MODELING OF THE INFLUENCE OF THERMIC TREATMENT UPON THE MECHANICAL PROPERTIES OF ALUMINUM-TIN ALLOYS

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Abstract

In order to master and improve the quality and properties of the final products, the major industrial challenge lies in the possibility of controlling the morphology, size of microstructures that reside within the molded pieces, as well as their defects; this is the fundamental reason according to which we are more and more interested in mastering the growth and germination of such alloys, as well as the developing structures, at the time of solidification process. The modeling reveals as a valuable aid in the mastery of the formation of such heterogeneousness: segregation cells that are incompatible with industrial requirements. The whole work focuses upon the modeling of the segregation phenomenon of the four hypoeutectic alloys, Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn, as well as the tin effect upon certain mechanical properties of aluminum. Usually, the microstructure and mechanical behavior of such alloys as Al-Sn are directly influenced by some parameters such as composition, cooling velocity and homogenization process.

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I. Introduction

The extraordinary expansion of aluminum industry id owning to the numerous beneficial typical design features of this valuable metal; hence the unceasing demands for products made of aluminum or integration aluminum into their composition.

Nowadays, it is used in so many fields, and is the material of mobility! It is used in all current means of transport (vehicles, aeronautics, maritime transports, and rail transport) in the building trade and civil engineering; it is also employed in packing, electricity, electronics … in addition, during its use stage, aluminum exhibits many assets in terms of lasting development and presents a permanent material! It is endlessly 100% recyclable without losing its chemical and physical qualities.

As it is the case with all pure metals, the properties of aluminum are weak. So it is suitable to strengthen them, specially the mechanical ones.

Nevertheless, one can significantly improve these characteristics by means of cold hammering, addition of alloy elements or thermic treatment, according to the case [1]. Since the range of alloys is very extended, this allows finding that which is more convenient to the use envisaged constraints. Therefore the mechanical properties of aluminum can be modified with the addition of other metals, specially tin; though this latter is rather rare, its uses are very prevalent thanks to its good resistance to corrosion, absence of toxicity and mainly ability to improve aluminum mechanical properties.

The purpose of this work is to model the phenomenon of (Al-Sn) alloys segregation; this consists basically of first studying the influence of homogenization, while systematically varying the three parameters: time, temperature and composition, then the influence of tin addition and cooling velocity upon the various mechanical properties of the aimed alloys.

One can then imagine the whole stake in understanding and mastering the morphology and evolution of the solidification interface.

II. Equipments and methods

The works concerned with the solidification modeling are essentially focused upon the calculus of the evolution of the thermic field in casting. This temperature field is obtained via the resolution of the equation of heat diffusion.

The whole sphere is made up of a solid and liquid, and the problem of heat diffusion with stage transformation may be expressed by the following formula [2]:

$$\text{div}\left(\overrightarrow{\text{KgradT}}\right) + \dot{Q} = \rho c_p . \frac{\partial T}{\partial t} \quad (1)$$

With:

K is the thermic conductivity;

ρ is the voluminal density;

c_p is the specific heat ;

$\dot{Q}$ is the source term bound to the liberation of melting latent heat.

$$\dot{Q} = \rho L . \frac{\partial f_s}{\partial t} \quad (2)$$

With :

L is the melting latent heat;

f_s is the solid fraction.

The speed of a solution diffusion increases with temperature (network vibration) and expresses itself as follows:

$$D_i = D_i^0 . \exp\left(-\frac{Q_i}{RT}\right) \quad (3)$$

With:

D_i^0 is the pre-exponential term ;

Q_i is the activation energy ;

R is the perfect gases constant;

T is the temperature expressed in Kelvin.

Before any micro-structural investigation, it is necessary to perfectly study the balance diagram between Al-Sn phases in order to know the phases susceptible of being encountered. The alloy Al-Sn [4] (figure1), is a simple eutectic, the melting temperatures of pure aluminum and tin are respectively 660.452 °C and 231.968°C [5] under which the alloy is

heterogeneous; the aluminum solubility in tin is 2.4% molar. Tin is weakly soluble in aluminum (<0.01%) [6], so one single eutectic exists at 97.6% [4].

