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Effect of Copper and Magnesium on the Microstructure of Centrifugally Cast Al-19%Si Alloys

Chester Contatori[1,2,a*], Antonio Augusto Couto[1,3,b], Jan Vatavuk[3,c], Arnaldo A. Ciquielo Borges[1,2,d], Nelson Batista de Lima[1,e], Renato Baldan[4,f]

[1]Instituto de Pesquisas Energéticas e Nucleares (IPEN), 05508-000, São Paulo, SP, Brasil

[2]Instituto Federal de São Paulo (IFSP), 01109-010, São Paulo, SP, Brasil

[3]Universidade Presbiteriana Mackenzie (UPM), 01239-010, São Paulo, SP, Brasil

[4]Universidade Estadual Paulista (UNESP), 18409-010, Itapeva, SP, Brasil

[a]chester.contatori@gmail.com, [b]acouto@ipen.br, [c]janvatavuk@uol.com.br, [d]arnaldo.ifsp@gmail.com, [e]nblima@ipen.br, [f]renatobaldan@gmail.com

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Abstract: Hypereutectic Al-Si alloys can be used in applications that require high wear resistance. Such wear resistance is achieved by the presence of hard primary silicon particles, allied to the formation of Mg_2Si intermetallic phase when magnesium is added in this alloy. Centrifugal casting generates a gradient in the microstructure of hypereutectic Al-Si alloys that can favor such applications. Cylindrical components of Al-19%Si alloy containing added copper and magnesium contents were processed by centrifugal casting. The purpose of this study is to investigate the formation and segregation of particles of primary silicon (β) and Mg_2Si in Al-19%Si alloy containing additions of copper and magnesium. Because the density of silicon (2.33 g/cm^3) and Mg_2Si (1.88 g/cm^3) is lower than that of aluminum (2.67 g/cm^3), centrifugal casting causes primary silicon (β) and Mg_2Si particles to concentrate more at the outer wall of the centrifuged pipe. In this study, primary silicon (β) and Mg_2Si particles were found to be retained at the outer wall of the pipe. It is believed that the rapid cooling of the molten metal in the region of contact with the mold, whose temperature is lower than that of the molten metal, allied to the centrifugal force, prevented the particles from migrating to the inner wall of the pipe. The microstructure shows a gradient in the distribution of these phases, enabling the production of a functionally graded material. The addition of copper and magnesium leads to the formation of Mg_2Si and $Al_5Cu_2Mg_8Si_6$ phases, reducing the amount of primary β phase (Si) particles. In all the evaluated conditions, a tendency is also observed for a gradual increase in the segregation of silicon towards the inner wall along the entire length of the centrifuged pipe.

Introduction

Aluminum alloys containing 5-20% of Si (weight percent) are the most common industrial alloys. These alloys typically consist of a primary aluminum (α) or silicon (β) phase and a eutectic microstructure (Al-12.6%Si) composed of these two elements. The primary Si particles in hypereutectic Al-Si alloys are hard and increase the wear resistance of these alloys, but reduce their mechanical strength and ductility. If the distribution of these hard silicon particles in hypereutectic Al-Si alloys is altered to concentrate them at the inner wall of cylindrical components, the inner layers will be more wear resistant while the outer and central layers will be highly ductile and tough.

The use of centrifugal casting enables one to control the distribution of phases along the radial direction of the cylindrical component to form a functionally graded material. This study may have a positive effect for a possible application in automotive cylinder sleeves, considering the need for wear resistance to withstand the abrasion caused by the piston rings on the inner surface of the sleeve when the engine is running. Since the specific density of silicon (2.33 g/cm^3) is lower than that of aluminum (2.67 g/cm^3), centrifugal casting leads to a higher concentration of primary silicon particles at the inner wall of the centrifuged pipe where high wear resistance is required, while the silicon content in the rest of the pipe will be lower, thus preventing embrittlement of the alloy due to high silicon content [1-5]. The addition of copper in hypereutectic Al-Si alloys also increases the density of the alloy in the liquid state, presumably favoring the migration of primary silicon particles toward the inner wall of the pipe during the centrifugal casting process. The addition of magnesium enables the formation of hard particles of Mg_2Si intermetallic phase with a density of 1.88 g/cm^3, which also presumably migrate to the inner wall of the cylindrical component, further increasing the wear resistance of the inner wall. The main characteristic sought in the centrifugal casting of Al-Si alloys is a functionally graded material [6-9].

