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Design criteria used for optimization of the solution treatment for 3xxx series cast alloys

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Abstract: This paper presents the overview of the selected design criteria used for laboratory optimization of Heat Treatment processes used for the 3xxx series alloys. The current economy characterized by high energy costs and competitiveness in the automotive market has forced Heat Treatment providers to redesign their processes in order to make them more energy efficient. The existing Heat Treatment standards have been available to the metal casting community for decades. They do not reflect the continuously changing economy, which is driven by cost reduction. For this reason each single Heat Treatment procedure must be customized for a given application. A system of functional criteria has must be developed that can be easily adapted for a given Heat Treatment optimization study.

Keywords: Cast alloys, Heat Treatment, Thermal Analysis, microstructure

1. INTRODUCTION

Growing demands to reduce vehicle emissions and to increase service performance of cast components has forced automotive manufactures to strive for continuous product development. Moreover, rising energy costs have prompted them to redesign production processes in order to make them more energy efficient [2-4, 7]. Reduction of the Heat Treatment process time is especially important from the economic point of view. Thermal processing adds significantly to the final component cost. Therefore, it is often necessary to customize Heat Treatment routines to specific applications. This type of customized procedure can be developed through trial and error experiments in industrial settings; however, doing so is costly and time consuming because of the scale of the operations involved. For this reason laboratory metallurgical simulations are crucial especially when they accurately represent the conditions created in a large complex component that are heat treated by industry [2, 4].

The goal of this paper is to present the overview of the selected design criteria used for optimization of the Heat Treatment for the 3xxx series of cast alloys.

2. EXPERIMENTAL PROCEDURES

The laboratory metallurgical experiments were performed using test specimens extracted from various commercial 3xxx series cast components manufactured using sand castings as well as the die casting process. Moreover, synthetic alloys prepared under laboratory conditions were used with Si varying from 7 up to 11% and Cu ranging from 1 to 4%. The advanced Thermal Analysis and Heat Treatment operations were performed using the Universal Metallurgical Simulator and Analyzer (UMSA) [5]. Moreover, conventional resistance Heat Treatment furnaces were used for selected Heat Treatment operations. Classical metallurgical evaluations were performed following the completion of the experiments.

3. RESULTS AND DISCUSSIONS

The maximum Solution Treatment temperature that a given component can be subjected to depends predominantly on the alloy's chemistry. It is known that the maximum Solution Treatment temperature corresponds to the beginning of the alloy melting. This temperature can be detected by laboratory techniques such as Thermal Analysis that is used to identify the metallurgical reactions during heating cycles [2, 6]. Thermal Analysis performed during the solidification process only is not satisfactory to properly set up further Heat Treatment operations due to the thermal histeresis effect (i.e., the temperature shift between melting and cooling cycles). For this reason the information obtained from the heating cycle has to be used to design the Solution Treatment operations.

There are some factors that have to be considered. For example, the test sample size to be tested has to be representative to address issues like micro and macro segregation of low melting point phases. This is particularly important for components manufactured using sand or investment castings, where solidification rates were close to equilibrium conditions. Thermal Analysis instruments that deal with samples up to a few milligrams do not meet these requirements to the full extent.

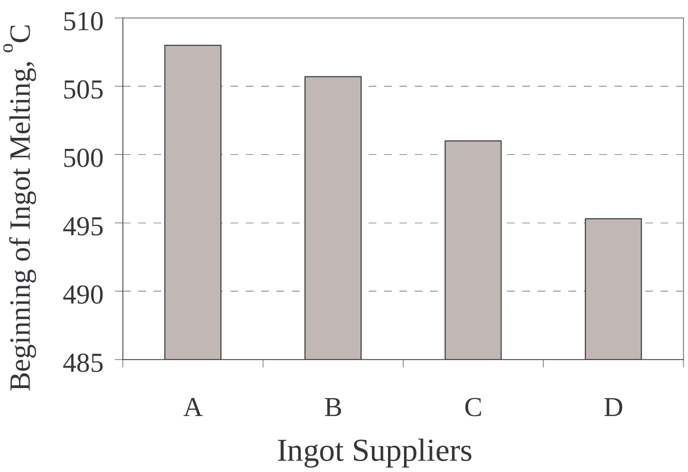

Figure 1. Beginning of Ingot melting Temperature (Incipient Melting) for the 319 alloy from four different ingot suppliers.

