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# Obtention rheocast structure for Al-4.5wt%Cu alloy: comparison ultra-refining and electromagnetic stirring

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**Materials**

## ABSTRACT

**Purpose:** the present work analyses the mechanisms involved in the formation of the rheocast (globular) structure for the Al-4.5wt%Cu alloy, produced by electro-magnetic stirring (EMS) of the liquid during solidification, under the following basic conditions: pouring temperatures of 750 and 800°C with and without addition of a grain refiner. The objective is to directly compare between the electro - magnetic stirring and ultra - refining as methods of obtaining rheocast materials, as well as to verify the possibility of using these methods together. The general purpose is to develop a new Aluminum-Copper based alloy for thixoforming.
**Design/methodology/approach:** the experimental apparatus was made of a wrapped metallic ingot mould surrounded by a sequence of induction coils and a power source that generated an estimated power of electromagnetic field with 1200Watts, which was enough for a fixed amount of 1kg of moulting metal). The macro and microstructures ingots obtained had the characterized by optical microscopy to measure the grain size, globular size and the roundness of the globular structures (to verify the efficiency of the globularization).
**Findings:** In the present paper the combination of electromagnetic stirring, lower pouring temperature and grain refiner addition proved to be the best way to produce Al-5.5wt%Cu rheocast alloy.
**Research limitations/implications:** the principal objective is to compare electro-magnetic stirring and ultra-refining to determine the better structure (level of globularization), determining the factor of larger influence: the grain refiner or the electro-magnetic induced field.
**Originality/value:** Aluminum-Copper alloys specially designed for semi-solid applications are a new area in the semi-solid field, and this paper presents in primary hand the results for the AA 2xxx series.
**Keywords:** Metallic alloys; Rheocast; Aluminium-copper alloys; Electromagnetic stirring; Ultra-refining

## 1. Introduction

Rheocasting is an emerging technology that is applied to obtain components from the conformation of metals and alloys in the semi-solid state. There are many advantages presented by this method: a lower consumption of energy, a wide variety of alloys and geometric forms, excellent mechanical properties, an increase in the lifetime of the processing equipment, an excellent surface finish and high dimensional quality, among others qualities [1,2,3].

Formation of pieces in the rheocast state, or semi-solid state, is possible due to the morphology of this structure: a globular primary phase wrapped in a secondary phase. When heated to a temperature between the temperatures *solidus* and *liquidus*, the secondary phase liquefies, acting as a lubricant during the conformation of the material. This morphological modification of the primary phase can be achieved in several ways, such as the

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stirring of the material during solidification or the use of grain refining [1, 4, 5, 6, 7, 8, 9]

This stirring can be done in several ways, in particular mechanical stirring or electromagnetic stirring. The first one is very limited due to contact between the rotor and the liquid metal that can cause contamination of the material.

Electromagnetic stirring is already being used because it permits continuous production of ingots and there is no contact between the induction reels and the metallic bath. Besides, this stirring type has very low consumption energy to ingot-produced ratio, which justifies its extensive application [3, 5, 7, 9, 10, 11].

Electromagnetic stirring final microstructure has a small disadvantage in relation to mechanical stirring as there is a limitation of the depth of the magnetic field used that restricts the size of the ingot produced. In addition inside ingots larger than 80mm diameter, called pre-rheocast structures, are formed by broken dendrite arms. On the other hand, mechanical stirring results in a more globular structure a due to efficiency of the stirring [8, 12, 13, 14].

However, good control of the parameters that form the magnetic field such as induced power, inductor type, use of alternate electric fields and control of the stirred mass, can improve the final microstructure. Stirring time and addition of inoculants (or grain refiners) can also control the final microstructure [4, 9].