Because of solubility limits of alloy elements, we will restrict the study of the balance diagram of the Al-Sn alloy to fields of chemical composition contained between 0 and 4% in weight for the element tin, and to homogenization temperatures of 600°C that remain inferior to the aluminum fusion temperature: 200°C represents a temperature below the eutectic bearing, and 400°C as average temperature between the two.
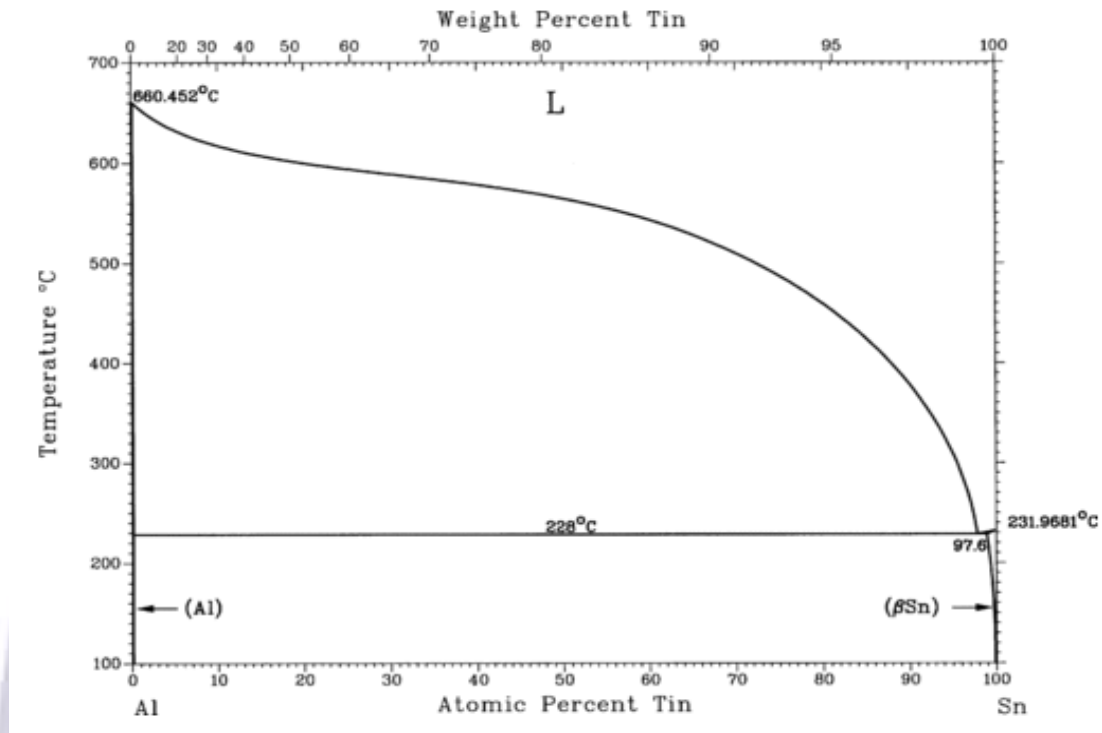

Figure1 : Al-Sn phase diagram [4]

During our study, we suppose that the geometrical form of our alloys is a cylindrical ingot of 100um long.

III. Result and interpretation

The great majority of the thermo-mechanical properties of the alloy are stemming from the type of microstructure obtained by the interaction of various physicochemical parameters at the time of solidification.

These parameters are, on the one hand, due to physical conditions of solidification, and on the other hand, to the alloy chemistry (added alloy elements: Sn in this case).

The metallographic observations brought on figure 2 are characterized by the existence of segregation cells for all the four previously studied compositions.

3.1 structural study of Al-Sn alloys
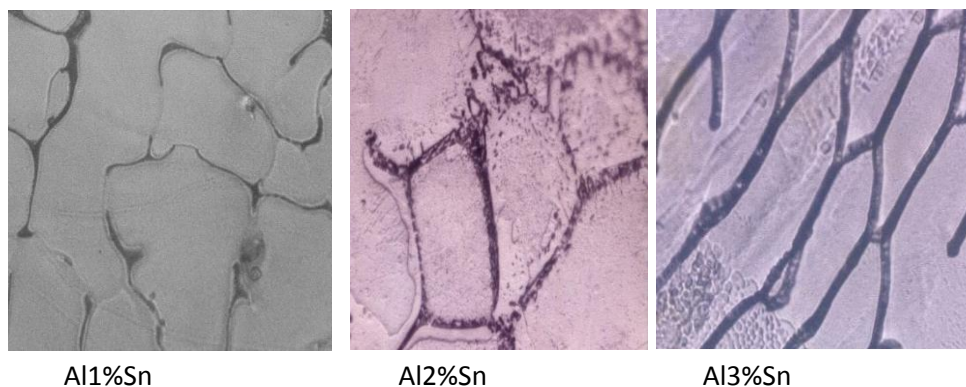

Al1%Sn   Al2%Sn   Al3%Sn

Figure2 : The mould structure after alloys quenching: Al1%Sn, Al3%Sn and Al4%Sn

The alloys quenching structure is characterized by the presence of segregation cells. We notice as the tin content increases (from 1% to 4%), the segregation cells rate becomes more and more important.

