ORIGINAL PAPER

MODELING OF THE INFLUENCE OF THERMIC TREATMENT UPON THE MECHANICAL PROPERTIES OF ALUMINUM-SILICON 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.*

On the one hand, the whole work focuses upon the modeling of the homogenization effect according to the three parameters: time, temperature and composition, and seeing each one influence upon the silicon concentration according to the distance between the surface and the core of the ingot, on the other hand, the purpose of this work is to model the influence of silicon addition upon the cooling process and various mechanical properties of aluminum.

Usually, the microstructure and mechanical behavior of such alloys as Al-Si are directly influenced by some parameters such as composition, cooling velocity and homogenization process.

Keywords: *Mechanical properties, modeling, homogenization, the AlSi alloys.*

1. 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.

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Since the range of alloys is very extended, this allows finding that which is more convenient to the use envisaged constraints. The most remarkable effect of silicon upon aluminum alloys is the improvement of shaping characteristics (molding). The addition of silicon to pure aluminum greatly increases the fluidity, the resistance to hot cracking and the characteristics of the liquid metal flow. The composition most commonly used in foundry aluminum alloys is that of the Al-Si family [2].

On the one hand, the whole work focuses upon the modeling of the homogenization effect according to the three parameters: time, temperature and composition, and seeing each one influence upon the silicon concentration according to the distance between the surface and the core of the ingot, on the other hand, the purpose of this work is to model the influence of silicon addition upon the cooling process and various mechanical properties of aluminum.

2. MATERIALS 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 [3].

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

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 [4]:

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

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-Si phases in order to know the phases susceptible of being encountered.

Casting pieces made from aluminum alloys are mainly made of aluminum-silicon alloys [5]. Silicon increases the flowability of aluminum and allows the metal to completely fill all the desired cavities. In addition, silicon prevents hot cracking and slightly increases the strength of the metal by forming hard particles or silicon fibers during solidification [5].

As shown in Fig. 1, the Al-Si binary system has a eutectic point of 12.6% Si (atomic%). The maximum solubility of silicon in aluminum is 1.5% (atomic%) at the eutectic temperature; On the other hand, only 0.016% (atomic%) of aluminum is soluble in silicon at 1190 ° C [5].

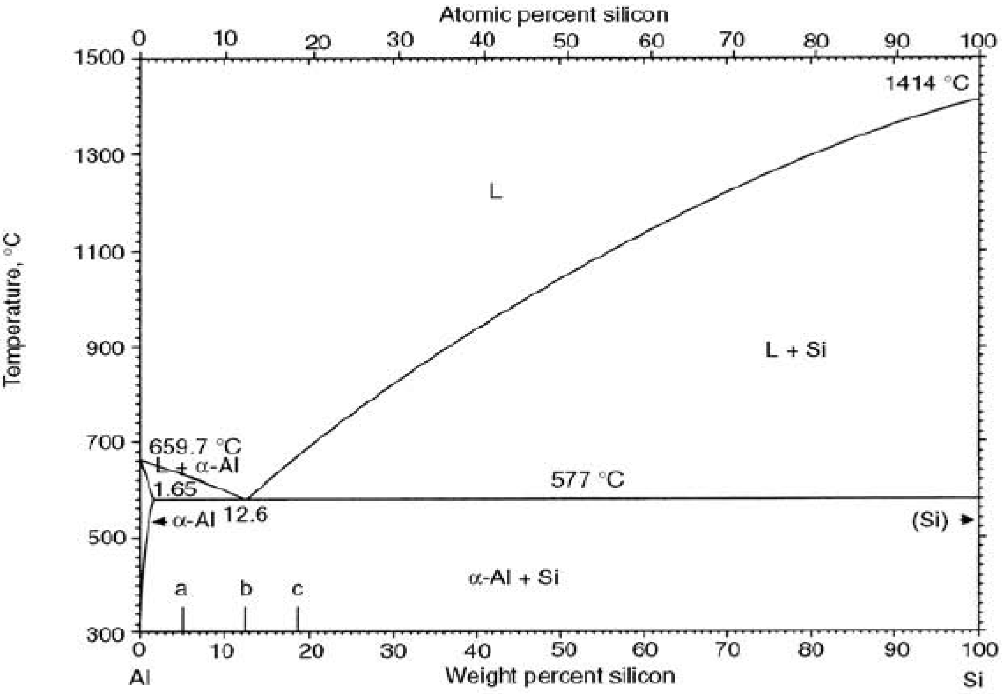

Figure 1. Al-Si phase diagram [6].

