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Effect of Scandium on Mechanical Properties of Aluminum Silicon Casting After Elevated Temperature Exposure

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Recently, it was found that Sc addition refines grain size and modifies eutectic silicon. However, many engineering properties have not been studied in details including the effect of scandium on the high temperature stability of A356, especially after age hardening process. In this study, different levels of Sc and Sc with Zr additions were added to A356 before casting in the permanent mold. Zr was used together with Sc because it was previously reported that Zr increased the effectiveness of Sc in many areas. The A356 samples were age hardened before heating up at different elevated temperatures and for different durations. The samples were then tested for their hardness. It was found that 0.2 and 0.4 wt.% Sc additions and Sc with Zr addition into A356 increased hardness and improved the hardness stability at T6 condition after elevated temperature service due to slower over aging response.

Keywords: *mechanical property; eutectic silicon; aluminum silicon alloy; scandium; zirconium; elevated temperature*

1. Introduction

Unlike other alloying elements, Sc is still considered as a new promising element to refine grains, reduce hot cracking susceptibility, and specially increase the recrystallization temperature to reach about 600°C in wrought aluminum alloys [1]. In addition, Sc can also reduces hot tearing susceptibility and increases corrosion resistance in the high strength aluminum alloys [2]. However, Sc is considerably scarce and is mainly commercially refined in the city of Zhovti Vody, Ukraine. These may be the reasons why Sc has not been widely used in other parts of the world but in aerospace in Russia and also in making baseball bat, light weight bicycle frame, and gun [1]. Recently, Fujikawa [3] showed that Sc addition in pure aluminum could improve mechanical properties, thermal properties, and weldability. Verma et al. [4] concluded that Sc addition in pure aluminum reduced grain sizes by 50% smaller than the master alloy Al-5Ti-1B in the same amount did. Due to scarcity and high cost of Sc, Zr was introduced as partially substituted element for Sc [5-6]. Without sacrifice of high temperature properties, Sc with Zr can refine grain very effectively and also increase thermal stability [7]. However, limited researches have been presented to use Sc in Al-Si casting alloys.

Recently, Prukkanon et al. [8] reported that Sc addition in A356 modified the eutectic silicon to a fibrous structure. However, the effect of Sc addition on mechanical propertt of A356 aluminum alloys has not been studied. In this study, the effect of scandium on the high temperature stability of A356, especially after age hardening process, is presented.

2. Experimental Procedure

This study was done to better understand how scandium may affect the mechanical property after elevated temperature exposure after precipitation hardening.

A 1400 grams of A356 primary ingot was melted in a silicon carbide crucible by a 12-kW induction furnace. The master alloys of Al-2 wt.% Sc and Al-10 wt.% Zr were used to adjust the chemical compositions according to the designed experiment. There were five sets of Sc and Zr additions into A356, i.e., no addition, 0.6 wt.%Sc, 0.4 wt.% Sc, 0.2 wt.% Sc and 0.2 wt.% Sc and 0.2 wt.% Zr. The nominal compositions of all samples are listed in Table 1. Argon was then purged through a stainless steel tube (6-mm inside diameter) coated with zircon into the melt to degas hydrogen. The degassing time was 1 minute with flow rate 4 L/min at 0.2 MPa in each experiment. The molten aluminum alloy was carefully skimmed to remove dross and other impurities before pouring into a stainless steel cup as shown in Fig. 1. All experiments were done with true five replications. Each hardness test on specimen was performed for three times.

After castings, the specimens were solution treated in an electric resistance furnace set at 540 °C. The solution treatment time was set at 5 h before quenching each specimen in a water bath held at 30 °C. The quenched samples were then artificially aged at 155 °C for 8 h. To ensure the accuracy of temperature setting during solution treatment and aging, the temperature of specimen was monitored during the process by using a K-type thermocouple embedded in at least one of the specimens connecting to a data acquisition system.

