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NUMERICAL SIMULATION OF THE SOLIDIFICATION OF A STEEL RAIL-WHEEL CASTING AND THE OPTIMUM DIMENSION OF THE RISER

NUMERIČNA SIMULACIJA STRJEVANJA JEKLENEGA KOLESA ZA VAGONSKO KOLO IN OPTIMALNA VELIKOST

Vladimir Grozdanić
University of Zagreb, Metallurgical Faculty, Aleja narodnih heroja 3, 44103 Sisak, Croatia

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In this paper we investigate the solidification simulation of a steel rail-wheel casting in a sand mould. The mathematical model is solved numerically using the finite-difference implicit-alternating-direction method and the program is written in the FORTRAN 77 computer language for a DX-4S personal computer. On the basis of the simulation it is possible to study computer-aided casting design, which involved changing the width of the web that connects the flanged rim to the hub of the wheel. It is also possible to determine the optimum height of the classical riser attached to the top of the wheel hub to avoid casting defects and, with a high degree of confidence, produce a sound casting.

Key words: simulation, solidification, steel rail-wheel casting, computer-aided casting design, optimum height of riser

V modelu opisujemo simulacijo strjevanja v peščeni formi. Matematični model je numerično rešen z uporabo metode končnih razlik z implicitno alternacijo smeri, napisano v jeziku FORTRAN 77 za osebni računalnik DX-4S. Simulacija omogoča računalniško podprto načrtovanje s spremembo širine mreže, ki povezuje obod s pestom kolesa. Omogoča tudi določitev optimalne višine napajalnika, ki prepreči nastanek livarskih napak in izdelkov zdravih ulitkov z veliko stopnjo verjetnosti.

Ključne besede: simulacija, strjevanje, ulitek za vagonsko kolo, računalniško podprto načrtovanje, optimalna višina napajalnika

1 INTRODUCTION

Being able to numerically simulate the solidification of a steel rail-wheel casting has great practical importance because it is possible to see the heat transfer and solidification of a casting using a computer. On the basis of this it is possible to use computer-aided casting design to avoid casting defects, and in this way the casting is not required. The casting defects in a wheel are the shrinkage cavity and the porosity. They usually appear during casting and solidification in the flanged rim connected to the hub through a web. In practice these defects are usually eliminated by placing chills or sand with greather thermal diffusivity than the silica sand, e.g. chromitte sand, around the fanged rim. The second way is to place between the hub and flanged rim of the wheel an exothermic padding, which makes it possible to feed the rim from the hub. The third possibility, which was investigated in this paper, is computer-aided casting design, involving a change of the width of the web. This possibility is the most economic in practice, and relatively easy for the numerical simulation of the wheel's solidification. The casting defects may also appear in the hub, however, they can be eliminated by changing the height of the riser, which is placed on the top of the wheel hub.

It is important to emphasize that the casting was bottom gated through the hub. This arrangement preserved the radial symmetry of the casting and facilitated the use of a two-dimensional simulation to represent the three-dimensional heat transfer and solidification.

2 MATHEMATICAL MODEL

The mathematical model of the solidification of the steel rail-wheel casting, which is shown in **Figure 1**, is based on the two-dimensional Fourier's partial differential equation of heat conduction[1]:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (1)$$

with adequate initial and boundary conditions.

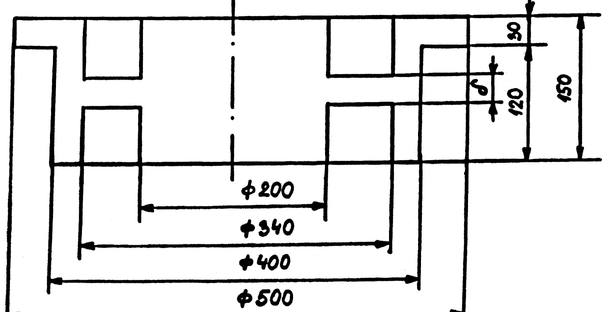

Figure 1: Schematic presentation of the steel rail-wheel casting
Slika 1: Shema ulitka za vagonsko kolo

Initial conditions. At time t = 0 the temperature of the mould and its outer surface are T_s, the temperature of the metal in the mould is equal to the pouring temperature T_p, and the surface of the riser is T_R. The initial temperature distribution on the boundary surfaces is obtained on the basis of the thermal balance of the system[2]:

$$T_i = \frac{\rho_m c_{pm} T_p + \rho_s c_{ps} T_s + \rho_m \Delta H_f}{\rho_m c_{pm} + \rho_s c_{ps}} \quad (2)$$

