논 문

Characterization of Cast-Forging Process in Hypereutectic Al-15wt.%Si alloy

Eok-Soo Kim[†], Kyung-Mook Lim, Young-Myung Hong, Yoon-Sung Han*, and Kwang-Hak Lee**

Pusan & Ulsan R&D Center, Korea Institute of Industrial Technology, Pusan 609-735, Korea
*Ulsan Industrial Promotion Techno-park, Ulsan 683-804, Korea
**School of Materials Science & Engineering, University of Ulsan, Ulsan 680-808, Korea

Abstract

과공정 Al-15wt.%Si 합금의 주단조 공정의 적용을 위해 주조 예비성형체를 제작하는 과정에서 P 와 Sr 을 첨가하여 과공정 Al-Si 합금의 응고과정에서 발생하는 초정 Si 과 공정 Si 의 미세화 개량처리를 행하였다. 미세화 조직의 변화에 따른 기계적성질 및 단조성을 조사하였으며, 미세화제로 첨가된 0.075wt.% Sr 과 0.1wt.% P 의 첨가에서 가장 효과적인 미세한 조직을 얻을 수 있었고, 인장강도와 연신율은 이들 첨가원가의 증가에 따라 향상되는 결과를 보였으나 일정 이상의 첨가에서는 더 이상의 향상은 없었다. 단조성 평가를 위한 열간가공 재현실험에서는 450℃에서 약 60N/mm2 의 하중이 필요함을 알 수 있었다. 열간단조 및 열처리 후의 인장강도와 연신율은 보다 많은 향상을 가져왔으며, 이는 압축가공에 의한 주조 예비성형체 내부에 잔존하던 주조결함의 제어와 열처리에 의한 조직의 개량 및 균질화 효과에 의한 것으로 판단된다.

Key words : Cast-Forging, Hypereutectic, Al-Si alloy

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1. Introduction

Recently, the automobile weight reduction technology has attracted an increasing amount of attention in the automobile industry due to serious energy saving and environmental problems. It is well known that the use of new materials with high strength and low density is the most effective method for the automobile weight reduction, so that the replacement materials of steel have been widely developed [1].

Among these light materials, Al alloys, the most representative light metals, are commonly used in automobile industry due to their superior properties such as high strength, corrosion resistance and recycling ability etc. Although Al alloys have been mainly applied to automobile components with low required strength such as engine and housing components, it is attempting to use Al alloys as raw materials for automobile body components. At the present time, these Al alloys components are mainly fabricated by casting.

Casting is the easiest and simplest method to fabricate automobile components having complex shape and makes the mass production possible. However, the casting defects such as porosity obstruct the use of cast Al in components required very high pressure resistance and sealing efficiency [2-3]. Also, forging can improve the mechanical properties of metallic materials by removing as-cast microstructure and making dense microstructure, which can be achieved by mechanical impacting. On the other side, the application of forging is restricted to simple components due to the high cost and the difficulty in fabricating complex components [4].

Cast-forging process simultaneously uses the merits of casting and forging. In cast-forging process, the near-net shape pre-form is made by casting and then the final components are produced by the only one step forging of the pre-form. Therefore, the process makes it possible to mass-produce the complex shape components and drastically improves the life time of metallic patterns. Since the process involves the forging step and uses Al casting raw alloys, the cast-forged components have the superior mechanical properties and the very low cost.

The hypereutectic Al-Si alloys are defined as Al based alloys involving Si higher than eutectic content (12.6 wt.%). Since Si has low density and the latent heat is 5 times higher than Al, Si reduces the weights of alloys and improves the castability. Also, the Al alloys involving Si can be the very effective wear resistant materials due to their high hardness. Because of excellent wear resistance of hypereutectic Al-Si alloys, they have been used in wear resistant components such as automobile cylinder blocks, fork shifts, and reaction support shafts. However, primary Si precipitated as large plate shape and needle shape

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[†]E-mail : osgim@kitech.re.kr

eutectic Si during solidification have detrimental effects on mechanical properties of the hypereutectic Al-Si alloys. Therefore, these precipitations must be modified and refined simultaneously [5]. In particular, the refining of primary Si and the modification of eutectic Si are more important in the cast-forging process in order to obtain good forging and mechanical properties. AlCuP alloys and Al-Sr alloys were respectively used as eutectic Si modifier and primary Si refiner in this study.

In the present study, the new cast-forging method with high production ability, quality and low cost has been developed for automobile components by using the Al-Si cast alloys.

