MICROSTRUCTURE, THERMAL PARAMETERS AND MECHANICAL PROPERTIES OF TERNARY Al-7.0wt.%Mg-1.5wt.%Fe ALLOY

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ABSTRACT

Magnesium addition in Al-Fe alloys containing from 2.0 to 4.0wt.%Mg characterizes chemical composition of some commercial alloys 5xxx and 500.x series. Although such multicomponent alloys have recognized commercial importance, experimental correlations between solidification thermal parameters > microstructure > mechanical properties are yet to be determined. The present study aims to evaluate these experimental correlations through microstructural analysis, determination of thermal variables (cooling rate-$\dot{T}$ and growth rate-V_L), ultimate tensile strength (σ_u) and elongation-to-fracture (δ) along the directionally solidified Al-7.0wt.%Mg-1.5wt.%Fe alloy casting under unsteady-state condition. Samples were obtained by upward directional solidification (DS), followed by characterization through optical microscopy and scanning electron microscope (SEM). Microstructure growth law were established from microstructure parameters as secondary (λ_2) dendrite arm spacing. These values were correlated with $\dot{T}$ and V_L. A microstructural variation between 8 µm and 64 µm was found referring to λ_2 along the casting length. Further, due to an expressive variation of λ_2, together with the presence of Mg in solid solution with the Al-rich matrix as well as the formation of Mg intermetallic particles, the σ_u and δ values were found to vary between 300MPa and 150 MPa, and between 12% and 5%, respectively. The tensile properties associated with the best microstructural condition provided higher mechanical strength and ductility compared with values typically reported for 5086 alloy in wrought condition.

Keywords: Metals and alloys, Microstructure, Solidification, Al-Mg alloys, Casting.

INTRODUCTION

Focusing mainly on weight reduction and corrosion resistance, aluminium alloys have been increasingly used as potential substitutes for some applications which steel remains employed. Considering the increasing of alloys applications in the automobile and aeronautic industry, weight factor is directly related with energy efficiency, and aluminium is about three times less dense than steel and magnesium about 30% less dense than aluminium (1,2). The most significant methods in manufacturing of aluminium alloys are casting processes. These alloys are compliant to several of the most usual casting processes due to its good fluidity and low melting point. Product properties are quite affected due to the microstructures and microsegregations of the cast developed during solidification (3).

The directional solidification technique has been extensively used in binary aluminium alloys analysis. Several solidification studies in recent decades have characterized aspects of macrostructure, microstructure and solute segregation analysis and the porosity formation (4,5). These studies can be divided into two categories: directionally solidified under steady-state (6,7) and unsteady-state conditions (8,9). In the first situation, the temperature gradient (G_L) and growth rate (V_L) are independently controlled and maintained constant throughout the experiment. By contrast, the unsteady-state condition allows free thermal parameters variation, as growth rate (V_L) and cooling rate ($\dot{T}$), which approximates this experimental method with industrial process reality involving metals solidification, such as: sand casting, die casting, continuous casting and welding. Systematic investigation of ternary systems having commercial composition or very close to that commonly employed in the manufactured of engineering components, is another way to approximate the solidification studies from industrial process.

The solidification process and material characteristics to be solidified has direct influence in the structure formation, which determines the final properties of a casting. The casting parts obtained exhibits mechanical characteristics that depends on aspects inherent to its solidification, as grain size, dendritic spacing, chemical composition heterogeneities, inclusions and porosity size, shape and distribution. The aluminium alloys solidification understanding has fundamental importance for planning manufacturing process, since allows the factors knowledge that influence microstructure and, consequently, the product quality (10).

