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The Sensibility of Thermophysical Property Data for Simulating Casting Processes[1]

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The numerical simulation of casting processes is finding a steadily growing acceptance in the foundry industry worldwide. Advanced computer technologies like MAGMASOFT® have turned out to be powerful tools for continuous process optimization. The availability of accurate thermophysical data for all material groups in the whole casting system is a very important aspect in this context, as the simulation results used to analyze the casting process are very much dependent on the material data applied. Especially with sand mold materials, the definition of thermophysical properties becomes more complicated, as they exhibit a nonreversible behavior during the process due to the thermal decomposition of the binder materials and the evaporation of the water contained in the sand. Hence, the cooling power of the mold will be stronger during the heating cycle at the beginning of the process and weaker at the end when the system is cooling again. For iron castings, showing a solid-state phase transformation after an extended cooling time in the mold, this aspect may become very important. This paper gives an insight into the required accuracy of the thermophysical properties by analytical and numerical methods, using the MAGMASOFT® simulation code.

KEY WORDS: casting simulation; iron castings; molding sand; nonreversible thermal behavior; thermophysical properties.

1. INTRODUCTION

The numerical simulation of casting processes has become a widely used tool in the foundry industry, leading to a better understanding of the filling and solidification processes and, consequently, to an obvious improvement

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in foundry practice. Accurate thermophysical property data for the whole casting system are needed for reliable simulation results. In this work, we will focus mainly on material data for molding sands, because they reveal, in contrast to the casting alloys, a very special, nonreversible behavior with the applied thermal treatment in a casting process.

Only a few publications deal with the topic of the measurement of different molding sand characteristics [1–6]. However, they generally do not consider both the heating and cooling cycles. But due to their nonreversible thermal behavior, the sand mold materials will exhibit different cooling power during heating compared to cooling. This aspect becomes extremely interesting for solid-state transformations, taking place after longer cooling times, e.g., in iron casting simulations.

2. THERMOPHYSICAL DATA OF MOLDING SAND

Sand mold materials do not only contain the pure sand but are also generally bonded, e.g., with bentonite and water for the case of the widely used green sand, or with, e.g., some chemical resin bond. Due to the moisture content of air, the chemically bonded sands are also not completely dry but may contain a water content of about 0.2%.

During the casting process, the temperature of the sand mold increases at first, leading to the monotonic temperature dependent change of the material properties density ρ, thermal conductivity λ, and specific heat capacity c_p. At a temperature of about 100°C, the water contained in the sand reaches its point of transition from the liquid to the gaseous phase. At this temperature, all the thermal energy coming from the casting process has to be supplied for the evaporation process until the transformation is complete, i.e., the sand temperature will not rise before all the water has evaporated. Consequently, this transformation leads to a strong peak in the apparent specific heat capacity curve and to an increased cooling power of the mold in the casting system. The vapor will migrate through the sand mold, away from the metal–mold interface, until it reaches colder areas where condensation will take place [5]. The temperature increases further during the continued casting process, and when temperatures of 100°C or above are reached in those areas, the process sequence of vaporization, transport of the vapor to colder areas, and condensation will be repeated.

Following a further increase of the sand temperature, we find a second effect other than the evaporation of water; at temperatures of about 300 to 600°C, the binder in the sand mold will start its thermal degradation, leading to additional changes of the thermophysical properties of the molding material.

During cooling of the casting system, the molding sand will now exhibit a different temperature dependent behavior of the material properties compared to the heating process. The water has been evaporated and may now only partly condense again, and also the binder has lost its original properties. Experimental investigations have shown that the thermal conductivity of the mold will decrease with a reduced water content [6]. Consequently, this effect must also be expected for the cooling process of the sand, and it can be assumed that the other thermal properties will change in a similar way as well, due to the loss of water and the decomposition of the binder. Additionally, the apparent specific heat capacity curve will exhibit no peaks according to any thermal reaction or transition. Figure 1 indicates the estimated change of thermophysical properties for green sand.