In view of the above, our purpose is to evaluate the effects of the addition of copper and magnesium on the microstructure of centrifugally cast hypereutectic Al-19Si (wt%) alloy. This study focuses on the segregation of primary silicon and Mg_2Si particles at the inner wall of centrifugally cast pipes.

Materials and Methods

Al-19Si and Al-19Si-5Mg-5Cu (wt%) alloys were cast in air in an induction furnace from commercially pure raw materials. The molten alloys were poured at 750ºC into a centrifugal mold rotating at 1700 rpm. The resulting centrifuged pipes had an external diameter of 117 mm, internal diameter of 97 mm, were 480 mm in length, and weighed about 4 kg. Ring-shaped samples were cut from various regions of each cast pipe, as illustrated in Figure 1. These regions represent the beginning of the casting, i.e., the region of the mold where the metal was poured, the middle, and the end where the molten metal fills the centrifugally moving mold. Samples for metallographic analysis were taken in three directions from these rings. The metallographic samples were prepared by conventional techniques of cross-sectioning, embedment, sanding, polishing and examination by optical microscopy and scanning electron microscopy coupled to energy dispersive X-ray spectroscopy (SEM-EDS) for chemical analysis. Figure 1 shows micrographs recorded in the radial direction on side three. In this analysis, 14 images were recorded from the outer wall to the inner wall, as depicted in Figure 2. This scheme of observations was performed on six lines per sample. The alloys were also analyzed by X-ray diffraction (XRD). The thermodynamic calculation program JMatPro was used to identify out-of-equilibrium phases, together with the microstructural analysis.

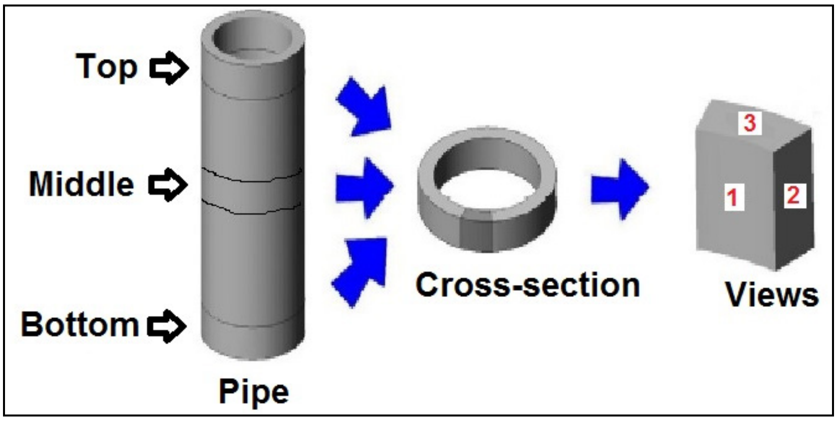

Fig. 1: Schematic cross-section of centrifugally cast pipes.

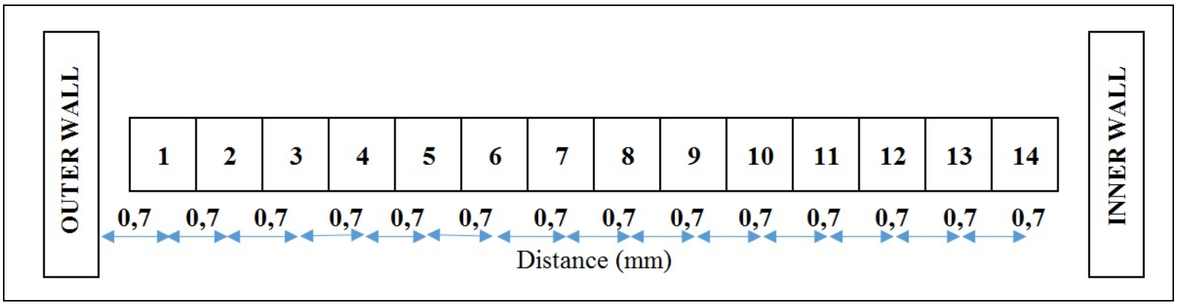

Fig. 2: Schematic of micrographic observations along the thickness of the pipe.