The literature contains many examples of ternary Al-Mg-X alloys, its thermal treatments and final properties, however, solidification systematic studies of binary and ternary Al-Mg-based composition are scarce. One of these studies correlate cooling rates to Al-rich and eutectic phase formation. The effect of cooling rate and composition on solidification and segregation of binary Al-Mg alloys, with magnesium content ranging between 2.46 and 11.07wt.% was investigated by Liu and Kang [(11)]. According to these authors, alloys with low magnesium content had a restricted microstructure of α-Al dendrites, and the eutectic phase only occur with increasing magnesium content and on the final stage of solidification. The formation and growth of the eutectic phase (α-Al + Al_5Mg_8) depends on the cooling rate, nevertheless, the magnesium concentration in the eutectic progressively decreases with cooling rates >190K.min^{-1}. Even at high cooling rates low magnesium alloy content allows a single-phase α-Al structure to be formed. The eutectic reaction becomes possible by increasing the magnesium content. The eutectic fraction decreases continuously with the increase in cooling rate [(11)].

The aim of the present study is to perform transient directional solidification experiment with Al-7.0wt.%Mg-1.5wt.%Fe alloy. For this, a water-cooled directional solidification apparatus was used to obtain as-cast samples for a wide range of cooling and growth rates. The occurrence of secondary dendrite arms within the solidified alloy is examined in order to permit its effects on the mechanical properties to be evaluated. It is intended to establish the experimental dependence of dendritic features, represented by the secondary, λ_2, dendrite arm spacing, on the growth rate. Furthermore, machined samples extracted from the Al-Mg-Fe alloys will be subjected to tensile mechanical tests in order to allow correlations between the mechanical properties and microstructure parameters to be determined, bringing a more significant contribution due to permit design of operational solidification conditions aiming specific application properties.

EXPERIMENTAL PROCEDURE

The vertical upward solidification apparatus used in this experiment is detailed in figure 1. It was designed to permit unidirectional solidification of metals in transient heat flow conditions. Rapid cooling gives to this device the ability to produce ingots with large variation in the resultant cooling rates and dendrite arm spacing values along the casting, i.e., refined and coarse dendritic arrays in a same casting. Heat is directionally extracted only through a water-cooled low carbon steel bottom (SAE 1020), promoting vertical upward directional solidification [12].

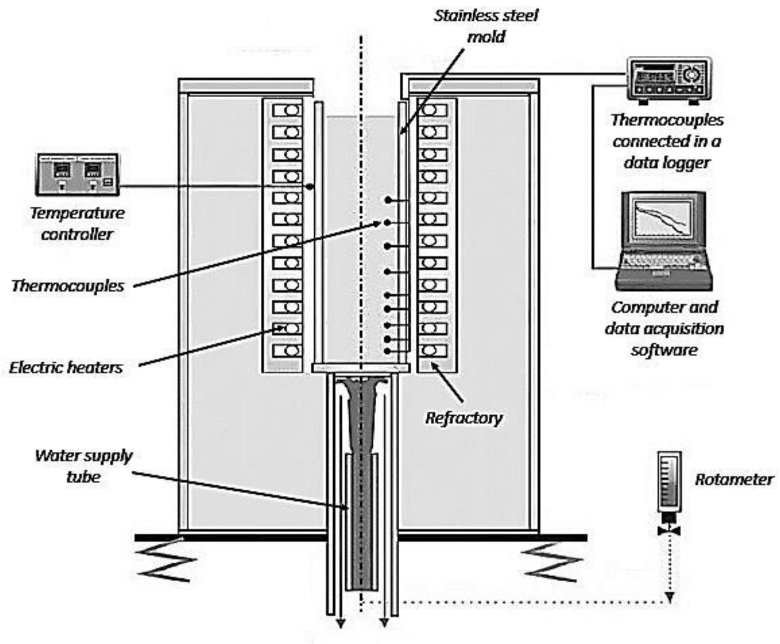


Fig. 1. Directional solidification system for transient heat flow conditions and the devices used to monitor solidification.

The alloy was poured in a stainless steel split mold having an internal diameter of 60mm, wall thickness of 5 mm and a height of 160 mm. As soon as the water flow was started, the electric heaters were turned off. To prevent radial heat losses, the lateral inner mold surface was covered with a layer of insulating alumina. K-type thermocouples inserted along the casting length during solidification process allowed continuous temperature measurements.

