range of 445-455^oC of Peak F.

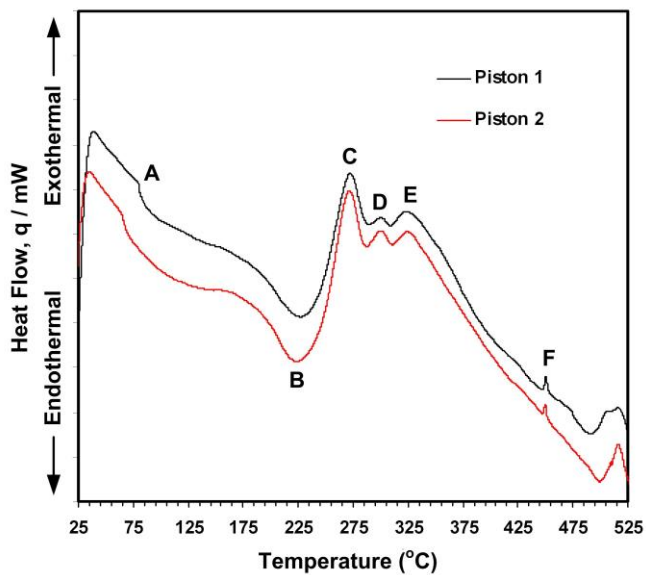

Figure 5. DSC curves during heating of the as-quenched Al-Si piston alloys

4. CONCLUSION

The solution treatment time has strong effects on the eutectic Si both the morphology and particle distribution. Solution treatment of 2 to 4 h is sufficiently to achieve the hardness and fully modified microstructure compared to the 10 h solution treatment. The short solution treatment is very useful to increase the productivity and to reduce the manufacturing cost of the Al-Si piston.

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