The heat flux dQ/dt through the mold away from the hot metal surface can be described by the following equation:

$$\frac{dQ}{dt} = \frac{1}{\sqrt{\pi}} \sqrt{\lambda \rho c_{\mathrm{p}}} \frac{\Delta T}{\sqrt{t}} \tag{1}$$

where t = time and ΔT = temperature difference between sand and environment [7].

If we look at the heat diffusivity $\sqrt{\lambda \rho c_{\mathrm{p}}}$, our assumptions for the changes in the sand properties during the cooling process result in a decrease to about 2/3 of the primary heat diffusivity values. Integration of Eq. (1) and comparison with the case of an unmodified heat diffusivity for the cooling process will yield a difference in cooling power of about 10%.

3. NUMERICAL SIMULATION

The numerical simulation of casting processes offers the foundryman a variety of features to be used for a detailed process analysis, giving insight into how the variation of different parameters may influence the casting results.

To investigate the effect of a varying cooling power of the molding sand due to the change of its material properties during heating and cooling, a new algorithm concerning the solidification simulation has been implemented for evaluation purposes. A simple cubic test geometry with an edge length of 100 mm was chosen for the solidification simulation tests of a ductile iron alloy. A sand mold with an edge length of 200 mm was assumed, and control points have been defined in the casting and in the sand at various distances from the metal-mold interface to monitor the

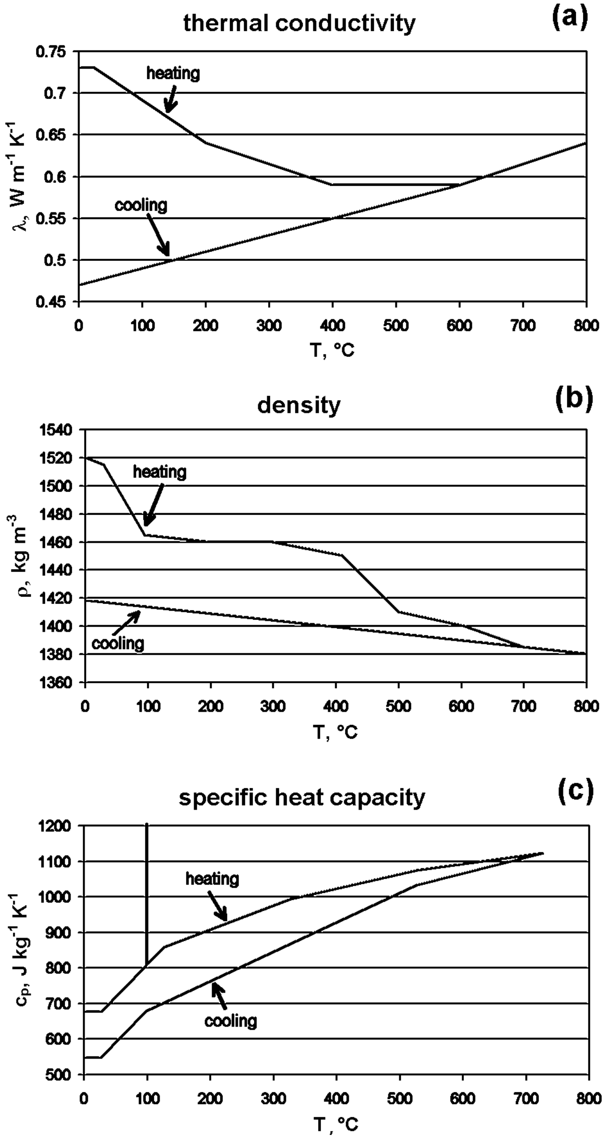

Fig. 1. (a) Thermal conductivity, (b) density, and (c) specific heat capacity of green sand as a function of temperature for the heating and cooling process as used for the simulation (with an estimated decrease of the thermophysical properties during cooling).

