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# MORPHOLOGY AND PHASE FORMATION DURING THE SOLIDIFICATION OF ALCUSI TERNARY EUTECTIC SYSTEM[1]

*C. Morando*[2]
*O. Garbellini*[3]
*O. Fornaro*[2]
*H. Palacio*[3]

**Abstract**

The microstructure of ternary alloys in the Al rich corner of the AlCuSi system were analyzed in order to determine the solidification path in the different structural regions expected from the equilibrium phase diagram. The analysis was based on theoretical models developed in the literature for solidification of simple ternary eutectic system alloys under simple lever rule assumptions. Optical microscopy was used to study the microstructure formed in each case. The observations were consistent with model predictions, providing in that way an example of a methodology for use in ternary and multicomponent alloys.
**Key words:** Ternary eutectic systems; Solidification structures; AlCuSi alloys.

1 *Technical contribution to the 18th IFHTSE Congress - International Federation for Heat Treatment and Surface Engineering, 2010 July 26-30th, Rio de Janeiro, RJ, Brazil.*
2 *PhD, IFIMAT, Fac.Cs.Exactas, UNCPBA, Pinto 399, B7000GHG, Tandil, Buenos Aires; Consejo Nacional de Investigaciones Científicas y Técnicas-CONICET, Argentina*
3 *PhD, IFIMAT, Fac.Cs.Exactas, UNCPBA, Pinto 399, B7000GHG, Tandil, Buenos Aires; Comisión de Investigaciones Científicas de la Pcia.Bs.As-CICPBA, Argentina.*

## 1 INTRODUCTION

Primary manufacturing processes such as ingot casting, continuous casting, squeeze and pressure casting and secondary manufacturing processes such as welding and soldering, involve solidification as an important stage of the process. Many commercial materials are multicomponent alloys, whose mechanical or functional properties are determined by the microstructure that develops during the solidification and subsequent processing stages. One of the essential challenges to materials science is to understand how solidification microstructures form and how they can be controlled by selecting the alloy composition and processing parameters. Thus, a detailed understanding of microstructure formation is important in turn to dictate the performance of the final product.[1]

Fundamental knowledge on solidification has been developed mainly for pure materials and for binary alloys exhibiting single phase growth (solid solution) and/or two phase growth in eutectic and peritectic class reactions.[2]

The classical analytical description for steady-state eutectic growth in binary alloys, developed by Jackson and Hunt,[2] describes the relationship among the undercooling $\Delta T$, the growth velocity $v$ and the lamellar spacing $\lambda$ in the case of regular (i.e non faceted-non faceted) growth at low velocity for phases with an equal density:

$$\Delta T = k_1 \lambda v + \frac{k_2}{\lambda} \qquad (1)$$

McCartney et al.[3] already gave an onset for extending the Jackson and Hunt theory for binary alloys to univariant two-phase coupled eutectic growth as part of the description of the different microstructural regions within a ternary eutectic system, yielding to a Jackson and Hunt type of expression.

While binary alloys have extensively been studied for decades both from theoretical as experimental points of view for multicomponent alloys, with three or more component, the process of microstructure formation during solidification is less understood especially for cases where multiphase reactions occur along the solidification path of the alloy.[4]

Unidirectional solidification studies have been performed by several authors in ternary alloys to investigate the morphological stability in such systems and the nature and dynamic behavior of the patterns forming in coupled growth.

The most systematic work has been performed by McCartney et al.[3,5] describing some of the microstructural regions ocurring in ternary eutectic systems by extension of the known analytical expression in binary alloys for stability of the solid/liquid interface and the competitive growth criterion. Considering a simple ternary system and assuming that each of the three primary phases, α, β and γ, grows in a non faceted fashion, and nucleate easily, a number of different structural regions are then to be expected.[3] The composition ranges of each of these, for a fixed growth velocity and temperature gradient, and schematic growth interfaces predicted are also given.[3]

Himemiya and Umeda[6-8] extended Jackson and Hunt's model to three-phase planar invariant coupled growth in a ternary eutectic for different geometrical arrangements of the growing phases. They also extended their method to set up a microstructural selection map in the case of ternary eutectic solidification based upon analytical growth models.

