THERMAL STRESS ANALYSIS OF A DIRECTIONALLY SOLIDIFIED Al-1wt%Ni ALLOY CASTING

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Abstract

The main goal of this work was to analyze the thermal and stress fields obtained by both experimental and theoretical techniques. Firstly, an Al-1wt%Ni hypoeutectic alloy was directionally solidified under upward unsteady-state heat flow conditions. The heat was directionally extracted only through a water-cooled bottom made of carbon steel AISI 1020. Numerical simulations were carried out by using the technique of finite elements (FE) and the commercial application Ansys. A stainless steel split mold was used in this process. The lateral inner mold surface was covered with a layer of insulating alumina to minimize radial heat losses. The thermal contact condition at the metal/mold interface was standardized with the heat-extracting surface at the mold bottom. The overall transient metal/coolant heat transfer coefficient was determined by the IHCP (Inverse Heat Conduction Problem) method. Therefore, after the solidification simulation, the thermal stress fields of the casting-mold system were determined. It was possible to determine the whole thermal field of the studied casting-mold system, which includes the effects of different thermal variables, such as: cooling rates, thermal gradients and convective fields. The casting shrinkage has also been modeled and the simulated thermal profile has fitted well the experimental evidences. In sum, it was possible to observe the evolution of the solidification process connected with the different phenomena that occur in this process, particularly thermal and stress fields.

Key words: Al-Ni castings; Thermal analysis; Thermal stress; Directional solidification.

ANÁLISE DO STRESS TÉRMICO NA SOLIDFICAÇÃO DIRECIONAL DA LIGA Al-1wt%Ni

Resumo

O objetivo deste trabalho foi analisar o campo térmico e o stress térmico obtidos pelas técnicas teórico e experimental. Inicialmente, foi realizada a solidificação direcional vertical ascendente da liga Al-1wt%Ni em condições transitórias de extração de calor. A base do molde foi fabricada em aço carbono AISI 1020, por onde o calor foi extraído direcionalmente através do fluxo de água fria. A simulação numérica foi realizada pela técnica de elementos finitos e software Ansys. Como molde para este processo foi usado o aço inoxidável, a parte lateral interna deste molde foi coberto com alumina isolante para minimizar as perdas de calor radial. A condição de contato térmico na interface metal/molde foi padronizada com a superfície de extração de calor da base na condição polida. O coeficiente de transferência de calor transiente no contato metal/molde foi determinado pelo método do problema inverso de condução de calor. Por meio do processo de simulação da solidificação, foi determinado o campo de stress térmico do sistema metal fundido-molde. Através deste estudo do sistema metal fundido-molde foi possível determinar as diferentes variáveis térmicas, entre elas, a velocidade de resfriamento, gradiente térmico e campos convectivos. O rechupe que se apresenta na fundição também foi simulado, mostrando concordância com os resultados experimentais. De maneira geral, foi possível observar a evolução do processo da solidificação ligado com os diferentes fenômenos que ocorrem neste processo, particularmente o campo térmico e o campo do stress térmico.

Palavras-chave: Fundição Al-Ni; Análise térmica; Stress térmico; Solidificação direcional.

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1 INTRODUCTION

Casting processes are widely used to produce metal components. The demand for high precision casting parts continues to increase due to exacting demands from the automotive and aero-industries. Much research has been devoted toward process development for the production of high quality casting goods at low costs. From a macroscopic point of view, casting processes involve the coupling of solidification heat transfer and fuid flow. Three different flow mechanisms may be identified: (a) mold filling through the gating system, (b) residual flow due to the incoming momentum and (c) the natural-convection-driven flow in the mold can be considered during the casting process. From the heat transfer point of view, the solidification and thermal stresses due to shrinkage are important physical phenomena. Solidification includes the phase transition from a molten metal to a solid state due to heat removal from the mold/chill and segregation during solidification. The shapes of casting parts can change during the solidification process if there is severe thermal stress in the mold or in the casting part itself. These complicated physical phenomena during casting require complicated numerical methodologies in order to permit the process to be analyzed. As a result, unrealistic restrictions are often imposed in order to render a model tractable.[1]

The solidification process is an integral manufacturing procedure in the production of many engineering and structural components, having a direct influence on the integrity of castings and their thermal and mechanical behavior during service. Due to the high temperatures inherent to the solidification process and the subsequent cooling of the metal, undesirable residual stresses and deformations can be produced. Such stresses can be simulated permitting the casting operational parameters to be previous established with a view to minimize quality problems.