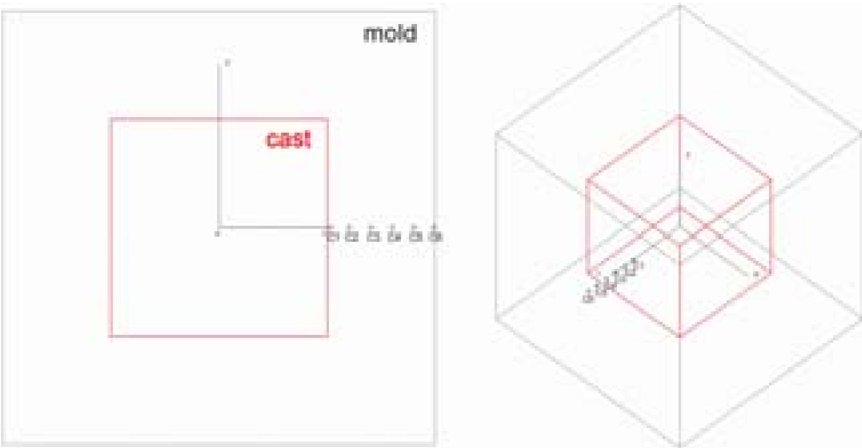

Fig. 2. Geometry and "virtual measuring" (C1 to C6) points for the solidification simulation.

calculated temperature field during the simulation process (Fig. 2). Different thermophysical green sand properties for the heating and cooling process of the mold, according to Fig. 1, have been applied during the simulation. Four different test simulations were carried out with the MAGMASOFT® simulation software, using a special iron module [8]; one of these simulations takes into account a change of all the thermal properties together during heating and cooling, and the others consider the thermal conductivity, the density, and the specific heat capacity separately. These simulations have been compared to a "standard" simulation, not taking into account any variation of sand properties for the heating and cooling cycle.

4. RESULTS

The results of the simulations will be discussed through evaluation of the temperature curves in the sand mold and the microstructural and mechanical properties of the casting, calculated for long cooling times.

Generally, compared to a "standard" simulation, the consideration of altered material properties during the cooling process only causes a minor reduction of the solidification time of the iron casting. The influence of the variation of density is smallest of the single thermal properties, leading to a reduction of solidification time of only 0.15 s (0.0123%). The influence of the specific heat capacity is largest with a reduction of solidification time of

2.95 s (0.242%). The single influences of the thermal properties sum up to a total of 3.93 s (0.322%) reduction of solidification time, for the case that all properties are taken into account.

If we consider the extended cooling period after solidification when the phase transformation takes place, the influence of a difference in the sand properties between the heating and cooling process becomes somewhat more significant (Fig. 3). The largest influence of the alteration of the sand data during the cooling cycle is detected in the immediate vicinity of the interface after cooling times of about 80 to 100 min. In case all thermal properties are taken into account, an average increase of sand temperature or decrease of cooling time of about 15% is detected due to the reduced cooling power of the mold. This corresponds to the estimated value of about 10%. If we look at the single properties, the density has the smallest influence with average temperature differences of about 5 to 10°C. In this case, the temperatures are lower compared to the "standard" calculation, which is due to an obviously increased cooling power with lowered density values during the cooling process, while the separate variation of the thermal conductivity or the specific heat capacity during the cooling process leads to a decreased cooling power with an increase of sand temperature of about 30 to 40°C.

The influence of the modified thermal parameters decreases somewhat with increasing distance from the interface. At a distance of 49 mm from the interface, close to the outer side of the mold box, maximum temperature deviations of about 15°C compared to the standard simulation are found.