Hirt and Zillgen [8] analysed the influence of the use of grain refiner Al-Ti-B together with electromagnetic stirring on the microstructure of Al-7wt%Si and Al-1,0wt%Mg-1,0wt%Si, and they observed that the action of these two methods generates a very uniform structure with a very intense refining of the structure of the material. In this way, it is possible to make microstructural changes in the material, so that the most likely globular structure is obtained, without subsequent heat treatments that increase the costs and limit the process [11, 13, 15, 16]. But, from this work is impossible to predict if the ultra – refining presented by the alloys tested is due to the electromagnetic stirring or the grain refining. It's necessary to achieve the principal influence in the morphological change.

The objective of this work is to reproduce the experiments of Vivés [3, 5] and Hirt [8] in a simplified electromagnetic stirring system, capable of producing ingots of up to 1kg. This system is the origin of a system of semi-continuous casting for the production of ingots with a length of up to 1 meter. Besides this objective, this work aims to discover the formation of the rheocast structure is due to the ultra-refining or to electromagnetic stirring.

## 2. Experimental procedure

For the present case the AA 2024 (Al-4.5wt%Cu-0.20wt%Si-0.30wt%Fe-0.15wt%Mg) alloy was used. The tests were conducted in a very simple apparatus shown in Figure 1. It consists of a motor stator with induced power and a system for field investment control, coupled to a casting mould of austenitic stainless steel with a diameter of 42mm and a length of 500mm, in which the liquid metal was cast and stirred by the electromagnetic drawing forces, with changes in the directions of the electromagnetic field for periods of 2 seconds.

The mass of the ingot was maintained at 900g. The test temperares (pouring temperatures) were: 750 and 800°C, with and without the addition of grain refiner (0.2wt% of Titanium, i.e., 4g of Al-5.0wt%Ti-1.0wt%B alloy).

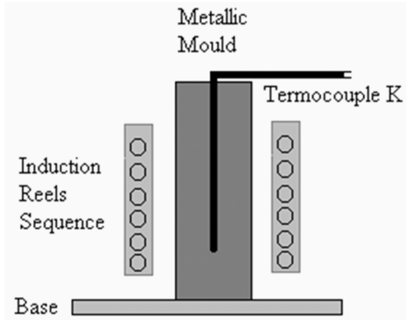



Fig. 1. General overview of the electromagnetic stirring apparatus for the rheocast production

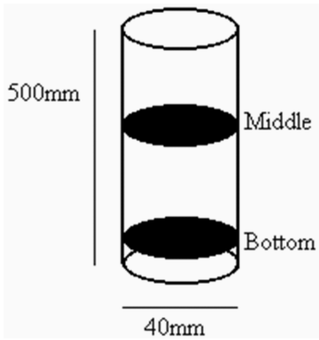



Fig. 2. General overview of the sample obtained

Firstly, the AA 2024 alloy was melted in a primary furnace, its temperature was measured and it was poured in the casting metallic mould to initiate the solidification with and without stirring (power of 1200W and reversions time of 2seconds) until the completely solidification.

In the tests that used grain refiner, this was added to the liquid metal before the pouring and quickly dissolved. Under all the conditions tested, a fixed thermocouple was used inside the cast mould to measure the temperature of the material starting at its liquid state and continuing up to its total solidification in order to obtain the solidification curve for the alloy analysed, and measure the solidification rate.

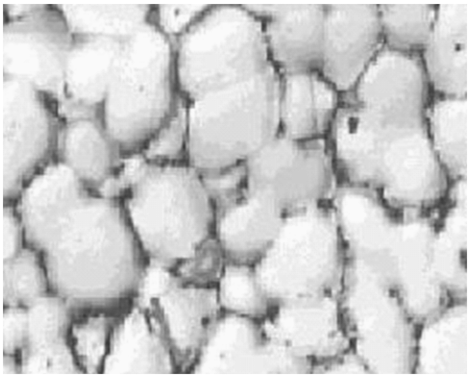
To compare stirring efficiency, the same conditions were also used for the samples melted conventionally, with and without the presence of grain refiner (in the same proportions).