According to Liu, Kang e Xiang,[2] the understanding of thermal stress development can be extremely useful to the prediction of hot tearing and cold cracks. Due to the complexity for coupling a solidification model with the mechanical behavior, little work has been done in order to model the stress evolution of shaped castings.

The present study aims to analyze the thermal and stress fields during directional solidification, of an Al-1wt%Ni alloy casting. The bottom of the casting was kept in contact with a metallic water-cooled surface, while the other surfaces were maintained in adiabatic condition. Numerical simulations were performed by using a finite elements technique and the software Ansys. Experimental results were obtained and used as support to validate the theoretical calculations.

2 MATHEMATICAL MODELLING

The heat transfer equation for the Stefan problem is:[3,4]

$$\frac{\partial H}{\partial t} - \nabla.(k\nabla T) = 0 \qquad (1)$$

Enthalpy (H) is a unique function of temperature:

$$\left(\frac{\partial H}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right) - \nabla.(k\nabla T) = 0 \qquad (2)$$

For Stefan problem the enthalpy is defined as follows:

$$H = \int_{T_{ref}}^{T} \rho c dT \quad , \tag{3}$$

where H (J/m^3) is the enthalpy, k (W/m.K) is the thermal conductivity, ρ (kg/m^3) is the density, c (J/kg.K) is the specific heat and T (K) is the temperature. The enthalpy evolution represents all effects concerning phase transformation, which is an advantage of using the enthalpy formulation in the heat transfer equation.[5]

The boundary condition of the bottom part of the problem (heat extraction surface) is given by Eq. (4):

$$-k\frac{\partial T}{\partial n} = h_i(T - Text) \tag{4}$$

The interfacial heat transfer coefficient (h_i) is the global transfer coefficient and it is dependent both on temperature and time. This coefficient includes the gap between the casting metal surface and mold, the thickness of the mold and the environment in the external part of the mold. The external surface temperature of the mold is defined as T_{ext}. The variable ∂n included in Eq. (4) can be ∂x or ∂y. The h_i time-dependent profile was determined in a previous work by Canté[6] and was used in this study according to the power function law: h_i=11,000(t)$^{-0.17}$.

The stress–strain relationship can be obtained according to the following equation:[7]

$$\{\sigma\} = E(\{\varepsilon\} - \alpha\{\Delta T\}) , \tag{5}$$

where {σ} is the stress tensor; {ε} is the strain tensor, ΔT is the temperature gradient; E is the Young's modulus and α is the thermal expansion coefficient. Eq. (4) restricts the stress-strain analysis to the elastic behavior of the material.

The stress was represented by the equivalent Mises stress (σ_m), and it is given by the expression:

$$\sigma_m = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} , \tag{6}$$

where σ_1, σ_2 and σ_3 are the major stresses.

Considering the previous exposed, the vertically unidirectional solidification of a binary eutectic alloy is the target problem. Figure 1(a) shows the initial and boundary conditions considered to solve this problem. In addition, Figure 1(b) shows the implemented grid imposed to the main domain of the problem.