The beginning of the melting temperature for the 319 alloy (Al-7%Si-3.5%Cu) is approximately 495 to 507^{o}C depending of the level of impurities. Exceeding this temperature during a single step Solution Treatment results in localized melting of the Cu enriched phases. This phenomenon is called Incipient Melting (IM). The beginning of IM can be significantly affected by the addition of impurity elements, particularly low melting points like: Sn and Pb. Existing alloy chemistry specifications allow for these additions even up to 0.1% wt. Optical Emission

Spectroscopy (OES) analysis is used to validate compliance of the ingot chemistry with the engineering specifications prior to entering the casting plant. However OES data is not adequate for prediction of the ingot melting temperature. Figure 1 presents the beginning of the melting temperature detected for 319 ingots (Al-7%Si-3.5%Cu) provided by four (4) different suppliers. These ingot chemistries are within the engineering specifications however they exhibit significant differences (up to 12^{o}C) in the beginning of the melting temperatures. Consequently all analyzed ingots cannot be Solution Treated under identical conditions to avoid the detrimental IM phenomenon. If so, the Heat Treatment provider must be aware of the potential risk of Incipient Melting and its negative consequences on the cast component mechanical properties.

It was observed that the Solution Treatment temperature above Incipient Melting resulted in sudden spheroidization followed by coagulation of the Cu enriched phases. In turn this reduced the dissolution rate of the alloying elements in the metal matrix and consequently the hardness after the Natural/Artificial Aging operations. Exemplary micrographs of the 319 alloy Solution Treated at 500^{o}C (i.e., ~5^{o}C below the IM temperature) and 530^{o}C (i.e. ~25^{o}C above the IM temperature) are presented in Figures 2a-b. Studies performed outside the scope of this work indicate that the Incipient Melting temperature can be increased up to 10^{o}C by reducing the heating rate to the Solution Treatment temperature. It is known that slow heating rates help to dissolve some of the Cu enriched phases before reaching the Solution Treatment temperature [6].

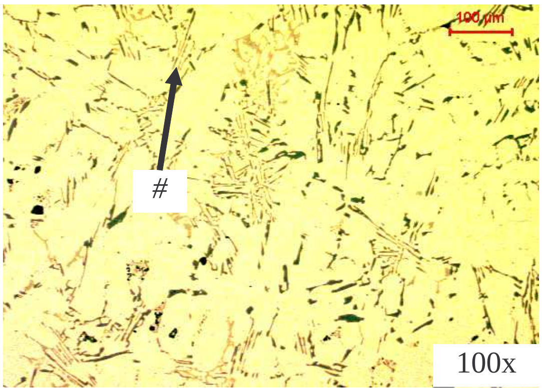

Figure 2a. Light Optical Microscope (LOM) micrograph of the 319 alloy test sample Solution Treated at 500^{o}C (i.e., ~5^{o}C below IM temperature). Note undissolved Cu enriched phases in the characteristic eutectic morphology (#1).

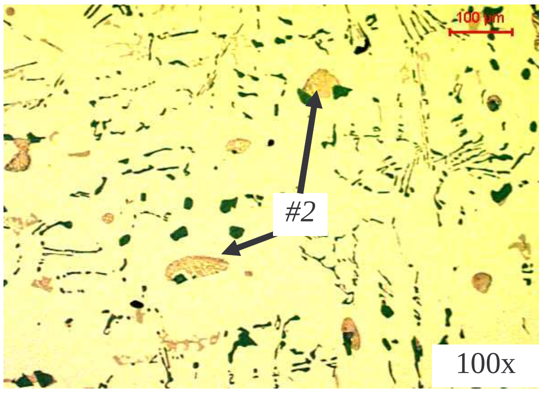

Figure 2b. Light Optical Microscope (LOM) micrograph of the 319 alloy test sample Solution Treated at 530^{o}C (i.e., ~25^{o}C above IM temperature). Note localized IM (#2) visible as a coagulation of undissolved Cu enriched phases.

Another alternative method to minimize the risk of IM is utilization of a multi step Solution Treatment process. First, the component is heated to the temperature below the Incipient Melting temperature for a period of time necessary to dissolve most of the Cu based phases in the solid solution. Next, the component temperature is increased above the Incipient Melting temperature and is kept for a required time [7]. This helps to accelerate thermal modification of the structural constituents like the Al-Si eutectic without risk of IM of the Cu based phases. The rate of thermal modification can be accelerated for castings solidified with a faster solidification rate (permanent mould, die casting etc.) and/or with the addition of chemical modifiers. The overall Heat Treatment process duration must be justified from the economical point of view.

Conventionally, the Solution Treatment process is followed by the quenching operation. Quenching effectiveness has to be selected with respect to the required retention of alloying elements in the solid solution and a quenching stress that is acceptable for a given component. Quenching effectiveness can be flexibly controlled by the proper selection of the quenching medium [1].

4. CONCLUSIONS

The results presented in this paper highlight some of the metallurgical issues that have to be considered when designing new or optimizing existing heat treatment processes. Advanced metallurgical laboratory simulations are a must nowadays to properly setup Heat Treatment parameters. This is particularly important for the ever changing economy driven by cost reduction. Existing Heat Treatment standards do not meet these requirements. This is the justification for advanced laboratory optimization studies.

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