Modern light metals processing technologies are very complex and involve a diverse set of variables that must be quantitatively evaluated. The most effective way to design new casting processes that deliver specified metallurgical and mechanical properties is to develop a method of simulating the "real-time" process within a test sample of sufficient size. The results can then be analyzed and the required optimizations can be performed.

This paper presents a novel method of simulating the industrial casting processes in a laboratory environment using an experimental apparatus based on the principle of high frequency induction heating. The applicability and accuracy of the proposed analytical method is demonstrated, for example, by simulation of the solidification and heat treatment of a test sample composed of two dissimilar materials.

The simulation can be used to develop a stress model for an engine block made from an aluminum based alloy with iron cylinder liner inserts.
1. Introduction

The way in which aluminum alloy melts are processed and the manner in which cast components are heat treated, influence their metallurgical structures and ultimately their mechanical properties [2, 3, 5, 6, 8, 13, 14]. In other words, the solidification process of a casting determines how that casting will perform in service. An important goal of aluminum casting research is to simulate the solidification processes of production castings in the laboratory. This is frequently done in order to design production processes that yield specified mechanical properties. Unfortunately, automotive foundry production occurs on a scale that makes laboratory simulation difficult. A number of variables are introduced in the foundry environment that cannot be replicated in traditional laboratory settings. Therefore, laboratory simulations have been only marginally accurate.

Recently, automotive foundries have become more aware of rising energy costs. This has prompted companies to redesign production processes in order to make them more energy efficient [11, 12]. For this reason, “traditional” solution treatment and artificial aging processes, which are well documented in the literature, are proposed to be replaced with “hybrid” processes about which very little is known [11, 12]. Such a "hybrid" process could conceivably combine casting, solution treatment, air and/or water quenching and artificial aging into a single continuous production cycle. Research in the design and analysis of such “hybrid” processes, from a physical metallurgical perspective, is currently being conducted [8]. Special attention is being paid to aluminum based alloy engine blocks with cast in iron cylinder liners. Dissimilarity of the materials having different thermal expansion coefficients leads to the development of excessive stresses during manufacturing. Therefore, factors like alloy chemical composition, cooling rate during the solidification process and heat treatment parameters (temperature, time, quenching rate etc.) have to be tailored for specific production processes in order to minimize the consequences of thermal expansion coefficient differences.

The changes to be introduced into the production processes have created the need for a laboratory simulation system that is multifunctional, more sophisticated and able to provide accurate analytical capabilities. At present, the simulation of a continuous production process in a traditional laboratory requires a melting furnace, a heat treatment furnace as well as a quenching facility. Moreover, because the sample is being manually moved from station to station, continuous temperature measurement and recording is virtually impossible. Therefore, what occurs within the sample at key stages of the process becomes lost in an experimental “black box”, and researchers conducting this type of work can only know the net effect of the entire process on the outcome variables of interest. There are some instruments currently available that can only partially fulfil these requirements [1]. In general, they are unable to replicate the real multistage casting processes under laboratory conditions. For example, when the simulation process has to be complemented by the analysis of the “Energy Signature” (Thermal Analysis) of the sample in order to correlate the results to the structure as well as mechanical properties of the material tested. Universal Metallurgical Simulator and Analyzer (UMSA) [7, 9] possesses the ability to simulate a variety of Temperature / Time depended processes, which are difficult to perform using standard laboratory equipment. The temperature signal coming from the test sample itself (not from the furnace chamber temperature sensor) and the fact that the heating power is directly generated in the test sample, allows for precise Temperature / Time process control and for a wide range of simulation capabilities. Additionally, based on the analysis of the first derivative of the recorded temperature signal the energy quantity associated with various metallurgical reactions can be measured [4, 7, 8].
The goal of this paper is to present the applications of the induction heating based system known as UMSA for the simulation of foundry processes. To demonstrate the usefulness of this system, the following simulations are presented: the isothermal holding during the solidification process and the development to the structural damage of a test sample composed of two dissimilar materials, when subjected to variable heat treatment processes.

