Vol. 23, n.° 1, enero-junio de 2025
ISSN impreso: 1657-6527 • ISSN en línea: 2145-8502

FUENTES
EL REVENTÓN ENERGÉTICO

Effect of solidification growth and cooling rates on pro-eutectic Alα phases, massive silicon crystals, eutectic mixture and hardness in Al-12.6wt.%Si-xBi alloys

Efecto de las tasas de crecimiento de solidificación y enfriamiento en las Fases proeutécticas de Alα, cristales masivos de silicio, mezcla eutéctica y dureza en aleaciones de Al-12.6wt.%Si-xBi

Fernando Sousa da Rocha[1], Raquel de Sales França[2], André Cruz da Costa Maciel[3], Maria Adrina Paixão de Sousa da Silva[3], Thiago Antônio Paixão de Sousa Costa[2], Otavio Fernandes Lima da Rocha[2], Antonio Luciano Seabra Moreira[1*]

[1] Research Group on Solidification - GPSOL, Graduate Program in Mechanical Engineering, Federal University of Pará
[2] Research Group on Physical Metallurgy and Transformation - GPEMET, Federal Institute of Education, Science and Technology of Pará
[3] División de Procesos Industriales. Universidad Tecnológica de Tabasco, México.

E-mail: alsm@ufpa.br

Recibido: 15 de septiembre de 2024. Aceptado: 30 de mayo 2025.

Abstract

Casting experiments were carried out with Al-12.6wt.%Si-xBi alloys (x = 0 and 3.2wt.%) using a water-cooled upward solidification apparatus. A typical complex solidification microstructure was obtained consisting of primary Al-rich and massive Si crystals pro-eutectic phases surrounded by an irregular eutectic phases mixture given by Aleutectic + Si crystals while in the Al-12.6wt.%Si-3.2wt.%Bi alloy the observed eutectic mixture also consisted of Bi globules. The Al-rich pro-eutectic primary phase was formed by a dendritic network and was noted for high growth (G_R) and cooling rates (C_R) values whereas the massive Si crystals were verified for lower G_R and C_R. The microstructural scale length was measured by secondary and eutectic dendritic spacings (λ_2 and λ_{Si}, respectively), and lower λ_2 and λ_{Si} values were achieved for higher G_R and C_R results. A transition from fibrous/spheroidal eutectic Si to flake eutectic Si crystals was evidenced for G_R and C_R equal to 0.94 mm/s and 6.5 ºC/s, respectively. Vickers and Rockwell F hardness tests (HV and RH) were performed and the results showed that microstructure affect RH, however, not significantly HV. In addition, the experimental growth laws given by $\lambda_2 C_R^{1/2}$ = Constant and $\lambda_{Si} G_R^{1/2}$ = Constant agreed with the theoretical predictions proposed in the literature.

Keywords: Unsteady-State Upward Solidification; Microstructure; Hardness; Al-Si-Bi Alloys.

Forma de citar: Sousa, F. da R., França, R. de S., Maciel, A. C. da C., Silva, M. A. P. de S. da, Costa, T. A. P. de S., Rocha, O. F. L. da, & Moreira, A. L. S. (2025). Effect of solidification growth and cooling rates on pro-eutectic Alα phases, massive silicon crystals, eutectic mixture and hardness in Al-12.6wt.%Si-xBi alloys. *Revista Fuentes, el Reventón Energético*, 23(1), 73-82, doi:https://doi.org/10.18273/revfue.v23n1-2025005.

Resumen

Se realizaron experimentos de colada con aleaciones Al-12.6wt.%Si-xBi (x = 0 y 3.2wt.%) utilizando un aparato de solidificación ascendente enfriado por agua. Se obtuvo una microestructura de solidificación típica y compleja, compuesta por fases proeutécticas de cristales primarios ricos en Al y Si masivo, rodeadas por una mezcla irregular de fases eutécticas formada por cristales eutécticos de Al + Si. En la aleación Al-12.6wt.%Si-3.2wt.%Bi, la mezcla eutéctica observada también contenía glóbulos de Bi. La fase primaria proeutéctica rica en Al se formó mediante una red dendrítica y se destacó por valores elevados de velocidad de crecimiento (G_R) y tasas de enfriamiento (C_R), mientras que los cristales masivos de Si se verificaron para menores valores de G_R y C_R. La escala de la microestructura se midió a través de los espaciamientos dendríticos secundarios y eutécticos (λ_2 y λ_{Si}, respectivamente), logrando valores más bajos de λ_2 y λ_{Si} para mayores resultados de G_R y C_R. Se evidenció una transición de cristales de Si eutéctico fibroso/esferoidal a cristales de Si eutéctico en forma de lámina para valores de G_R y C_R iguales a 0.94 mm/s y 6.5 ºC/s, respectivamente. Se realizaron pruebas de dureza Vickers y Rockwell F (HV y RH), cuyos resultados mostraron que la microestructura afecta RH, aunque no significativamente HV. Además, las leyes experimentales de crecimiento, dadas por $\lambda_2 C_R^{1/2}$ = Constante y $\lambda_{Si} G_R^{1/2}$= Constante, coincidieron con las predicciones teóricas propuestas en la literatura.

Keywords: Solidificación Ascendente en Estado no Estacionario; Microestructura; Dureza; Aleaciones Al-Si-Bi.

