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Effect of non-equilibrium heat treatments on microstructure and tensile properties of an Al-Si-Cu alloy

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A B S T R A C T

The influence of heat treatment on the morphology of ß-Al_5FeSi inclusions in Fe-rich Al-Si-Cu was investigated and the tensile properties were improved. Samples were sand casted and subjected to various T6 heat treatments. Metallographic samples were examined by optical microscopy as well as scanning electron microscopy (SEM) and the average length and area fraction of the Fe-rich phases were quantified with image analysis software. It was found that a minimum solution temperature at 520–525 °C and solution time of 1 h is required for a significant fragmentation and dissolution of the detrimental long-needle-like ß-Al_5FeSi inclusions. Solution time longer than 2 h leads to incipient melting of Cu-rich phases and coarsening of the eutectic Si. Tensile specimens were machined from the heat-treated samples and tensile tests performed. The highest ultimate tensile corresponds to the samples heat treated at 525 °C for 1.5 h. Fracture surface observations indicate a transgranular cleavage mechanism for the non-treated specimens, and massive ß-Al_5FeSi platelets were identified as main crack initiation sites. After heat treatment, a mixed fracture mode and dissolved ß-Al_5FeSi phases were observed.

1. Introduction

The car industry demands optimization of both process and material reliability, which requires a thorough understanding of the relationship between the manufacturing process, microstructure and mechanical properties. One of the most important alloys in the automotive industry is the Al-Si-Cu system, essential in modern lightweight vehicles and currently used for a wide range of components, such as engine blocks, cylinder heads and chassis components [1].

More than half of all the aluminum currently produced in the EU originates from recycled raw materials and that trend is on the increase due to its ecological and economic advantages. The production of recycled aluminum requires 95% less energy than primary aluminum, which leads to a significant reduction of the CO_2 emission and productions costs [2,3].

Nevertheless, there is a number of accumulated elements in recycled aluminum which can only be removed with a very costly process from the melt. This limits the use for high-performance applications, where fatigue reliability has to be ensured. In this sense, iron is of particular interest because it is present in much higher concentrations in recycled aluminum, and as a consequence, brittle intermetallic inclusions are formed. The most detrimental Fe-rich compound, especially for Very-High-Cycling-Fatigue, is the long-needle-like ß-Al_5FeSi phase, which generates high local stress concentrations, from which cracks initiate and cause premature failure [4–6].

Several studies have suggested non-equilibrium T6 heat treatment, with solution temperature above the final solidification temperature of the alloy, in order to avoid the detrimental effect of high iron concentration in the Al-Si-Cu alloys. Narayanan et al. [7] studied the dissolution of the ß-Al_5FeSi intermetallic inclusions for different solution treatments of Fe-rich Al-Si alloys and Tillova et al. [8] reported the effect of heat treatment on the morphology of iron-rich inclusions in recycled Al-Si-Cu.

The limited knowledge existing on the improvement of mechanical properties of iron rich near-to-eutectic Al-Si-Cu alloys after heat treatment requires further research and a deeper understanding of the fragmentation and dissolution process of the ß-Al_5FeSi. In this work, the effect of non-equilibrium heat treatment on the microstructure and mechanical properties of Al-Si-Cu alloy with high iron content was studied. Several microstructural features were analyzed, with special focus on the morphology of ß-Al_5FeSi phases, whose area fraction and average size were quantitatively evaluated. The influence of the fragmentation and dissolution of the iron-rich compounds on the mechanical properties

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Table 1
Chemical composition of the Al-Si-Cu alloy (wt%).

Si	Cu	Mg	Fe	Zn	Mn	Ni	Ti	Al
12.96	1.52	0.68	0.6	0.48	0.17	0.05	0.04	Rest

Table 2
Combination of solution temperature and time in the Design of Experiments.

Heat treatment	Solution temperature [°C]	Solution time [h]
1	525	7
2	495	7
3	525	1
4	495	1
5	525	4
6	495	4
7	510	7
8	510	1
9	510	4

Table 3
Combination of ageing temperature and time.

