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A novel approach to the design and optimisation of aluminium cast component heat treatment processes using advanced UMSA physical simulations

L.A. Dobrzański [a], M. Kasprzak [b], W. Kasprzak [a,c], J.H. Sokolowski [c,]*
[a] Division of Materials Processing Technology, Management and Computer Techniques in Materials Science, Institute of Engineering Materials and Biomaterials, Silesian University of Technology, ul. Konarskiego 18a, 44-100 Gliwice, Poland
[b] Department of Power Electronics, Electrical Drives and Robotics (KENER), Silesian University of Technology, ul. B. Krzywoustego 2, 44-100 Gliwice, Poland
[c] Light Metals Casting Technology Group, University of Windsor, Room 218, Essex Hall, 401 Sunset Avenue, Windsor, Ontario, N9B 3P4, Canada
* Corresponding author: E-mail address: jerry@uwindsor.ca

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Methodology of research

ABSTRACT

Purpose: The goal of this publication is to present a new laboratory methodology for simulation of industrial melting, solidification and heat treatment using the patented Universal Metallurgical Simulator and Analyzer (UMSA) Technology Platform [10]. Two examples to demonstrate UMSA's capabilities are presented for optimized heat treatment processes at the request of the North American automotive industry.
Design/methodology/approach: The unique UMSA Platform was used to rapidly physically simulate very complex industrial heat treatment processes using stationary macro test samples and computer controlled heating and cooling source.
Findings: The UMSA simulations proved to be very accurate in order to simulate the non-linear temperature/time profile of the solidification process combined with the continuous heat treatment operation. Moreover, the complex industrial heat treatment process was successfully replicated for an 800g test sample and the targeted structural and mechanical properties were met.
Research limitations/implications: Selected examples of the heat treatment have been presented for aluminum based alloys only. The current research addresses Mg and Ti based alloys and thermal processing under vacuum and inert/active environments.
Practical implications: The presented methodology is capable of dissecting all processes and linking the cast component's optimized performance with individual production steps. The technical capabilities of the UMSA Platform have been recognized and have already been applied by industrial partners.
Originality/value: The simulation method that is presented here will greatly improve the ability of laboratory investigators to simulate and assess the effects of the heat treatment variables.
Keywords: Heat treatment; Castings; Aluminium alloys; Laboratory simulations; Mechanical properties

1. Introduction

High energy costs, competitiveness and the need for high performance automotive components has forced manufacturers to redesign their heat treatment processes that are often based on old concepts that are a few decades old. Unfortunately the existing heat treatment R&D methodologies do not reflect on these new stringent requirements [5,7-9,12-15]. Therefore, advanced laboratory physical simulation platforms and methodologies are required to minimize costly plant experiments. Industrial trials often cannot provide a continuous high resolution thermal signature of the structural transformations and corresponding metallurgical samples for each production step and/or sub-steps that are vital for optimization of both technology and components.

The presented UMSA Platform methodologies demonstrate the quantum leap ability of rapid laboratory simulations, assessment and optimization of the industrial heat treatment process parameters and cast component characteristics. These parameters and characteristics can be assessed at any time during the UMSA experiments. In the last few years the UMSA Platforms and contract research were commissioned by the North American, Indian and Japanese automotive industries and academia (including the University of Windsor, Canada and the Silesian University of Technology, Poland) and rendered new materials and processes resulting in very substantial cost savings [1-4,6]. The custom made UMSA Platforms have a wide range of engineering capabilities specific to the given industrial technologies (i.e. sand, semi-permanent or high pressure die-casting technology). Several scientific research and commercial programs jointly executed by the University of Windsor, Canada and the Silesian University of Technology, Poland extensively utilize the UMSA Technology Platform [4,6].

This paper presents two examples of the UMSA simulation of the heat treatment studies performed on Al-Si cast components.