To reveal the microstructure selected longitudinal samples of the Al-Mg-Fe alloy casting were polished and etched with a solution of NaOH in water. The secondary dendrite arm spacing (λ_2) was measured from acquired images of the optical microscopy with an Olympus Inverted Metallurgical Microscope (model GX51) by examining longitudinal sections of the casting. The intercepted method on longitudinal samples was employed to determine the secondary dendrite arm spacing (λ_2). This method is typically used in the examination of longitudinal sections in the heat flow direction, measuring the length between the center of a particular secondary branch to another center aligned with the first [13].

Microstructural characterization was complemented by the use of a scanning electron microscope (SEM-EDS) FEI (Inspect S50L). Transverse specimens machined for tensile tests were performed from the directionally solidified casting according to specifications of ASTM Standard E 8M/04. Theses specimens were tested in an Instron 5500 machine at a strain rate of about 3 x 10^{-3} s^{-1}. To ensure reproducibility four specimens of each selected position were examined.

RESULTS AND DISCUSSION

Fig. 2(a) depicts the macrostructure of the directionally solidified Al-7.0wt.%-1.5wt.%Fe alloy casting. A columnar macrostructure predominate along the entire length of the casting. Further, some representative longitudinal microstructures have been included in Fig. 2(b). The dendritic arrays located at different positions from the cooled surface of the casting reveal the coarsening of the dendritic arrangement. This is due to the differences in cooling rate associated with positions close to cooled surface of the castings (higher cooling rates) compared with those representing positions farther from the bottom of the castings (lower cooling rates). A representative SEM image related to the position of 8 mm from the cooled surface of the casting was included and the presence of Al_3Fe and Mg_2Al_3 intermetallic compounds (IMCs) can be noted in Fig. 2(c).

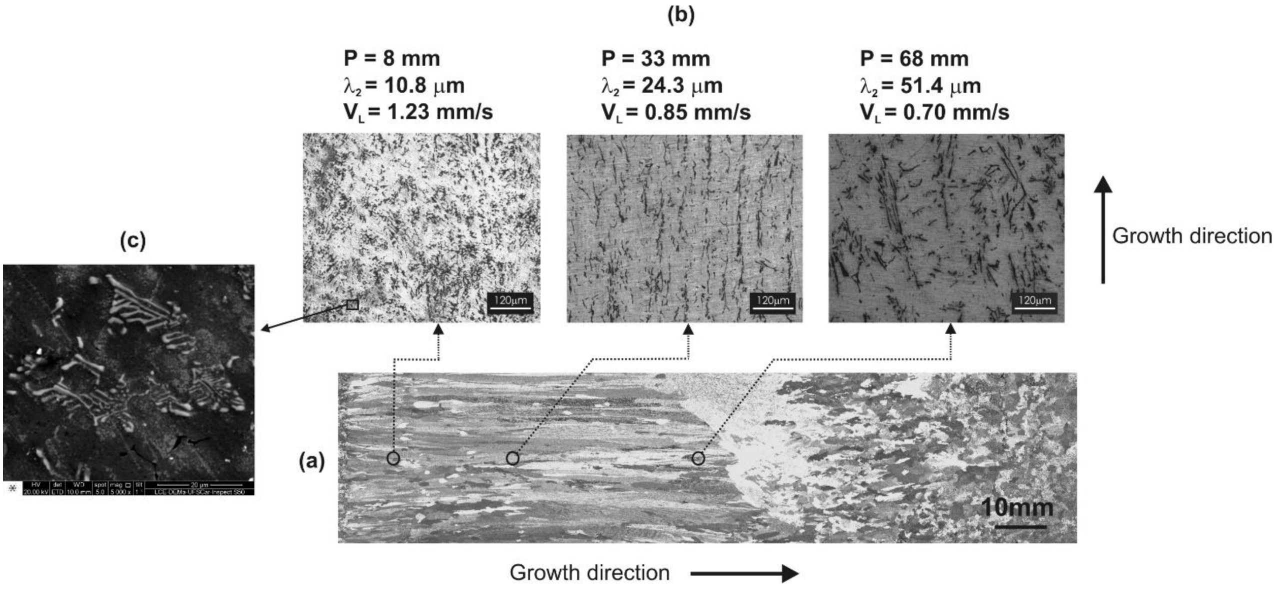


Fig. 2. (a) Directionally solidified macrostructure of the Al-7.0wt.%Mg-1.5wt.%Fe alloy casting and (b) longitudinal as-cast microstructures for different positions with

insertion of (c) a SEM image revealing the presence of Mg_2Al_3 and Al_3Fe phases. *P* is the position from the casting cooled surface.

