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Research paper

An artificial immune system algorithm applied to the solution of an inverse problem in unsteady inward solidification

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ABSTRACT

The numerical simulation and optimization in solidification involving geometries beyond one dimension normally requires expensive computational approaches in memory and data processing, generating consequently high cost associated with runtime execution. When boundary conditions are unknown, such as how heat is extracted from the casting surface, which is a typical inverse heat transfer problem (IHTP), the search for such conditions by trial-and-error makes the whole process less feasible. In this sense, this work introduces the application of an artificial immune system (AIS) algorithm as a possible meta-heuristic alternative, with a view to returning acceptable objective values to converge on a set of acceptable solutions. In the present work, the search process of the heat transfer coefficient (h_g) at the casting surface during two-dimensional inward solidification of Al-1.5 wt.%Fe alloy castings of Cartesian and Cylindrical geometries in chilled molds is optimized. Two water-cooled solidification apparatuses were designed to *in situ* melt the alloy by a set of electrical resistances, in which heat is extracted only through the chilled faces of the molds. The thermal history during solidification was obtained via thermocouples placed at different positions in the castings. A Finite Difference heat transfer model integrated to an optimized version of the artificial immune network algorithm, which uses the experimental thermal profiles as inputs, has been applied to solve the IHTP through the search for acceptable values of heat transfer coefficient. It is shown that fast convergence of the developed algorithm can be achieved for a relatively small number of iterations. The mean relative errors associated with differences between simulated and experimental temperatures are shown to be 1% and 0.07% for Cartesian and Cylindrical geometries, respectively and expressions relating h_g to time have been determined for both geometries.

1. Introduction

Solidification simulation is vital in meeting today's challenging casting requirements and helping foundry industry to deliver more effectively better products. Although there is good availability of commercial simulation programs, there still exist some fundamental particular aspects not provided in off-the-shelf software packages due to their generalist conception of the physical phenomena. In contrast to software developed for the mass market, the custom software, also known as tailor-made software, is specially designed to target specific or complex needs of the casting industry.

One of the most difficult tasks in simulation is the accurate representation of the boundary conditions [1]. Nonreflecting boundary conditions for the time-dependent regimes are common in readymade casting software, e.g., the heat transfer coefficient at the metal/mold interface (h_i), which changes over time due to the development of increasingly gaps between the casting and mold surfaces, is generally assumed constant due to the disablement of coupling the transient behavior of this coefficient in the computational code [2].

The way heat is transferred through the metal/mold interface is one of the most important boundary conditions to be characterized in casting processes. The interfacial heat transfer coefficient (h_i) plays a critical role in controlling the solidification rate of the casting and therefore determines the final microstructure and the resulting mechanical properties [3–9]. Consequently, when analyzing the solidification of castings, the reliability of the simulated results depends largely on the way h_i is modeled.

The equation describing the h_i transient behavior has been theoretically demonstrated and experimentally analyzed [10], following the format $h_i = a \cdot t^{-m}$, where "a" and "m" are constants, and "t" is the time. These constants, according to experimental evidences [4,11–14], depend on mold characteristics: material, surface roughness and

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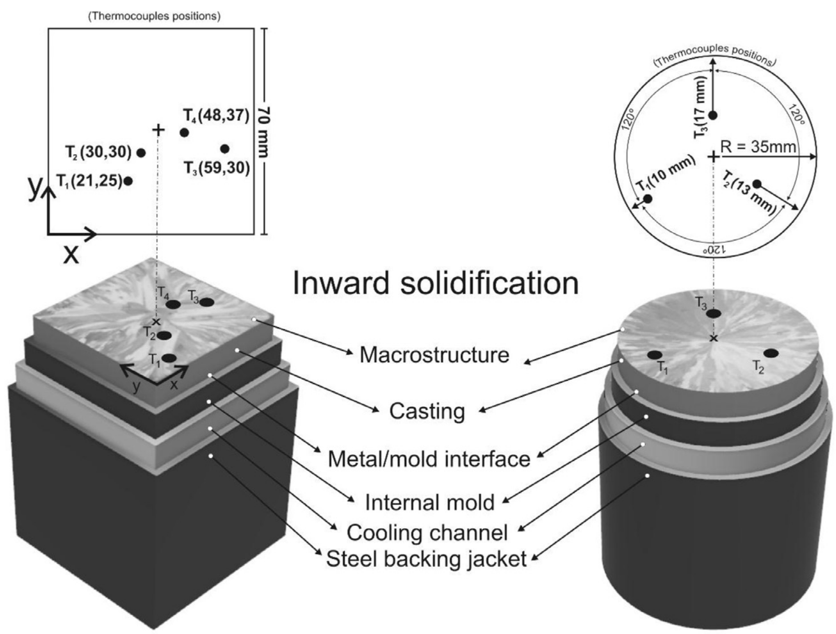

Fig. 1. 3D schematic view of water-cooled apparatuses for experimental solidification procedures.

thermally induced expansion; and on alloy features: composition, pouring temperature, wettability of the molten alloy over the mold surface, direction of solidification and thermal and volumetric contraction.