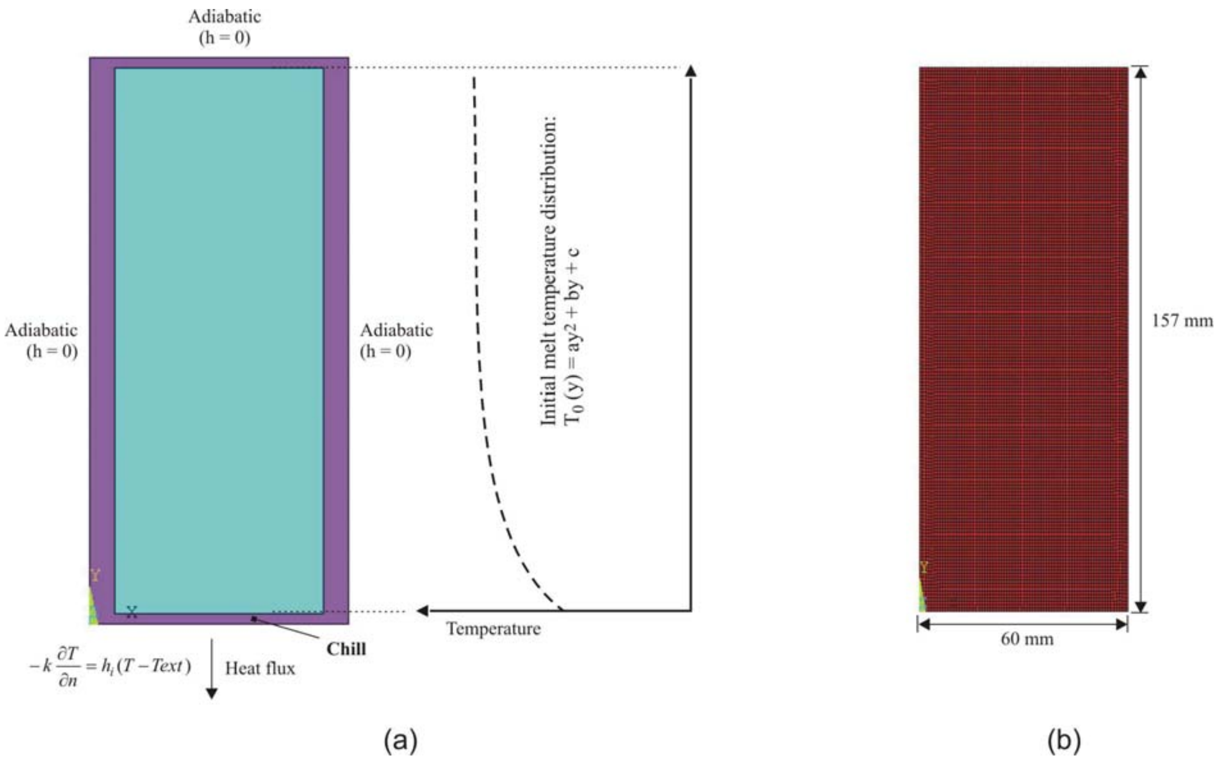

Figure 1. a) Schematic representation of the problem; b) FE grid configuration of the main domain.

3 EXPERIMENTAL PROCEDURE

Figure 2 shows the casting assembly used in the experiments. It can be seen that heat is directionally extracted only through a water-cooled bottom made of carbon steel (SAE 1020), promoting vertical upward directional solidification. A stainless steel split mold was used having an internal diameter of 60 mm, height 157 mm and a 5 mm wall thickness. The lateral inner mold surface was covered with a layer of insulating alumina to minimize radial heat losses. The bottom part of the mold was closed with a thin (3 mm) steel sheet.