2. Experimental Procedure

2.1 Alloy design and preparation

The commercial AC4C Al alloys were used in this study. The AC4C Al alloys are based on Al-Si type hypereutectic alloys and involve small amount of Cu and Mg. The hypereutectic Al-Si alloys were prepared by the addition of Si up to 14.5~15.5wt.% during melting process. The metallic Si was melted at 800~830°C and held for 20 minutes. Then, the melt was poured into the pre-heated metallic patterns after degassing treatment at 750°C. The chemical composition of the prepared hypereutectic Al-Si alloys is shown in Table 1. Fig. 1 shows a metallic mold used in this study.

2.2 Modification and refinement treatments

AlCuP alloys and Al-Sr alloys were respectively used as eutectic Si modifier and primary Si refiner. Table 2 shows the chemical compositions of the modifier and refiner. In order to determine the optimum contents, the casting experiments were performed with various amounts of the modifier and refiner. In the case of the refiner, AlCuP alloys were added on previously prepared Al-Si alloy melt with amounts of 0.05, 0.075, 0.1 and 0.2wt.% at 850°C. Also, Sr, the eutectic Si modifier, was added on the melt with amounts of 0.05, 0.075, 0.1 and 0.15wt.%. at 700°C by using Al-Sr raw alloys. And then the optimum amounts of AlCuP and Sr were determined by the observation of cast specimen microstructure. In order to observe the effects of simultaneous refining effects of eutectic and primary Si, AlCuP and Sr were respectively added on the melt at 850°C and 700°C, respectively.

Table 1. Chemical composition of the hypereutectic Al-Si alloy used in the present study.

Elements	Si	Cu	Mg	Zn	Fe	Mn	Ni	Al
Hypereutectic Al-Si alloy	14.5~ 15.5	0.2~ 0.3	0.2~ 0.4	<0.3	<0.5	<0.4	<0.1	Bal.

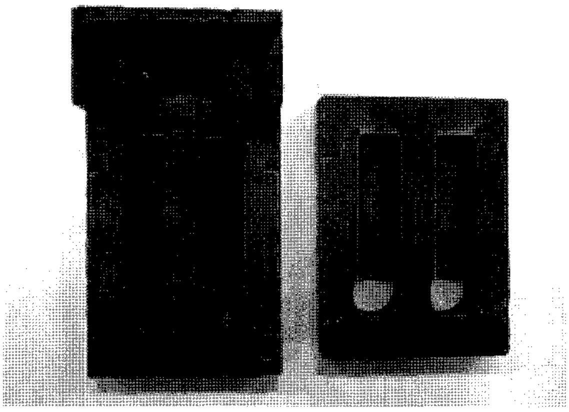


Fig. 1. Gravity casting mold used in this study.

Table 2. Chemical compositions of the refiner and modifier.

Elements	Ti	B	Fe	V	Sr	Si	P	Cu	Al
Al-Sr	-	0.17	-	-	9.61	0.02	0.001	-	Bal.
AlCuP	-	-	-	-	-		1.4	20	Bal.

2.3 Mechanical and forging properties evaluation

To evaluate the mechanical properties of hypereutectic Al-Si alloys, the tensile strength, hardness and wear resistance were measured, and the microstructure was also observed. The tensile strength was measured by the UTM (Universal Testing Machine, AG-25TE, Shimadzu) with a test speed of 0.5 mm/min at room. The wear resistance testing was performed by using the SUGA type wear tester and the wear resistance was evaluated by measuring the weight losses of specimens after 1200 times double stroke under 3.92N.

The optimum forging condition of the cast pre-form was determined by the high temperature deformation simulation experiments. The high temperature deformation simulation was performed by using the Al-Si alloy pre-form with the optimized composition. The optimum composition was selected by the microstructure observation and mechanical properties evaluation according to amounts of the modifier and refiner. Fig.2 shows the specification of test sample for the tensile strength testing and high temperature deformation simulation. The forging properties of the alloys were evaluated by high temperature deformation testing. The deformation testing was performed under a strain rate of 0.01 mm/sec. The testing specimens were heated to the target temperature with a heating rate of 5°C/sec and held

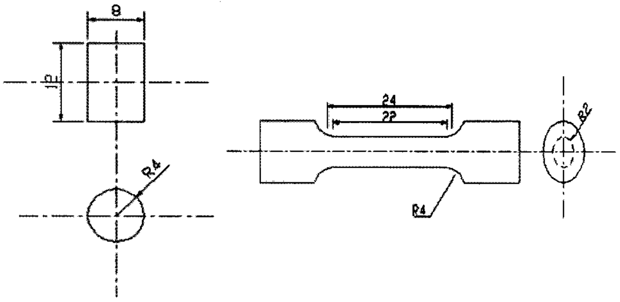


Fig. 2. The specification of forging and tensile test specimen.

at this temperature for 2 minutes followed by compressively being deformed. The compression rates were 30 and 40%, and the compression temperatures were 400, 450 and 500°C. From the compression test of the specimens, the relationship between the forging temperature and compression load were clarified. Also, the necessary forging loads were calculated for real forging process.