Results and Discussion

The micrographs in Figure 3 are representative of the microstructure of the Al-19%Si alloy in the regions close to the outer, central, and inner walls of the pipe. In these micrographs, note the primary β phase particles visible in the microstructure close the outer wall (Fig. 3 (a)). This is because solidification in this region occurs rapidly due to the colder wall of the mold, which entraps these particles. The particles are thus prevented from moving along the outer wall of the pipe since the solidification time in this region is too short to enable them to move, given the centrifugal force to which they are subjected. In the central region, note that only the eutectic microstructure is visible (Fig. 3 (b)). As they approach the inner wall of the pipe, the primary β phase particles undergo intense segregation (Fig. 3(c)). This large amount of β phase (primary silicon) close to the inner wall of the pipe is due to the centrifugal force, which causes these less dense particles of primary silicon (2.33 g/cm^3) to segregate in the molten aluminum (2.67 g/cm^3). The micrographs recorded along the thickness of the pipe do not show significant differences between the beginning, central and final casting regions.

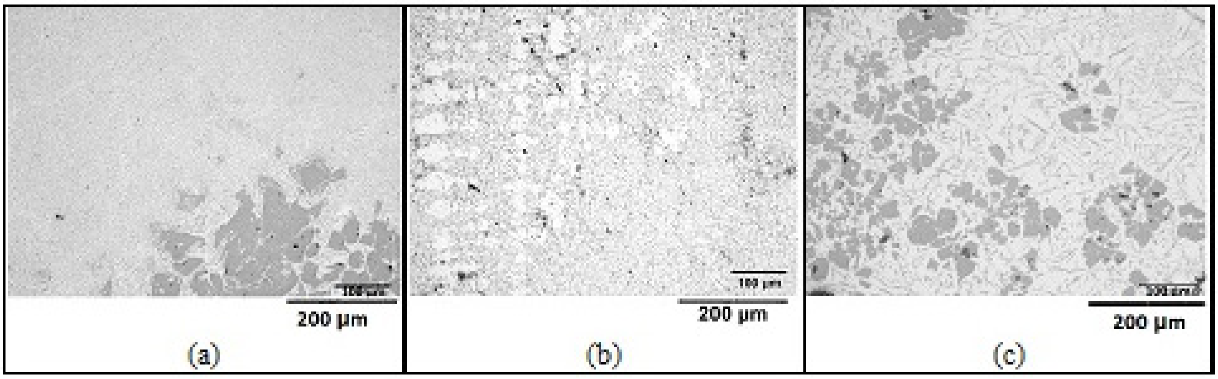

Fig. 3: Representative micrographs of Al-19%Si alloy in the regions near the outer (a), central (b) and inner (c) walls of the centrifuged pipe.

Figure 4 shows optical micrographs representative of the microstructure of Al-19Si-5Cu-5Mg (wt%) alloy in the regions close to the outer, central and inner walls. These micrographs show a similar behavior to that observed in the Al-19Si alloy, i.e., trapping of particles of primary β and Mg_2Si phases, a central region practically without primary β and Mg_2Si phases but with the eutectic microstructure of aluminum with these phases, and a larger amount of these primary phases near the inner wall of the pipe. This larger amount of primary β and Mg_2Si phases near the inner wall of the pipe is caused by the centrifugal force, which segregates these less dense particles of primary silicon (2.33 g/cm^3) and Mg_2Si (1.88 g/cm^3) in the molten aluminum (2.67 g/cm^3).