Samples were removed from the bottom and the middle (in Figure 2) for each test, in order to characterise the macrostructure and the microstructure. The samples were prepared for 600 mesh and chemically etched (15ml HF, 4.5ml $HNO_3$, 9.0ml HCl, 271ml $H_2O$), to obtain the macrostructure. For the microstructure, the samples were prepared up to 1200 mesh and electrochemically polished with I1 solution (in a current of 1A for 40s).

The measurement of grain size (for macrostructure) and globular size (for microstructure) was made by the intercept method (manual counting). The macrostructure and microstructure were captured by a system of image analyses coupled to the optical microscope to the measurement of roundness, although the lack of secondary phase ($CuAl_2$) at the grain boundary generated many mistakes at the time of calculation. Thus the image outlines to the measure of roundness were first worked on using the Paint Shop Pro software, where the outlines were drawn manually.

The approach used was based on reinforcing the un-revealed contours, due to the small amount of secondary phase present in the alloy, but which can be observed under the microscope. After treatment the image was analysed using Image System Analyse and the mistakes in the measurement of globule size and roundness were corrected. Figure 3 illustrates the method used.

a)



b)

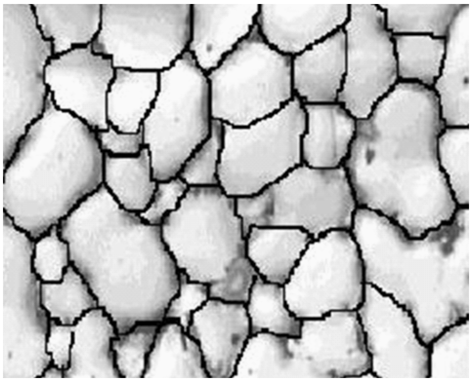


Fig. 3. Microstructure showing the sample under the condition: a) before image treatment and b) after image treatment

## 3. Results and discussions

With the thermocouple aid coupled to the casting mould, the solidification curves for all the conditions tested were offset by a positive amount from the original curves. Although the results weren't conclusive, it could be affirmed that the small differences seen were due to the thermal inertia of the devices used in the tests. The apparatus generated a cooling rate of 35 ± 12°C/min for the poring temperature of 800°c and 30 ± 12°C/min for the pouring temperature of 750°C

### 3.1. Macrostructure

The rheocast ingots obtained were characterised for the macrostructure. The macrostructures shown in Figure 4 represent the bottom position of the sample. The structure presents a significant difference with relation to the size of the grain obtained: all rheocast samples presented smaller grain size than as-cast samples, that indicates the efficiency of the electromagnetic stirring as a method to reduce the grain size. But for the higher pouring temperature (800°C), both structures presented a greater grain size and a very heterogeneous structure. This is due to the influence of the lower cooling rate and the low efficiency of the magnetic fields in the bottom area.

The as-cast samples drained at 750°C show a typical dendritic formation starting at the wall and moving towards the centre of the ingot as well the microstructure of the tests drained at 800°C. Therefore, the higher the pouring temperature, the larger the grain size. The same occurs with the rheocast structure obtained (behaviour identical to the dendritic material), but with a smaller grain size.

Figure 5 represents the middle position for the same situation. In the middle of the ingot the effect of the magnetic fields are more strong than the bottom position, and the effect on the macrostructure is more visible. For this condition all rheocast samples presents a very homogenous structure with smaller grain size than the as-cast condition. For optical view is possible to observe that the structure of Al-4,5wt%Cu with electromagnetic stirring and ultra refining is better than the structure without the stirring, but this structure presents similar structure to the samples without the grain refiner. The macrostructures obtained allowed measurement the grain size for both materials. Table 1 shows this data for all the samples produced with electromagnetic stirring and also for the structure obtained conventionally (dendritic).