If we consider that the mechanical properties of a ductile iron casting develop after an extended cooling period, some significant differences can

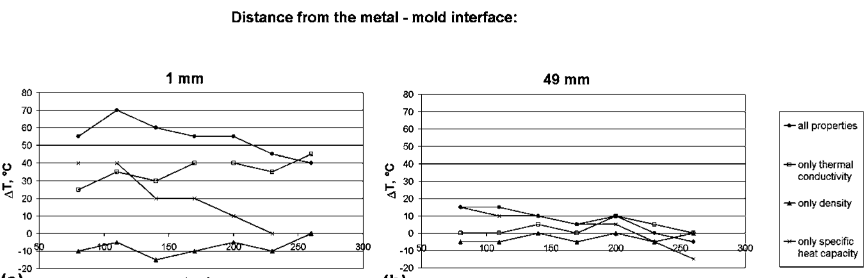

Fig. 3. Temperature differences in the sand mold compared to a "standard" simulation as a function of cooling time for (a) 1 mm distance and (b) 49 mm distance of the "virtual measuring" points from the metal-mold interface.

be noticed due to the change of the material properties during the cooling cycle. The largest influence is found close to the face centers of the cubic test geometry. In these areas, the reduced cooling power of the sand leads to an average increase of approximately 7% of the ferrite content and consequently to the same reduction of the pearlite content (Fig. 4). The mechanical properties are generally reduced by the modified sand data; on the face centers of the cube, the Brinell hardness is decreased by about 9 to 11 HB, the tensile strength by about 20 to 25 MPa (Fig. 5), and the yield stress by about 13 to 15 MPa.

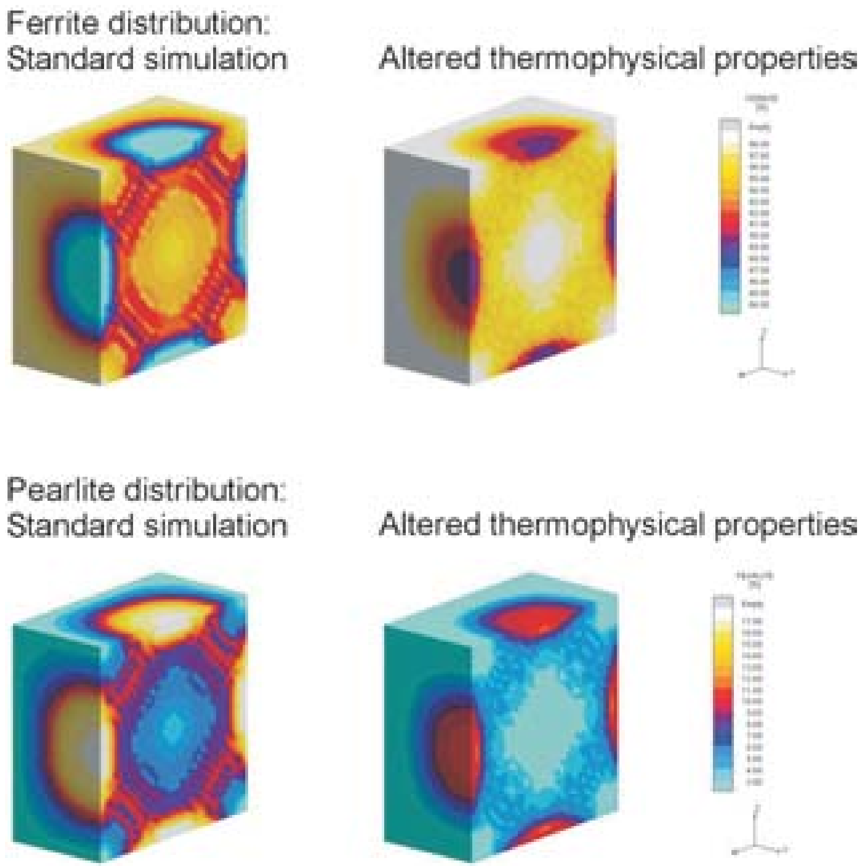

Fig. 4. Influence of the altered thermophysical properties on the microstructural characteristics: increase of ferrite and decrease of pearlite content by a maximum of approximately 7%.