Table 1. Chemical compositions of A356 aluminum ingots (wt. %)

Alloys	Element (wt.%)								
	Si	Mg	Zn	Sc	Fe	Mn	Ni	Ti	Zr
A356	7.26	0.35	0.007	0.00	0.20	0.007	0.010	0.13	0.00
0.2% Sc	7.38	0.36	0.009	0.23	0.15	0.006	0.011	0.09	0.00
0.4% Sc	7.19	0.34	0.008	0.393	0.12	0.004	0.006	0.09	0.00
0.6% Sc	7.20	0.31	0.008	0.59	0.06	0.004	0.007	0.07	0.00
0.2%Sc +0.2%Zr	7.21	0.32	0.008	0.22	0.10	0.005	0.006	0.07	0.21

After artificial aging, the samples were put into the furnace at various temparatures, i.e. 150, 250, and 350 °C for different durations, i.e. 1, 2, 3, 4, and 5 hours. All specimens were cut at 10 mm from the bottom for metallographic and hardness tests. The samples were ground with SiC-based emery paper, rinsed with water, and then polished using diamond suspension to a 0.1 µm finish. The etchant used for micrograph examination was 1mL HF(48%) in 200mL H_2O. The top portion of the sample was used for microstructure observation to determine modification effects. The samples from each experimental condition were prepared for macrograph examinations to determine grain refinement effects. The etchant used for macrograph examination was Poulton's reagent.The microstructures were examined using optical (OM) for its effect on modification of eutectic silicon.

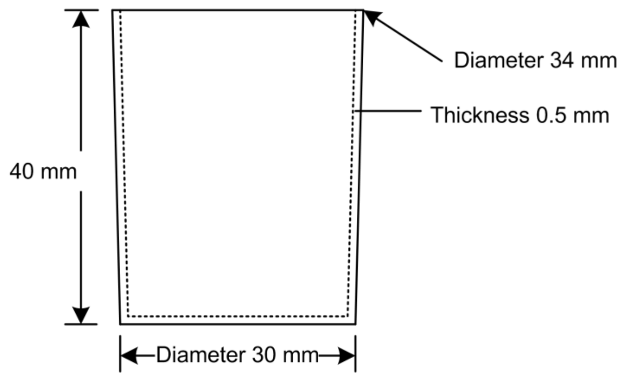

Fig. 1 Austenitic stainless steel cup for microstructure and hardness testing (0.5 mm in thickness)

3. Results and discussions

The results of grain refinement and modification eutectic silicon experiments are shown in Figure 2 and 3. It can be clearly seen that Sc and Sc with Zr additions can significantly refine A356 grain size. The eutectic silicon morphology of the unmodified alloy (A356) is relatively coarse with a plate-like structure with sharp edges. From Fig 3, additions of 0.4wt.%Sc and 0.6wt.%Sc results in a significant effect on the size and morphology of the eutectic silicon. For the 0.2 wt.% Sc treatment, the eutectic morphology was finer and somewhat fibrous. The 0.4 wt.% Sc treatment resulted in complete fibrous structure.