From the Table 1 it is observed that the grain size of the rheocast structure is smaller than the dendritic structure for all conditions tested. From Tables 1 and 2 is possible to observe that the rheocast structure is more homogeneous than the as-cast structure: this structure presents the lower standard deviation. This is due to the homogenisation caused by the stirring during the solidification. Under the two conditions, dispersion increases with the pouring temperature, which promotes a lower rate in the solidification process.

### 3.2. Microstructure

The microstructures obtained allowed measurement the globule size and roundness. Table 2 shows this data for all the samples produced with electromagnetic stirring and also for the structure obtained conventionally (dendritic).

The as-cast without grain refiner is incapable to produce rheocast structure. Only the as-cast with grain refiner is effective to produce rheocast structure. So the ultra refining of the as-cast structure is a effective method to produce rheocast material, even with little and imperfect globularization. (Figure 6).

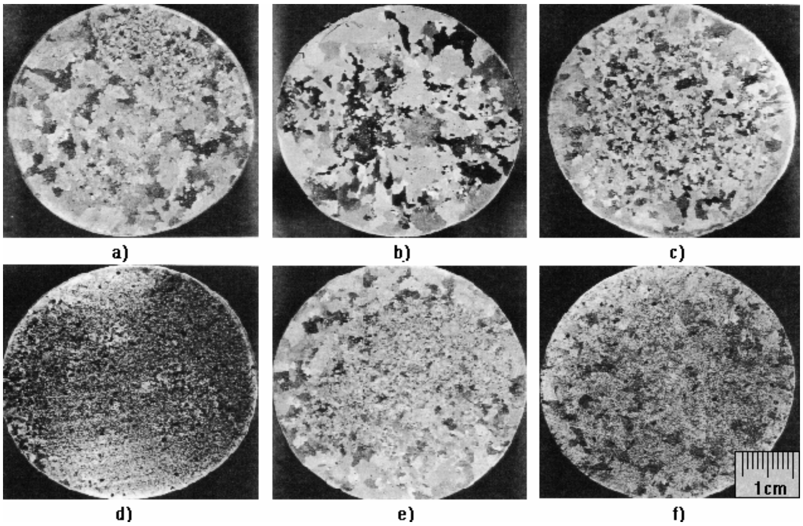



Fig. 4. Macrostructures obtained for the bottom position, in the following conditions: a) and b) as-cast at 750°C and 800°C without grain refiner; c) as-cast at 750°C or 800°C with grain refiner (identical structures), d) and e) rheocast at 750°C and 800°C without grain refiner and f) rheocast at 750 or 800°C with grain refiner (identical structures)

Table 1.
Grain size for the Al-4.5%Cu alloy in the as-cast and as-rheocast condition

| Condition | Pouring Temperature (°C) | Addition Of Grain Refiner | Bottom Position Grain Size(μm) | Middle Position Grain Size(μm) |
|---|---|---|---|---|
| Rheocast (electromagnetic stirring) | 750 | No | 206 ± 43 | 153 ± 23 |
| | 800 | No | 259 ± 91 | 178 ± 38 |
| | 750 | Yes | 172 ± 43 | 142 ± 22 |
| | 800 | Yes | 185 ± 53 | 151 ± 43 |
| As – Cast Conventional | 750 | No | 1615 ± 304 | 1245 ± 257 |
| | 800 | No | 2798 ± 790 | 3176 ± 1390 |
| | 750 | Yes | 220 ± 102 | 270 ± 109 |
| | 800 | Yes | 360 ± 190 | 410 ± 215 |