3. Results and Discussion

3.1 Microstructure change according to the modification treatment

Fig. 3 shows the as-cast microstructure of hypereutectic Al-Si alloys without the modifier and refiner fabricated in this study. The very large sized primary Si and eutectic Si were observed in Fig. 3.

The microstructures of the as-cast hypereutectic Al-Si alloys with the primary Si refiner are shown in Fig.4 according to Sr contents. As shown in Fig. 4, Sr addition below 0.075% had little effect on the modification of hypereutectic Al-Si alloys and the satisfactory modification effect could be observed in the alloys with 0.075wt.% Sr. Also, the best modification effect was obtained at 0.1wt.% Sr addition and 0.15wt.% Sr addition had the similar effect to that of 0.1wt.% Sr addition.

From these results, 0.075wt.% Sr addition was determined as optimum Sr addition content for the primary Si refining.

Fig. 5 shows the as-cast hypereutectic microstructure of Al-Si alloys according to the amount of AlCuP addition. Although increasing amount of AlCuP reduced the primary

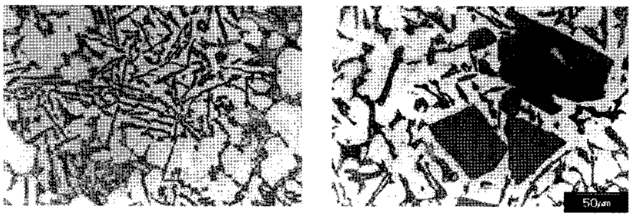
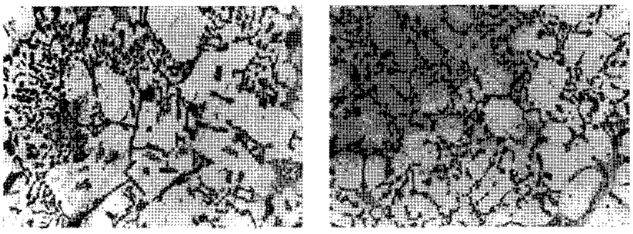
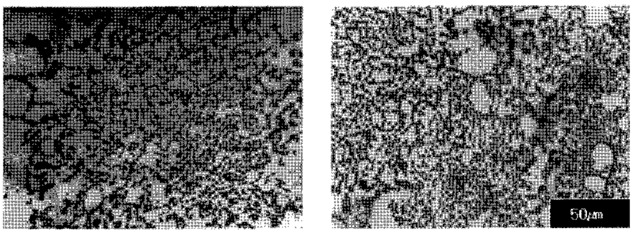


Fig. 3. Microstructure of hypereutectic Al-Si alloys without the modifier and refiner: (a) eutectic Si and (b) primary Si.

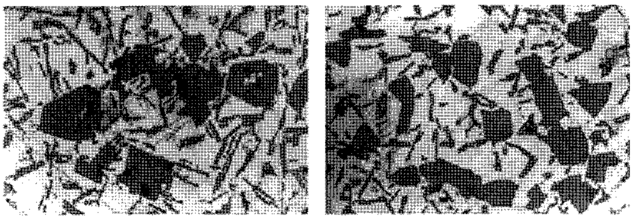


(a) 0.05 wt.% Sr (b) 0.075 wt.% Sr

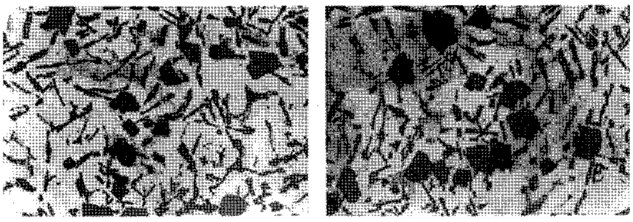


(c) 0.1 wt.% Sr (d) 0.15 wt.% Sr

Fig. 4. Microstructure of the Sr added hypereutectic Al-Si alloys according to Sr contents.