The cooling curves corresponding to the thermal responses of thermocouples inserted along the length of the Al-7.0wt.%Mg-1.5wt.%Fe alloy casting are shown in Fig. 3(a). The thermal readings have been used to provide plots of position from the metal/mold interface and the corresponding time of the *liquidus* front passing by each thermocouple. The derivatives of these functions with respect to time gave values for the growth rate (V_L), as shown in Fig. 3(b). The cooling rate was determined along the castings lengths, by considering the thermal data recorded immediately after the passage of the *liquidus* front by each thermocouple. The resulting experimental $\dot{T}$ values are shown in Fig. 3(c).

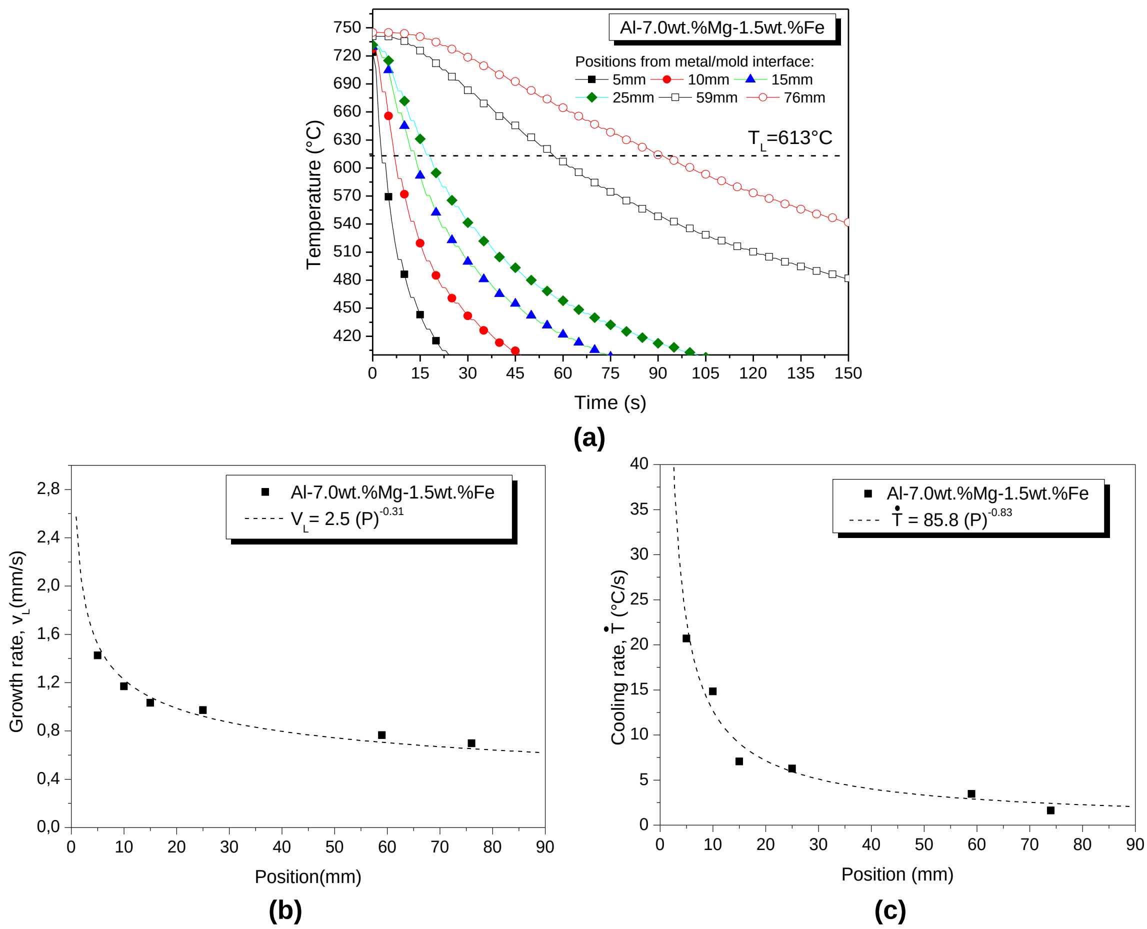