2. Experimental procedures

UMSA experiments were performed using cylindrical samples with a diameter of φ = 16-50mm and a length of l = 18-100mm machined from the secondary 319 alloy (~7%Si, ~3%Cu, Al - balance). Computer controlled UMSA melting, melt treatment and solidification conditions of the test samples rendered identical as-cast structures that are present in the critical section(s) of the solidified casting. Presented experiments were performed using two different UMSA Platforms. One of the UMSA Platform's Testing Chamber is shown in Figure 1 [10,11]. Compressed gases (up to 10atm) and atomized water were used to simulate various quenching rates. Selection of quenching rates was based on industrial requirements for the control of mechanical properties and quenching stresses in the engine cast components. Controlled heat treatment parameters (time, temperature, heating/cooling-quenching rates) were input into the UMSA via software including numerical data from the heat treatment facility which were used for the exact duplication of the industrial processes. The test samples were instrumented with sensitive thermocouples and the thermal history of each cycle was computer recorded and analyzed while the test samples were characterized using metallurgical techniques [5,8].

Fig. 1. Multifunctional, Environmental UMSA Platform Testing Chamber (the University of Windsor, Canada). This chamber is the main functional UMSA component

3. Industrial requirements and experimental results

3.1. Industrial requirements

A minimum of 96 μHV25 (microhardness) and the shortest possible processing time. Figure 2 presents two UMSA continuous temperature vs. time traces of the test samples cooled to approximately 480 and 300^{o}C after the solidification process (the so called Transfer Temperature (TT)) and reheated to the Solution Treatment temperature of 500^{o}C (Solution time is the same for process #1 and #2) followed by compressed gas quenching (at rate of 10^{o}C/s). Next the test samples were Artificially Aged at 200^{o}C for 2 hrs. The total manufacturing time was 330 mins for the optimum process #1 conditions and 370 mins for process #2. Metallurgical analysis revealed that process #1 with a higher TT has a μHV25 of 103 that is 10% higher than the test sample cooled to $\approx$300^{o}C, Figure 3. Inadequate μHV25 resulted from process #2 and could be compensated by a longer Solution Treatment time; however, this is not acceptable from the manufacturing cost point of view. An optimized TT significantly improves both the productivity and casting mechanical properties. This integrated technology of cast component solidification and heat treatment processes utilizes a considerable amount of latent heat released during the solidification operation [5,8]. It is also interesting to notice that the UMSA Platform can quantify the processing energy costs.

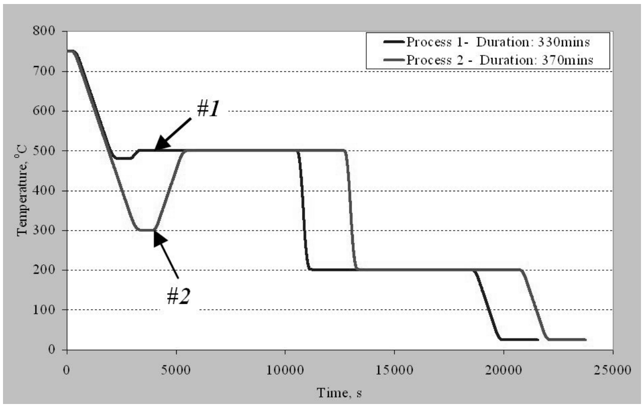

Fig. 2. Time vs. Temperature plot of "ideal" UMSA simulated industrial processes

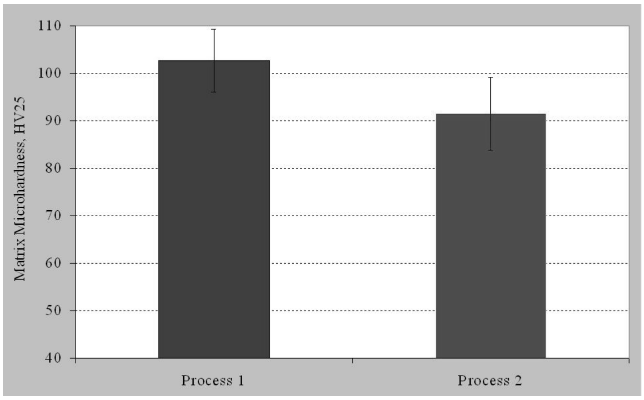

Fig. 3. Matrix Microhardness (HV25) of the test samples subjected to thermal processing