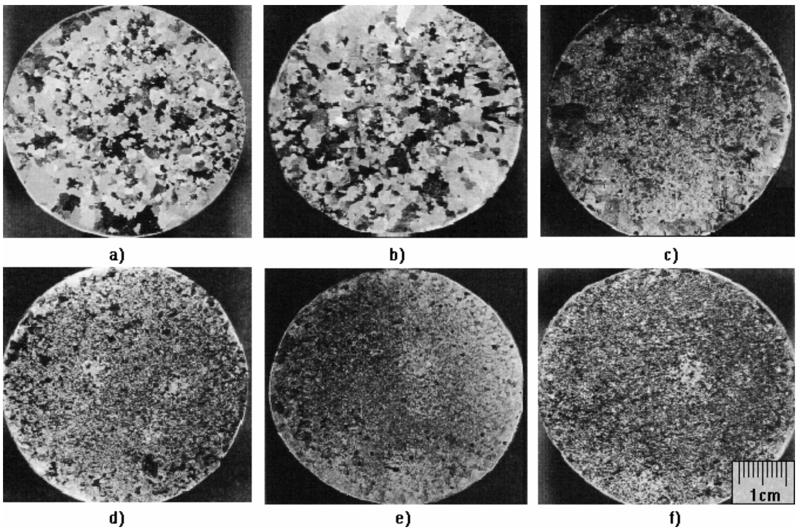



Fig. 5. Macrostructure obtained for the middle position, in the following conditions: a) and b) as-cast at 750°C and 800°C without grain refiner; c) as-cast at 750°C or 800°C with grain refiner (identical structures), d) and e) rheocast at 750°C and 800°C without grain refiner and f) rheocast at 750 or 800°C with grain refiner (identical structures)

From Table 2 it can also observed that under the two conditions tested, dispersion increases with the increase in the pouring temperature due to the lower cooling rate that promotes a heterogeneous solidification. There is time to coarsening phenomena occurs. The rheocast structure presents a smaller globular size than as cast structure except for the bottom position. In this position the solidification occurs firstly and there is no time for the a effective stirring, but for the middle position all rheocast condition presented smaller globular size than as-cast.

The combination of electromagnetic stirring and addition of grain refiner is the better way to produce rheocast structure: smaller grain size (96µm) and the better globular structure (roundness about 1.72). The better structure achieved is the rheocast structure produced by a electromagnetic stirring of Al-4.5wt%Cu with the addition of grain refiner.

When one compare Table 1 (macrostructure) with Table 2 (microstructure) it can be seen that for rheocast material a globule is different than a grain. In another words one grain in the macrostructure can contain one or more globules. (For the bottom position the solidification process occurs quickly and there is no time for a efficient globularization, so the comparison will be executed with the middle position). There is following relationship for this situation (grain size/globule size) for the middle position:

- For rheocast material: range of 1.34 to 1.47.
- Without grain refiner: range of 1.40 to 1.46.
- With grain refiner: range of 1.34 to 1.47.
- For As-Cast material: range of 2.29 to 3.01.

This relation indicates that the formation of the rheocast structure is more strongly dependent of the stirring forces than the use of inoculants, because the expectation for electromagnetic stirring is one rheocast globule to be a one grain. The formation of the rheocast material produced by electromagnetic stirring occurs following the steps: first the solidification of small grains with dendritic geometry in one substrate (the wall mould in this case); the separation of this small grain from the wall by the stirring forces and the growing of this small grain in the middle of the ingot. This nucleotides are stable because the continuos cooling of the alloy.

The principal phenomenon is the increase of the efficiency of the crystal multiplication mechanism. The structure initial is dendritic but there is no preferential way of growing in the middle of the ingot: this causes the globularization of the dendrite. With the use of grain refiner there are more substrates to nucleate the grain and the production of globules should be better, but the relation changes from 1.40 and 1.46 to 1.34 and 1.47 globule for each grain, that is to say, there is no significant difference when we use the inoculant.

For as-cast condition with the grain refiner we can say that the process to produce rheocast material using the grain refining is less efficient because one grain can contain 2.3 or 3 globules/grain, that is to say that coarsening phenomena is joining the globules during the solidification.