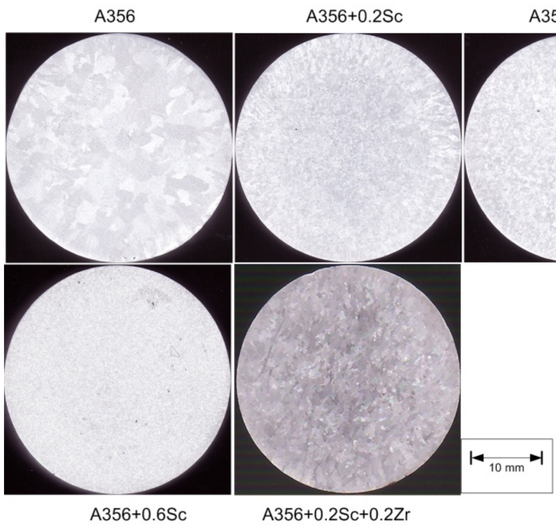

Fig. 2 Macrographs of A356 samples with different chemical compositions

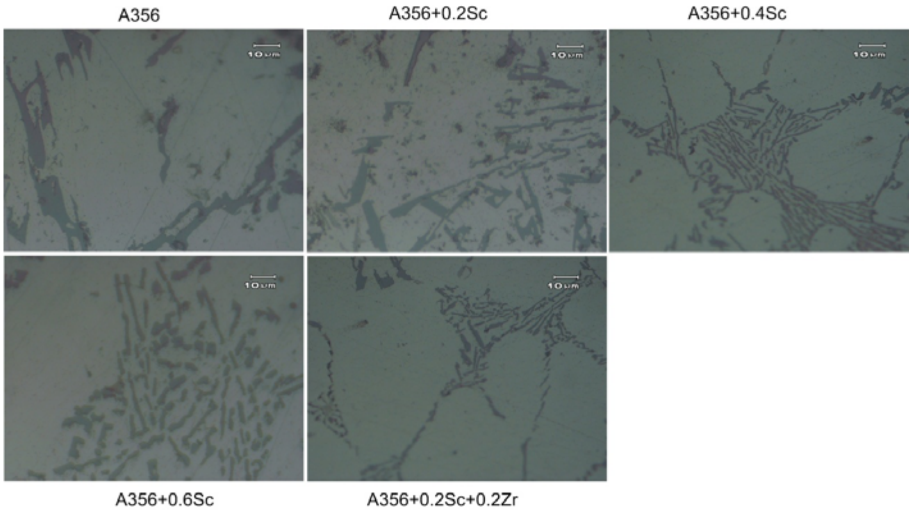

Fig. 3 Micrographs of samples cast into austenitic stainless mold

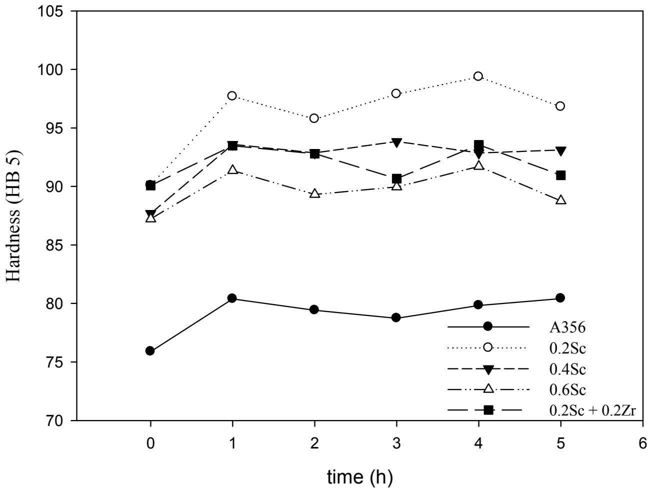

Fig. 4 Effects of Sc and Sc+Zr additions on hardness of samples exposed at 150 °C for various time

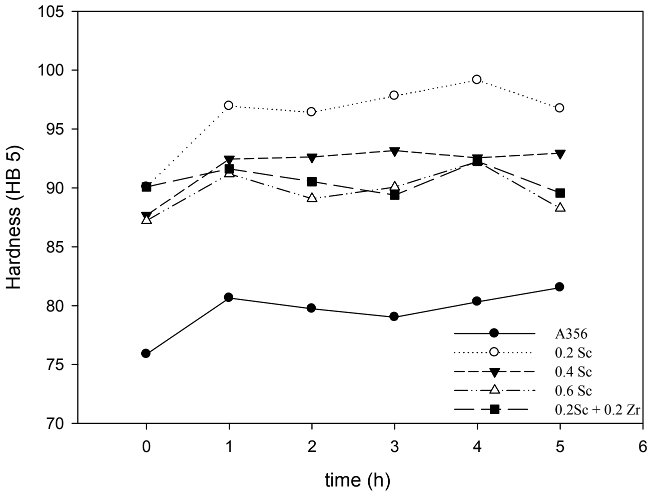

Fig. 5 Effects of Sc and Sc+Zr additions on hardness of samples exposed at 250 °C for various time

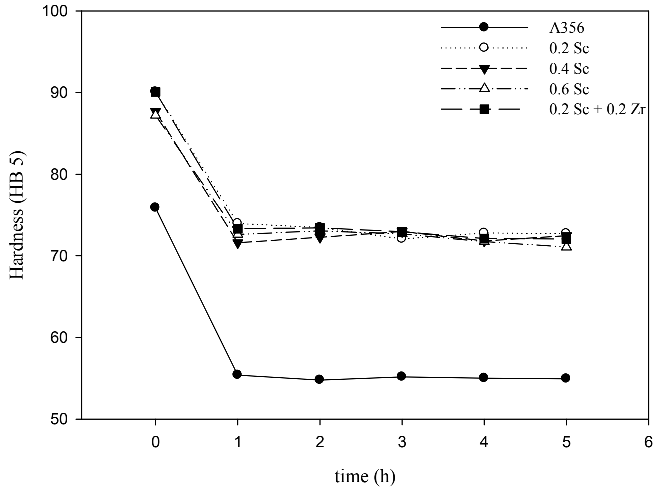

Fig. 6 Effects of Sc and Sc+Zr additions on hardness of samples exposed at 350 °C for various time