The purpose of the present work is to characterize the variety of microstructures arising in Al-rich corner of AlCuSi alloys during controlled solidification and to classify

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them taking into account the various possible types of solidification paths corresponding to the different structural regions of phase diagram. The evaluation is proposed in terms of microscopic observations of the microstructure observed and equilibrium considerations of the ternary phase diagram.

## 2 MATERIALS AND METHODS

AlCuSi alloys of eight different compositions were prepared by melting a pre-weighted quantity of pure Al, AlCu and AlSi master eutectic alloys in an electric resistance furnace under argon gas flow protection.

The molten alloys were forced to flow on a rectangular sectioned channel, of dimensions 369x116x39 mm, under depress-casting for the determination of the fluidity. A description of the experimental setup and detailed procedures for processing can be found in References.[9,10] Samples for metallographic examination were sectioned longitudinally from the prepared castings (corresponding to each alloy), mounted, mechanically and electrolitically polished and etched with: 7,5ml $HN_3$ + 5ml HCl + 2,5ml HFl in $H_2O$. The microstructure was analyzed using an optical microscope (OM). In addition, solidification paths were determined by the presence of different phases from the metalography.

The nominal composition of the alloys investigated as well as the present phases according to equilibrium considerations are listed in Table 1 and also plotted on the Al-rich corner of the AlCuSi liquidus projection[11] in Figure 1.

The Lever calculations are based on the AlCuSi equilibrium phase diagram[11] and a complete mixing in the liquid and complete diffusion in the solid at each temperature are assumed, i.e., equilibrium solidification.[12]

**Table 1.** Compositions and constituent phases of the alloys investigated

| Alloy Nº | Composition | Constituent phases |
|---|---|---|
| 1 | Al-33.2%Cu | BE: (Al)-$Al_2Cu$ |
| 2 | Al-11.7%Si | BE: (Al)-(Si) |
| 3 | Al-27.5%Cu-5.25%Si | TE: (Al)-(Si)-$Al_2Cu$ |
| 4 | Al-5%Cu-9%Si | $\alpha$-(Al)+(Al)-(Si)+(Al)-(Si)-$Al_2Cu$ |
| 5 | Al-21%Cu-6%Si | |
| 6 | Al-5%Cu-12.5%Si | (Si)+(Al)-(Si)+(Al)-(Si)-$Al_2Cu$ |
| 7 | Al-21%Cu-2%Si | $\alpha$-(Al)+(Al)-$Al_2Cu$+(Al)-(Si)-$Al_2Cu$ |
| 8 | Al-21%Cu-4%Si | $\alpha$-(Al)+(Al)-(Si)-$Al_2Cu$ |

BE: binary eutectic
TE: ternary eutectic

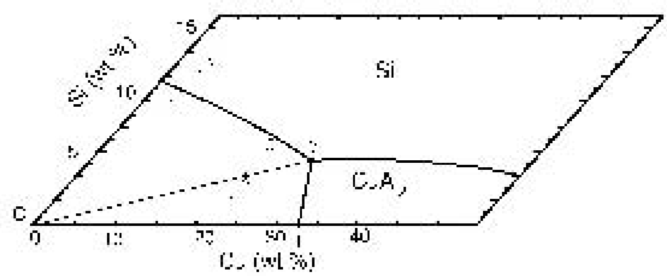


**Figure 1.** Projection of the liquidus surface for AlCuSi system showing composition of alloys investigated.

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## 3 RESULTS AND DISCUSSION

The alloys selected for the present work were chosen as representatives of four different structural regions predicted by McCartney et al.[3] in simple ternary eutectic systems and the various types of solidification path according to the equilibrium diagram, thus, the presence of different phases from metallography was considered. In microstructures, the primary product of solidification is the coarsest and usually has a dendrite structure for the (Al) or faceted crystals for the (Si). The secondary and tertiary structures are successively thiner. Following McCartney et al.[3] the results are thus divided into four groups as follows:

**1) Region 2 and 4: For alloys of two or three phase coupled growth**

Typical optical micrographs of eutectic alloys Al-33%Cu, Al-11.7%Si and Al-27.5%Cu-5.25%Si are shown in Figure 2 a, b and c) respectively. The alloy Al-33%Cu (Alloy 1) exhibits a regular lamellar morphology consisting of two non-faceted phases: (Al) (white phase) and θ-$Al_2Cu$ (black phase) as shown in Figure 2a), whereas the alloy Al-11.7%Si (Alloy 2) exhibits an irregular eutectic microstructure consisting of a faceted phase and a non-faceted one, as shown in Figure 2b). The Si-rich phase present in faceted platelike, grows preferentially into the liquid with a halo of α-(Al) phase. Figure 2c) shows a microstructure of the eutectic ternary alloy Al-27.5%Cu-5%Si (Alloy 3) formed by three-phases mixture of (Si) (gray) and θ-$Al_2Cu$ (black) in a α-(Al) matrix (the white area).