Because of solubility limits of alloy elements, we will restrict the study of the balance diagram of the Al-Si alloy to fields of chemical composition contained between 1 and 12% in weight for the element silicon, 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.

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

3. RESULTS AND DISCUSSION

3.1. *STRUCTURAL STUDY OF AL-SI ALLOYS*

Aluminum-silicon alloys can be classified into three broad categories in Fig. 2, based on the eutectic point: from 2% to 9% Si, the alloy is in the hypoeutectic zone; As regards the eutectic alloys, they may contain from 10% to 13% Si; And those with more than 14% Si are classified as hypereutectic alloys [5].

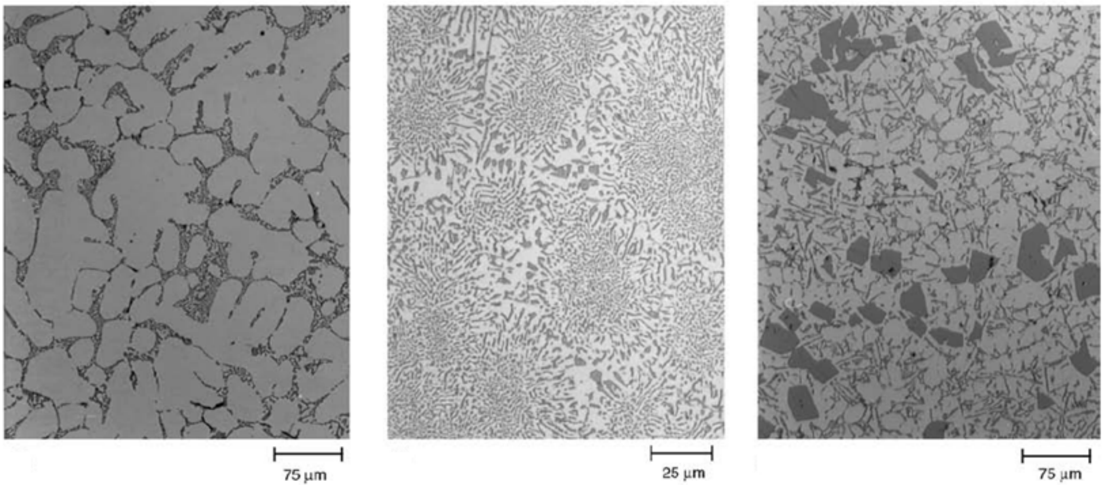

Figure 2. Microstructure of the Al-Si alloy; A: hypoeutectic alloys, b: eutectic alloys c: hypereutectic alloys [6].

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 Silicon concentration according to the distance between the surface and the core of the ingot.

3.2.1. Time influence

The Fig. 3 shows the silicon 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%Si 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 Si at the surface increases and goes from a minimal value of 0.13 (wt %) at 3 hours to 0.25 (wt %) after 18 hours, contrarily to the ingot core, the concentration in silicon slightly decreases between 3 hours and 18 hours and goes from 0.45 to 0.28(wt %); nevertheless, we can also notice that the concentration in silicon 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 different stages may occur.

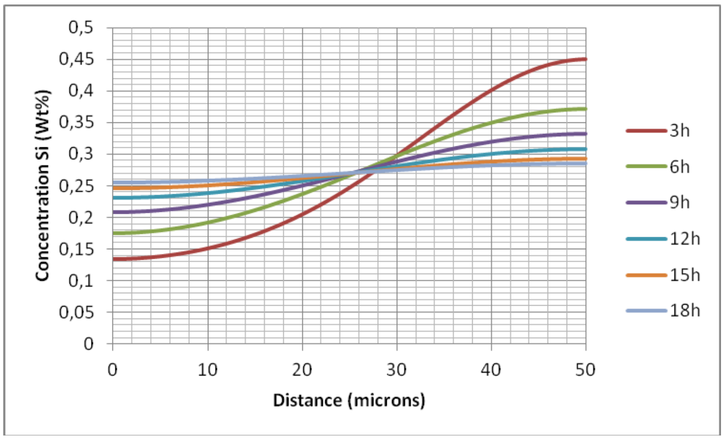

Figure 3. Silicon concentration evolution according to the distance between the surface and the ingot core at the price of time of the Al1%Si alloy at the temperature of 400°C.