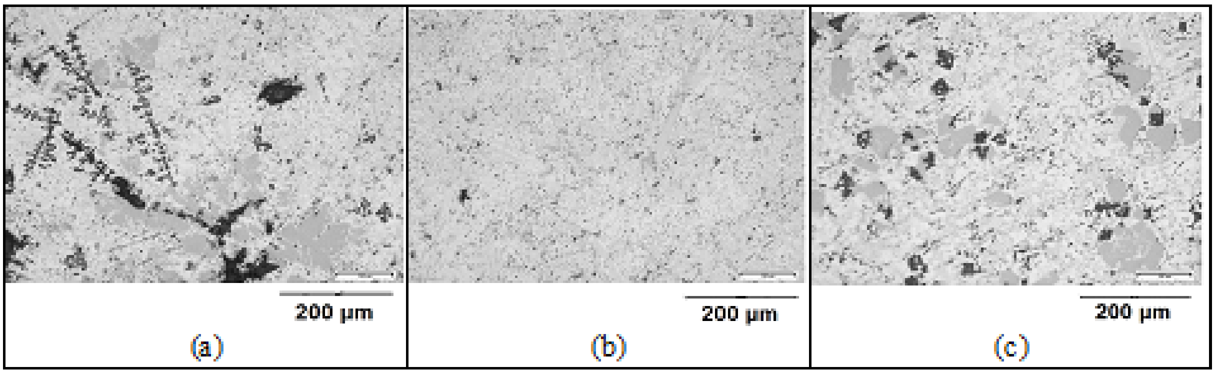

Fig. 4: Representative micrographs of Al-19Si-5Cu-5Mg alloy (wt%) in the regions: (a) near the outer wall, (b) in the center, and (c) near the inner wall of the centrifuged pipe.

Other phases are observed in Al-19Si-5Cu-5Mg (wt%) alloy. The XRD analysis revealed not only α-aluminum and β-silicon but also the intermetallics Mg_2Si and $CuAl_2$, as indicated in the diffractogram in Figure 5. The phases in the microstructure were identified by SEM-EDS, in conjunction with the thermodynamic simulation of the phases that were formed in this alloy during non-equilibrium solidification (Scheil-Gulliver model). Figure 6 shows an optical micrograph of the Al-19Si-5Cu-5Mg alloy, in which the phases are identified. In this micrograph, note the presence of the primary β phase (Si) in gray, the α phase (Al) in white, and the Mg_2Si phase in black. The $CuAl_2$ and the $Al_5Cu_2Mg_8Si_6$ phases are finely dispersed throughout the microstructure. Because of the rapid cooling, the Mg_2Si phase crystallizes as a dendritic structure. The formation of these silicon-containing phases in the Al-19Si-5Cu-5Mg alloy contribute to decrease the amount of particles of primary β phase when compared to the Al-19Si alloy.