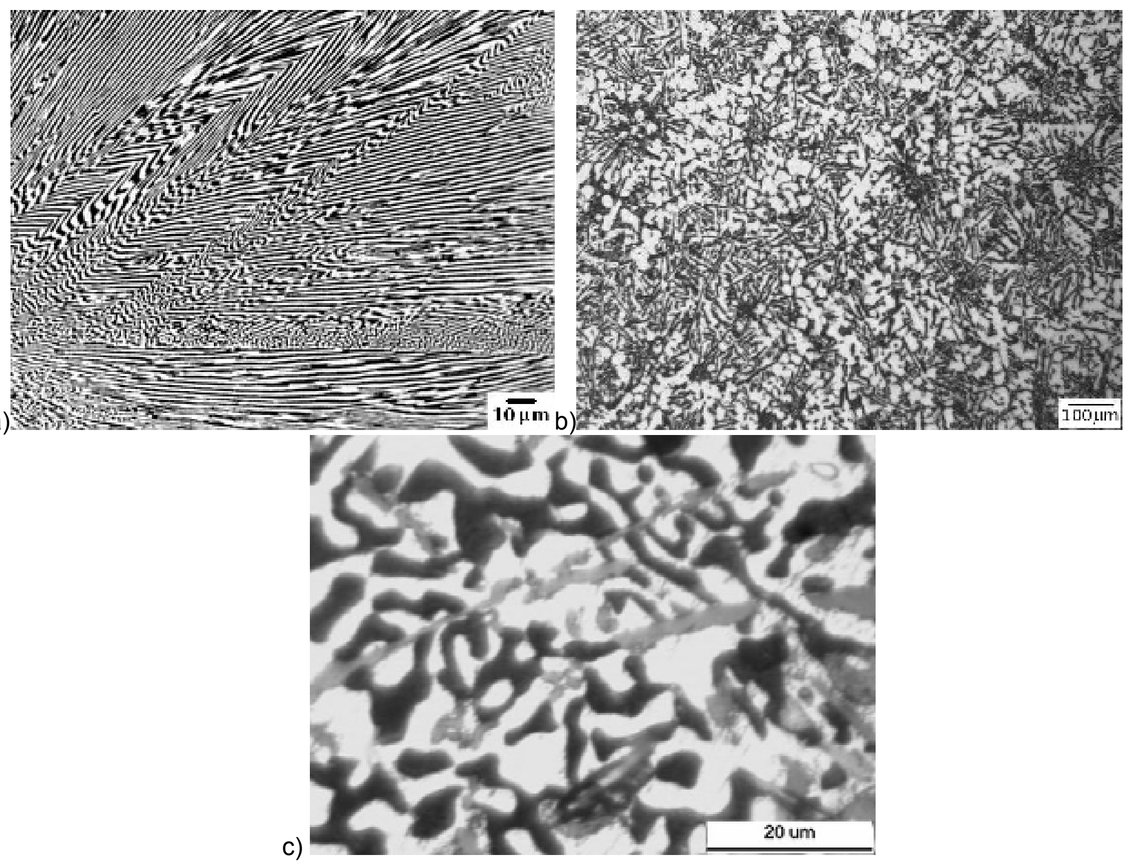
a) b) c)



**Figure 2.** Solidification microstructures corresponding to a) Al-33%Cu, b) Al-11.7%Si and c) Al-27.5%Cu-5%Si eutectics.

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**2) Region 5b: For alloys away from the eutectic valleys side of the eutectic groove between (Al) and (Si)**

For the microstructures of the alloys with high silicon content, Al-5%Cu-9%Si (Alloy 4) and Al-21%Cu-6%Si (Alloy 5) shown in Figure 3a and b), regions of α-(Al) primary phase dendrites, secondary AlSi eutectic structure where (Al) and (Si) together form two-phase dendrites with a complex-regular morphology, and a very fine AlCuSi ternary eutectic structure formed by (Al) + θ-$Al_2Cu$ +(Si) are identified.