Boundary conditions. The outer surface of the mould is at a constant temperature T_s, as is the riser T_R. On the mould-metal contact surface the continuity of thermal flow exists and boundary conditions of the fourth kind [3] are valid:

$$k_m \frac{\partial T_m}{\partial n} = k_s \frac{\partial T_s}{\partial n} \quad (3)$$

Thermal properties. The thermal properties of the mould and the metal are temperature dependent and they are taken from reference[4].

Latent heat of fusion. The latent heat of fusion incorporated in the equation for the specific heat of metal (method of modified specific heat):

$$\Delta H_f = \int_{T_s}^{T_l} (c^*_p - c_p) dT \quad (4)$$

The latent heat of fusion is equal 271 kJ/kg[4] and is evolved over a temperature range of 38 °C. The liquidus and solidus temperatures for low-carbon cast steel with 0.2 %C are determined from the equilibrium diagram Fe-C [5] and are equal: liquidus at 1516,5 °C and solidus at 1478,4 °C. The heat that evolves during the peritectic reaction[(6)]:

$$\delta + 1 \rightarrow \gamma \quad (5)$$

This quantity of heat is equal to 81 kJ/kg and evolves in the temperature range from 1481 °C to 1491 °C[4].

3 IMPLICIT ALTERNATING DIRECTION METHOD

The mathematical model for the solidification of a steel wheel is numerically solved by means of the implicit alternating direction method[7]. The basic characteristic of this method is that the time interval is divided into two equal time steps ($\Delta t/2$). In the first step the space derivation in equation (1) is approximated implicitly in z, and explicitly in the r direction. For the second step $\Delta t/2$ the procedure is reversed. It can be shown with the equations:

$$\frac{T^{n}_{i,j-1} - 2T^{n}_{i,j} + T^{n}_{i,j+1}}{(\Delta r)^2} + \frac{T^{n}_{i,j+1} - T^{n}_{i,j-1}}{2r_j \Delta r} + \frac{T^{*}_{i-1,j} - 2T^{*}_{i,j} + T^{*}_{i+1,j}}{(\Delta z)^2} = \frac{1}{a_{i,j,n}} \frac{T^{*}_{i,j} - T^{n}_{i,j}}{\Delta t / 2} \quad (6)$$

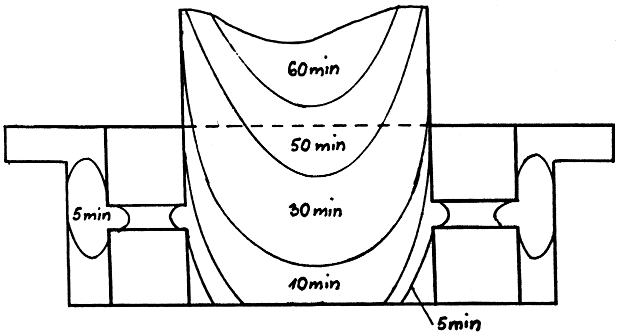

Figure 2: Shift of isosolidus (1478 °C) in the steel rail wheel with a web width of δ = 20 mm and a riser height of 100 mm

Slika 2: Premik izosolidusa (1478 °C) v jeklenem vagonskem kolesu s širino mreže δ = 20 mm in z napajalnikom, visokim 100 mm

$$\frac{T^{n+1}_{i,j-1} - 2T^{n+1}_{i,j} + T^{n+1}_{i,j+1}}{(\Delta r)^2} + \frac{T^{n+1}_{i,j+1} - T^{n+1}_{i,j-1}}{2r_j \Delta r} + \frac{T^{*}_{i-1,j} - 2T^{*}_{i,j} + T^{*}_{i+1,j}}{(\Delta z)^2} = \frac{1}{a_{i,j,n}} \frac{T^{n+1}_{i,j} - T^{*}_{i,j}}{\Delta t / 2} \quad (7)$$

where $a_{i,j,n}$ is the thermal diffusivity in the net point (i,j) at temperature $T^n_{i,j}$ at the beginning of the time step for the mould and the metal.