2. Experimental Procedures

The experiments were carried out using cylindrical specimens ($\phi = 16\text{mm}$ and $l = 15\text{mm}$) machined from a 319 alloy with the following chemical composition, see Table 1.

Table I Chemical Composition of the 319 Aluminum Alloy

<table>
<thead>
<tr>
<th>Alloy Type</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
<th>Sr</th>
<th>Ni</th>
<th>Sn</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>319</td>
<td>7.70</td>
<td>3.38</td>
<td>0.38</td>
<td>0.27</td>
<td>0.23</td>
<td>0.08</td>
<td>0.12</td>
<td>0.0007</td>
<td>0.018</td>
<td>0.0033</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Additionally, for some experiments, cylindrical inserts machined from ductile cast iron ($\phi = 10\text{mm}$ and $l = 15\text{mm}$), were inserted into the 319 sample having a predrilled hole of 10mm in diameter. The simulations and Thermal Analysis were performed using the Universal Metallurgical Simulator and Analyzer (UMSA) [7, 9], an instrument designed for analysis of the thermal processes of metal samples. UMSA combines a sophisticated melting and heat treatment “furnace”, with a quenching station and a Thermal Analysis apparatus.

Thermal Analysis was performed in order to identify the metallurgical reactions during heating and cooling cycles and in order to estimate the effect of isothermal holding during the solidification process. Next, the test samples were heated to a liquid state inside the UMSA apparatus and allowed to cool to the ambient temperature after the power was turned off. This procedure was repeated for subsequent samples, except that they were held at "holding temperatures" between 540 and 470°C for periods of 90 minutes before being allowed to cool to the ambient temperature. The K-type thermocouples connected to the UMSA Data Acquisition System were used to record the sample temperature with an accuracy of +/-0.5°C.

Additionally, the 319 aluminum alloy test samples with cast iron inserts were subjected to the solution treatment at 495°C for 90 minutes, followed by natural cooling to room temperature. For the remainder of this paper, this process is referred to as the “Interrupted Process”. The solution treatment temperature of 495°C was selected in order to avoid the incipient melting of Cu based phases. For comparison purposes, the isothermal holding during the solidification process was performed at 495°C for 90 minutes. For the remainder of this paper, this process is referred to as the “Continuous Process”. Due to the small sample size, natural convection cooling after solution treatment at 495°C created a sufficiently high cooling rate to saturate the aluminum solid solution. The calculated cooling rate from 495 to 200°C was about 0.9°C/s. This would cause the increase in hardness after the natural or artificial aging.

Samples for metallographic observations and matrix microhardness measurements were ground with abrasive paper and polished using BUEHLER equipment. The final polishing was carried out using commercial 0.05µm slurry. The area fraction of the Cu enriched phases in the samples was evaluated using a LEICA QW-550 Image Analysis System (IAS) linked to a Leica
DMR Light Optical Microscope (LOM). Twenty-five (25) analytical fields were measured under 500x magnification for each sample and the median Cu enriched phase volume fraction was determined. After the "Continuous" and "Interrupted" heat treatment processes, the number of cracks found on the 319 alloy / cast iron insert interface were manually counted using the LEICA QW-550 Image Analysis System (IAS). Next, the number of cracks was divided by the length of the cast iron insert circumference and expressed as the number of cracks per 1 mm, Crack Density (CD). Metallographic observations were performed using the JEOL JSM 5800 Scanning Electron Microscope (SEM) in the Back Scattered Electron (BSE) mode. The matrix Vickers microhardness was measured using a BUEHLER microhardness tester under a 25g load for 15s (HV25). Twenty measurements were taken per sample and the median microhardness was determined. Microhardness measurements were performed two weeks later so that the material could naturally age. In order to evaluate the effect of dissolution of Cu enriched phases and other structural constituents on the strengthening effect of the solid solution the matrix microhardness measurements were chosen in place of overall macrohardness measurements.

