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Effect of the T6 Heat Treatment on Microhardness of a Directionally Solidified Aluminum-Based 319 Alloy

Igor Alexsander Barbosa Magno[a], Fabricio Vinicius Andrade de Souza[a], André dos Santos Barros[a], Marlo Oliveira Costa[b], Jacson Malcher Nascimento[a], Thiago Antônio Paixão de Sousa Costa[b], Otávio Fernandes Lima da Rocha[a,b]*

[a]*Universidade Federal do Pará - UFPA, Rua Augusto Corrêa, 1, 66075-970, Belém, PA, Brazil*
[b]*Instituto de Educação, Ciência e Tecnologia do Pará, Avenida Almirante Barroso, 1155, 66093-020, Belém, PA, Brazil*

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Aluminum alloys of the ANSI series 319 present Si and Cu as the main alloying elements and the mechanical strength of these alloys can be improved by the precipitation of the metastable Al_2Cu phase during the ageing heat treatment. In this paper, the Al-5.5wt.%Si-3wt.%Cu alloy was elaborated and solidified in a water-cooled horizontal directional solidification device. The as-cast ingot was subjected to the precipitation hardening heat treatment (T6 heat treatment), which consisted of: solution for 5 h at 490°C±2°C, followed by quenching in water at 60°C±2°C and ageing for 3 h at 155°C±2°C, and cooling-air. Secondary dendrite arm spacing (λ_2) measurements were carried out before and after T6 heat treatment. The mechanical strength of the alloy was investigated by the microhardness test. It has been found that the heat treatment did not influence the λ_2 values, however, highest HV values have been observed for the heat-treated samples.

Keywords: *T6 Heat Treatment, Microstructure, Al-Cu-Si Alloys.*

1. Introduction

It is known that among metals of major industrial interest, aluminum is a new material, compared, for example, with iron, copper, tin, lead, etc. The industry's interest in aluminum is due to its high strength/weight ratio. In addition, it is corrosion resistant and has a high electrical and thermal conductivity. Other elements in controlled composition are added to improve specific properties. Addition of Si, for example, increases the fluidity and decreases the solidification shrinkage, resulting in an increase in castability. The addition of copper to the Al-Si alloy causes the formation of Al_2Cu phase and other intermetallic compounds, which increases mechanical strength and enables hardening by heat treatment. In unmodified alloys copper is present primarily as Al_2Cu or Al-Al_2Cu-Si eutectic phase.

Aluminum-based multicomponent alloys, especially those of the 319 series [Al-(3-4)wt.%Cu-(5.5-10)wt.%Si] have attracted attention of many researchers, engineers and designers as promising structural materials and are now being employed with growing frequency in automotive industry or aerospace applications[1]. In 319 alloys, the copper intermetallic phase (Al_2Cu), the porosity size and distribution, the morphology, size, and distribution of eutectic silicon particle, and the degree of supersaturation of Cu in the α-Al matrix, after solution heat treatment, are the main parameters expected to control the mechanical propertie[1,2]. Is is known that the increasing on hardness is due to Al_2Cu phase precipitation in the aluminum dendritic network and changes on silicon morphology[1,2].

The Aluminum Association has standardized the definitions and nomenclature for heat treatment, which involves the following stages[3].

1. Solution treatment at a relatively high temperature to dissolve the Al_2Cu intermetallic, formed during solidification;
2. Quenching, usually to temperature controled, to obtain a supersaturated solid solution;
3. Age hardening, to cause precipitation from the supersaturated solid solution, either at room temperature (natural ageing) or at an elevated temperature (artificial ageing).

It is observed by the solidification path of the investigated Al-Cu-Si alloy that three main phases are formed, which are: (1) Al-rich primary phase (α-Al), constituted of a dendritic network; (2) secondary phase, with lamellar silicon particles and (3) tertiary phase, formed by the Al_2Cu -stoichiometric intermetallic compound. The iron element is present in the composition of aluminum-based alloys, it is often regarded as an undesirable impurity as it forms long and brittle β-Al_5FeSi plates that initiate and link fracture, in addition to other Fe intermetallics that appear with the solidification. Costa et al[1] has presented the solidification path of the Al-3wt%Cu-5.5wt%Si alloy and the Figure 1 schematizes the phase transformations that occur the its during solidification. The defects, the morphology of eutectic and the morphology of intermetallic phases have an important effect on the ultimate mechanical properties of the casting[1-4].