1. Introduction

It is necessary to understand the mechanism of formation and variation of the dendritic and eutectic spacings involved during the solidification process to investigate microsegregation pattern which influences the mechanical (Kurz & Fisher, 1981) (Okamoto & Kishitake, 1975) (Carvalho et al, 2013) (Reyes, et al, 2017) (Costa et al, 2021) (Kaya, Çadirli, Gündüz, 2007) manufacturing (Silva et al, 2018) (Costa et al, 2019) (Yehorov, Silva, Scotti, 2019) (Wan et al, 2014) (Zedan et al, 2022) (Adineh, Doostmohammadi, Raiszadeh, 201), electrical (Kaya et al, 2010) (Kaygısız, Maraşlı, 2017) (Aksoz et al, 2010) (Bayram, Maraşlı, 2018) (Kaygisiz, Marasli, 2017) (Çadırlı et al, 2017), and corrosion (Silva et al, 2021) (Kubacki, Brownhill, Kelly, 2019) (Yin et al, 2018) (Medjahed et al, 2018) (Barros et al, 2020) (Zhou et al, 2008) properties as well as the homogenization kinetics of solidified alloys. Eutectic alloys are the basis of many engineering materials and this has contributed to the fact that a large number of theoretical and experimental works have been developed on the relationship between microstructure and solidification conditions since the mode of nucleation and growth of the eutectic phase within the dendritic array will strongly influence the geometry of the feeding paths through the solid structure which in turn will affect porosity formation during the last stages of solidification.

Theoretical and experimental studies have been reported in the last decades to examine the effect of thermal solidification variables on primary, secondary, tertiary dendritic, and eutectic spacings. Dendritic and eutectic spacings, for instance, have been studied concerning the solidification process (Carvalho et al, 2013) (Costa et al, 2021) (Silva et al, 2028) (Zhou et al, 2008) (Nikrityuk, Eckert, Grundmann, 2006) (Mullins & Sekerka, 1964) (Correa et al, 2021) (Acer et al, 2017) (Bayram, Maraşlı, 2018) (Du et al, 2018) (JSpinelli, Ferreira, Garcia, 2004) (Spinelli, Peres, Garcia, 2005) (Silva et al, 2012) (Quaresma, Santos, Garcia, 2000) (Boussaa et al, 2016) (Böyük, 2012) (Zedan et al, 2022) (Fracchia, Gobber, Rosso, 2021).

Directional solidification of eutectic alloys, for example, has received considerable attention due to the alignment of fibers or plates in some of these eutectics produces attractive directional physical or mechanical properties (Reyes et al, 2017), Costa et al, (2029). The achievement of even better properties of Al-Si alloy components, as example, requires intensive investigations on the control of some variables involved during solidification process such as thermophysical properties of molten metal as well as growth and cooling rates (Zedan et al, 2022) (Fracchia, Gobber, Rosso, 2021) (Grum, Kisin, 2003) (Kaya, Çadırlı, Gündüz, 2003). It is well known that in Al-Si alloys the ductile Al matrix can be reinforced with hard and brittle silicon particles. In this case the morphology of this alloying element is as a flake-like one decreasing ductility and thus supplying a fracture path (Uthayakumar et al, 2012). However, in many applications, mechanical components made of Al-Si alloys that perform under critical conditions subject to mechanical and thermal stresses need to exhibit high ductility and fatigue strength. To improve these properties, the morphology of the silicon is modified by inoculating specific elements into the liquid (Barzani et al, 2023).

Research with aluminum alloys containing Bi has been developed in recent decades due to the great potential these alloys have for the manufacture of components used in various parts of automotive, aeronautics and aerospace industries subjected to friction conditions (Costa et al, 2019) (Ratke et al, 2010) (Dai et al, 2013) (Freitas et al, 2014).

The results of these studies highlight that Bi act as a solid internal lubricant to the alloy (self-lubrication). Considering Bi as an alloying element that offers versatile conditions for its already established applications, using it in ternary Al-Si-Bi alloys as materials in tribological services the main purpose of this work is to investigate the effect of solidification thermal parameters, such as growth and cooling rates (G_R and C_R), on microstructure and hardness in Al-12.6wt.%Si-xBi alloys (x=0 and 3.2wt%).

2. Experimental methodology

The investigated alloys were prepared from its pure elements of high purity (Al ≅ 99.7%, Si ≅ 99.5%, and Bi ≅ 99.9%). Once the compositions of both alloys were confirmed, a greater volume of liquid metal was poured into a cylindrical mold of a water-cooled ascending solidification device, a very well-known directional solidification technique (Reyes et al, 2017) (Costa et al, 2019) (Spinelli et al, 2004 (Spinelli et al, 2005) (Silva et al, 2012).

In order to determine the thermal solidification parameters, G_R and C_R, a thermal mapping was carried out using eight type K thermocouples inserted in the cylindrical mold from the heat transfer surface and eight cooling curves were obtained for both studied alloys.

The generated thermal data were used to determine experimental G_R and C_R, according to the techniques presented in (Rocha et al, 2020). As monotectic alloys have two solidification fronts, such as the Al-12.6wt.%Si-3.2wt.%Bi alloy, it is worth mentioning that the assumed *liquidus* temperature (T_L) have been the ones corresponding to the beginning of the formation of Al-rich primary phase (Al-α). The experimental methodology used to determine G_R and C_R can be seen in (Carvalho et al, 2013), (Costa et al, 2021) (Costa et al, 2019), (Rocha et al, 2020).

Cross and longitudinal samples at positions from the metal-mold interface of the directionally solidified alloy were electropolished and etched with acid solution (NaOH 5 pct) for microscopic examination, as seen in Figure 1a, and λ_2 values were measured by averaging the distance between adjacent side branches of dendrites on the longitudinal section of samples, as seen in Figure 1b. On the other hand, the eutectic spacings (λ_{Si}) values were measured on the transverse section of samples, perpendicular to the growth direction, as can be observed in Figure 1c. The assumed λ_2 and λ_{Si} values were the averages among 20 measurements performed for each sample from the cooled mold plate.

Cast samples were submitted to Vickers microhardness (HV) tests which were carried out following the ASTM E384 standard using a test load of 50 g and a dwell time of 10 s. The HV values adopted were the average of at least 20 measurements in each sample. In addition, F-type mechanical hardness tests (RH, F 1.59/60) were performed on solidified samples from the refrigerated base, as per ASTM E 18 Standard Test Methods using a load of 60 kgf, diameter sphere of 1.59 mm, and a dwell time approximately of 4 s. At least three measurements were made by as-cast samples. It is important to highlight that according to the mentioned standard the assumed hardness type, i.e., Rockwell F, is recommended for soft materials.