3.2 The homogenization influence

For the following study, we are interested in understanding the homogenization effect according to the three parameters: time, temperature and composition, and seeing each one influence upon the tin concentration according to the distance between the surface and the core of the ingot.

3.2.1 Time influence

The figure 3 shows the tin concentration evolution according to the distance between the surface and the core of the ingot at the price of time, and to the alloy Al1%Sn at the temperature of 400°C. We notice that there is a mixture of the two metals with a tendency for the information of a solid homogeneous solution. In fact, in keeping prolonged time, the concentration in Sn at the surface increases and goes from a minimal value of 0.04 (wt %) at 3 hours to 0.19 (wt %) after 18 hours, contrarily to the ingot core, the concentration in tin slightly decreases between 3 hours and 18 hours and goes from 0.47 to 0.19 (wt %); nevertheless, we can also notice that the concentration in tin has a tendency to be uniform in very point between the surface and the core of the ingot over 18 hours.

Qualitatively speaking, it seems that the atoms of each element move at the price of time from the rich areas in this element towards the poor ones that become rich, more accurately under the influence of a concentration gradient which is the driving force of the diffusion phenomenon. Therefore, it is necessary to keep a sufficient homogenization time so that the chemical species diffusion between the divers stages may occur.
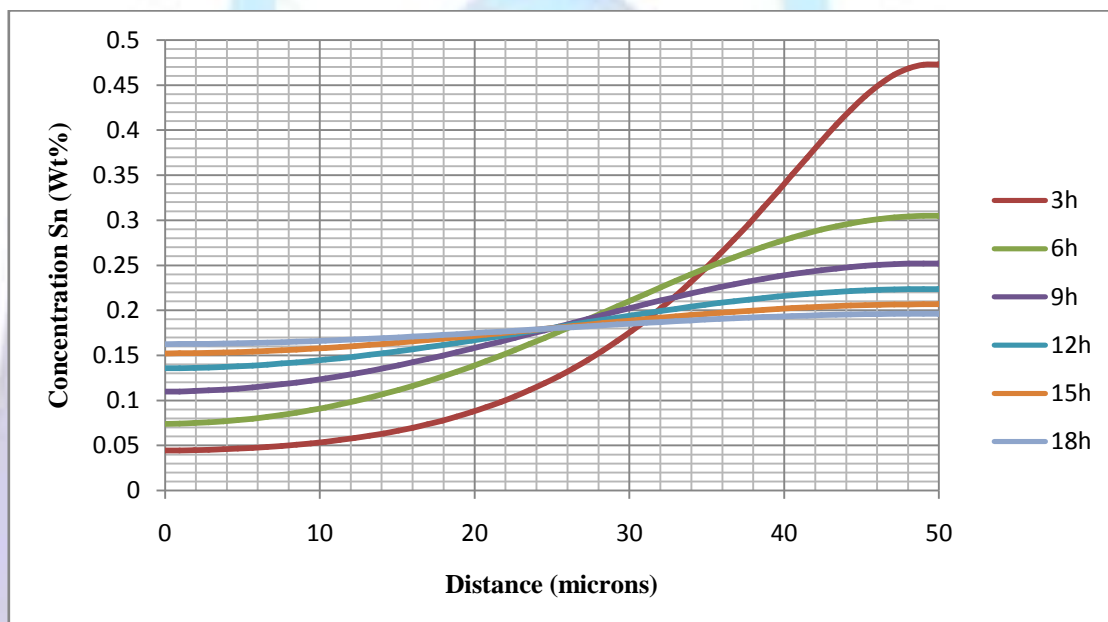

Figure 3: Tin concentration evolution according to the distance between the surface and the ingot core at the price of time of the Al1%Sn alloy at the temperature of 400°C.