*e-mail: otvrocha@oi.com.br

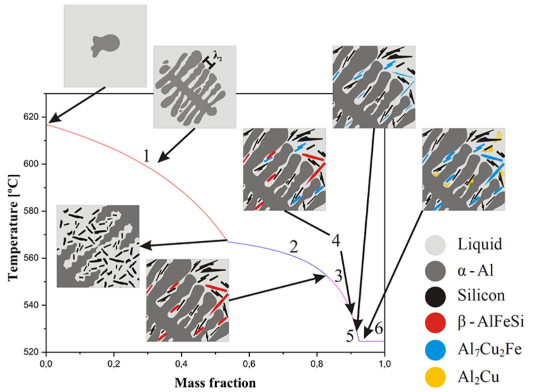

Figure 1. Solidification path of the investigated alloy: Reactions occurring during the solidification process.

Thus, this work aimed to characterize and quantify the microstructure, before and after T6-heat treatment, in samples of a horizontally solidified Al-5.5wt%Si-3.0wt%Cu alloy. Standard metallographic techniques were applied to characterize and quantify the secondary dentrite arm spacings. Finally, microhardness measurements (HV) have been carried out and plotted with position along the casting ingot.

2. Experimental Procedure

The casting assembly used in the horizontal directional solidification (HDS) experiment has been detailed in a previous article[5,6]. This solidification setup was designed in such way that heat was extracted only through the water-cooled lateral metal/mold, promoting horizontal directional solidification. The directional solidification experiment was carried out with a nominal composition of Al-5.5wt.%Si-3.0wt.%Cu alloy. Continuous temperature measurements in the casting were monitored during the HDS through the output of a bank of fine type K thermocouples sheathed in 1.6 mm steel tubes and positioned at 5, 15, 30, 50, 70 e 90 mm from the chill. The results of experimental thermal analysis have been used to determine the displacement of the *liquidus* isotherm, i.e., a plot of position from the metal/mold interface as a function of time corresponding to the liquidus front passing by each thermocouple.

The T6 heat treatment, which was performed according to the methodology proposed by Costa et al[1] and Jerry et al[7], consisted of:

a) solution heat treatment for 5h at 490ºC ± 2ºC;
b) quenching in warm water at 60ºC ± 2ºC;
c) immediate aging for 3 h at 155ºC ± 2ºC;
d) air cooling.

The solution treatment aimed to dissolve the equilibrium Al_2Cu intermetallic particles in the Al-rich matrix (α-Al) and with the quenching in warm water to obtain a supersaturated solid solution ($\alpha\text{-}Al_{SSS}$) with the formation of an Al_2Cu-intermetallic metastable phase dispersed in $\alpha\text{-}Al_{SSS}$ solution, whose phase was precipitated with the artificial aging treatment. Figure 2 shows a schematic representative of the stages performed during the T6-heat treatment.

The rectangular shaped ingot was sectioned along its longitudinal axis to reveal the macrostructure. One of the sectioned parts of the as-cast ingot was used to develop the heat-treatment. Samples for metallographic analysis have been extracted from the as-cast and heat-treated ingots. In order to characterize and quantify the dendritic structure, selected longitudinal sections of the as-cast and heat-treated part (in positions 3, 5, 10, 15, 20, 30, 40, 50, 60, 80 and 100 mm from the metal/mold interface) were polished and etched with an acid solution (NaOH 5%) for microstructural analysis. The secondary dendrite arm spacing was measured by averaging the distance between adjacent side branches on longitudinal sections of primary dendrite stalks[8]. Figure 3a presents the macrostructure of the investigated alloy, showing the removal region of the samples for analysis of the microstructure. Figure 3b shows the methodology developed for λ_2 measuring.