The median was chosen as the criterion of analysis in this study because it is less influenced by extreme scores, the presence of which is a concern in both the measurement of microhardness and Cu enriched phase area fraction.

Figure 1: First derivative curve vs. Temperature during cooling and heating for the 319 alloy test sample. The main metallurgical reactions during heating and solidification are:

1. beginning of dissolution of Cu enriched phases, i.e., 497°C – pointed out by a black arrow, end of dissolution of Cu enriched phases, i.e., 522°C – pointed out by a gray arrow,
2. dissolution of Al-Si eutectic,
3. dissolution of Al dendrite network,
4. nucleation of Al dendrite network - 598.4°C,
5. nucleation of Al-Si eutectic - 562.7°C,
6. nucleation of Cu enriched eutectic - 495.3°C.
3. Results

3.1. Influence of Isothermal Holding on Structure and Matrix Microhardness

Thermal Analysis for the 319 alloy test sample revealed that three main metallurgical reactions can be recognized during the solidification process: the nucleation of the Al dendrite network - 598.4°C, the nucleation of the Al-Si eutectic phase - 562.7°C and the nucleation of the Cu enriched phases - 495.3°C (Figure 1). The incipient melting of the copper enriched phases during heating will occur when the temperature exceeds 497°C. Therefore, for the given experimental conditions, the one-step solution treatment temperature should not exceed this temperature [13, 14].

Determination of the Cu enriched phase area fraction showed that isothermal holding of the test sample during solidification decreased the area fraction when compared with the as-cast sample (area fraction ~ 2.6%) (Figure 2). The smallest Cu enriched phase area fraction after isothermal holding occurred in the temperature range between 500 and 530°C. The matrix microhardness measurements showed the reverse trend: isothermal holding during solidification increased the microhardness of the Al matrix when compared with the as-cast material (HV25 = 78). The changes in the matrix microhardness could be correlated with the area fraction of the Cu enriched phases. Figure 2 shows that the maximum microhardness of approximately 120-122 HV25 corresponds to the minimum area fraction of the Cu enriched phases (i.e. 0.2-0.4%).

Figure 2: Area Fraction of the Cu enriched phases and Matrix Microhardness HV25 for the 319 alloy test samples isothermally held at various temperatures for 90 minutes during the solidification process.
A comparison of the first derivative vs. temperature plots obtained from Thermal Analysis for the as-cast sample to those isothermally held at 500 - 530°C (Figure 3) showed a decrease in the area attributed to the Cu enriched phase reactions in the samples' "Energy Signatures". It is plausible that the metallurgical reaction "Energy Signature" can be estimated using the area between the first derivative curve and the baseline curve. This hypothesis is under investigation by the authors [4, 10].

3.2. Structural Damage of Test Sample, Composed of Two Dissimilar Materials, Subjected to Various Heat Treatment Processes

The Thermal Analysis was performed during the single heating and cooling process of the 319 test sample with the 10mm ductile cast iron insert showing negligible differences in the cooling rate recorded by the temperature sensor placed in the 319 alloy and cast iron insert (Figure 4). The main metallurgical reactions during heating and cooling cycles can be recognized on the Temperature vs. Time curve in which characteristic temperatures correspond to paragraph 3.1 (Figure 1). Figure 5 presents the Temperature vs. Time plots for the 319 alloy test sample with cast iron inserts subjected to the "Continuous" and "Interrupted" Processes. The test sample cooling rate during the solidification between liquidus and solidus temperatures was about 0.7°C/s. This relatively high cooling rate can be attributed to the small mass of the test sample. The cooling rate after the solution treatment, calculated between temperatures of 495 and
200°C, was about 0.9 °C/s. The total cycle time for the “Continuous Process” is about 40% shorter than for the “Interrupted Process" due to the elimination of the heating time required to reach the solution treatment temperature.