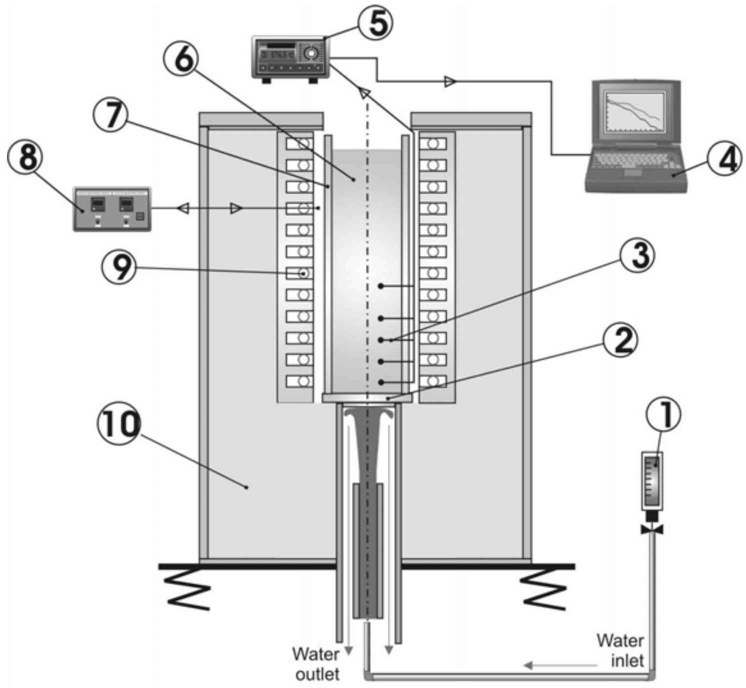

Figure 2. Schematic representation of the experimental setup: 1) rotameter; 2) heat-extracting bottom; 3) thermocouples; 4) computer and data acquisition software; 5) data logger; 6) casting; 7) mold; 8) temperature controller; 9) electric heaters; 10) insulating ceramic shielding.

The solidification experiment was performed with the Al-1wt%Ni hypoeutectic alloy. The thermophysical properties of this alloy and of the 1020 carbon steel chill are summarized in Table 1 and Table 2, respectively. Enthalpy profiles as a function of temperature and liquidus temperatures were obtained by Thermo-Calc* computations.[8]

The initial melt temperature (T_p) was set at 10% above the liquidus temperature (T_{Liq}) of the alloy. The thermal contact condition at the metal/mold interface was also set with the heat-extracting surface at the mold bottom being polished.

Continuous temperature measurements in the casting were monitored during solidification via the output of a bank of fine type K thermocouples (made from 0.2 mm diameter wire) sheathed in 1.6 mm diameter steel tubes, and positioned at 4, 8, 39, 54, 67 and 90 mm from the heat-extracting surface at the bottom. The thermocouples were calibrated at the melting point of aluminum exhibiting fluctuations of about 1°C. All of the thermocouples were connected by coaxial cables to a data logger interfaced with a computer, and the temperature data, read at intervals of 0.1 s, were automatically acquired.

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* *Thermo-Calc software is an exclusive copyright property of the STT Foundation (Foundation of Computational Thermodynamics, Stockholm, Sweden).*

Table 1. Thermophysical properties of the Al-1wt%Ni alloy.

Temperature (K)	Thermal conductivity (W/m.K)	Temperature (K)	Enthalpy (J/m^3)x10^8
929 (liquidus)	Liquid state - 87	321	0.0595
914 (solidus)	Solid state - 202	410	0.2860
-	-	609	0.8146
-	-	736	1.1922
-	-	825	1.4439
-	-	928	1.7963
-	-	931	2.4508
-	-	932	2.8032
-	-	1065	3.2311
-	-	1203	3.6842
	-	1388	4.2883

Table 2. Thermophysical properties of 1020 carbon steel chill [8,9]

Temperature (K)	Enthalpy (J/m^3)x10^9	Temperature (K)	Thermal conductivity (W/m.K)
341	0.08734	473	48.6
384	0.25109	573	44.4
449	0.52102	673	42.6
508	0.74236	773	39.3
573	1.01528	873	35.6
648	1.34279	973	31.8
722	1.67031	1023	28.5
811	2.16157	1073	25.9
882	2.54367	1173	26.4
929	2.87118	1273	27.2
984	3.25327	1373	28.5
998	3.96288	1473	29.7
1019	4.12664	-	-

The thermal histories recorded during directional solidification were used as supportive data to Ansys platform,[10] which is able to compute thermal stress values. Some mechanical and thermal properties of the Al-1wt%Ni alloy were used as input data to this program. These data are summarized in Table 3, where the Young's Modulus (E) was obtained from a recent study regarding to mechanical properties of directionally solidified Al-Ni alloys.[6] Once specific data for the studied alloy was not found in the literature, the Poisson coefficient (ν) and the thermal expansion (α) for pure aluminium were adopted for these calculations. The water-cooled bottom made of carbon steel (SAE 1020) was considered as a fixed element.

Table 3. Mechanical and thermal properties of the Al-1wt%Ni alloy and of the 1020 carbon steel chill.