3.2.2 Temperature influence

For the three temperatures of maintenance: 200°C, 400°C and 600°C, the silicon concentration evolutions according to the distance between the surface and the ingot core, of the Al1%Si alloy at the end of 3 hours, are born on Fig. 4.

We notice that the concentration in Si at 600°C presents the highest concentration 0.99 (wt %) and it remains constant, while, at 400°C, we note a progressive enrichment in Si from the surface 0.13 (wt %) to ingot core 0.45 (wt %); these values tend to equilibrium values tend to equilibrium values. As for the temperature 200°C, the concentration in Si 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 41 microns: the variation is surely feeble but also detectible.

Furthermore, the comparison of the concentration in Si in every point of the ingot shows that the concentration of equilibrium in Si is higher at 600°C. We can therefore suggest that the diffusion of silicon in solid solution is sufficiently fast to reach the limit of solubility from the first moments at high temperature.

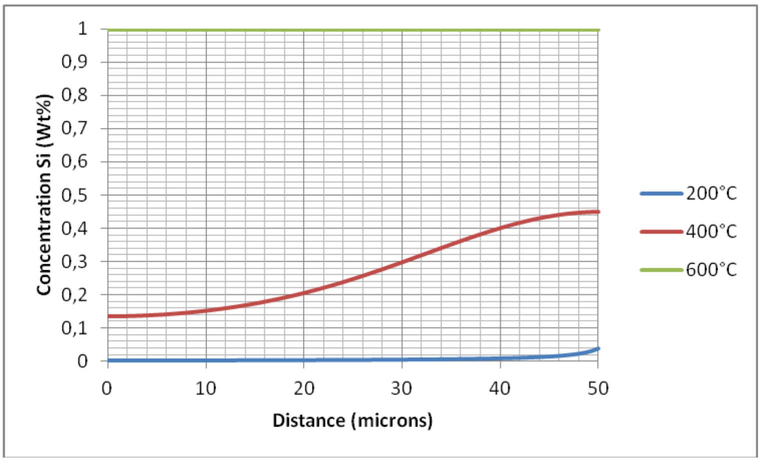

Figure 4. Silicon concentration evolution according to the distance between the surface and ingot core at temperature of 200°C, 400°C and 600°C of Al1%Si alloy at the end of 3 hours.

3.2.3 Silicon influence

In order to study silicon influence, we have dealt with four different compositions: Al1%Si, Al2%Si, Al4%Si and Al12%Si. The silicon concentration evolution is represented in following figures:

The Fig. 5 shows silicon 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. We notice that the curves of Al1% Si, Al2% Si and Al4% Si alloys follow the same rate of variation: a progressive silicon enrichment from the surface to the ingot core is observed, however the Si concentration remains constant for the Al 12% Si alloy containing more silicon.

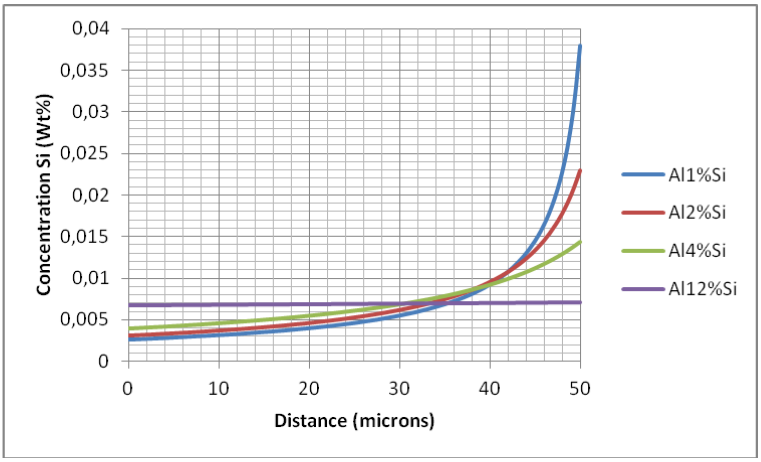

Figure.5. Silicon concentration evolution according to the distance between the surface and ingot core at the temperature of 200°C of the following alloys Al1%Si, Al2%Si, Al4%Si and Al12%Si at the end of 3 hours.

