Effect of copper additions and heat treatment optimization of Al-7% Si Aluminum Alloy

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In an Industrial context increasingly oriented towards the never ending strive for weight reduction, aluminum alloys are driving steel and cast iron out of the automotive market. Despite the well-known good performances of these alloys, tailoring them suitable for high temperature applications such as a cylinder heads in automotive is still a challenge. In this perspective, the present work focuses on the T6 heat treatment cycle optimization of a commercial foundry aluminum alloy. A Sr-modified and grain refined Al- 7% Si alloy with 3 different levels of Cu additions (0, 0.5 and 1 wt.%) has been selected. The effects of various parameters like solution heat treatment time (up to 12 h) at 803 K (530°C) and artificial aging time (up to 15 h) at 428 K (155°C) were investigated and optimized. Hardness measurements were conducted for each experimental condition. Results have been combine with microstructural investigations carried out to achieve the maximization of Al-matrix reinforcement, finding the best Si particles size-distributions compromise.

KEYWORDS: ALUMINIUM ALLOYS - CASTING - CU ADDITIONS - HEAT TREATMENT OPTIMIZATION- SI PARTICLES DISTRIBUTION

INTRODUCTION

Aluminum alloys are candidate materials for accelerated high strength components where weight saving, and thus better fuel efficiency, are important criterions [1]. Among them, the application of hypoeutectic Al-Si alloys in Automobile, Aerospace and Marine sectors offers an optimum solution on account of their light weight, excellent castability [2] and formability, good mechanical properties [3,4], and high wear and corrosion resistance. Higher strength can be eventually achieved by performing solution heat treatment and subsequent age hardening. In recent years, the process of heat treatment for Al-Si Alloys containing Cu and/or Mg element has been investigated in certain aspect [5]. The age-hardening mechanisms responsible for strengthening is based on the formation of metastable precipitates, promoted by the presence of Cu and Mg, during decomposition of a metastable super saturated solid solution obtained by solution treatment and quenching.

However, the applications are restricted to low temperature, because precipitation-hardened Al-alloys, typically belonging to the Al-Si-Cu and Al-Si-Mg system, do not withstand temperature above 473 K (200° C). Therefore, contemporary automotive engines operate at the highest temperatures reaching up to 523 K (250° C) [6] creates demanding operating requirement for existing Al-Si alloys. Tailoring them suitable for high temperature applications such as a cylinder heads in automotive is still a challenge. In this context the present study proposes an indication toward the heat treatment optimization, and thus microstructural features optimization of one the most employed foundry alloy, known as A356, containing different level of Cu (0, 0.5 and 1 wt.%), with final aim to obtain in the next future, a competitive material for high temperature applications.

Besides the strengthening achieved through the precipitation hardening mechanism, is worth to consider the role of the Si-particles in reinforcing the Aluminum matrix. Indeed, cast Al-Si-Cu-Mg can be ascribed as in situ-metal matrix composites

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(MMC) [7]. The effect of cupper addition on the heat treatment optimization has been performed by analyzing the hardness and electrical conductivity response at different solution heat treatment and aging times. Based on previous studies [7,8]. results have been combine with microstructural investigations carried out to achieve the maximization of Al-matrix reinforcement, finding the best Si particles size-distribution compromise.

MATERIALS AND METHODS

The experimental materials used in this study were produced by Hydro in Norway. Commercial Sr-modified A356 alloy was melted in a boron-nitride coated clay-graphite crucible at 1023 K (750 °C), and grain refined by means of Al-5Ti-1B master alloys additions. Cu was added to the melt in form of pure cupper grains according to the targeted nominal concentrations of 0, 0.5 and 1 wt%, molten metal was successively stirred and allowed to settle for 30 min to ensure complete dissolution. Alloys were then degassed with argon gas for 5 min just prior to be poured in a cupper mould of 60x100x40 mm. The temperature of the die was kept at 323 K (50 °C) during the casting trials. Samples from the three different melts were taken and analysed by optical emission spectroscopy (OES). The chemical composition of the alloys is given in Tab. 1.