Al-1wt%Ni alloy [11]		
E=57.2x10^9 Pa	T (K)	Thermal expansion coefficient, α (K^{-1} ×10^{-6})
ν= 0.33	293	24
1020 carbon steel chill [11]		
E=205x10^9 Pa	T (K)	Thermal expansion coefficient, α (K^{-1} ×10^{-6})
ν= 0.29	373	11.7

4 RESULTS AND DISCUSSION

Figure 3 shows the recorded cooling curves corresponding to the thermal responses of five thermocouples inserted into the casting at different positions from the cooled surface.

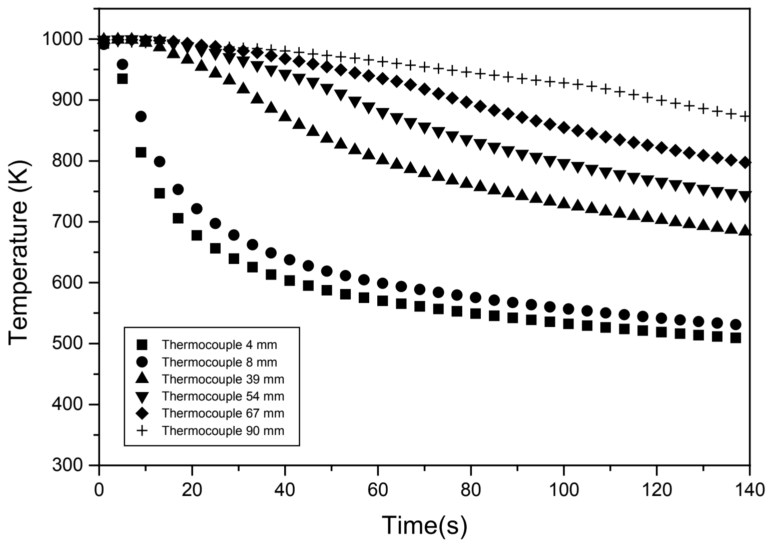
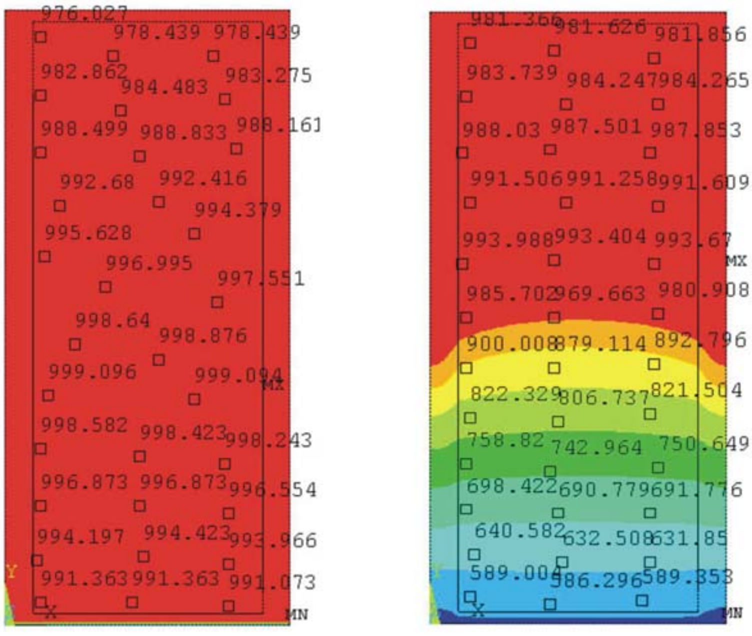


Figure 3. Experimental cooling curves for five thermocouples inside the Al-1wt%Ni alloy casting.

Figure 4(a) shows the initial melt temperatures, which were imposed as initial condition. Such distribution followed a polynomial function as described in Fig. 1. This expression was obtained by using the recorded temperatures at different positions along the casting immediately before starting solidification. The obtained expression was:

$$T\,(K) = 989.54 + 318.88\,(y) - 2661.63(y^2) \qquad (7)$$

Figure 4(b) shows the calculated thermal field after 50 seconds of solidification. It can be seen that solidification advances from bottom to the top of the casting. In Figure 4(b) red region refers to the liquid. Some specific points were chosen in order to show the temperatures at different points along the Al-1wt%Ni alloy casting.