3.2.2 Temperature influence

For the three temperatures of maintenance: 200°C, 400°C and 600°C, the tin concentration evolutions according to the distance between the surface and the ingot core, of the Al1%Sn alloy at the end of 3 hours, are born on figure 4. We notice that the concentration in Sn at 600°C presents the highest concentration 0.58 (wt %) and it remains constant, while, at 400°C, we note a progressive enrichment in Sn from the surface 0.04 (wt %) to ingot core 0.47 (wt %); these values tend to equilibrium values tend to equilibrium values. As for the temperature 200°C, the concentration in Sn does not seem to be affected, because the diffusion speed of the chemical species is considerably slower in the solid phase than in the liquid one, the concentration remains nil and begin to increase but above 26 microns: the variation is surely feeble but also detectible.

Furthermore, the comparison of the concentration in Sn in every point of the ingot shows that the concentration of equilibrium in Sn is higher at 600°C. We can therefore suggest that the diffusion of tin in solid solution is sufficiently fast to reach the limit of solubility from the first moments at high temperature.
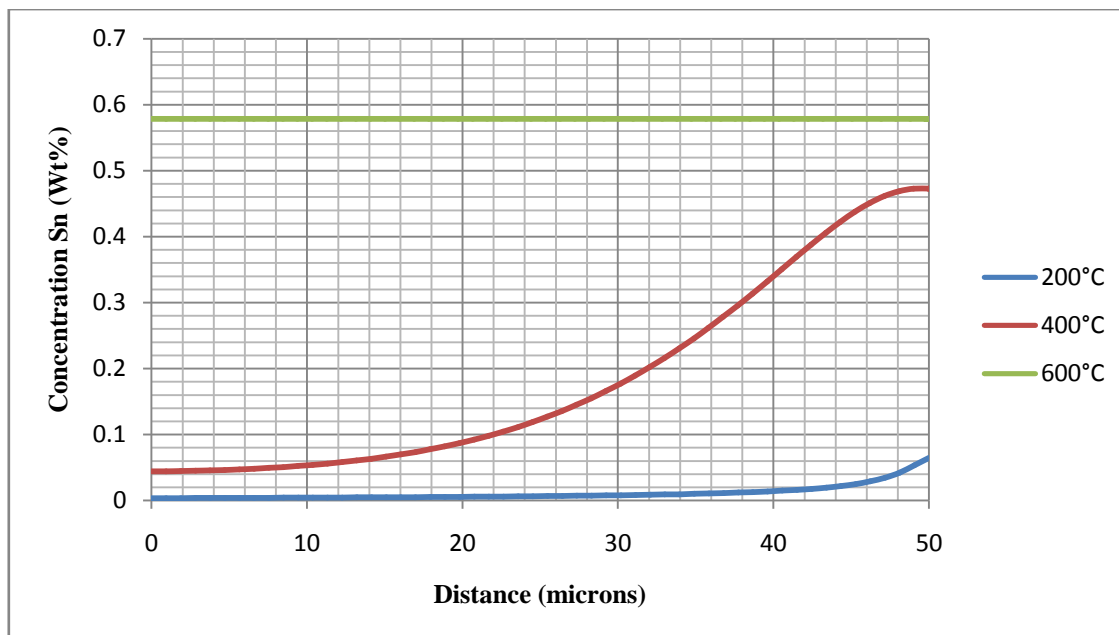
Figure 4: Tin concentration evolution according to the distance between the surface and ingot core at temperature of 200°C, 400°C and 600°C of Al1%Sn alloy at the end of 36 hours

3.2.3 Tin influence

In order to study tin influence, we have dealt with four different compositions: Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn. The tin concentration evolution is represented in following figures:

The figure 5 shows tin concentration evolution according to the distance between the surface and ingot core, at the temperature of 200°C of the four concerned alloys at the end of 3 hours. From the surface until the distance of 43 microns, we notice that the curves possess hardly the same rate of variation, above distance, the Al1%Sn alloy follows its progression and reaches a maximal value of 0.0645 (wt %), the Al2%Sn alloy does not exceed 0.0382 (wt %), while the two other alloys containing more tin: Al3%Sn and Al4%Sn take minimal values that even begin slightly diminishing before reaching the core of the ingot with very feeble concentrations in tin, respectively 0.0242 and 0.0105 (wt %).
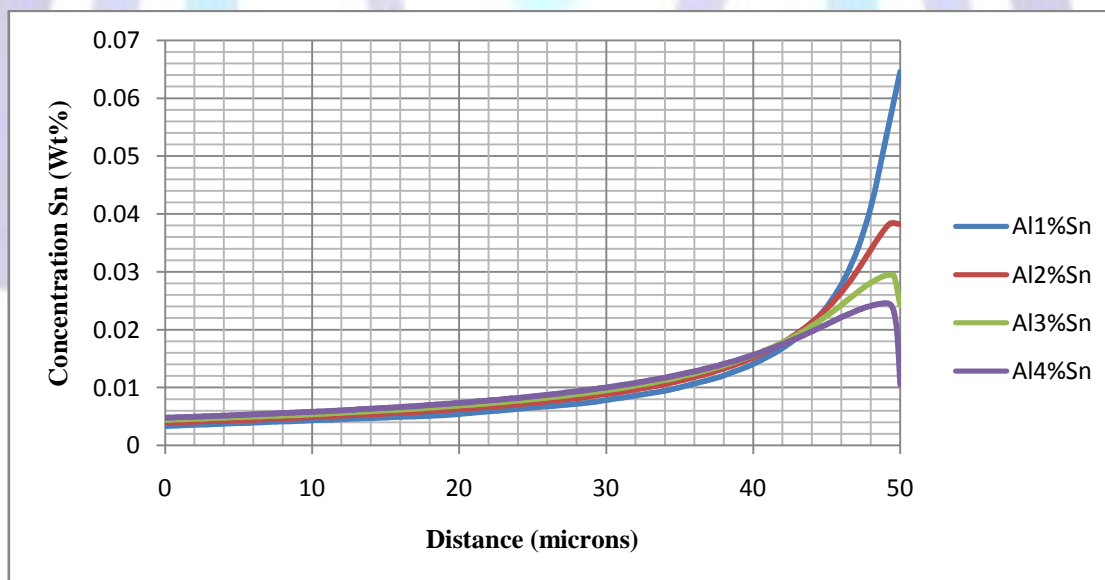

Figure 5: Tin concentration evolution according to the distance between the surface and ingot core at the temperature of 200°C of the following alloys: Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn, and at the end of 3 hours.

Tin concentration evolution according to the distance between the surface and ingot core after 3 hours, at the temperature of 400°C of the following alloys, Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn is represented in figure 6. We notice a progressive increase of the values of tin concentration; in fact, at the surface of the ingot, the alloys containing more tin have the highest concentration; on the other hand, we clearly see that in the neighborhood of 33 microns and as we are

approaching the core, tin concentrations in alloys containing less tin become the highest, the Al1%Sn alloy reaches a maximal value of 0.4727 (wt %) whilst the Al4%Sn alloy does not exceed a concentration of 0.2629 (wt %).
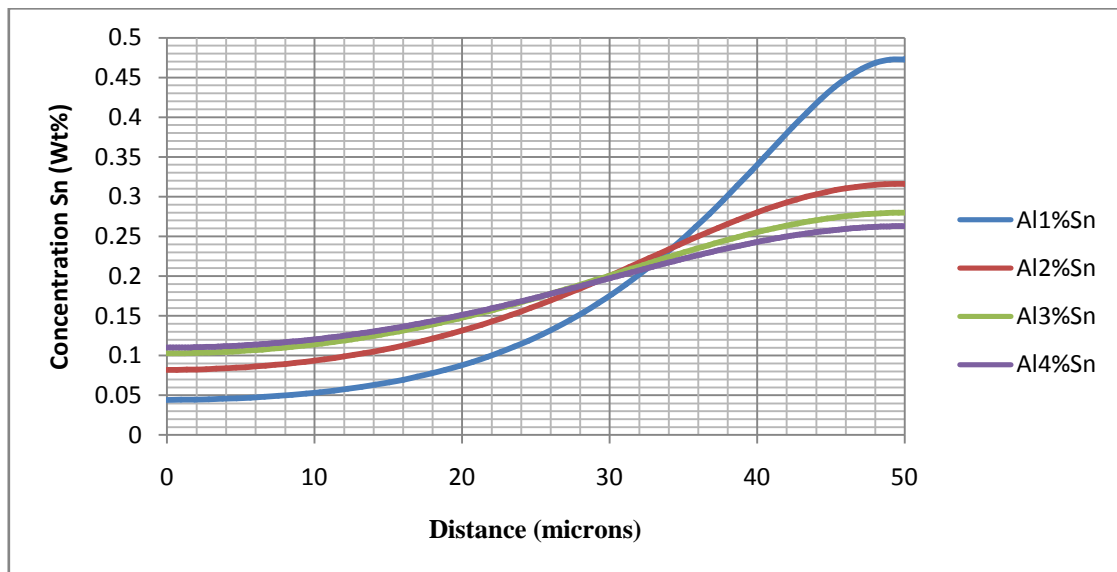

Figure 6: Evolution concentration evolution according to the distance between the surface and ingot core at the temperature of 400°C of the following alloys: , Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn, and at the end of 3 hours.