The determination of "*a*" and "*m*" coefficients from the h_i function belongs to a class of ill-posed problems known as inverse heat transfer problem (IHTP), which consists of iterative inverse algorithms aimed to minimize the difference between numerical and measured transient temperature data at known locations in the casting [15]. Computer processing time can be drastically reduced during the search of h_i through the application of artificial intelligence (A. I.) techniques, since the number of iterations is significantly shortened. Some studies have reported the positive association between A.I. techniques and IHTP algorithms to ascertain heat transfer coefficients in continuous and static casting processes: genetic algorithms [16–19], heuristic search [20–21], neural networks [22–24] and swarm intelligence algorithms [25–26]. Particularly, over the last years, improvement on evolutionary computation introduced many new approaches and absorbed metallurgy as the latest achievement of applications. It can be expected, as computer technology evolves, that the biological inspired metaheuristics in metallurgy applications will be more effective and will achieve more widespread use [27–34].

These algorithms are designed to mimetically describe some biological approach and are usually designated by meta-heuristics, where meta is the biological abstraction and heuristics are the techniques used to search any solution. In this context, other techniques based on neuron structures (Artificial Neural Networks), evolution concepts (Evolutionary Strategy and Genetic Programming), Swarm Intelligence (Bee and Ant algorithms) and immunology theories would be considered. The last one provided some meta-heuristics designated by artificial immune systems (AIS), which is still narrowly exploited to unravel complexities in metallurgy optimization problems. This last metaheuristics will be adopted in the present study, i.e. an optimized (opt) version of the artificial immune network (aiNet) algorithm, called as opt-aiNet algorithm. The application of AIS for determining "*a*" and "*m*" coefficients from the h_i function has not yet been performed, to the best knowledge of the authors. The closest work to the proposed analysis was carried out by Hetmaniok et al. [35], in which the authors applied an approach of AIS, named Immune Recruitment Mechanism, to a condition of one-dimensional solidification of a pure substance, with h_i approximated to constant values applied in three periods of time. Considering industrial processing conditions, as-cast products are made from alloys and modeling h_i as step function is far from the reality of a transient heat flow regime associated with the solidification of alloys, mainly for foundry processes involving chilled molds.

The aim of the present work is to determine the transient heat transfer coefficient at the casting/mold interface during two-dimensional inward solidification of Al-1.5 wt.%Fe alloy castings in chilled molds with Cartesian and Cylindrical geometries. In order to apply the inverse solution method, measurement of cooling curves within the metal will be carried out and used as input data into a numerical heat transfer model, based on the finite difference method, which will be used to compute the temperature field within the casting during the solidification process. The developed opt-aiNet algorithm is aimed to speed up the search for the heat transfer coefficient that minimizes the difference between simulated and experimental thermal profiles. The search is based on the integration between a hypermutation operator, which is introduced to spread antibodies clones along the entire search space, and a selection procedure called suppression, which performs local and global search relating each antibody in the population to set a subnet with a view to selecting local best solutions following a general ranking classification of the global antibodies that will survive for the next iteration.

2. Experimental procedure

Two solidification apparatuses (Fig. 1) were designed to *in situ* melt the alloy by a set of electrical resistances. After achieving the desired melt superheat, they are switched off and water starts flowing to extract heat only through the chilled faces of the molds.

The molds consisted of square and circular tubes, made of low carbon steel (SAE 1020), about 4 mm thick, 200 mm height, and having inner dimension of 70 mm (both sides and diameter, respectively). In order to obtain a uniform *finish* across the chilled surfaces in contact with the molten alloy, a 1200 grit SiC paper was used to grind the surfaces.

The castings were transversally sectioned, ground and etched with an acid solution to reveal the macrostructure (Poulton's reagent: 5 mL of H_2O; 5 mL of 48% HF; 30 mL of HNO_3; 60 mL of HCl). As shown in Fig. 1, columnar grains have prevailed along the cross sections, roughly