(a) (b)

Figure 4. (a) Initial distribution of temperature and (b) temperature field at 50s.

A good agreement between experimental and theoretical thermal histories was obtained and can be seen in Figure 5. Positions corresponding to 4 and 8 mm from the metal/mold interface were chosen as references to validate the thermal calculations. At these positions, which are closer to the water-cooled mold surface, higher cooling rates can be observed.

Some discrepancies can be noted in the first stages of solidification and after 40 seconds. These differences can be attributed to the lack of confident thermophysical properties in the literature. The thermal conductivities for the Al-1wt%Ni alloy were considered constant values for solid and liquid phases. If temperature-dependent thermophysical properties were available in the literature, better results could be obtained.

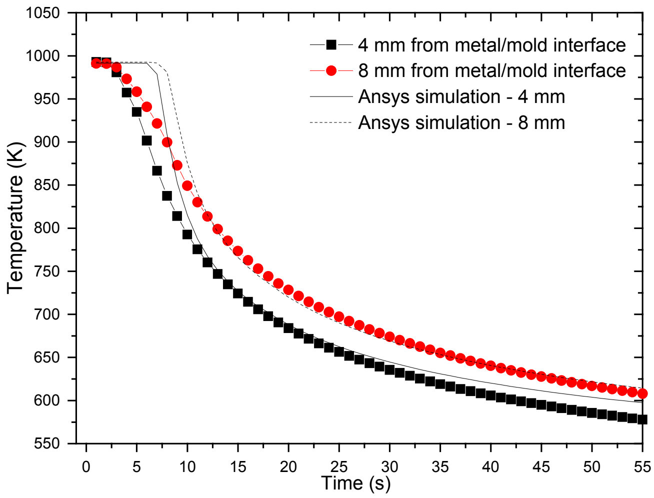
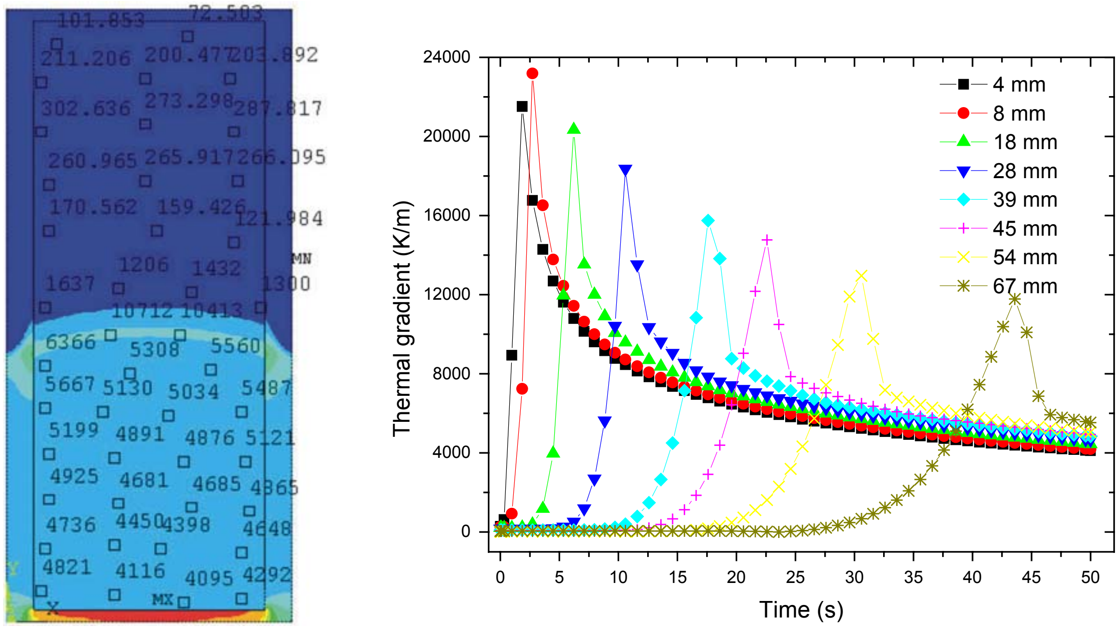


Figure 5. Comparison between experimental and theoretical thermal profiles of Al-1wt%Ni alloy.