3. Results and discussion

Figure 2 shows the obtained profiles from the solidification process of both investigated alloys. As can be noted, in both cases the cooling system plays a critical role in the process since it imposes a large temperature difference when in contact with the mold promoting higher values for G_R and C_R at the beginning of the process, as shown in Figure 2b. The Bi addition did not significantly affect the G_R and C_R values to the point that a single experimental mathematical expression was proposed to predict the C_R variation along the length of the solidified ingot. On the other hand, the obtained G_R and C_R values decrease at more distant positions from the cooled base.

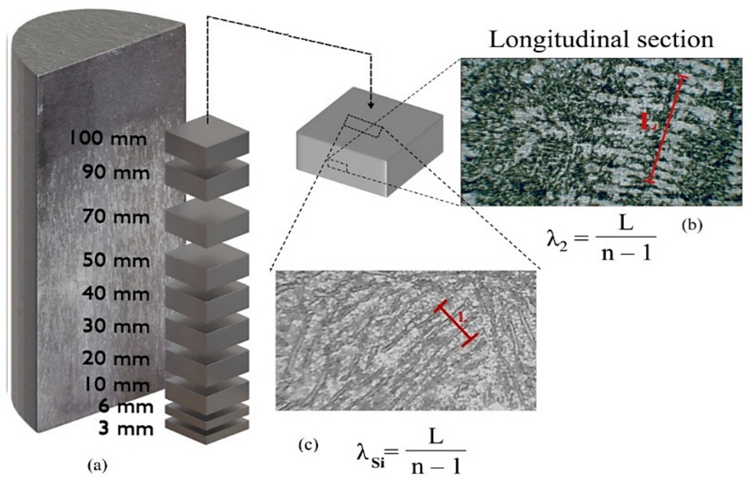

Figure 1. Methodology used to measure the length of the microstructural scale: (a) Schematic representation of the as-cast samples from the bottom. Source: adapted from [46]; (b) λ_2 measurement technique; (c) λ_{Si} measurement technique.

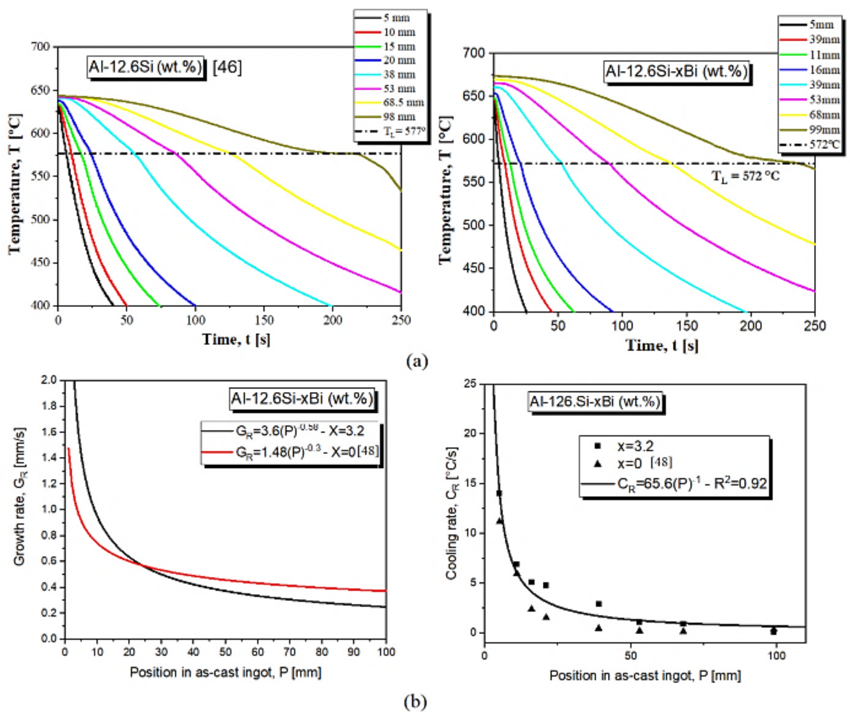

Figure 2. (a) Thermal data resulting from the solidification process; (b) experimental growth and cooling rates. Source: own elaboration.

Solidification microstructures were revealed in several samples along the length of the ingot for both examined alloys as shown on the macrostructures of Figure 3 in two positions from the cooled mold. The heat extraction in transient regime imposed by the upward solidification device promoted the formation of a complex multiphase microstructure consisting of diffuse (solid Al-α solution) and faceted (massive Si crystals) proeutectic phases as well as an irregular eutectic (mixture of flack-like acicular Si and Al-α). The solidification of a eutectic alloy involves a high-efficiency diffusive coupling process which can be faster than the isolated growth of a single phase, such as primary dendrites, even for alloys with a pro-eutectic composition. In solidification of alloys with exact eutectic composition, under high growth rate conditions, dendritic formation may eventually occur (Garcia, 2007).

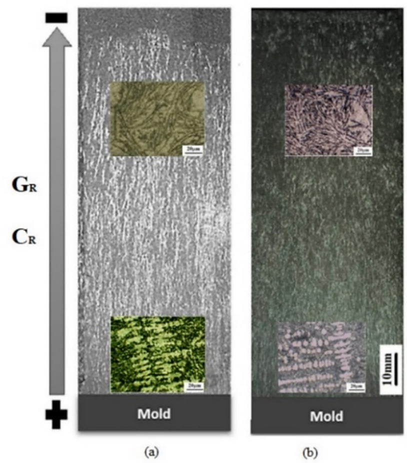

Figure 3. - Typical solidification structures for the Al-2.6wt.%Si-xwt. %Bi alloy: (a) x = 0, adapted from [46] and (b) x = 3.2%wt.%.

Scanning electron microscopy analysis and EDS element mapping (SEM/EDS) were performed to show more accurately the microstructural formation of investigated ternary alloy under the assumed solidification conditions as indicated in Figure 4. Fe intermetallic phase, always expected in Al-Si alloys, was also observed as shown in the point microanalysis, composing the following eutectic mixture Al-α + flack-like acicular Si + Fe intermetallic, plus globular Bi for the Al-12.6wt.%Si-3.2wt.%Bi. system.