3.2. Industrial requirements

To develop an optimum quenching procedure for considerable temperature variations throughout the casting load and to obtain a casting hardness HB of 85. Figure 4 presents the cast components temperature vs. time traces from 8 thermocouples (imbedded in critical sections and various casting locations with respect to the heat source) subjected to the solution treatment for approximately 11 hrs followed by compressed gas quenching and artificial aging at approximately 225°C for 4hrs. The ideal linear temperature/time profile simulation (as in Figure 2) does not reflect the complexity of the temperature profile present in the industrial environment. Optimization of the quenching operation was performed on an 800g UMSA test sample using series #1 while the industrial temperature vs. time profile was imported to the UMSA software, Figure 5. The metallurgical analysis revealed that the required macro hardness of 85HB was achieved and the Al-Si eutectic AFS modification level (SiML) quantified by the UMSA software was 1.

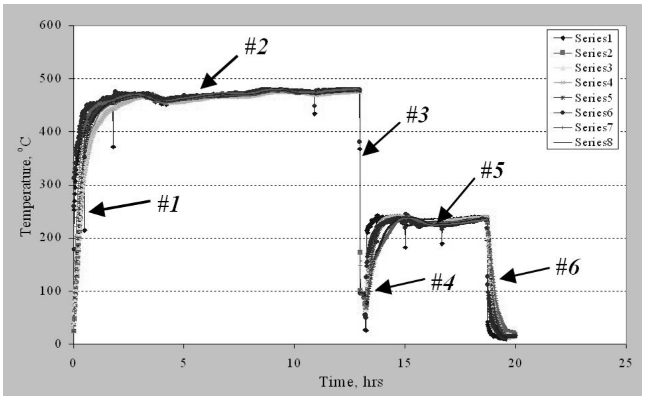

Fig. 4. The industrial heat treatment profiles of the Al-Si cast component. The numbers correspond to individual operations like #1 heating, #3 quenching, etc.

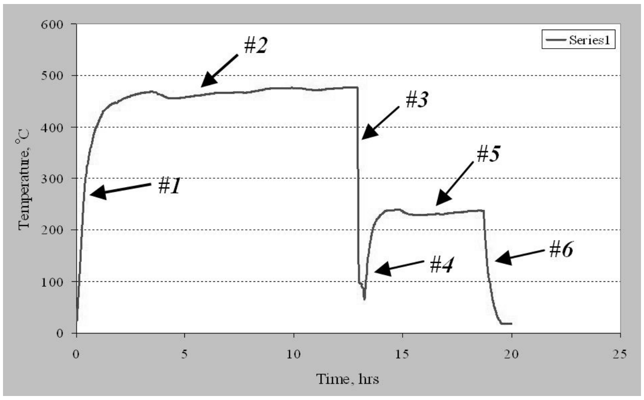

Fig. 5. The industrial heat treatment process simulated by the UMSA Platform based on the digital data from the selected thermocouple

4. Conclusions

The UMSA Platform proved to be an indispensable testing and analytical research tool for the development of novel solidification and heat treatment processes rendering exceptional metallurgical characteristics of the cast components. The advantages of the UMSA Platform include:

- direct and continuous characterization of metallurgical reactions during the solidification and heat treatment processes,
- rapid test sample temperature field response to the programmed values,
- a sufficient test sample size allowing for structure analysis and mechanical testing,
- low thermal capacitance and the time constant of the heating system,
- high dynamic control of the output power.

A combination of the above mentioned UMSA capabilities allows investigators to rapidly simulate very complex industrial processes using stationary test samples and clean as well as controlled density heating energy.

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