Tab. 1 - Chemical composition (wt%) of the alloys as measured by OES and their classification

CU-CONTAINING ALLOYS: CHEMICAL COMPOSITIONS AND CODES									
Alloy	**Si**	**Fe**	**Mg**	**Cu**	**Ti**	**B**	**Sr**	**Al**	**CODE**
A356	6.92	0.09	0.25	**74 ppm**	0.09	10.4 ppm	98.9 ppm	bal.	Cu0
A356 + 0.5 wt% Cu	6.58	0.09	0.27	**0.49**	0.10	6.2 ppm	167 ppm	bal.	Cu0.5
A356 + 1 wt% Cu	6.23	0.08	0.26	**1.15**	0.11	7.1 ppm	193	bal.	Cu1

For annealing heat treatment an air circulating furnace was used. The alloys were heat treated from room temperature with a heating rate of 250 °C/h up to annealing temperatures of 803 K (530°C). At the annealing temperature the samples were kept for 0, 2, 5, 8, 10, and 12 h and then quenched into cold water. Samples from the three experimental conditions were solution heat treated at 803 K (530°C) for 2, 3, 5, 8, 10,12 h and then quenched in a water bath at 293 K (20 °C). Once optimized the solution heat treatment, the chosen samples were stored 1h at room temperature and consequently aged at 428 K (155°C) for 1, 2, 4, 6, 10 and 15 h. Different measurements were performed on the alloys, including electrical conductivity measurement by Foerster Sigmatest 2.069 and Vickers hardness measurement by a Leica VHNT micro hardness tester. Vickers Hardness (HV) measurements were done with 500 g load. Samples for microstructural investigations were cut from the tensile specimens, embedded in phenolic resin and prepared using standard grinding and polishing procedures. Microstructure analyses were performed using a LEICA DMi8 polarized light optical microscope (OM).

RESULTS AND DISCUSSION

Fig. 1 shows the Vickers hardness and the Electrical conductivity (boxes implemented in the main tables) evolutions of the three alloys as a function of annealing time for the two heat treatment conditions: a) solution heat treatment (SHT) at 803 K (530°C) and b) aging at 428 K (155°C). It can be seen that the chemical composition has a strong influence on the hardness values. Increasing the Cu content results, as many researchers stated [9,10,11], in an overall increase in hardness and, in a corresponding decrease in electrical conductivity as more solute atoms undergo to solid solution.

The hardness curve shown in Fig. 1a, reflects the coexistence of two counteracting phenomena: on one side there is the spheroidisation and the coarsening of the Si-particles responsible of the initial decay in hardness and, on the other side, there is the solid solution strengthening promoted by the annealing permanence at high temperature. According to Mulazimoglu [12] the electrical conductivity (box in Fig.1a) of Al-Mg-Si alloy is significantly influenced by changes in morphology of the eutectic Silicon, and in particular, has been found that the electrons flow more easily through the finer eutectic silicon in the modified alloy than in the coarse acicular silicon present in the unmodified alloys.

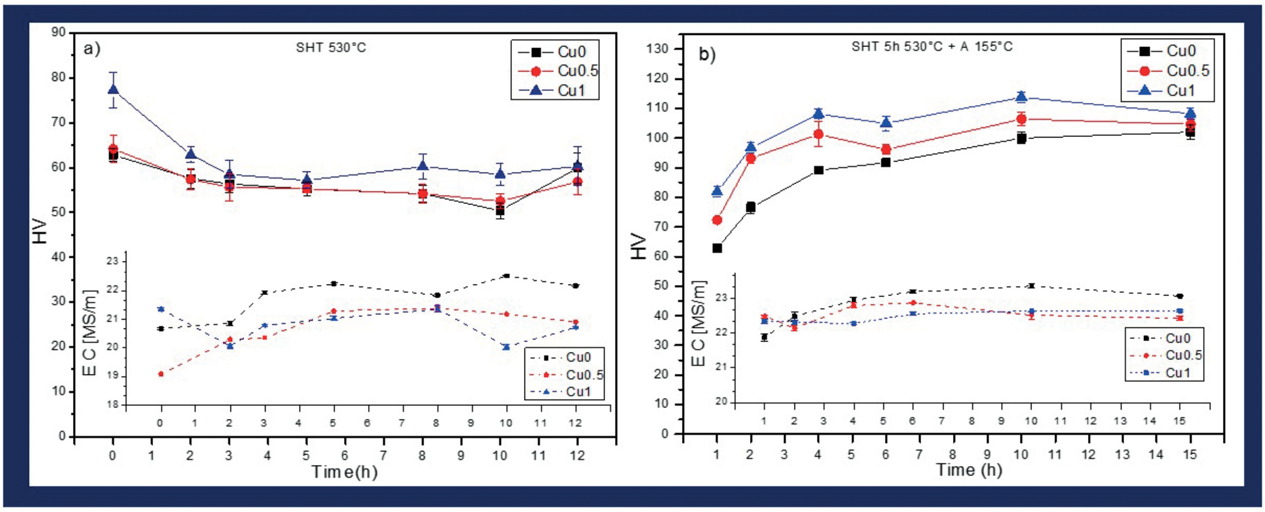

Fig. 1 - Evolution of Vickers Hardness and Electrical Conductivity with time during
a) Solution Heat Treatment at 803 K (530°C) and b) Aging at 428 K (155°C)