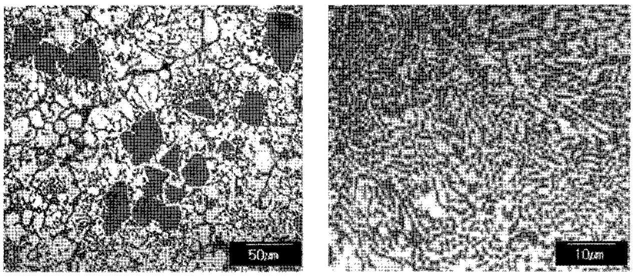


(a) 0.05 wt.% P (b) 0.075 wt.% P



(c) 0.1 wt.% P (d) 0.2 wt.% P

Fig. 5. Microstructure of the P added hypereutectic Al-Si alloys according to P content.



(a) (b)

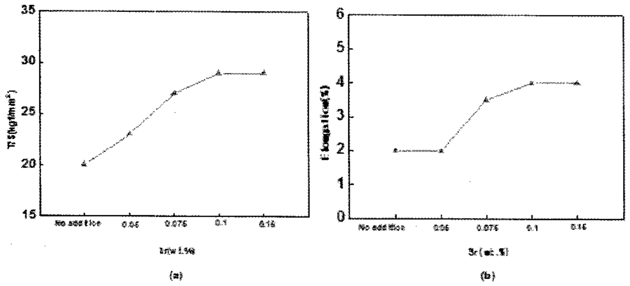
Fig. 6. Microstructure of the 0.075wt.%Sr and 0.1wt.% P added hypereutectic Al-Si alloys.

Si size, AlCuP did not affect on the eutectic Si modification. As shown in Fig. 5 (c), the excellent refinement of the primary Si was observed in the hypereutectic Al-Si alloys involving 0.1wt.% P and more refinement could not be obtained above 0.1wt.% P addition. It has been reported that the refinement of the primary Si by P addition is attributed to AlP precipitation which act as nucleation sites for the primary Si [6-7]. Since AlP precipitations previously existed in AlCuP alloys, the refinement effect of the primary Si was easily obtained in the present study. 0.1wt.% AlCuP addition was determined for the optimum content for the eutectic Si modification.

Fig. 6 shows the as-cast microstructure of the hyper eutectic Al-Si alloys with 0.075wt.% Sr and 0.1wt.% AlCuP. The primary Si precipitations were refined below 50 μm and the eutectic Si were modified as textile type precipitation.

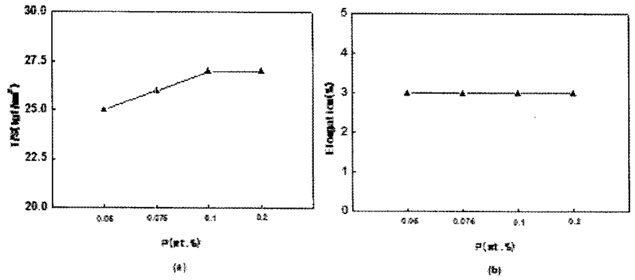
3.2 Mechanical properties change according to the modification treatment

Fig. 7 shows the tensile strength and elongation of the hyper eutectic Al-Si alloys as a function of Sr content and these results well agreed with the change of microstructure. In other words, the tensile strength and elongation increased with the increasing degree of the modification and refinement of eutectic Si. 0.1wt.% Sr addition increased the tensile strength and elongation from 20 kgf/mm^2 and 2% to 27 kgf/mm^2 and 4% respectively. The improvement on the mechanical properties of the hypereutectic Al-Si alloys resulted from the change of eutectic Si from large needle type to fine textile type.



(a) (b)

Fig. 7. Variations of (a) the tensile strength and (b) elongation of the Sr added hypereutectic Al-Si alloys according to Sr content.



(a) (b)

Fig. 8. Variations of (a) the tensile strength and (b) elongation of the P added hypereutectic Al-Si alloys according to P content.

Fig. 8 shows the tensile strength and elongation of the hypereutectic Al-Si alloys with 0.075wt.% Sr according to AlCuP content. When 0.1% wt.% P was added, the hypereutectic Al-Si alloys with 0.075wt.% Sr showed the best mechanical properties. Its tensile strength and elongation were 27 kfg/mm^2 and 3% respectively. That's because the primary and eutectic Si precipitations were successfully modified and refined.

3.3 Forging properties change according to the modification treatment

Fig. 9 shows the relationship between deformation resistance and the stroke-load. The increasing temperature during compressive deformation reduced the deformation resistance, and the deformation resistance was about 3500N in the area of specimen used in this study at 450°C. These results mean that about 60N load is substantially needed per unit area of the forging objects and this value is the important factor for industrial forging process. This is because a forging machine and metallic die can be correctly selected by the precise calculated load. The forging load (F) can be calculated by the equation (2) [6].

$$F = C_1 \cdot K_f \cdot S \tag{2}$$

Here, C$_1$, K$_f$ and S mean a coefficient, the deformation resistance and the contact surface respectively.