The Vickers microhardness test consisted of applying a load through a pyramidal of square base shape indenter made of diamond and supposed to carry out on flat, polished and clean surface. The corresponding positions were 3, 5, 10, 15, 20, 30, 40, 50, 60, 80 and 100 mm. Microhardness tests

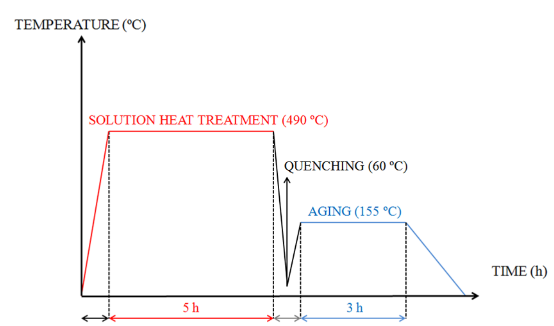

Figure 2. Schematic representation of the stages of the T6-heat treatment applied in this work.

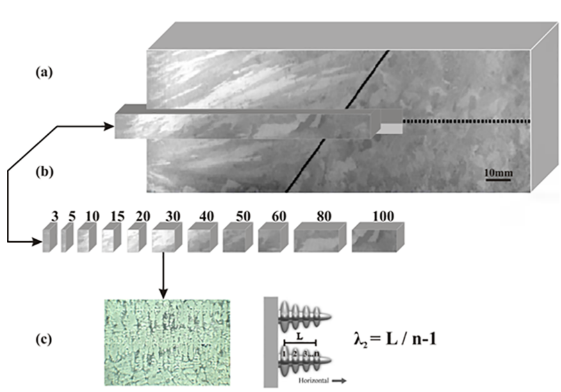

Figure 3. (a) Solidification macrostructure, (b) Removal of samples for microstructural analysis and (c) Technique used for λ_2 measuring.

were conducted on each sample using a 50 g load and a dwell time of 10 s, as proposed by Çadirli[9] and Kaya et al[10]. The adopted Vickers microhardness values are the average of at least 20 different measurements on the transverse section of each sample, using the methodology proposed by Barros et al[11] and Guimaraes[12]. The minimum distances for indentations have been defined by ASTM E384[13], ASTM E-92[14] and ASM HANDBOOK[15]. Representative scheme of HV measurement in the analyzed samples can be seen in Figure 4.

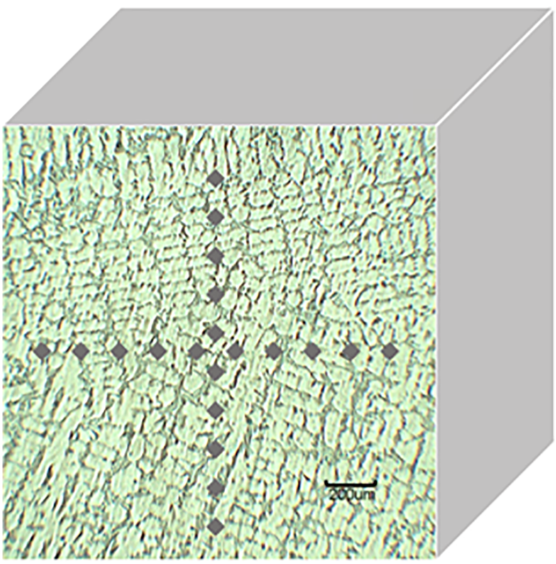

Figure 4. Representative scheme of HV measurements in as-cast and heat-treated samples of the investigated alloy in this work.

3. Results and Discussion

Typical microstructures of as-cast and heat-teated samples of the investigated alloy are shown in Figure 5. It is observed that the secondary dendrite arm spacings were sufficiently distinct to make reasonably accurate measurements along the casting length. Figure 6 shows the average (and, minimum and maximum) λ_2 experimental values as a function of distance from the metal-mold interface. It is evidenced λ_2 increase with the distance from the heat-extracting surface. This can be explained by the fact that the use of a water-cooled mold imposes higher values of tip growth rates and cooling rates near the casting surface and a decreasing profile along the casting due to the increasing thermal resistance of the solidified shell with distance from the cooled surface. However, the T6-heat treatment applied in the as-cast samples has not affected the secondary dendritic spacing. This can be confirmed by the Figure 6 that a single dendritic growth law has been found for both as-cast and heat-treated samples, give by $\lambda_2 = 6.8(P)^{0.44}$.