The figure 7 describes the evolution after 3 hours of the tin concentration according to the distance between the surface and ingot core, at the temperature of 600°C of the following alloys: , Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn, we see clearly that the value of concentration remains constant for each alloy, respectively in 0.5782, 0.5733, 0.5692 and 0.5647 (wt %); therefore the alloys containing less tin recognize the stagnation of the concentration in a higher value. We conclude, consequently to this, that with more tin, the diffusion of tin in solid solution is sufficiently speedy at this temperature to reach the limit of solubility at the end of 3 hours.
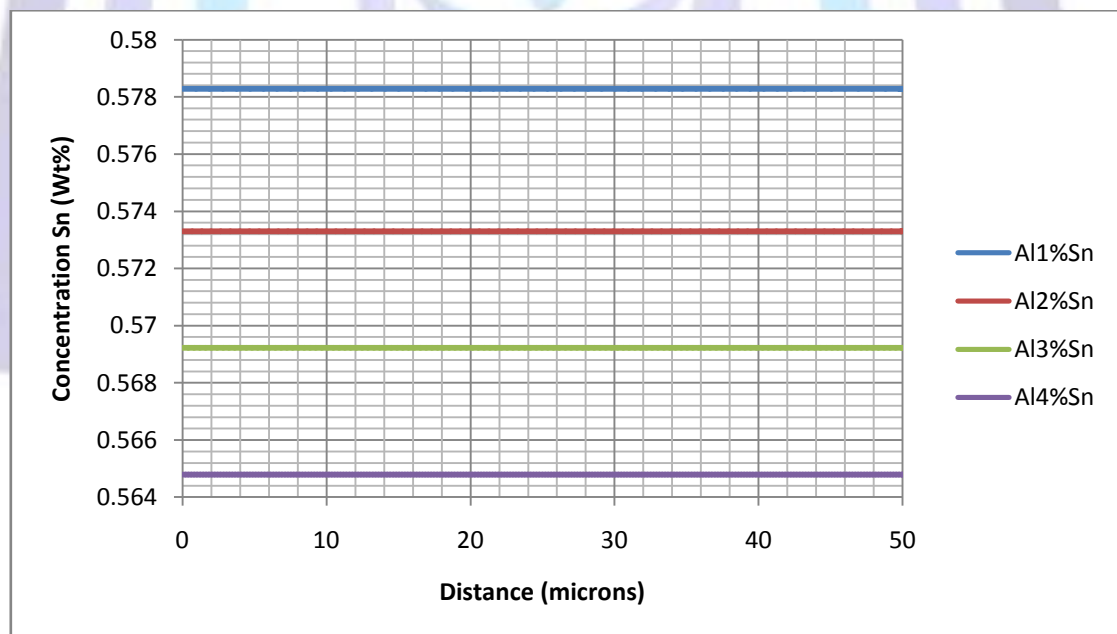

Figure 7: Tin concentration evolution according to the distance between the surface and ingot core at the temperature of 600°C of the following alloys: Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn, and after 3 hours.

Tin influence is then translated by the activation of diffusion phenomenon, the driving force of homogenization treatment that allows reducing composition heterogeneousness due to segregation phenomenons that appear in the solidification structure.

3.3 studies of mechanical properties

3.3.1 Cooling velocity

The figure 8 represents cooling curves of the following alloys Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn representing the temperature according to time. The curves of thermic analysis evolve according to the composition of each alloy as illustrated in the aforementioned figure; we obviously find again the initial linear cooling of the liquid.

We notice the existence of a bearing at 659°C for Al1%Sn alloy under which the temperature goes on evolving. The curves of the following alloys Al2%Sn, Al3%Sn and Al4%Sn respectively represent the first points of inflexion at 657°C after 41s, 655°C at 42 s and 654°C at the time of 45s corresponding to a change of phase (Liq <-> Liq + Al) a transformation non isothermal, the increase of the solid fraction occurs while the temperature diminishes.

A second rupture of slope representing the crossing of the area (Al + E) is recorded at the curves of cooling of the following alloys Al2%Sn, Al3%Sn and Al4%Sn respectively to 585°C at 368s, 535 °C at 411s and 415 °C after 529 s where the last liquid drop disappear.

It is important to understand that solidification has begun at the first change of slope and ends at the first inflexion point.