Figure 6(a) shows the temperature gradient (G) evolution along the casting length at 50 seconds. The upper part of the casting (dark blue field) is still liquid, and at this part lower temperature gradients have prevailed. On the other hand, higher gradients can be observed close to the bottom of the casting. Such distribution is typical when strong heat extraction is imposed to the material during directional solidification. A larger spectrum of gradients (as observed in this case) is useful in order to evaluate its influence on the residual stresses.

The water-cooled mold imposes higher values of thermal gradients close to the casting cooled-surface and a decreasing profile along the casting length due to the increasing thermal resistance of the solidified shell with increasing distance in casting.

Figure 6(b) shows the time-dependent profiles of thermal gradients determined at 8 different positions from the metal/mold interface. It can be observed that the thermal gradients tend to become stable after decreasing from higher initial values. The time to achieve such stability is dependent on the relative position in the casting. Further, it was noted that the time to achieve the peaks concerning these profiles is much lower than the time required to the stability of G. This is mainly evident in the positions closer to the heat-extraction surface.



(a) (b)

Figure 6. a) Thermal Gradient distribution at 50 s (Unit: K/m) and b) Temperature gradients (at different positions) as a function of time.

Figure 7 shows the evolution of both heat flux and thermal gradient along the casting length at 50 seconds. Both variables show a typical behavior at 70 mm from the metal/mold interface. As can be seen in Figure 4(b), this is the position of the solidification front at this time. The heat flux tends to abruptly decrease as a consequence of latent heat release, while thermal gradient reaches a maximum value. The solid field (up to 70 mm) is characterized by higher values of both variables when compared to the liquid volume.

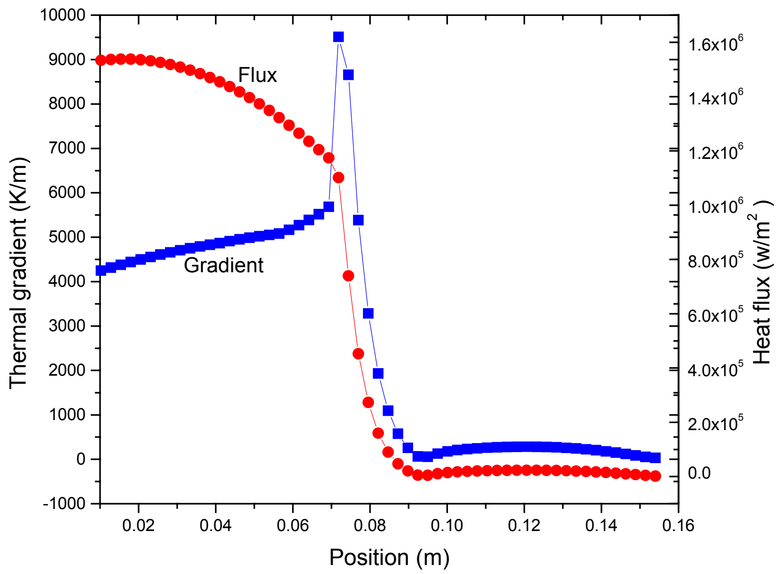
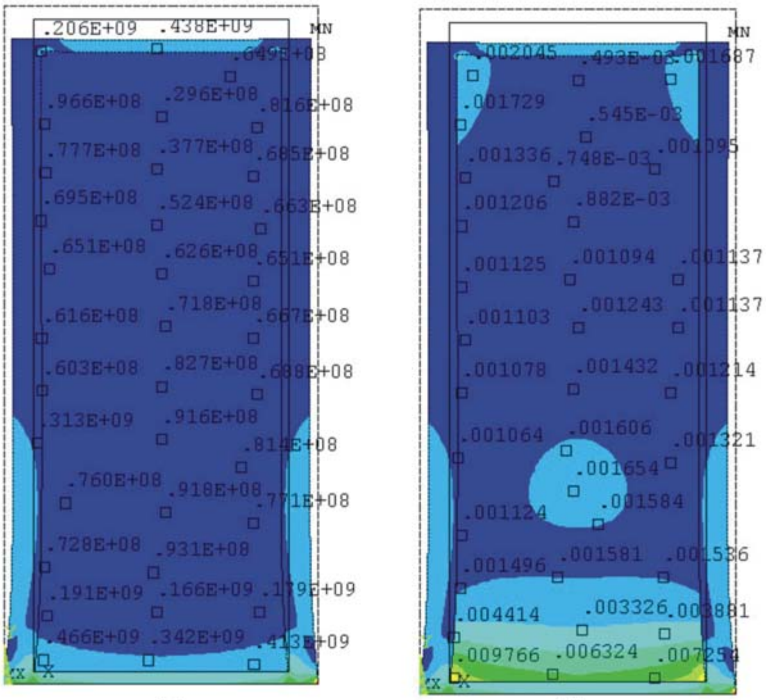