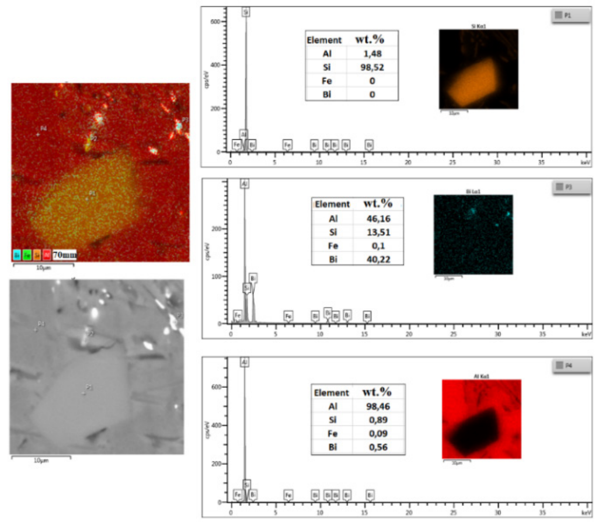

Figure 4. SEM microstructure and EDS elements microanalysis for an as-cast sample of Al-12wt.%Si-3.2wt.%Bi alloy at the position corresponding to 70 mm from the heat transfer surface.

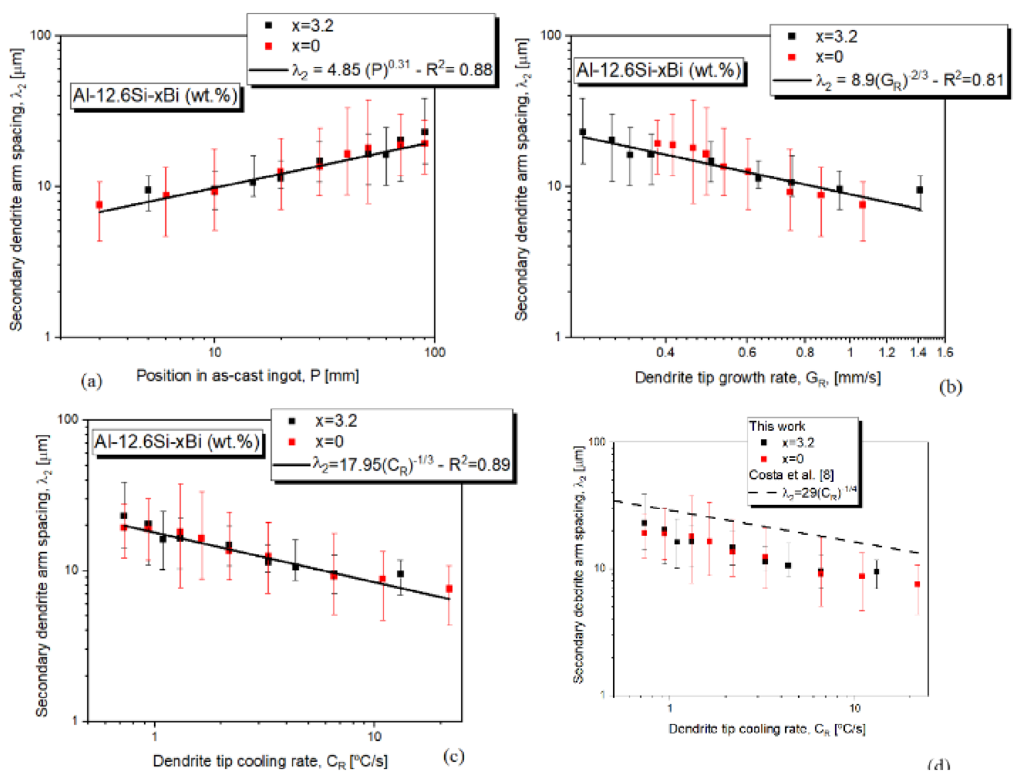

Figure 5. λ_2 variation as a function of: (a) ingot position; (b) G_R; (c) C_R, and (d) Comparison with literature [8].

Figures 5 and 6 show the λ_2 and λ_{Si} evolution as a function of position from bottom to top of as-cast ingot. Smaller λ_2 and λ_{Si} results were found for positions closer to the heat transfer surface due to the effect of the water-cooled system. The obtained λ_2 values are in full agreement with the classic Bouchard-Kirkaldy (BK) (Bouchard & Kirkaldy, 1997) mathematical model proposed for theoretical prediction of secondary dendritic growth as a function of G_R, given by the following relationship $\lambda_2.G_R^{2/3}$ = Constant. This has demonstrated that the Bi addition to the Al-12.6wt.%Si (wt.%) alloy did not affect the λ_2 growth law. A good agreement was noted with the reached results for the directionally solidified Al-9Si-xBi alloys (Costa et al, 2029), as shown in Figure 5d.

Figure 6 presents experimental results on the dependence of the eutectic spacing (λ_{Si}) as a function of thermal solidification parameters. Power-type mathematical expressions characterize the λ_{Si} variation as a function of both G_R and C_R. It was found that the eutectic spacing decreased with increasing G_R and C_R according to −1/2 and –1/4 exponents values, as shown in Figures 6b e 6c, respectively. These results agree with the classical eutectic growth theory given by the mathematical relation $\lambda_2 G_R^{1/2}$ = Constant, developed by Jackson-Hunt (Jackson&Hunt, 1996), as well as with experimental results for upward solidified Al-xSi alloys (Reyes et al, 2016) (Reyes et al, 2017).

Figures 7 and 8 show an interrelationship between Rockwell F and Vickers hardness (RH and HV) with G_R, C_R and λ_{Si}. It was observed finer dendritic and eutectic microstructures played a major role in obtaining RH and HV for higher C_R and G_R values in these as-cast positions. The Bi globules contained in the eutectic mixture of Al-12.6wt.%Si-3.2wt.%Bi alloy seem to have been the main responsible for the lower Rockwell F hardness values. In addition, larger Bi globules were noted for lower G_R and C_R values.