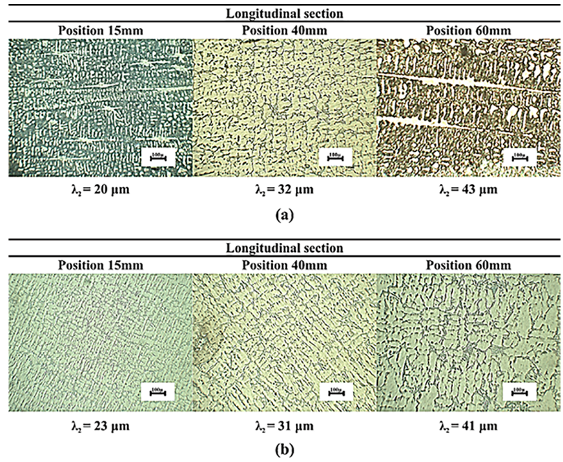

Figure 5. Revealed micrographs of the investigated alloy, showing the dendritic microstructures of the samples: (a) as-cast and (b) heat-treated

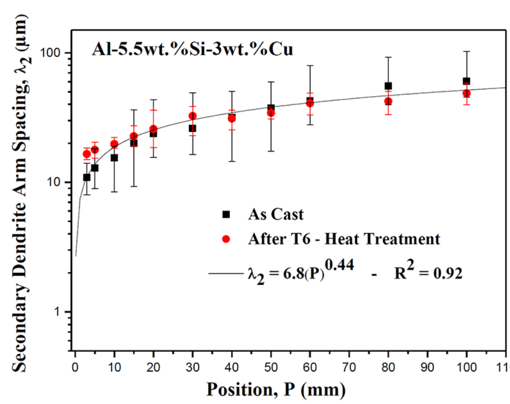

Figure 6. Correlation between the secondary dendrite arm spacing with *liquid* isotherm position.

In order to analyze the combined effects of the dendritic microstructure and the solution heat treatment on the change of Si morphology, a more detailed analysis of the optical microstructures of two position of each sample (as-cast and heat-treated) has been carried out using an image processing software (Image J) and Figure 7 shows the resulting microstructures. It is observed that the operational parameters (temperature and time) established for the solution treatment applied in this work have been more efficient for refined dendritic structures, i.e., for smaller λ_2 values, since more spheroidized Si particles have been obtained in positions closer to the cooled interface.

The dependence of the microhardness (HV) with the distance (P) from the metal/mold interface can be seen in Figure 8. It