In analogy with this study, it is possible to correlate the undetected effects of the increased supersaturation of the matrix on the electrical conductivity to the same behavior. Solution heat treatment, accompanied by evolution in the shape of the eutectic silicon, presumably masks the effect of the supersaturation of the matrix on the electrical conductivity. Both the data curves start to stabilizes at a corresponding time of 5h, suggesting a good compromise between the dissolution of the hardening elements and the spheroidisationd and coarsening of the Si-particles. Hence, 5h exposure at 803 K (530°C), has been selected as the optimized SHT for the alloys considered.
With reference to the aging treatment (Fig. 1b) Cu-containing alloys revealed, in agreement with previous findings [5,13], two aging peaks at 4 h and 10 h, whereas the Cu-free alloy offers an increasing tendency, leading to the highest hardness value at 15 h. It has been reported [5] that, at the early stage of aging, fine and profuse GP zone homogeneously distribute in the matrix effecting sensibly the strengthening. On the other hand, in the stage of transition from GP zone to metastable phases, the density of GP zone decrease for dissolution, and the metastable precipitates size are too small to effectively resist the movement of dislocation, driving the aging response between two aging peaks of Al-Si-Cu-Mg alloy. During the aging Si, Mg and Cu leaves the Al lattice to produce coherent precipitates at the expense of the SS, hence electrical conductivity rises. Similar trends were observed in Al-Mn rich alloy by A.M. Muggerud [14].
In order to endorse the heat treatment optimization selection, representative micrographs are presented in Fig. 2. As cast microstructures (a and b in Fig. 2) show mainly equiaxed Al-dendrites gathered with the Eutectic phase. Si particles grow and coarsen as a consequence of the selected heat treatment involving 5h at 803 K (530°C) followed by 10 h ageing at 428 K (155°C), referred as Peak Aged in Fig. 2. Comparing the Cu-free and the 1 wt% Cu -containg alloys(c and d in Fig. 2) is possible to notice the beneficial influence of Cu on the Si particles spheroidisation, even though the phenomenon is accompanied by a more evident Si-particles agglomeration.

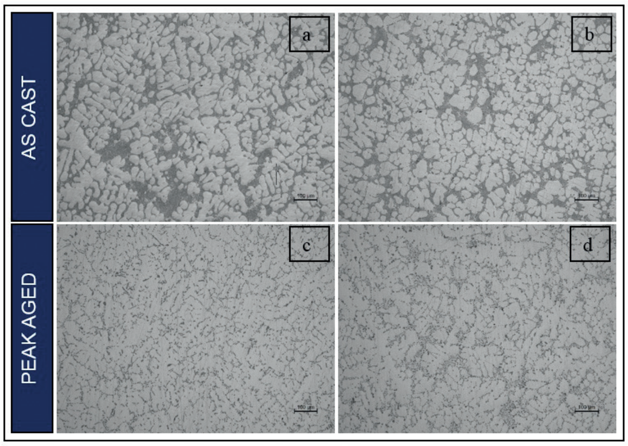

Fig.2 - Cu-free and Cu-containing alloys (1 wt% Cu) micrographs in both as cast (a, b) and peak aged (c, d) conditions

Heat treatment optimization and Cu- additions exert a significant role on the size of Eutectic Si-Particles. In order to evaluate the influence of these parameters, a distribution of the Si- particles equivalent diameter have been presented in Fig. 3.