The microstructure of Al-5%Cu-12.5%Si (Alloy 6) shown in Figure 3c) revealed a few randomly distributed primary (Si) particles highly faceted with acicular AlSi eutectic formed by (Al)+(Si), and a low volume fraction of fine ternary eutectic formed by (Al) + θ-$Al_2Cu$ +(Si).

**3) Region 5b: For alloys away from the eutectic valley side of the eutectic groove between (Al) and θ-$Al_2Cu$**

For the alloy with low silicon content Al-21%Cu-2%Si (Alloy 7), (Figure 3d), the microstructure revealed the presence of primary dendrites α-(Al), secondary binary degenerated eutectic (Al) + θ-$Al_2Cu$ and fine ternary eutectic appearing between the dendrite arms. The binary eutectic degenerated, the α-(Al) solid solution part of eutectic solidified on the α-(Al) solid solution dendrites which were solidified first.

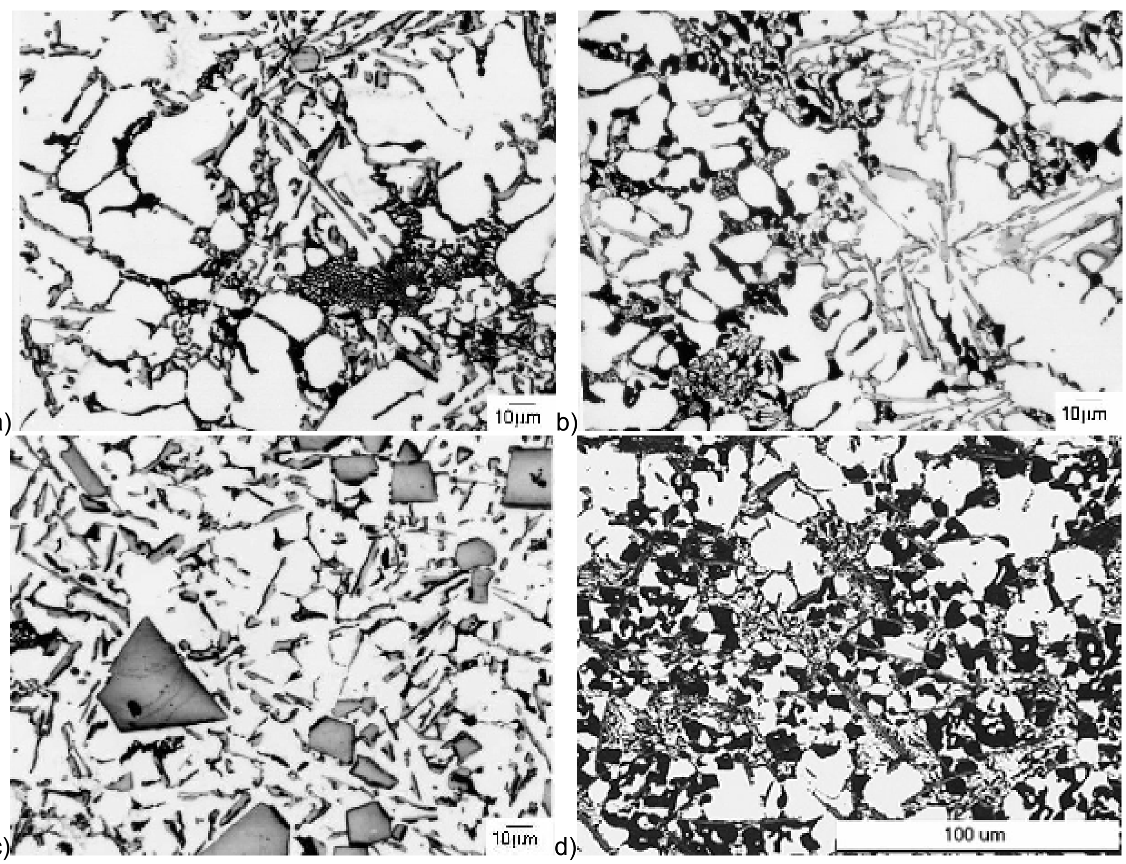
a) b) c) d)



**Figure 3.** Typical microstructures of longitudinal sections of a) Al-5%Cu-9%Si, b) Al-21%Cu-6%Si, c) Al-5%Cu-12.5%Si and d) Al-21%Cu-2%Si. White, grey and black phases are α-Al, Si and $Al_2Cu$ respectively; interdendritic fine scale phase is ternary eutectic.