The as-cast sample observed in Figure 6 shows this effect clearly, because it can be compared to the structures where globule size and roundness were measured. For the structure without grain refiner, it was impossible to measure either the roundness or globule size since none were formed. The globule size generated for the structure with grain refiner, although similar (around 120µm) shows greater heterogeneity, as can be observed by the standard deviation (70 versus 50µm).

This is more important when roundness is compared, because it changes from 1.7 to 2.3 while the respective deviation pattern changes from 0.5 to 2.0. This indicates a highly heterogeneous structure.

In Figure 7 it is possible to see the same structure as that seen previously in the as-cast condition, but for the middle position, with and without the grain refiner. It can be observed that for the structure without the presence of the grain refiner globularization did not occur, and when the grain refiner is used globularization is effective, although the globule has a medium size similar to that seen in the rheocast structure. However, the heterogeneity of the structure is pronounced, as can be observed by the comparison of the standard deviation shown. The same occurs for roundness.

Table 2.
Globule size and roundness for the Al-4.5%Cu alloy in the as-cast and as-rheocast condition

| Condition | Poring Temperature (°C) | Addition Grain Refiner | Bottom Position | | Middle Position | |
|---|---|---|---|---|---|---|
| | | | Globule Size (µm) | Roundness (µm) | Globule Size (µm) | Roundness (µm) |
| Rheocast (electromagnetic stirring) | 750 | No | 143.5 ± 53.8 | 2.39 ± 1.09 | 108.9 ± 49.4 | 1.74 ± 0.61 |
| | 800 | No | 187.4 ± 45.8 | 2.57 ± 1.12 | 121.9 ± 45.0 | 1.75 ± 0.42 |
| | 750 | Yes | 110.9 ± 46.5 | 1.69 ± 0.56 | 96.5 ± 47.0 | 1.72 ± 0.52 |
| | 800 | Yes | 121.7 ± 64.5 | 1.73 ± 0.48 | 113.2 ± 38.3 | 1.77 ± 0.50 |
| As – Cast Conventional | 750 | No | No Glob* | No Glob* | No Glob* | No Glob* |
| | 800 | No | No Glob* | No Glob* | No Glob* | No Glob* |
| | 750 | Yes | 117.1 ± 65.7 | 2.16 ± 1.71 | 118.5 ± 81.9 | 2.08 ± 1.41 |
| | 800 | Yes | 128.9 ± 71.2 | 2.30 ± 2.47 | 136.0 ± 76.2 | 2.13 ± 1.68 |

*) No globular structure was detected. Roundness greater than 10.00.

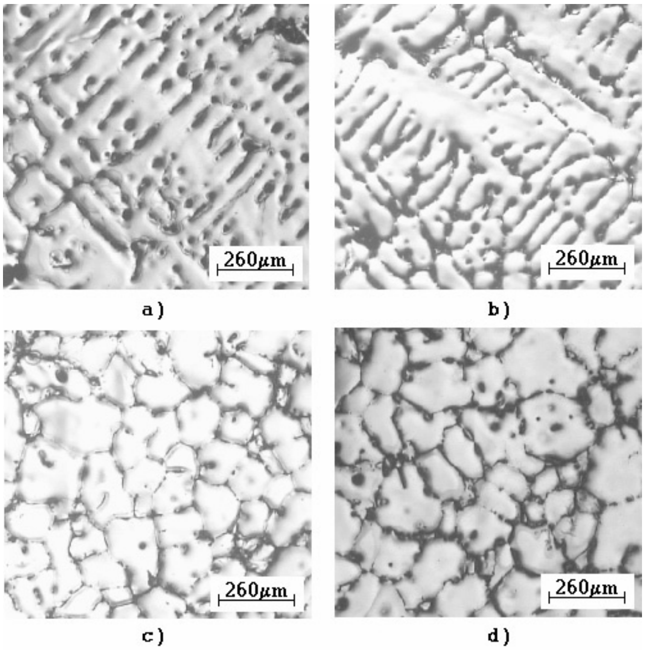



Fig. 6. Microstructure of the as-cast samples in the bottom position under the conditions: a) 750°C and b) 800°C without grain refiner; c) 750°C and d) 800°C with grain refiner