A system of simultaneous linear algebric equations for general and special cases in the system casting-mould is obtained, which has a tridiagonal form, and is solved by the Gauss-Jordan method of elimination[8]. The algorithm obtained is written in the FORTRAN 77 computer language and is solved on a DX-4S personal computer.

4 RESULTS AND DISCUSSION

For the numerical solving of the partial differential equation of heat conduction a space step of $\Delta r = \Delta z = 5$ mm and a time step of $\Delta t = 5$ s are used. The initial temperature of the mould is 25 °C, the temperature of the melt is 1580 °C, and the temperature on the mould-casting and mould-riser contact surfaces is 1538 °C.

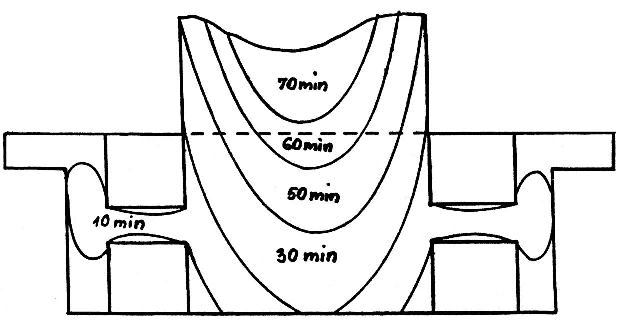

Figure 3: Shift of isosolidus (1478 °C) in the steel rail-wheel with a web width of δ = 30 mm and a riser height of 150 mm

Slika 3: Premik izosolidus temperature (1478 °C) v jeklenem vagonskem kolesu s širino mreže δ = 30 mm in z napajalnikom, visokim 150 mm

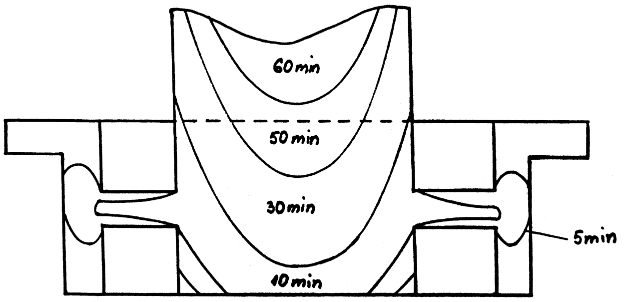

Figure 4: Shift of isosolidus (1478 °C) in the steel rail-wheel with a web width of δ = 30 mm and a riser height of 100 mm
Slika 4: Premik izosolidusa (1478 °C) v jeklenem vagonskem kolesu s širino mreže δ = 30 mm in z napajalnikom, visokim 100 mm

The simulation is performed for wheels that have different widths of the web that connects the flanged rim to the hub of the wheel. In **Figure 2** is a wheel with a web width of δ = 20 mm, where the casting defects appear.

It was concluded that a web width of δ = 30 mm was satisfactory from the viewpoint of feeding of the flanged rim from the hub of the wheel. To avoid casting defects (shrinkage cavity and porosity) in the hub, a simulation is performed for wheels on a hub with risers of different heights. By changing the height of the riser the point where the solidification finishes is established. In the case of a riser with a height equal to the height of the hub, the solidificaton finished in the riser immediately above the hub in a time of 70 min, as illustrated in **Figure 3**.

But, from the viewpoint of economy, the optimum solution is a riser with a height of 2/3 the height of the wheel hub, which is illustrated in **Figure 4**. In this case the solidification finished in the riser in a time of 60 min.

Consequently, with a change in the width of the web it is possible to influence the casting's design. At the same time, with the correct selection of riser height, it is possible, with a high degree of confidence, to produce a sound casting.

5 CONCLUSION

In this paper the solidification of a low-carbon steel rail wheel is numerically simulated. This is a typical example of casting a relatively complex geometry, a common occurrence in steel foundries. Although the thermophysical properties of the material in the observed system depend on the temperature, the simulation is performed on a DX-4S personal computer, whereas previously it was performed on large systems. On the basis of the simulation it is possible to determine the shift of the isosolidus in the casting, the solidification time, and the point where the casting defects occur. With adequate design and with the correct riser height it is possible, with a high degree of confidence, to produce a sound rail-wheel casting.

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Abbreviations used:

a - temperature conductivity
c_p - specific heat at constant pressure
ΔH_f - latent heat of fusion
k - thermal conductivity
n - vertical direction
r - space coordinate
t - time
T - temperature
z - space coordinate