The SEM observations of the cross-section of the test samples showed that numerous microcracks developed on the interface between the 319 alloy and the cast iron insert (Figure 6). It is believed that the cracks developed during the solidification process and were also extended during the additional solution treatment for test samples subjected to the "Interrupted Process". The reason for this is that the 319 alloy thermal expansion coefficient is approx. 2 times higher than for cast iron [10]. Additionally, SEM observations revealed the interface layer between the 319 alloy and the cast iron insert (Figures 6 and 7). The X-ray microanalysis determined that the layer is composed of O, Al, Si, Mn and Fe. It is believed that it was created during the test sample solidification, due to the interaction between the liquid 319 alloy and the cast iron insert. The layer was heavily cracked, due to the presence of stress which developed during solidification as well as through further heat treatment (Figure 7).

The microhardness measurements of the test sample with the 10mm ductile cast iron insert showed that the isothermal holding during solidification at 495°C for 90 minutes ("Continuous Process"), increased the aluminum matrix microhardness to 106HV25. This is about 5% more
than compared with the “Interrupted Process” (Figure 8) and about 26% more compared with the as-cast material (Figure 2).

The Image Analysis results showed that the test sample subjected to isothermal holding during the solidification process ("Continuous Process") had a lower Crack Density than the test sample subjected to the “Interrupted Process”. The number of cracks found on the interface can be correlated with the metal matrix microhardness. Test samples with higher hardness i.e., 106HV25, subjected to the “Continuous Process”, had a 10% lower Crack Density (i.e., 1.7) for the “Interrupted Process” (Figure 8). It is believed that matrix microhardness is not the only metallurgical factor influencing the ability of the test sample to sustain the stress created due to thermal expansion coefficient differences between the 319 alloy and cast iron. The morphology of the structural constituents, like Si and Cu based phases, which are affected by the heat treatment, have to be considered as well. Under given stress conditions, caused by the thermal expansion / contraction differences between dissimilar materials these could become the crack nucleation sites. The decohesion between structural constituents and metal matrix, under a given stress level, could be extended by the linking process. This can lead to rapid fracture through the metal matrix [10].
Figure 6: Scanning Electron Microscopy (SEM) micrograph (BSE image) of the 319 alloy test sample (#1) and the cast iron (#2) interface with numerous micro cracks which (#3) developed during solidification of the test sample due to the differences in thermal contraction (220x).

Figure 7: Scanning Electron Microscopy (SEM) micrograph (BSE image) of the 319 alloy test sample (#1) and the cast iron (#2) interface with the iron rich layer (#3) which developed during solidification. Note that the layer is heavily cracked (1000x).
4. Conclusions

The analysis of the influence that isothermal holding has on structure and matrix microhardness showed that isothermal holding temperatures of between 500 and 520°C appear to be optimal. The temperatures in the above-determined range allow the majority of the Cu enriched phases to go into solid solution resulting in the maximization of matrix microhardness (HV25 ~ 120). Isothermal holding at a higher temperature results in a decrease in the matrix microhardness (HV25 = 109 at 530°C), while at a lower temperature, holding does not maximize the dissolution of the Cu enriched phases.

The analysis of structural damage of the test sample, composed of two dissimilar materials, showed that the Crack Density on the interface is lower for the test sample subjected to the “Continuous Process”. This process obtains a matrix microhardness 5% higher than for the “Interrupted Process”. The total cycle time for the “Continuous Process” is about 40% shorter than that for the “Interrupted Process”. The number of cracks can be correlated with the metal matrix microhardness. The combination of strength and ductility of the metal matrix and morphology of the structural constituents must be analyzed in order to understand the ability of the material to sustain stress. The information presented above, if complemented by additional

Figure 8: The Vickers microhardness (HV25) of the aluminum matrix and density of cracks (CD) found on the 319 alloy / cast iron insert interface for the test samples subjected to isothermal holding during the solidification process at 495°C for 90 minutes (“Continuous Process”) and solution treated at 495°C for 90 minutes (“Interrupted Process”).
dilatometry studies can be used to develop a stress model for automotive components made from aluminum-based alloys with cast in structural iron elements.

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References