It was observed the effect of G_R and C_R on the characteristics of eutectic silicon crystals for the position equal to 10 mm from the heat transfer interface, that is, at the instant when G_R and C_R assume values approximately equal to 0.94 mm/s and 6.5 ºC/s, a transition from fibrous or spheroidal-like eutectic Si to flakes-like eutectic Si has been observed, as noted in Figure 8. Furthermore, it was also found that λ_{Si} fibrous or eutectic did not affect RH values. These results were affected only by the microstructure in the eutectic mixture formed by flake-like Si crystals, as confirmed in Figure 8a.

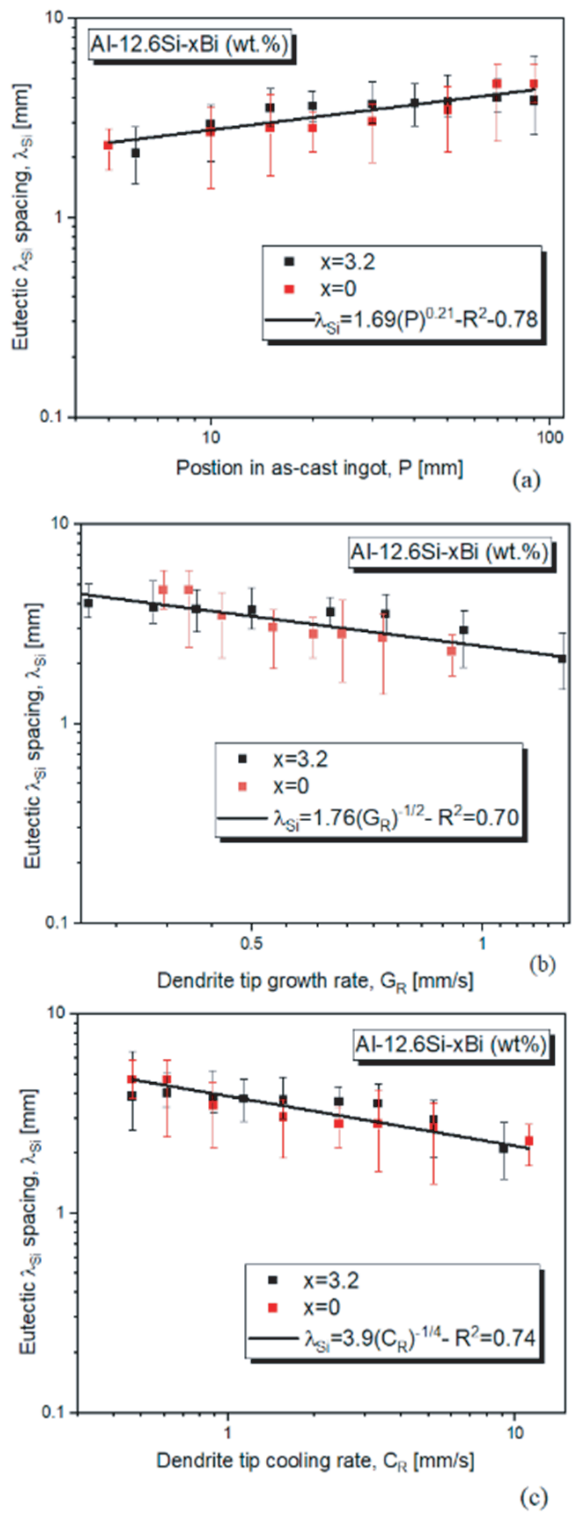

Figure 6. Eutectic Si spacing as a function of growth and cooling rates. R^2 is the determination coefficient.

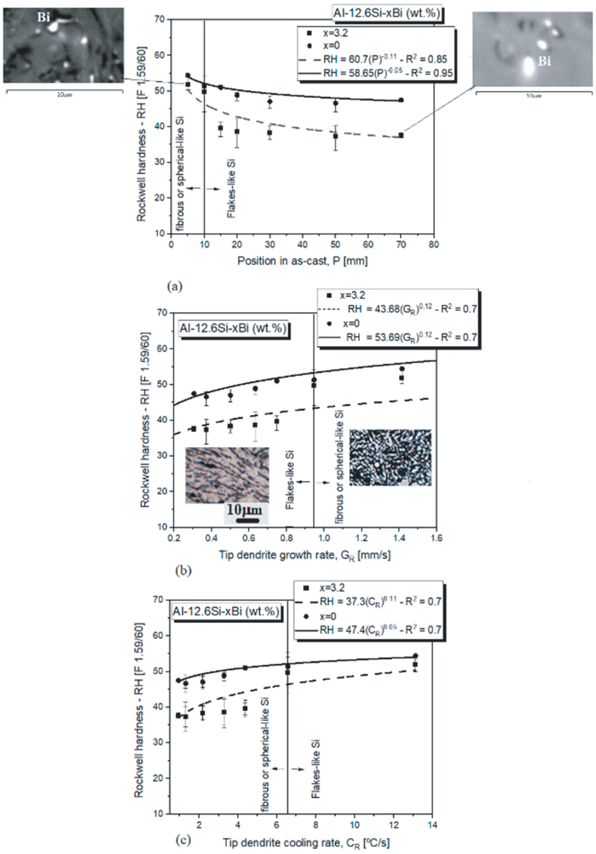

Figure 7. Rockwell F hardness as a function of: (a) As-cast ingot position; (b) Growth rate; (c) Cooling rate.