Silicon 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%Si, Al2%Si, Al4%Si and Al12%Si is represented in Fig. 6.

We notice a progressive increase of the values of silicon concentration of Al1%Si, Al2%Si and Al4%Si ; in fact, at the surface of the ingot, the alloys containing more silicon have the highest concentration but as we are approaching the core, silicon concentrations in alloys containing less Si become the highest, However, the Al 12% Si alloy containing more silicon retains a constant value Si concentration in all point of the ingot.

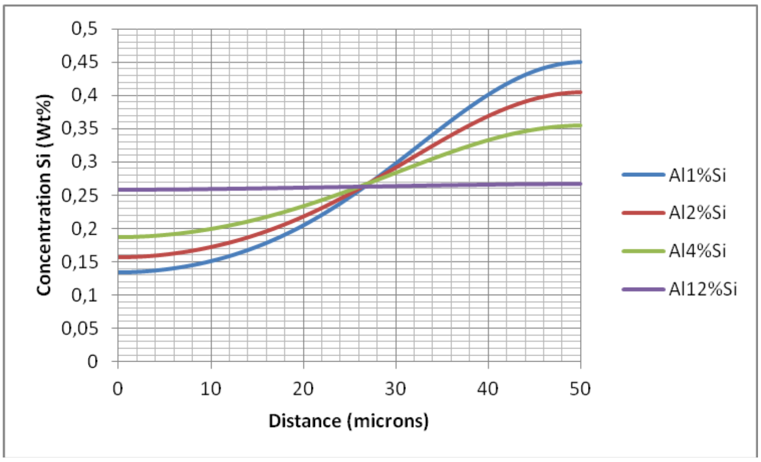

Figure 6: Silicon concentration evolution according to the distance between the surface and ingot core at the temperature of 400°C of the following alloys: Al1%Si, Al2%Si, Al4%Si and Al12%Si, and at the end of 3 hours.

The Fig. 7 describes the evolution after 3 hours of the silicon concentration according to the distance between the surface and ingot core, at the temperature of 600°C of the following alloys: , Al1%Si, Al2%Si, Al4%Si and Al12%Si.

We see clear that the value of concentration remains constant for each alloy, respectively: in 0.99(wt%) for Al1%Si and 1.10 (wt%) for Al2%Si and Al4%Si alloys. therefore the alloys containing more silicon recognize the stagnation of the concentration in a higher value.

We conclude, consequently to this, that with more Si, the diffusion of silicon in solid solution is sufficiently speedy at this temperature to reach the solubility limit after at the end of 3 hours for the αAl + Si phase, except the Al12%Si alloy where we note the stagnation at 0 (wt%), under these conditions, it's no longer a solid solution but a liquid phase.

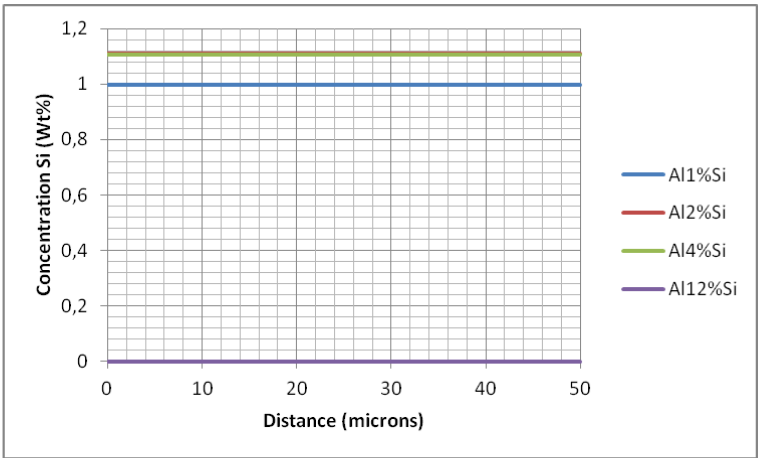

Figure 7. Silicon concentration evolution according to the distance between the surface and ingot core at the temperature of 600°C of the following alloys: Al1%Si, Al2%Si, Al4%Si and Al12%Si, and after 3 hours.