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**4) Region 5c: For alloys away from the eutectic valleys situated upon the border between 5b regions**

In Figure 4, Al-21%Cu-4%Si (Alloy 8) the observed regions are primary α-(Al) dendrites and ternary eutectic structure in the interdendritic spaces.

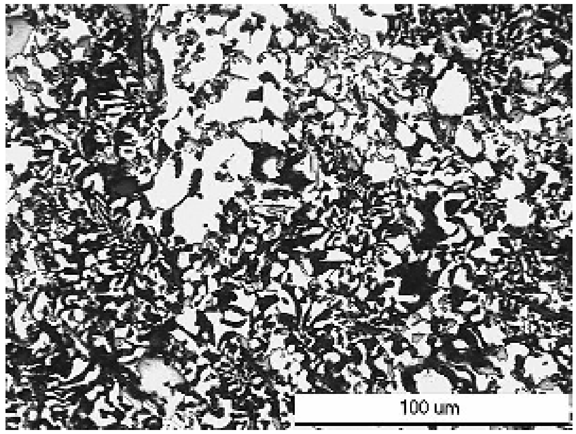


**Figure 4.** Typical microstructure of longitudinal section of Al-21%Cu-4%Si.

On the basis of the microstructure analysis, the solidification paths occurred as follows for each different ternary alloy under study:

**Alloys 4 and 5:** Solidification starts from liquid phase forming α-(Al) phase, trapping liquid containing Si and Cu. After that, the binary eutectic Al-Si nucleates and finally solidification end with the formation of a ternary Al-Si-$Al_2$Cu eutectic. Schematically:

$$\left.\begin{array}{l} Al-5\%Cu-9\%Si \\ Al-21\%Cu-6\%Si \end{array}\right\} \qquad L \rightarrow \alpha(Al) + AlSi + AlSi\theta(Al_2Cu) \qquad (2)$$

**Alloy 6:** For this family, the first nucleous corresponds to primary Si, after that binary Al-Si eutectic and ternary Al-Si-$Al_2$Cu eutectic is formed.

$$\left. Al-5\%Cu-12\%Si \right\} \qquad L \rightarrow Si + AlSi + AlSi\theta(Al_2Cu) \qquad (3)$$

**Alloy 7:** The solidification proceeds from liquid phase starting with α-(Al) dendrites trapping rich liquid. Solidification continues with formation of binary Al-$Al_2$Cu eutectic and then ternary Al-Si-$Al_2$Cu eutectic.

$$\left. Al-21\%Cu-2\%Si \right\} \qquad L \rightarrow \alpha(Al) + Al\theta(Al_2Cu) + AlSi\theta(Al_2Cu) \qquad (4)$$

**Alloy 8:** This alloy is right over a dominium interphase line. In this case, solidification proceeds from α-(Al) dendrites and then, following this line reaching the ternary composition Al-Si-$Al_2$Cu with no appreciable apparition of binary Al-Si or Al-$Al_2$Cu eutectics.

$$\left. Al-21\%Cu-4\%Si \right\} \qquad L \rightarrow \alpha(Al) + AlSi\theta(Al_2Cu) \qquad (5)$$

## 4 CONCLUSIONS

Al rich AlCuSi alloys of different compositions were solidified under controlled conditions. Generally AlCuSi system shows a combination of non faceted-non faceted AlCu eutectic and faceted-non faceted AlSi eutectic morphologies into an $\alpha$-Al matrix. In this way, theoretical models and phase diagram could be used to predict the existence of different structural regions for each studied composition under the solidification conditions used.

This work has showed the existence of several of these structural regions and the types of solidified structures observed were, in general, consistent with the phase sequence formed during solidification according to the lever calculations and model predictions[3]. The results provide an example of an analysis method for use in ternary and multicomponent alloys such as commercial Al alloys.

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