Figure 7. Variation of the thermal gradient and the heat flux along the casting at 50 s.

The calculated thermal stresses in the Al-1wt%Ni alloy casting are shown in Figures 8 and 9. The thermal gradient (determined by heat transfer simulation) was introduced into Eq 5, through the term ΔT. In spite of considering only elastic deformation, realistic results can be seen in Figure 8 considering both stress and strain values after 50 seconds of solidification. Plastic deformation contribution will be included in the calculations in the next step of this research. It is also possible to observe shrinkage regions at the top and close to the bottom of the casting. Length reductions in the directionally solidified castings are observed to be of the same order of magnitude of those calculated in this study.

Figure 9 shows that the highest values of stress/strains refer to the positions up to 20 mm from the metal/mold interface, where the highest cooling rates were imposed during solidification, which resulted in expressive temperature variations in this region. In contrast, lower values were observed in the liquid volume, where temperature is well distributed and low G values were generated.



(a) (b)

Figure 8. (a) Stress (Unit: Pa) and (b) strain in equivalent Von Mises in 50 s.

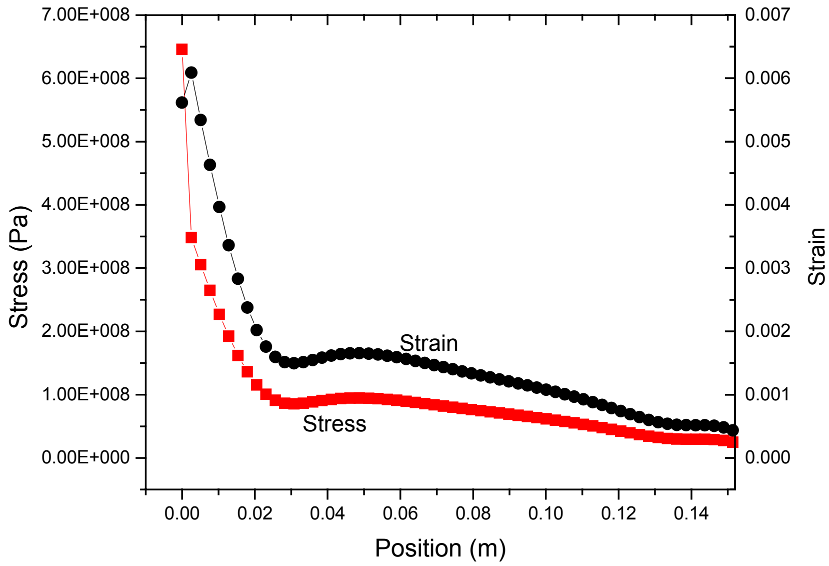


Figure 9. Variation of the stress and the strain in different positions of the casting, at 50 s.

5 CONCLUSIONS

It can be stated that the solidification process generates a thermal field which varies as a function of time, and this behavior influences the residual stress-strain along the casting. With a view on the castings final quality, the foundry industry must consider these phenomena in the project of castings. Hence, simulation results could be used to gain insight into the foundry process, by preprogramming solidification in terms of some particular level of residual stress-strain. The simulation of stress-strain fields by ANSYS coupled with the solidification theoretical evaluation is a promising and useful method to predict shrinkages and residual stresses into the casting, as shown in the present experimental/theoretical analysis.

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