Fig. 3. (a) Typical experimental thermal responses of thermocouples at six locations in casting from the cooled surface for the Al-Mg-Fe alloy sample; (b) growth rate and (c) cooling rate against position. T_L is the *liquidus* temperature.

As can be seen in Figure 3(b) e (c), higher V_L and $\dot{T}$ values are related with positions close to the low carbon steel bottom of the alloy casting decreasing along the casting length.

Plots of the λ_2 with V_L can be seen in Fig. 4, in which points are experimental average results of λ_2 together with their standard deviations. A -1.1 exponent seems to be appropriate in the power function equation relating λ_2 to the growth rate.

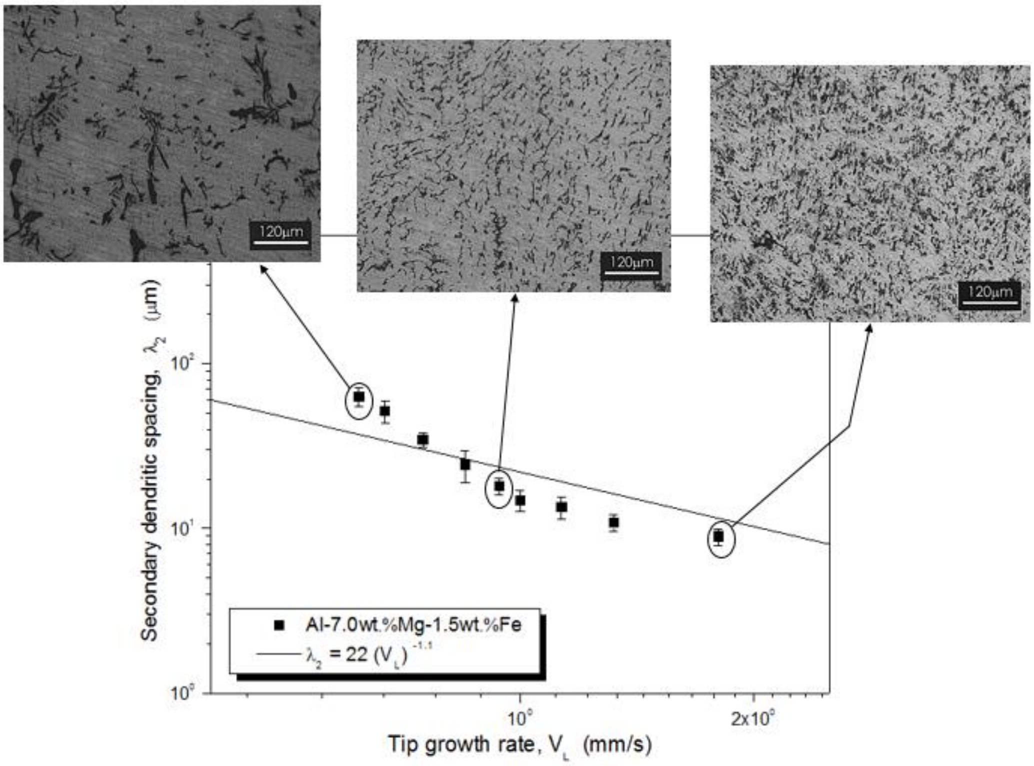


Fig. 4. Secondary dendritic spacing (λ_2) as a function of tip growth rate (V_L) for a Al-7.0wt.%Mg-1.5wt.%Fe alloy. Details of microstructure evolution are given by longitudinal optical images in different positions of ingot.