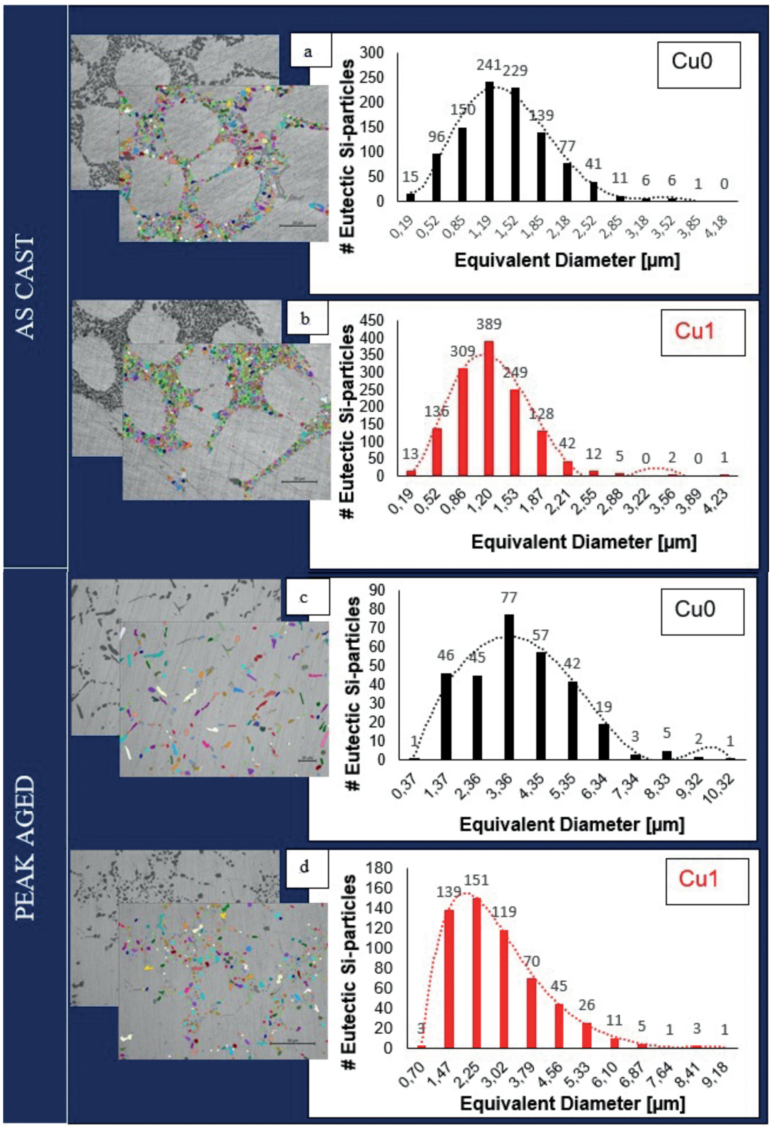

Fig. 3 - Distribution of the Eutectict Si-Particles' equivalent diameter. Comparison between Cu-free and Cu-containing alloys (1 wt% Cu) in both as cast (a, b) and peak aged (c, d) conditions

The distributions, performed using chi-square goodness-of-fit test have been plotted for representative alloys which encompass Cu-free and 1%wt Cu-containing alloys for both as cast (AC) and peak aged (PA) conditions, respectively a and b (AC), c and d (PA) in Fig. 3. As cast distributions revealed that Sr-modification strongly affect the Si-particles size, as compared to the unmodified alloys [15]. Equivalent diameters (ED) ranges between 0.2 to 4 µm, where the average is given at 1.2 µm for the two Cu-free and 1%wt Cu-containing alloys. The frequencies, and thus the number of Si-particles having an ED larger than 3 µm are negligible in the1%wt Cu-containing alloy, as compared to the Cu-free alloy which presents in contrast a more significant population density. Nevertheless, the higher Sr-content in the Cu-containing alloys, resulted after the casting, prevent us to address the decreasing Si-particles size phenomenon, indicated by the distributions, to the Cu addition.

Under the peak aged condition, individual particles coarsen with becoming rounded during the heat treatment and therefore an overall increase in Si-particles size is offered [16].
ED values ranges between 0,4 and 10 µm. Cu-free alloy's ED values result in a much wider distribution as compare to the 1%wt Cu-containing alloy, presenting an average value localized in correspondence of 3.4 µm versus 2.2 µm. Moreover, the tendency of the curve obtained in presence of Cu, shows a denser distribution in the proximity of the average ED value, suggesting beside the Sr-modification, a beneficial influence of Cu on the Si-particles size.

CONCLUSIONS

The present study proposes an indication toward the heat treatment optimization, and thus microstructural features optimization of one the most employed foundry alloy, known as A356,

containing different level of Cu (0, 0.5 and 1 wt.%), with final aim to obtain in the next future, a competitive material for high temperature applications. The effect of Cu addition on the heat treatment optimization has been performed by analyzing the hardness and electrical conductivity response at different solution heat treatment and aging times. Results have been combine with microstructural investigations carried out to achieve the maximization of Al-matrix reinforcement, finding the best Si particles size-distributions compromise.
It has been found that increasing the Cu content turns in an overall increase in hardness and, in a corresponding decrease in electrical conductivity as more solute atoms cohabit the Al-lattice. Both hardness and electrical conductivity curves stabilizes after 5h, suggesting the mutual cooperation between dissolution of the hardening elements and the spheroidisation and coarsening of the Si-particles. Hence, 5h exposure at 803 K (530°C), has been selected as the optimized SHT for the alloys considered.
Aging curve of the Cu-containing alloys revealed two peaks at 4 h and 10 h, whereas the Cu-free alloy offers an increasing tendency, leading to the highest hardness value at 15 h. Si, Mg and Cu leaves the Al lattice to produce coherent precipitates at the expense of the SS, hence electrical conductivity rises. Taking into account the two data responses, 10h exposure at 428 K (155°C), corresponding to the peak aged values, has been selected as the optimized aging for the alloys considered. The distribution of the Si-particles equivalent diameter revealed the beneficial influenced of Cu addition under the peak aged condition.

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