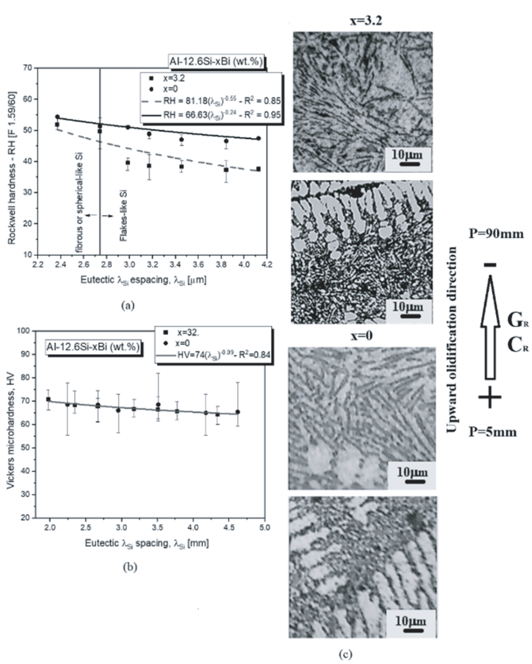

Figure 8. (a) Rockwell F hardness as a function of as-cast ingot position; (b) HV hardness as a function of as-cast ingot position; (c) Typical solidification microstructures for Al-12.6wt.%Si-xBi alloys (x = 0 and x = 3.2).

4. Conclusions

It was found a complex multiphase microstructure composed of primary proeutectic phases consisting of a dendritic solid solution of Al-α and massive Si crystals, surrounded by a irregular eutectic mixture formed by Al-α + Si + Fe intermetallic crystals. Furthermore, globule-like Bi particles were observed in the above-mentioned eutectic mixture and the Al-rich pro-eutectic primary phase was formed by a dendritic network which was notably evidenced for high growth and cooling rates. A transition from fibrous or spheroidal eutectic Si crystals to flake eutectic Si crystals was evidenced for G_R and C_R equal to 0.94 mm/s and 6.5 ºC/s, respectively. As-cast microstructure plays an essential role in mechanical characteristics, since Rockwell hardness (RH) and Vickers microhardness (HV) increase with decreasing of both λ_2 and λ_{Si}. It was also verified the Bi importance in the reduction of RH and HV. Therefore Al-Si alloys with Bi addition can be suggested for solid internal lubricant-like tribological applications.

5. Acknowledgements

The authors are grateful for the support given by the IFPA - Federal Institute of Education, Science and Technology of Pará, UFPA - Federal University of Pará, and Amazon Foundation for Studies and Research (FAPESPA) for the scholarship granted to the student Fernando Sousa da Rocha.

6. Author contributions

Otavio L. Rocha and Antonio L. Moreira developed the formalism and wrote the text. Fernando S. Rocha, Raquel F. Sales and André C. Maciel reviewed and researched on Transient Directional Solidification of Al-based ternary alloys. Adrina P. Silva and Thiago A. Costa performed graphic art and improved the text quality.

7. Referencias

Adineh M., Doostmohammadi H., Raiszadeh R.. (2019). Effect of Si and Al on the microstructure, mechanical properties and machinability of 65Cu-35Zn brass. *Iranian Journal of Materials Science and Engineering: 16, 21-32*. https://doi.org/10.22068/IJMSE.16.2.21.

Acer E., Çadirli E., EroH. l, Kaya H., Gündüz M. (2017). Effects of growth rates and compositions on dendrite arm spacings in directionally solidified Al-Zn alloys. *Metallurgical and Materials Transactions A: 48, 5911-5923*. https://doi.org/10.1007/s11661-017-4337-x.

Bayram Ü., Maraşlı N. (2018). Influence of Growth Rate on Eutectic Spacing, Microhardness, and Ultimate Tensile Strength in the Directionally Solidified Al-Cu-Ni Eutectic Alloy. *Metallurgical and Materials Transactions B: 49, 3293-3305*. https://doi.org/10.1007/s11663-018-1404-7.

Barros A., Cruz C., Silva A. P., Cheung N., . Garcia A, Rocha O., Moreira A. (2020). Length scale of solidification microstructure tailoring corrosion resistance and microhardness in T6 heat treatment of an Al-Cu-Mg alloy. *Corrosion Science and Technology: 55, 471-479*. https://doi.org/10.1080/1478422X.2020.1742410.

Barzani M. M., Farahany S., Yusof N. M., Ourdjini A. (2013). The Influence of bismuth, antimony, and strontium on microstructure, thermal, and machinability of aluminum-silicon alloy. *Materials and Manufacturing Processes:* 28(11) 1184-1190 https://doi.org/10.1080/10426914.2013.792425.

Bayram Ü., Maraşlı N. (2018). Thermal conductivity and electrical resistivity dependences on growth rate in the directionally solidified Al-Cu-Ni eutectic alloy. *Journal of Alloys and Compound: 753 695-702.* https://doi.org/10.1016/j.jallcom.2018.04.277.

Bouchard D., Kirkaldy J. S. (1997). Prediction of dendrite arm spacings in unsteady and steady-state heat flow of unidirectionally solidified binary alloys. Metallurgical and *Materials Transactions* B: 20, 651-663. https://doi.org/10.1007/s11663-997-0039-x.

Boussaa R., Hachani L., Budenkova O., Botton V., Henry D., Zaidat K., Hadid B., Fautrelle H. (2016). Macrosegregations in Sn-3wt%Pb alloy solidification: experimental and 3D numerical simulation investigations. *International Journal of Heat and Mass Transfer: 100, 680-690.* https://doi.org/10.1016/j.ijheatmasstransfer.2016.04.120.

Böyük U. Physical and Mechanical Properties of Al–Si–Ni Eutectic Alloy. (2012). *Metals and Materials International: 18, 933-938*. https://doi.org/10.1007/s12540-012-6004-5.

Çadırlı E., Büyük U., Engin S., Kaya H. (2017). Effect of silicon content on microstructure, mechanical and electrical properties of the directionally solidified Al-based quaternary *Journal of Alloys and Compound: 694, 471-479.* https://doi.org/10.1016/j.jallcom.2016.10.010.

Carvalho D. B., Guimarães E. C., Moreira A. L., Moutinho D. J., Filho D., J. M. Rocha, O. L. Rocha. (2013). Characterization of the Al-3wt.%Si alloy in unsteady-state horizontal directional solidification. *Materials Research: 16, 874–883* https://doi.org/10.1590/S1516-14392013005000072.