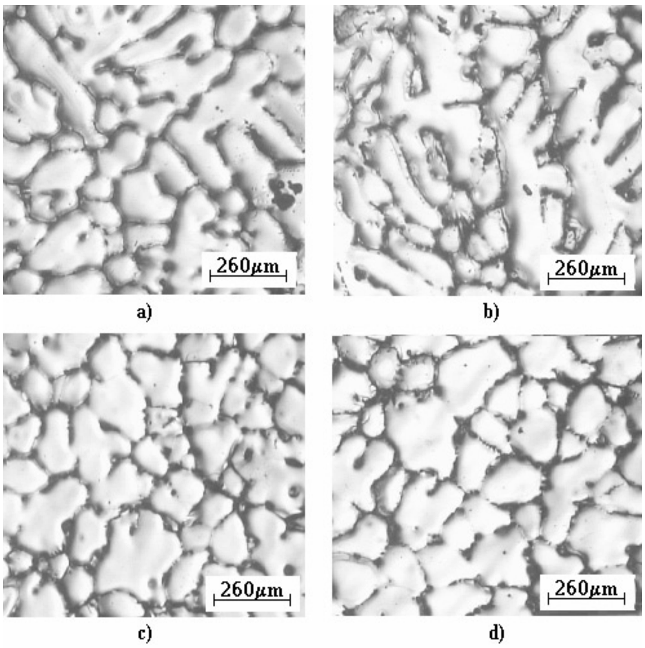



Fig. 7. Microstructure of the as-cast samples in the middle position under the conditions: a) 750°C and b) 800°C without grain refiner; c) 750°C and d) 800°C with grain refiner

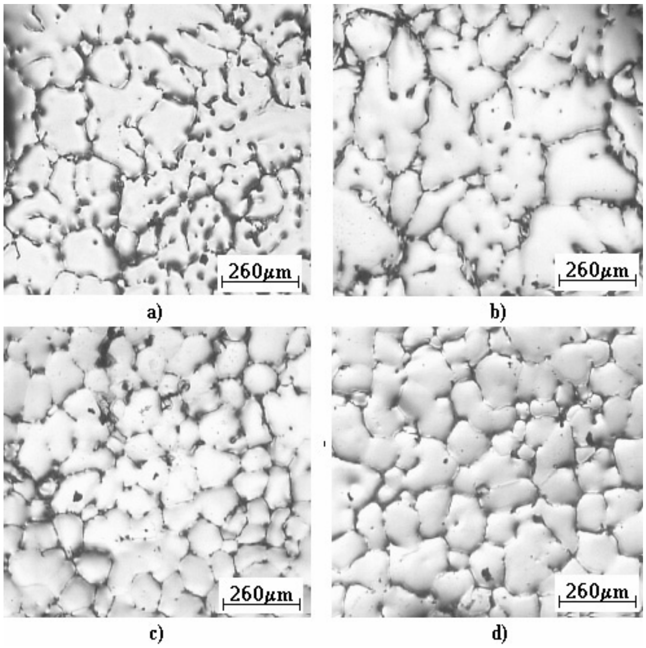



Fig. 8. Microstructure of the rheocast samples in the bottom position under the conditions: a) 750°C and b) 800°C, without grain refiner; c) 750°C and d) 800°C with grain refiner