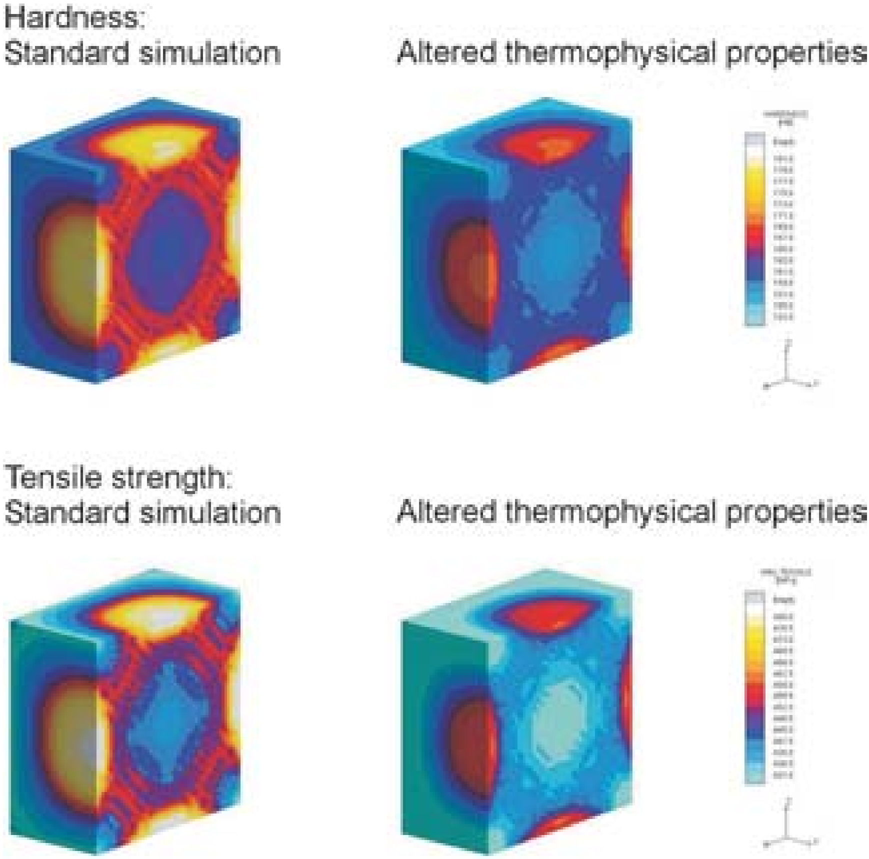

Fig. 5. Influence of the altered thermophysical properties on the mechanical characteristics: decrease of hardness and tensile strength.

5. CONCLUSIONS

The influence of the reduced cooling power of the molding sand during the cooling cycle compared to the heating cycle, resulting from the nonreversible behavior of the thermal properties of the sand, has been investigated in test simulations of a ductile iron casting. The results of the comparison between a simulation, not considering any nonreversible behavior of the sand properties, and calculations, taking into account altered thermophysical properties of the sand during cooling, indicate different influences on the casting properties.

If we consider only the solidification of the iron casting, the effect of the altered thermophysical data is negligible. Solidification times are changed by a maximum of about 4 s (0.3%).

However, if we look at the subsequent cooling, including the solid-state phase transformation, the influence of the reduced cooling power of the sand mold increases, leading to significant changes of the mechanical and microstructural properties of the cast iron.

It can therefore be concluded that it depends on the point of interest whether the influence of the nonreversible thermophysical sand data can be neglected in the simulation. For the case where only the casting behavior during filling and solidification is of interest, any nonreversible behavior can obviously be ignored. If, however, material properties developing after longer cooling times are to be considered, the alteration of the sand data should be taken into account.

It should be noted that a rather simple algorithm has been used for the test calculations, giving only a general and qualitative overview. A more detailed approach will have to be implemented to give more accurate and quantitative results. The resulting changes of microstructure and mechanical properties in the range of about 5 to 10% indicate that it will be worthwhile to spend these efforts not only on the numerical part, but also on a more accurate determination of the nonreversible behavior of the molding sand properties.

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