The addition of tin has an action on temperature as well as on the time of transformation. Tin slows down cooling process and its effect is translated by a slight increase of the solidification temperature and time.
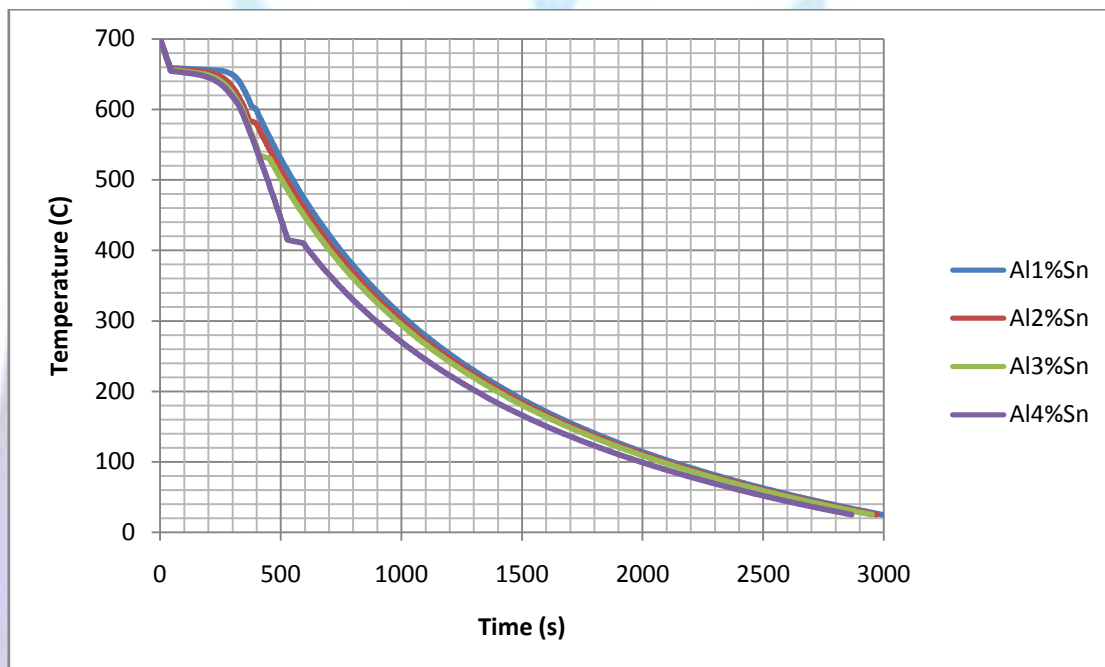

Figure 8: cooling curves of the following alloys: Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn.

3.3.2 The influence of the cooling velocity upon the mechanical properties

The figure below represents the evolution of hardness, proof stress and tensile stress according to the cooling velocity of the alloys: Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn.

We notice that the three parameters progressively increase as the cooling speed increases whatever the added tin percentage, this may be imputed to the impact of the cooling speed upon the alloy microstructure and the grains, which increases with the cooling speed decrease. Whereas, for many metallic materials, it has been proved that a certain link exists between size of grain and limit of proof stress via the relation of HALL-PETCH [7].

This latter indicates that the elastic limit σ_e is inversely proportional to the square root of the grain size "d":

$$\sigma_e = \sigma_0 + k_{HP}\,d^{-1/2} \quad (4) \; [8]$$

Where σ_0 is ideally the flow stress of the mono-crystal, and k_{HP} is the constant of HALL-PETCH. This relationship specifies that the bigger the again size is, the more elasticity limit decreases.