Fig. 10 shows the microstructure of the modified hypereutectic specimen after compressive deformation and heat treatment. The grains were oriented to the deformation

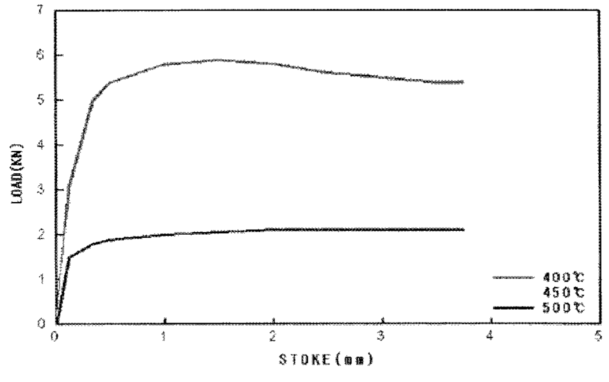


Fig. 9. The stroke-load graph of the hypereutectic Al-Si alloys hot deformed with 30% according to deformation temperature.

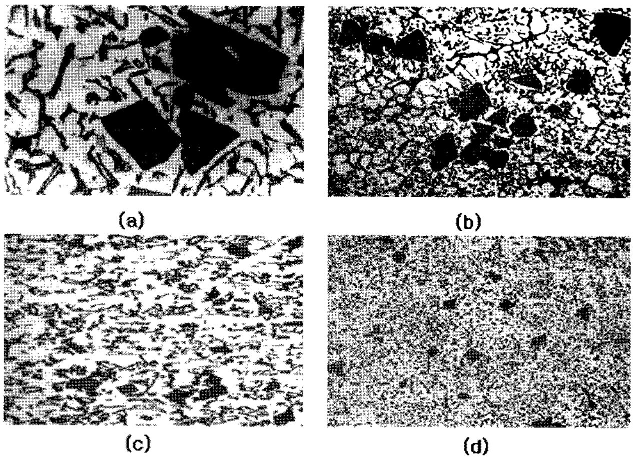
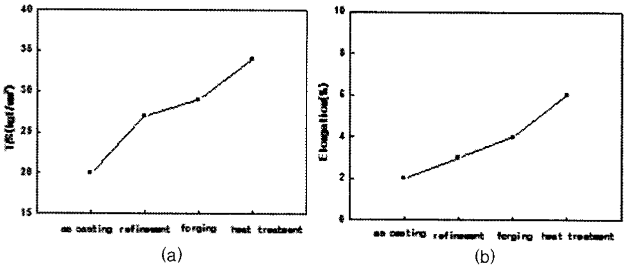


Fig. 10. Microstructure of the modified hypereutectic Al-Si alloys: (a) as-cast, (b) refined, (c) forged and (d) heat-treated.



(a) (b)

Fig. 11. Tensile strength and elongation of the hypereutectic Al-Si alloys.

direction and deformation rate had no effect on the microstructure. Also, large sized microstructure appeared at the high deformation temperature. Therefore, the forging temperature and rate were determined as 450°C and 30% for the application of the process.

The mechanical properties of the compressive deformed specimen with deformation temperature of 450°C and deformation rate of 30% were compared with those of the non-deformed specimen and these results were shown in Fig. 11. The tensile strength and elongation of hot forged specimen were 30 kgf/mm^2 and 4% respectively, which were higher than those of only refined specimen. Also, the further improvements of tensile strength and elongation were achieved by T6 heat treatment after forging. The improvement on mechanical properties of the modified hypereutectic Al-Si alloys after forging resulted from the precipitation refinement.

4. Conclusions

(1) The primary Si refined below 30 μm by adding 0.1wt.% P and 0.075wt.% Sr addition showed the best modification effect for the eutectic Si.

(2) The simultenous addition of 0.1wt.% P and 0.075wt.% Sr refined both the primary and eutectic Si. The tensile strength and elongation of this alloy were repectively 270MPa and 3%.

(3) The optimum compressive deformation temperature and deformation pressure were 450°C and about 60 N/mm^2.

(4) The tensile strength and elongation of the forged specimen were 300MPa and 4% respectively. These values were higher than those of refined specimen. Also, the further improvements of tensile strength and elongation were achieved by T6 heat treatment after forging. The tensile strength and elongation of the forged and heat-treated specimen were 340 MPa and 6% respectively

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