Silicon 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 Fig. 8 represents cooling curves of the following alloys Al1%Si, Al2%Si, Al4%Si and Al12%Si 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 654.45°C at 45.37s for Al1%Si alloy under which the temperature goes on evolving. The curves of the following alloys Al2%Si and Al4%Si respectively represent the first points of inflexion at 648.49°C after 51s and 636.22°C at 62.47s corresponding to a change of phase (Liq→Liq+α) a transformation non isothermal, the increase of the solid fraction occurs while the temperature diminishes.

A second rupture of slope after 576.91°C representing the crossing of the area (Al + E) is recorded at the curves of cooling of the following alloys Al1%Si, Al2%Si and Al4%Si respectively at 585°C at 405.65s , 410.70s and 451,37s where the last liquid drop disappear. Regarding the Al12%Si alloy which is very close to the eutectic, we notice the existence of a bearing from the temperature 576.91°C at 123.19s to 570°C after 762.18s.

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

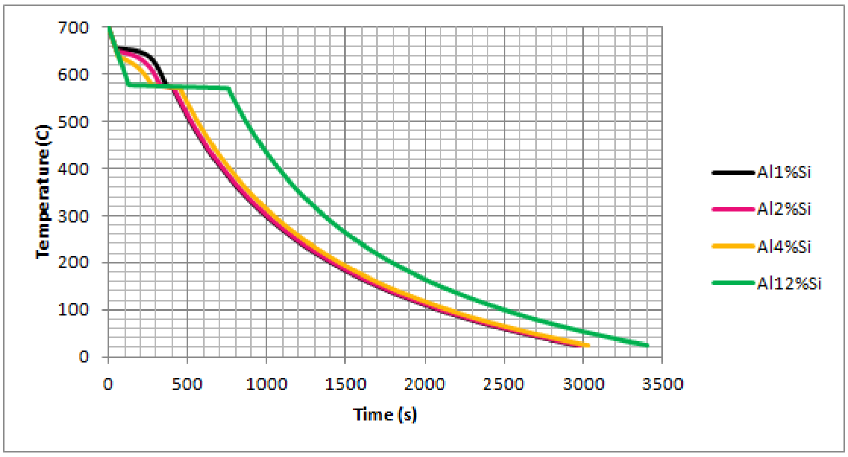

Figure 8. cooling curves of the following alloys: Al1%Si, Al2%Si, Al4%Si and Al12%Si.

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%Si, Al2%Si, Al4%Si and Al12%Si.

We notice that the three parameters progressively increase as the cooling speed increases whatever the added silicon 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 σe 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 kHP 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. For the Al1% Si alloy containing less silicon, we start with a value of 64.74 VPN for the proof stress, of 123.22 VPN for tensile stress and a hardness of 38.39 MPa at 100C / s, for this same cooling speed, the values of the previous properties decrease respectively in 3.42VPN, 6.82VPN and 2.1MPa in case of Al12%Si alloy; containing more silicon. So we note that silicon addition is translated by a strong decrease of the studies mechanical properties.

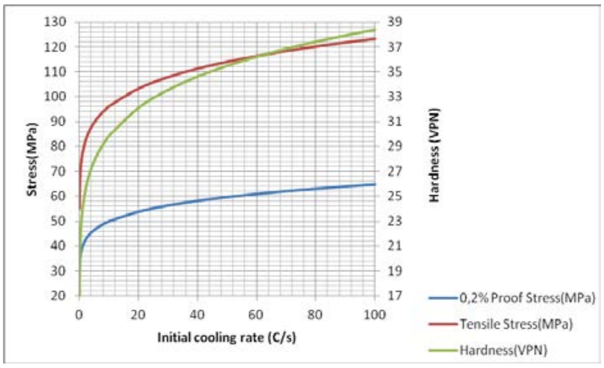

Figure 9. Evolution of hardness, proof stress and tensile stress according to cooling speed of Al1%Si.

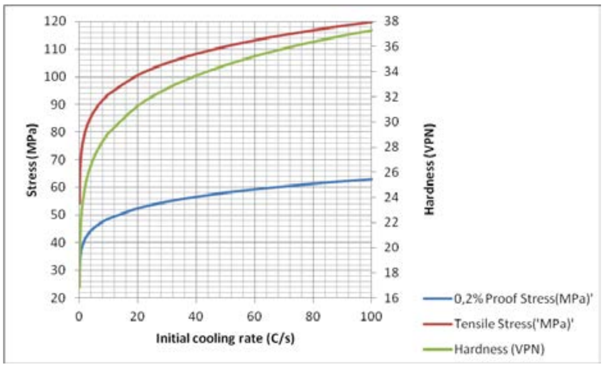

Figure 10. Evolution of hardness, proof stress and tensile stress according to cooling speed of Al2%Si.