The experimental σ_u and elongation-to-fracture (δ) scatters as a function of $\lambda_2^{-1/2}$ can be seen in Fig. 5. σ_u and δ values are correlated with the evolution of secondary dendritic spacing along the length of the castings, that is, higher $\lambda_2^{-1/2}$ values are associated with regions closer to the cooled bottom of the DS casting. σ_u increases significantly with the decrease in λ_2 for the Al-7.0wt%Mg-1.5wt%Fe alloy. As can be seen in Fig. 6, decrease on λ_2 is related to a decrease on the size of intermetallic particles such as Mg_2Al_3 (dark regions) and Al_3Fe (light regions) phases. δ increases significantly (3.5-12.5%) with decreasing λ_2 (increasing $\lambda_2^{-1/2}$) for the Al-7.0wt.%Mg-1.5wt.%Fe alloy.

Higher σ_u and δ values of 300MPa and 12.5%, respectively, are associated with the presence of the AlFe and MgAl intermetallics (see Fig. 6) acting as reinforcement phases. The lower dendritic spacing promotes a better distribution of these phases along the interdendritic areas. A combination of the mentioned hardening mechanism and more densely distributed Mg with the Al-rich dendritic matrix induces more efficient blockage of the movement of dislocations through the Al-rich phase during loading.