Heat treatment	Ageing temperature [°C]	Ageing time [h]
10	220	11
11	160	11
12	220	1
13	160	1
14	220	6
15	160	6
16	190	11
17	190	1
18	190	6

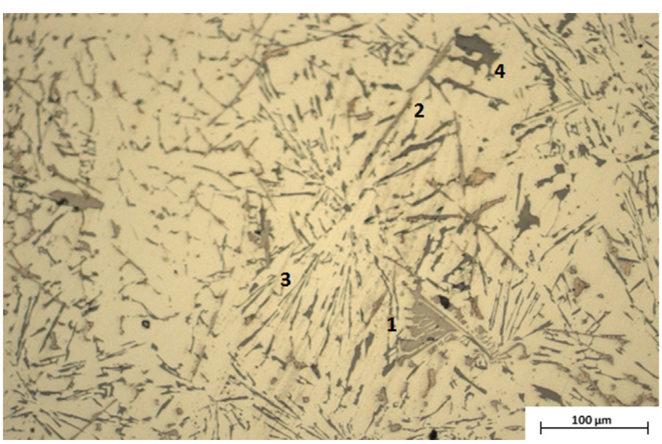

Fig. 1. Main inclusions of recycled Al-Si-Cu alloy: 1 – α-$Al_{15}(FeMn)_3Si_2$, 2 – β-Al_5FeSi, 3 – Euectic silicon, 4 – $CuAl_2$.

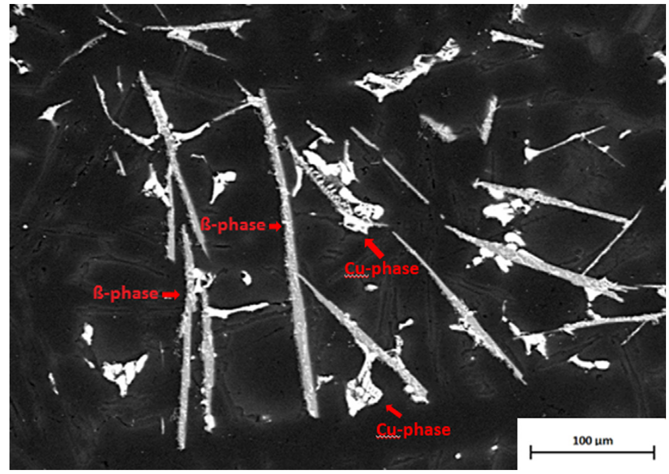

Fig. 2. Long needle-like ß-phases with Cu-rich intermetallics.

was studied by conducting tensile tests with as-cast and heat-treated samples.

2. Materials and experiments

The chemical composition of the Fe-rich near-to-eutectic Al-Si-Cu alloy used in the present work is given in Table 1. An Al–25%Fe master alloy was used in order to achieve the required Fe content in the Al-Si-Cu system. It contains 0.6 wt% of Fe with a relationship Mn: Fe of 0.28. The Fe content tends to form a considerable amount of ß-Al_5FeSi, although the Mn: Fe relationship used can promote partial substitution of ß-phase with the less detrimental α-$Al_{15}(Fe, Mn)_3Si_2$ [9].

The material was sand casted at 760 °C ± 5 °C in form of 4 mm thickness sheets in a sodium silicate mold at room temperature. Plates of 50 mm width were cut and heat treated at different levels of the standard T6 heat treatment.

Statistical Design of Experiments (DOE) was used as an experimental technique for analyzing the influence of different heat treatment parameters on the fragmentation and dissolution of Fe-rich inclusions. As a first step, solution temperature and time were selected as control factors with three levels. Non-equilibrium heat treatments, with a solution temperature above the solidification point of copper intermetallics, enable the dissolution of copper-rich phases and have been reported to increase mechanical properties in the range from 495 °C to 525 °C [10]. Moreover, several studies have concluded that the dissolution of iron rich intermetallics are a function of temperature and time when the time is below 7 h [7], and as a consequence, the range 1 h–7 h was selected. In both ranges a middle value was also analyzed in order to take into account possible non-linear relationships, resulting in heat treatment matrix shown in Table 2.

Heating and cooling rate are very important factors both in the dissolution and precipitation process, thus they have been carefully selected in order to promote the desired dissolution of inclusions. Kessler et al. reported that the dissolution process is incomplete and suppressed with increasing heating rate [11], and therefore, a maximum heating rate of 0.7 K/s was selected. Alloys with a high amount of excess silicon tend to have high critical cooling rates [12], therefore a cooling rate of 300 K/s was selected. In order to measure heating rates and determine cooling rates as function of water temperature, three thermoelements were riveted at three equidistant points along the length of the sample and connected to Yokogawa MV-100 mobile temperature recorder. A cooling rate of 300 K/s was obtained at 70 °C of water temperature in the temperature range of 450–200 °C, which is the range that has been found to have the most critical influence on the strength [13].

Immediately after the quenching process, samples were subjected to artificial ageing treatment at a temperature of 220 °C during 6 h. As second step, the optimal solution treatment in terms of microstructure and tensile properties was selected and the influence of ageing treatment was analyzed. An ageing temperature range between 160–220 °C and a time range between 1 h and 11 h was considered resulting in the following parameter matrix (see Table 3).