We notice that hardness and tensile stress follow the same variation as proof stress, therefore we understand that the values of hardness and tensile stress are closely connected to the proof stress limit. We note also that tin addition is translated by a slight decrease of the studies mechanical properties.
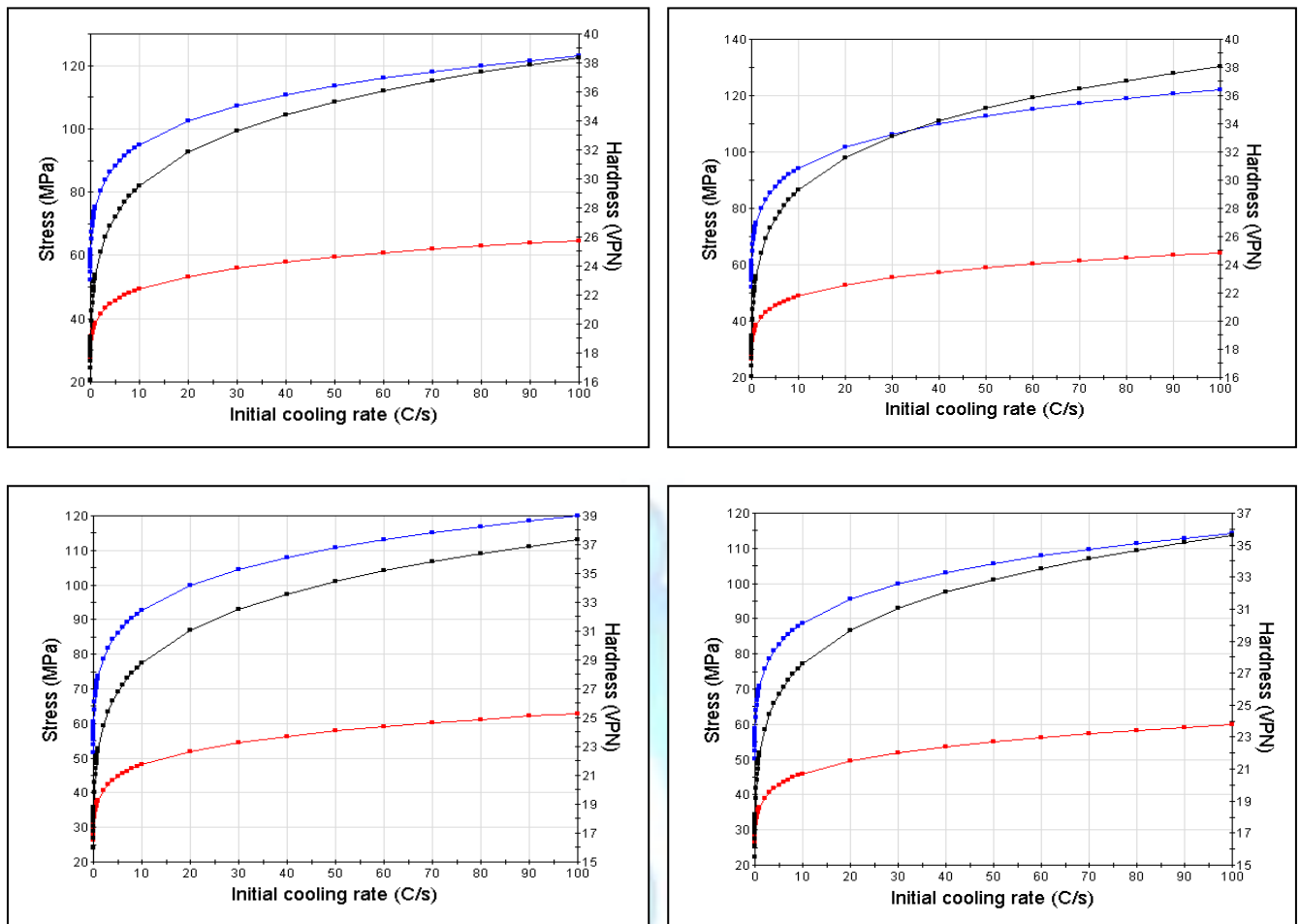
Figure9: Evolution of hardness, proof stress and tensile stress according to cooling speed of such alloys as Al1%Sn, Al2%Sn, Al3%Sn and Al4%Sn.

IV. Conclusion

Consequently to this study, it is necessary to keep a certain time of homogenization sufficient enough so that the diffusion of the chemical species between the various stages may occur.

Under the influence of a gradient of concentration which is the driving force of diffusion phenomenon, the atoms of each element move at the price of time from the rich areas (in the element) towards the poor ones that became rich.

At high temperature, tin diffusion in solid solution is sufficiently speedy to reach the limit of solubility at the first moments. The influence of tin is translated by the activation of diffusion phenomenon: the driving force of homogenization treatment that allows reducing the heterogeneousness of composition due to segregation phenomenons that appear during solidification process.

Tin addition has an action upon temperature as well as on time of transformation. Tin slows down the cooling process and its effect is translated by a slight increase of time and solidification temperature and therefore acts automatically upon the alloy microstructure.

The mechanical parameters (previously studied) progressively increase with the increase of the cooling velocity whatever the added tin percentage may be, all this is owing to the impact of the cooling speed upon the alloy microstructure and more accurately upon the grains size which increases with the cooling speed decrease.

According to this study, the alloys made of aluminum and tin require an industrial development. In fact, the alloys highly loaded in tin contribute to a better homogenization treatment whereas those that are lightly loaded in tin possess important mechanical properties.

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