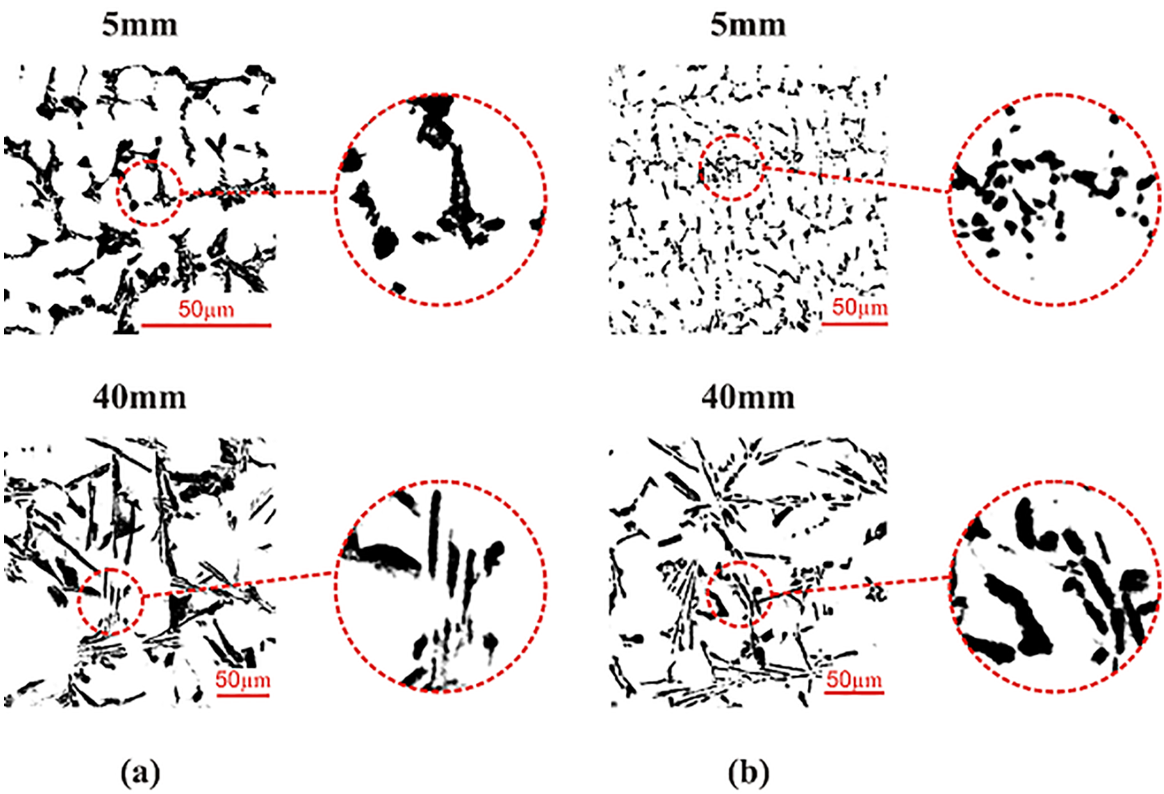

Figure 7. Typical microstructures of the as-cast and heat-treated samples. Si particle analysis in positions: (a) 5 mm and (b) 40mm, in relation to the metal/mold interface, respectively.

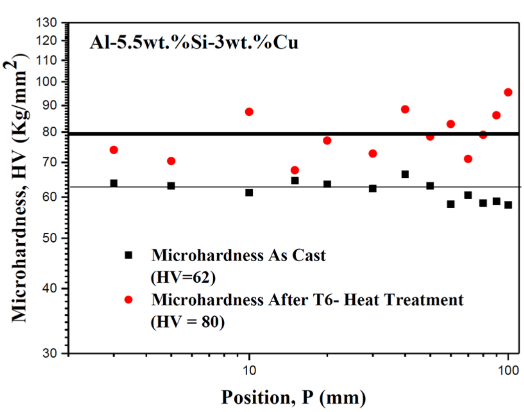

Figure 8. HV dependence as a function of λ_2 for the assumed conditions in this work: Effect of T6-heat treatment on as-cast samples.

can be observed that the HV values remain constant with the position variation, giving average experimental values equal to 62 kg/mm^2 and 80 kg/mm^2 for the investigated samples (as-cast and submitted to the T6 heat treatment, respectively). This also can be seen higher HV values (approximately 36 percent of increase in hardness) for the samples that have been subjected to the T6-heat treatment due to precipitation of the metastable Al_2Cu phase in the Al-rich matrix during the artificial aging process.

4. Conclusion

The following major conclusions can be drawn from the present study:

1. It has been found that the T6-heat treatment has not affected the secondary dendritic spacings of the as-cast samples and that a single experimental power law has been proposed to predict the λ_2 variation with the position from the metal/mold interface.
2. Si particles are better spheroidized for more refined dendritic microstructures, i.e., for lower λ_2 values.
3. The values found for HV have shown that the T6-heat treatment applied in the horizontally solidified aluminum-based multicomponent 319 alloy in this work has resulted in the increase of its mechanical strength, considering the higher HV values observed in the heat-treated samples.

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