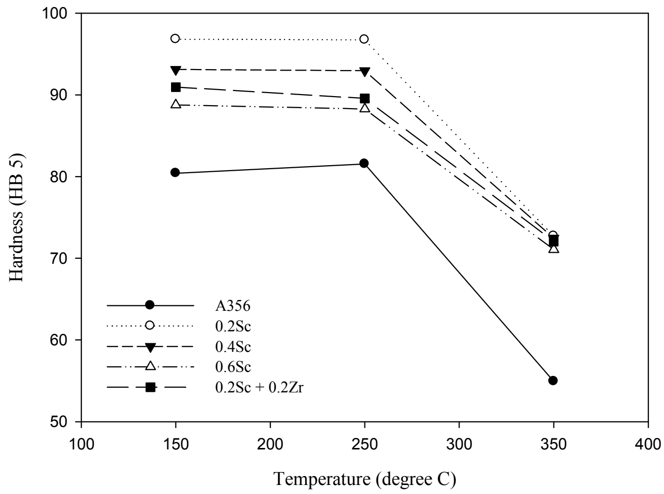

Fig. 7 Effects of Sc and Sc+Zr on hardness of samples exposed for 5h at different temperatures

Table 2 Percentage of hardness reduction after 5 h exposure at different temperature

Alloys	Percentage of hardness reduction after 5 h exposure		
	150 °C	250 °C	350 °C
A356	5.97	7.45	-27.60
0.2Sc	7.46	7.39	-19.27
0.4Sc	6.18	6.01	-17.35
0.6Sc	1.77	1.20	-18.52
0.2Sc+0.2Zr	0.97	-0.57	-20.02

The addition of Sc and Sc with Zr to A356 aluminum alloys essentially increases their hardness with increments of 11.3-14.2 HB depending on the chemical compositions. Even though, the high temperature exposure considerably reduces the hardness after bringing the temperature down to the room temperature. We found that the stability of hardness after high temperature exposure of A356 with Sc and Sc together with Zr significantly improves as shown in Figs. 4-6. Fig. 7 shows the decrease of hardness after high temperature exposure for 5 h. This condition was presented because it can be a representative of the worst case in this study. We found that A356 severely loses its hardness at 27.60%. On the other hands, all A356 samples alloyed with either Sc or Sc together with Zr loses their hardness in smaller magnitudes. The results in Table 2 suggest that the increase in hardness after subsequent holding at high temperature may be the result from further aging process. It can be seen that A356 alloys with Sc and Sc with Zr additions had slower response to subsequent aging process at 150 and 250 °C. This also means that Sc and Sc together with Zr can improve the stability of hardness of A356 after high temperature exposure (350 °C).

The increase in hardness after artificial aging and the improved temperature stability of these Sc-modified alloys as compared to conventional A356 may be associated with the presence of fine secondary precipitates of the ternary (AlScSi) and (AlScZr) phases.

4. Conclusions

The effect of scandium on mechanical properties of aluminum silicon casting after elevated temperature exposure has been examined. The following conclusions are drawn from the scope of this study.

1. The additions of 0.2 wt.%, 0.4 wt.% and 0.6 wt.% of Sc additions increases the hardness of A356 in addition to grain refinement and modification of their eutectic silicon.
2. Sc and Sc together with Zr can improve the stability of hardness of A356 after high temperature exposure. Both sets of alloys show lower tendency to overage during high temperature exposure.
3. Extra Zr addition does not show a significant improvement in grain refinement, hardness and stability of hardness after high temperature exposure. However, Zr improves the modification efficiency of eutectic silicon.
4. The increase in hardness after artificial aging and the improved temperature stability of these Sc-modified alloys as compared to conventional A356 may be associated with the presence of fine secondary precipitates of the ternary (AlScSi) and (AlScZr) phases.

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