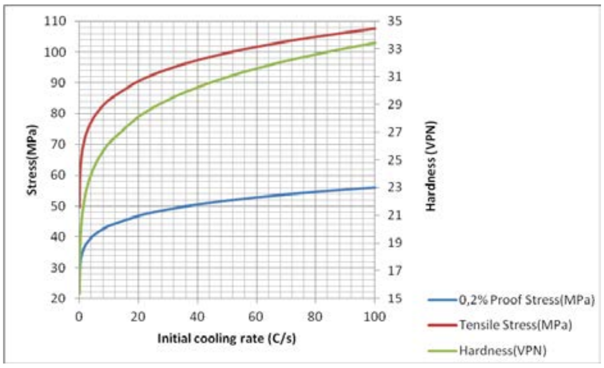

Figure 11. Evolution of hardness, proof stress and tensile stress according to cooling speed of Al4%Si.

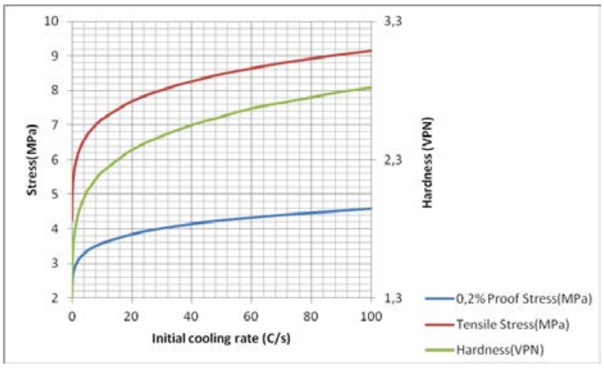

Figure 12. Evolution of hardness, proof stress and tensile stress according to cooling speed of Al12%Si.

4. CONCLUSIONS

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, silicon diffusion in solid solution is sufficiently speedy to reach the limit of solubility at the first moments. The influence of silicon 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.

Silicon addition has an action upon temperature as well as on time of transformation. Silicon 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 silicon 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.

Silicon addition (from 1% to 12%) strongly reduces the mechanical properties previously studied, due to the approximation of the eutectic structure (12.6% Si [6]) having an acicular or lamellar form, these alliances tend to show low strength and ductility [9].

Alloys with a predominantly eutectic structure must undergo modification in order to ensure adequate mechanical properties.

The quality of the cast product can be improved by grain refinement, this makes it possible to reduce the size of the primary grains of the α-aluminum phase which otherwise solidifies in a coarse grain structure.

La production des alliages Al-Si avec une structure et des propriétés mécaniques améliorées implique l'application de deux processus principaux: l'addition de tels éléments d'alliage comme Mg, Cu, Mn, et autres éléments semblables, pendant l'état liquide; et le traitement thermique [9].

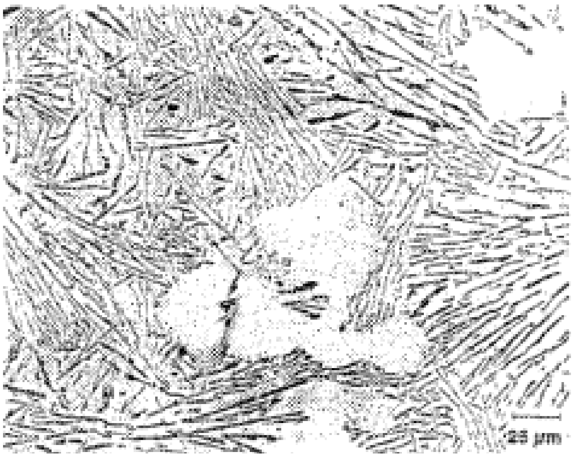

Figure 13. Microstructure of unmodified acicular eutectic alloy. The eutectic alloy has lamellar or acyclic silicon particles dispersed in the aluminum matrix. The presence of polyhedral particles of primary silicon may also be observed. [5].

The production of Al-Si alloys with improved structure and mechanical properties involves the application of two main processes: the addition of such alloying elements as Mg, Cu, Mn, and thermic treatment [9].

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