Correa E. G., Militão E. S., L. G. Nascimento, Ferreira I. F., Rocha O. L. (2021). Solidification thermal parameters, microstructural evolution and dendritic growth in an AlCuNi alloy. *Philosophical Magazine Letters: 1:101, 21-29.* https://doi.org/10.1080/09500839.2020.1837980.

Costa T. A., Dias M., Silva C., Freitas E., Silva A., Cheung N., Garcia A. *(2019).* Measurement and interrelation of length scale of dendritic microstructures, tensile properties, and machinability of Al-9wt%Si-(1wt%Bi) alloys. *International Journal of Advanced Manufacturing Technology: 105, 1391-1410*. https://doi.org/10.1007/s00170-019-04211-1.

Costa M. O., Barbosa C. R., Azevedo H. M., Machado G. H., Rocha F. S., Moreira A. S., Rocha O. L. (2021).Thermal analysis via horizontal solidification of Al3Cu2Si (mass%) alloy: thermal and microstructural parameters, intermetallic compounds and microhardness. Journal of Thermal Analysis and Calorimetry: 146, 2059-2071. https://doi.org/10.1007/s10973-020-10419-1.

Dai R., Zhang J. F., Zhang S. G., Li J. G. (2013). Liquid immiscibility and core-shell morphology formation in ternary Al–Bi–Sn alloys. *Materials Characterization : 81, 49-55.* https://doi.org/10.1016/J.MATCHAR.2013.04.006.

Du D., Fautrelle Y., Dong A., Shu D., Zhu G., Sun B., Li X. (2018) Effect of Ag content on the microstructure and crystallization of coupled eutectic growth in directionally solidified Al-Cu-Ag alloys. Metallurgical and *Materials Transactions A : 49, 4735-4747*. https://doi.org/10.1007/s11661-018-4799-5.

Fracchia E., Gobber F. S., Rosso M. (2021). Effect of Alloying Elements on the Sr Modification of Al-Si Cast Alloys. *Metals: 11(2), 342.* https://doi.org/10.3390/met11020342.

Freitas E. S, Silva A.P., Spinelli J. E., Casteletti L. C., Garcia A. (2014). Inter-relation of microstructural features and dry sliding wear behavior of monotectic Al-Bi and Al-Pb alloys. *Tribology Letters: 55(1), 111–120*. https://doi.org/10.1007/s11249-014-0338-8.

Garcia A. (2007). *Solidification: Fundamentals and Applications*. 2nd edition. Campinas/São Paulo. Unicamp Publisher. 399. ISBN: 978-85-268-0782-2.

Grum J., Kisin M. (2003). Influence of microstructure on surface integrity in turning. Part I: The influence of the size of the soft phase in a microstructure on surface-roughness formation. *International Journal of Machine Tools and Manufacture: 43, 1535-1543*. https://doi.org/10.1016/S0890-6955(03)00199-8.

G. Kubacki W., Brownhill J. P., Kelly R. G. (2019). Comparison of atmospheric corrosion of additively manufactured and cast Al-10Si-Mg over a range of heat treatments". *Corrosion: 75, 1527-1540.* https://doi.org/10.5006/3318.

Jackson K. A., Hunt J. D. (1966). Lamellar and rod eutectic growth. *Transactions of the Metallurgical Society of AIME: 236, 1129-1142*.

J. E. Spinelli, I. L. Ferreira, A. Garcia, "Influence of melt convection on the columnar to equiaxed transition and microstructure of downward unsteady-state directionally solidified Sn-Pb alloys", J. Alloys. Compoud, 384 2004) 217-226. https://doi.org/10.1016/j.jallcom.2004.04.098.

Kaya H., Böyük U., Engin S., Çadirli E., Marasli N. (2010). Measurements of microhardness and thermal and electrical properties of the binary Zn-0.7wt.%Cu hypoperitectic alloy. *Journal of Electronic Materials: 39, 303-311.* https://doi.org/10.1007/s11664-009-1061-3.

Kaya H., Çadirli E., Gündüz M. (2007) Dendritic growth in an aluminum-silicon alloy. *Journal of Materials Engineering and Performance: 16,12-21*. https://doi.org/10.1007/s11665-006-9002-2.

Kaya H., Çadırlı E., Gündüz M., Ülgen A. (2003). Effect of the temperature gradient, growth rate, and the interflake spacing on the microhardness in the directionally solidified Al-Si eutectic alloy. *Journal of Materials Engineering and Performance: 12, 544-551*. https://doi.org/10.1361/105994903100277201.

Kaygısız Y., Maraşlı N. (2017) Microstructural, mechanical, and electrical characterization of directionally solidified Al-Cu-Mg eutectic alloy. *Physics of Metals and Metallography: 118, 389-398.* https://doi.org/10.1016/j.jallcom.2014.08.056.

Kaygisiz Y., Marasli N. (2015). Microstructural, mechanical and electrical characterization of directionally solidified Al-Si-Mg eutectic alloy. *Journal of Alloys and Compound: 618, 197-203*. https://doi.org/10.1016/j.jallcom.2014.08.056.

ksoz S., Ocak Y., Maraslı N., Çardili E., Kaya H, Boyuk U. (2010). Dependency of the thermal and electrical conductivity on the temperature and composition of Cu in the Al based Al–Cu alloys. *Experimental Thermal and Fluid Science: 34v, 507-1516*. https://doi.org/10.1016/j.expthermflusci.2010.07.015.

Kurz W., Fisher J. D. (1981). Dendrite growth at the limit of stability: tip radius and spacing. *Acta Metallurgica: 29, 11-20*. https://doi.org/10.1016/0001-6160(81)90082-1

Medjahed A., Henniche A., Derradji M., Yu T., Wang Y., Wu R., Hou L., Zhang J., Li X., Zhang M. (2018). Effects of Cu/Mg ratio on the microstructure, mechanical and corrosion properties of Al-Li-Cu-Mg-X alloys. *Materials Science and Engineering A: 8, 241-249*. https://doi.org/10.1016/j.msea.2018.01.118.