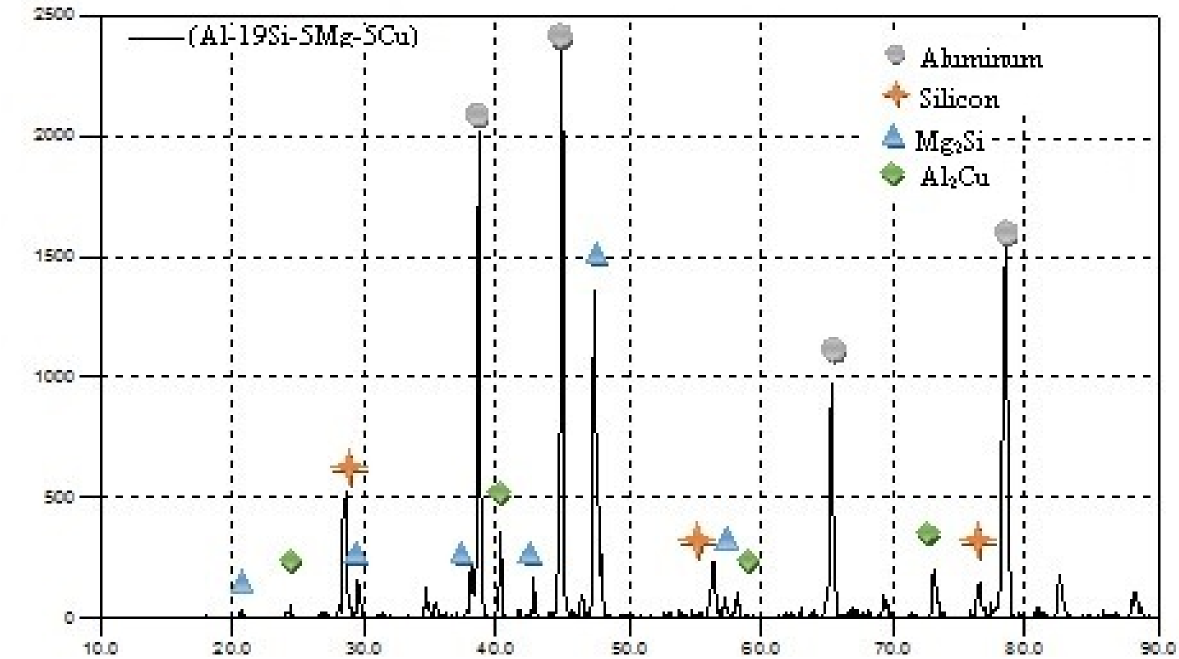

Fig. 5: X-ray diffractogram of the centrifugally cast Al-19Si-5Cu-5Mg (wt%) alloy.

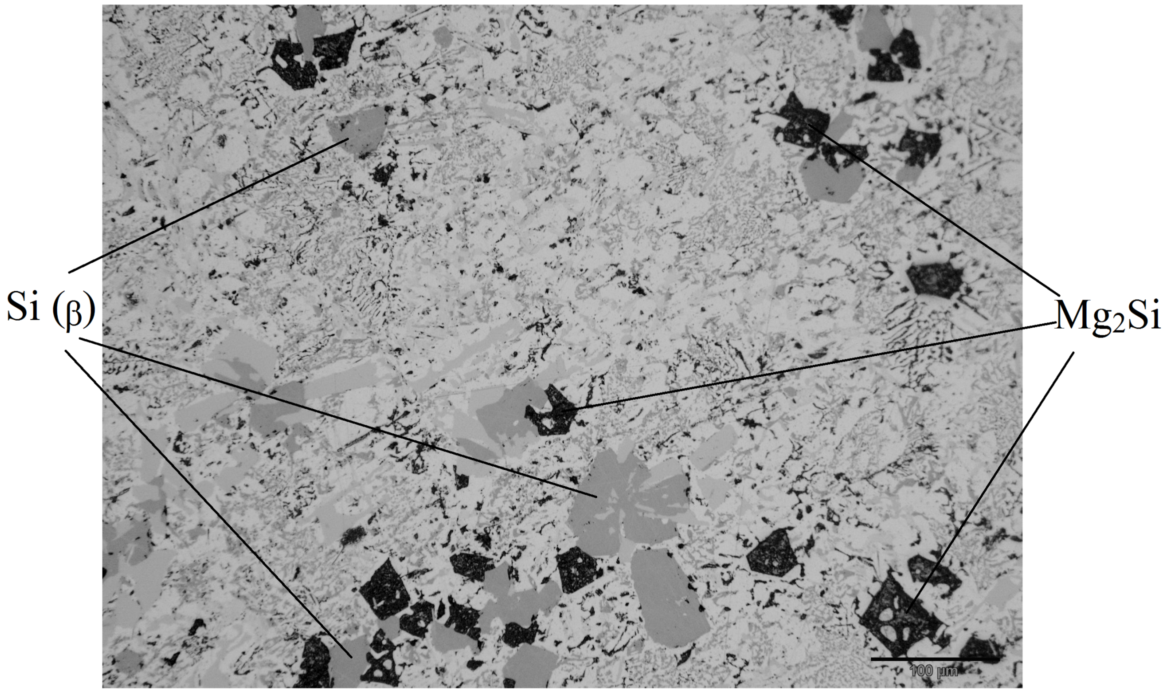

Fig. 6: Detail of the microstructure of the Al-19Si-5Cu-5Mg (wt%) alloy, with identification of the phases it contains.

Conclusions

Al-19%Si alloys with and without the addition of up to 5% of copper and magnesium processed by centrifugal casting presented Si and Mg_2Si gradually segregating toward the inner wall of the centrifuged pipes because of the lower density of these phases when compared to that of the matrix. The microstructure showed a gradient in the distribution of these phases, enabling the production of a functionally graded material. The addition of copper and magnesium led to the formation of Mg_2Si and $Al_5Cu_2Mg_8Si_6$ phases, reducing the quantity of primary β phase particles.

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