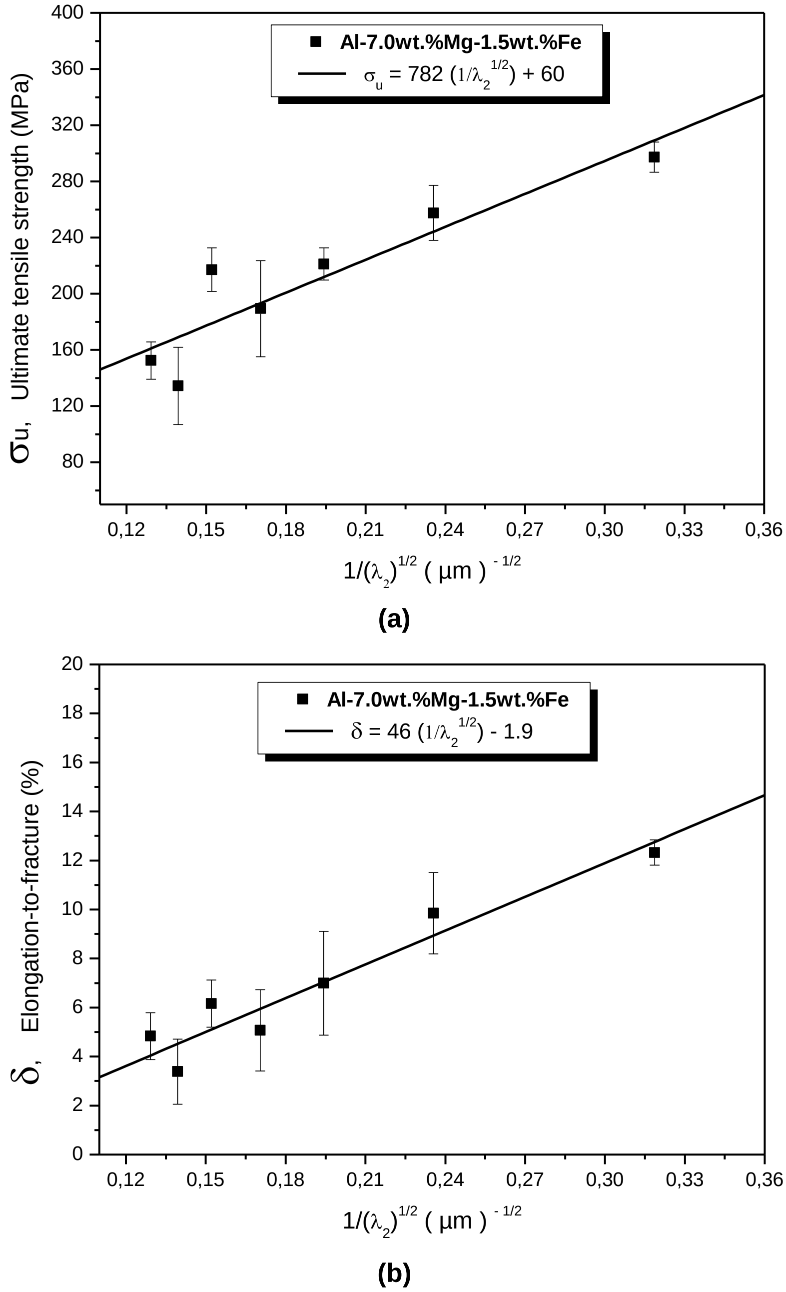
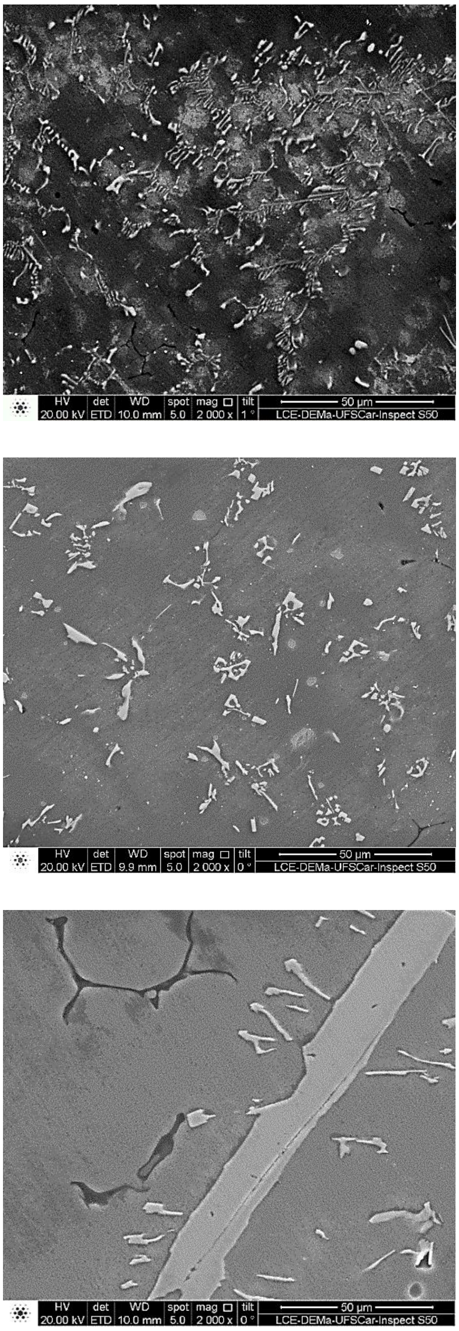


Fig. 5. Ultimate tensile strength (σ_u) and Elongation (δ) as a function of secondary dendritic spacing (λ_2) for a Al-7.0wt.%Mg-1.5wt.%Fe alloy.



P = 8 mm
$\dot{T}$ = 15.2 °C/s

P = 33 mm
$\dot{T}$ = 4.4 °C/s

P = 88 mm
$\dot{T}$ = 2.2 °C/s

Fig. 6. SEM images of the Al-7.0wt.%Mg-1.5wt.%Fe alloy observed along transversal sections of the unidirectionally solidified casting at positions 8mm, 33mm and 88 mm from the cooled bottom of the casting.

CONCLUSIONS

The Mg_2Al_3 and Al_3Fe intermetallic compounds are formed with the dendrite Al-rich phase for the DS Al-7.0wt.%Mg-1.5wt.%Fe alloy. Experimental Hall-Petch type formulations relating the ultimate tensile strength and elongation, with λ_2, have been proposed. Such knowledge allows that appropriate cooling rates could be tailored during casting with a view to attaining desired λ_2, and consequently suitable application properties for as-cast Al-Mg components.

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