Mullins W. W., Sekerka R. F. (1964). Stability of a Planar Interface During Solidification of a Dilute Binary Alloy. *Journal of Applied Physics: 35, 44-51*. https://doi.org/10.1016/B978-0-08-092523-3.50037-X

Okamoto T., Kishitake K. (1975). Dendritic structure in unidirectionally solidified aluminum, tin, and zinc base binary alloys. *Journal Crystal Growth: 29, 137-146*. https://doi.org/10.1016/0022-0248(75)90217-1.

P. Nikrityuk A., Eckert K., Grundmann R. (2006). A numerical study of unidirectional solidification of a binary metal alloy under influence of a rotating magnetic field. *International Journal of Heat and Mass Transfer: 49, 501-1515*. https://doi.org/10.1016/j.ijheatmasstransfer.2005.08.035.

Quaresma J., Santos C. A., Garcia A. (2000). Correlation between unsteady-state solidification conditions, dendrite spacings, and mechanical properties of Al-Cu alloys. *Metallurgical and Materials Transactions A:* 31, 3167-3178. https://doi.org/10.1007/s11661-000-0096-0.

Ratke L., Muller A., Seifert M., Kapserovich G. (2010). Monotectic Alloys and their Growth Morphologies. *Materials Science Forum: 649, 137-420.* https://doi:10.4028/www.scientific.net/MSF.649.137.

Reyes R. V., Bello T. S., Kakitani R., Costa T. A., Garcia A., Cheung N., Spinelli J. E. (2017). Tensile properties and related microstructural aspects of hypereutectic Al-Si alloys directionally solidified under different melt superheats and transient heat flow conditions. *Materials Science Engineering A: 685, 235-243*. https://doi.org/10.1016/j.msea.2016.12.096.

Reyes R. V., Kakitani R., T Costa. A., J Spinelli. E., Cheung N., Garcia A. (2016). Cooling thermal parameters, microstructural spacing and mechanical properties in a directionally solidified hypereutectic Al–Si alloy. *Philosophical Magazine : 96(6), 228-237*. https://doi.org/10.1080/09500839.2016.1192297

Rocha F. S., Costa T. G., Oliveira A. G., Costa T. A., Ferreira I. L., Rocha O. L. (2020). Transient heat flow parameters and microstructure of the upward solidified eutectic Al-Si alloy: a theoretical and experimental study. *Philosophical Magazine: 100, 2659-2676*. https://doi.org/10.1080/14786435.2020.1785646.

Silva A. P., Freitas E. S., Goulart P. R., Garcia A., Spinelli J. E. (2012). On the growth of the minority phase during downward transient directional solidification of hypomonotectic and monotectic Al-Pb alloys. *Journal of Materials Science: 47, 5581-5589*. https://doi.org/10.1007/s10853-012-6450-y.

Silva T. C., Barros A. S., Filho J. C., Moreira A. L., C. Barbosa R., Rocha O. L. (2021) Study of electrochemical corrosion in samples of a horizontally solidified AlCuSi alloy. *International Journal of Metalcastin: 16, 1191-1205*. https://doi.org/10.1007/s40962-021-00657-w.

Silva C., Layo L., Guimarães E., Júnior P., Moreira A., Rocha O., Silva A. (2018). Influence of thermal parameters, microstructure, and morphology of Si on machinability of an Al–7.0wt.%Si alloy directionally solidified. *Advances in Materials Science and Engineering*: 1-12. https://doi.org/10.1155/2018/9512957.

Spinelli J. E., Peres M. D., Garcia A. (2005). Thermosolutal convective effects on dendritic array spacing in downward transient directional solidification of Al-Si alloys. *Journal of Alloys and Compound : 403, 228-238*. https://doi.org/10.1016/j.jallcom.2005.06.010.

Uthayakumar M., Prabhakaran G., Aravindan S., Sivaprasad J. V. (2012). Influence of cutting force on bimetallic piston machining by a Cubic Boron Nitride (CBN) tool. *Materials and Manufacturing Processes: 27, 1078-1083*. https://doi.org/10.1080/10426914.2012.677913.

Wan L., Huang Y., Lv Z., Lv S., Feng J. (2014) Effect of self-support friction stir welding on microstructure and microhardness of 6082-T6 aluminum alloy joint. *Materials & Design: 55, 197-203.* https://doi.org/10.1016/j.matdes.2013.09.073.

Yehorov Y., Silva L. J., Scotti A. *(2019).* Exploring the use of switchback for mitigating homoepitaxial unidirectional grain growth and porosity in WAAM of aluminum alloys. *International Journal of Advanced Manufacturing Technology: 104 1581-1592.* https://doi.org/10.1007/s00170-019-03959-w.

Yin Y., Luo B., Jing H., Bai Z., Gao Y. (2018). Influences of quench cooling rate on microstructure and corrosion resistance of Al-Cu-Mg alloy based on the end-quenching test. *Metallurgical and Materials Transactions B: 49, 2241-2251.* https://doi.org/10.1007/s11663-018-1329-1.

Zedan, A. M. Samuel, H. W. Doty, V. Songmene, F. H. Samuel. *(2022).* Effects of free-cutting elements addition on the microstructure, hardness, and machinability of Al-11%Si-Cu-Mg casting alloys. *International Journal of Metalcasting: 16, 1915-1931.* https://doi.org/10.1007/s40962-021-00740-2.

Zedan Y., Songmene V., Samuel A. M., Samuel F. H., Doty H. W. (2022). Assessment of the influence of additives on the mechanical properties and machinability of Al-11%Si cast alloys: application of DOE and ANOVA methods", *Materials : 17(19), 3297*. https://doi.org/10.3390/ma15093297.

Zhou B. H., Jung H., N Mangelinck-Noe., Nguyen-Thi H., Billia B., Liu Q. S., Lan C. W. (2008). Comparative study of the influence of natural convection on directional solidification of Al-3.5wt%Ni and Al-7wt%Si alloys. *Advances in Space Research: 41, 2112-2117*. https://doi.org/10.1016/j.asr.2007.06.038.