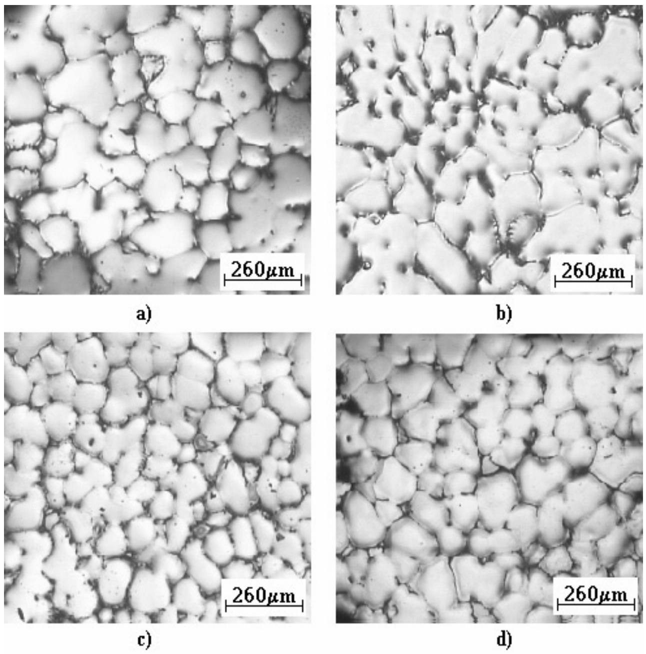



Fig. 9. Microstructure of the rheocast samples in the middle position under the conditions: a) 750°C and b) 800°C, without grain refiner; c) 750°C and d) 800°C, with grain refiner

In analysing the microstructures of the rheocast samples (Figure 8 and 9) in comparison with the data in Table 2, it can be observed that even for the area where solidification is fast, i.e., for the bottom position of the cast mould, there was enough stirring time to achieve the formation of the rheocast globular structure. It can also be seen that besides being more homogeneous (globule size varies from 96 to 122µm), the structure formed shows a smaller dispersion of data (standard deviation between 38 and 49µm). It still shows a roundness close to the ideal (1 to perfect circle), with a much lower standard deviation than that for the data obtained for the dendritic structure globularized with the use of the grain refiner.

In Table 2 and Figures 8 and 9 it is still possible to point out that no significant difference exists in the relative data for comparison of electromagnetic stirring with and without the use of the grain refiner, i.e., the use of the grain refiner is totally unnecessary for obtaining rheocast structure.

Since the combination of electromagnetic stirring and ultra-refining increases the cost of the final product, total globularization can be achieved only with the use of EMS.

Concerning the size of the globule obtained, it can be observed that the condition without the grain refiner, a decrease in average grain size and roundness occurs: this effect can be explained by the greater effectiveness of stirring, due to the longer stirring time. This fact doesn't occur under the condition with the grain refiner, which shows a small increase in these values, even though dispersion decreases [17].

This behaviour can be explained by the absence of a refrigeration system and temperature control that cause a disturbance in the growth behaviour of the globule, i.e., the temperature remained high enough to generate the thickening phenomenon. The high dispersion value found in all cases can be explained by the type of solidification employed, the air. This generated a high heterogeneity of microstructure, that can be reduced when these conditions are controlled [18].

## 4. Conclusions

In all cases of electromagnetic stirring, the formation of rheocast structures was observed, and the experiments carried out with grain refiners generated more homogeneous microstructures, with a smaller globule size. This difference is not very significant when the costs of the extra stage of refine are taken into account.

The use of grain refiners alone causes the formation of rheocast structures, even though the structure, the originating in this manner has a greater heterogeneity globule size and roundness than the structures generated with EMS, which in turn will affect the subsequent tixo-forming processes.

The best condition to obtain rheocast material is the EMS with 1200W/Kg from pouring temperature of 750°C, that generates a grain size of 153µm, globule size of 122µm and roundness of 1.75. The combined use o grain refiner can improve this situation (grain size of 142µm, globule size of 96µm and roundness of 1.72).

This simple experiment allowed us to innovate in obtaining rheocast structures because it showed that the electromagnetic stirring is more efficient than ultra-refining. Therefore, experiments of power control and stirring control of the entire metallic mass can be a cheap solution for the obtaining rheocast structures.

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