Modelling of phenomena in solid state for the steel casting cooled by liquid

A. Kulawik
Department of Mechanical Engineering and Computer Science, Czestochowa University of Technology
Dabrowski st. 73, 42-200 Czestochowa, Poland
Corresponding author: e-mail: adam.kulawik@icis.pcz.pl
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Abstract

In this paper a mathematical model of cooling process for steel castings is presented. Effect of convective motion of the coolant on material structure after cooling process is investigated. Mathematical and numerical model based on Generalized Difference Method for axisymmetric elements is used. To solve the Navier-Stokes equation the characteristic based split scheme (CBS) has been applied. The solution of the heat transport equation with the convective term has been obtained by a stabilized meshless method. To determine of the phase transformation the macroscopic model built on the basis of Time Temperature Transformation diagrams for continuous cooling of medium-carbon steel has been used. The temporary temperature fields, the phase transformation, thermal and structural strains for the cooled element and the fields of temperature and velocity for the coolant have been determined.

Keywords: heat treatment, phase transformation, convection, cooling of liquid coolant

1. Introduction

In casting processes the appropriate control of the cooling process of steel parts is important. Through this treatments the right phase composition is obtained. The control of these phenomena yields the desired mechanical and physical characteristics used in the design of machines and equipment. Predicting the characteristics of the material is particularly important in the casting process. Phase transformations in such the process could lead not only to the improvement of the properties of the workpiece, but also can cause significant temporary stresses leading to cracking of the material [1, 2].

The phenomena of cooling of castings process are difficult to model numerically because of their complexity and mutual coupling. The most important of these phenomena include the thermal, mechanical and phase transformations.

The modelling of the cooling castings process should devote significant attention to the model of thermal phenomena, because their quality is connected with the final results. In the modelling of the thermal phenomena it is usually assumed that the cooling conditions are approximated by the appropriate boundary conditions, with more or less closer to the real process conditions. However, this approach, especially in the modelling of liquid cooling processes, may lead to a large error of approximation. This occurs when the coolant is liquid, and also for geometrically complex parts of machines. The identical cooling conditions for all boundaries are unacceptable. The effects of gravity and the forced movement of the coolant cannot be ignored. Therefore, the model of heat transport for heat treatment processes should take into account the movements of the liquid cooling [3,4].

In the modelling phenomena of a cooling process, it is important to take into account the phase transformations. The paper presents the macroscopic model based on an analysis of TTT diagrams. Analysis of these diagrams allows to determine final parts of structures in cast element [1].

2. Heat transfer model

In presented paper a model of heat transfer for the coolant and the cooled axisymmetric element in the cooling process is described. The temperature fields are determined on the basis of
the heat transfer equation with convection term, which for axially symmetric space take the following form:

\[
\frac{\lambda}{r} \frac{\partial^2 T}{\partial r^2} + \frac{\partial}{\partial z} \left( \frac{\lambda}{r} \frac{\partial T}{\partial z} \right) - \rho C \left( \frac{\partial V}{\partial r} + V \frac{\partial}{\partial z} \right) + \rho C \frac{\partial T}{\partial t} = q_v
\]

where \( T \) [K] is the temperature, \( t \) [s] is the time, \( \lambda = \lambda(T) \) [W/mK] is the thermal conductivity, \( \rho \) [kg/m³] is the density, \( C \) [J/kgK] is the specific heat, \( V \) [m/s] is the velocity, \( q_v \) [J/m³s] is the volumetric heat source, \( r \) – is a distance from the symmetry axis.

In the thick-walled castings during cooling process occur the temperature changes induced particularly by the pearlite transformation. In equation the latent heat of the phase transformation is introduced.

Because the presented system matrix is highly asymmetric, it was solved by using the biconjugated gradients method. In this iterative method was used the Jacobi preconditioner [5].

3. Model of fluid motion

In modelling of the cooling process, especially when the coolant is a liquid, should be considered the behavior of the cooling medium. In this process the large changes in the intensity of movement are caused by convection or forced movement of liquid. The basis for the mathematical description of this movement is the Navier-Stokes equation with the free convection term.

The Navier-Stokes equation is defined as follows [6]:

\[
\begin{aligned}
\rho \left( \frac{\partial^2 V}{\partial r^2} &+ \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} \right) - \frac{\partial p}{\partial r} = \rho \left( \frac{dV}{dt} + V_r \frac{\partial V}{\partial r} + V_z \frac{\partial V}{\partial z} \right) \\
\rho \left( \frac{\partial^2 V}{\partial r^2} &+ \frac{1}{r} \frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} \right) - \frac{\partial p}{\partial r} = \rho \left( \frac{dV}{dt} + V_r \frac{\partial V}{\partial r} + V_z \frac{\partial V}{\partial z} \right)
\end{aligned}
\]

where \( \frac{dV}{dt} \) is the velocity component in the \( r \) or \( z \)-direction, \( \frac{\partial p}{\partial r} \) is the pressure, \( \frac{\partial p}{\partial r} \) is the acceleration component in the \( z \)-direction, \( \beta \) [1/K] is the volumetric thermal expansion coefficient, \( T_{ref} \) [K] is the reference temperature.

The Navier-Stokes equation (2) is solved only in a region filled with the coolant by means of a characteristic based split (CBS) scheme [2-4]. In this method an auxiliary velocity field \( \mathbf{V}^* \) is introduced to uncouple equations (2) and (3).

\[
\frac{V_r^* - V_r}{\Delta t} = \frac{\mu}{\rho} \left( \frac{\partial V_r}{\partial r} + \frac{1}{r} \frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} \right) - \left( V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z} \right)
\]

where \( V_r^* \) is the velocity component in the \( r \) or \( z \)-direction for the previous time step.

The final velocity field is corrected by the pressure increment so that is divergence free:

\[
V_r = V_r^* - \frac{\Delta t}{\rho} \frac{p_{rs}}{\partial r}
\]

By taking the divergence of (5) the following Poisson equation for the pressure is obtained:

\[
\frac{\Delta t}{\rho} \left( \frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} + \frac{\partial^2 p}{\partial z^2} \right) = \frac{\partial V_r}{\partial r} + \frac{\partial V_r}{\partial z}
\]

The final velocity field is corrected by the pressure increment:

\[
V_r = V_r^* + \frac{\Delta V_r}{\Delta t} = \frac{\Delta t}{\rho} \left( p_{rs} \right)
\]

The momentum and Poisson equations were solved by GDFM using an implicit time scheme for \( i \)-th node of the grid.

4. Model of phase transformations

The Time-Temperature-Transformation (TTT) diagram for C45 steel is used in presented model of phase transformations. The basis for the mathematical description of this process is the equation of Avrami for cooling process [1,2,7,8]:

\[
\eta_j(T) = \min \left\{ \eta_{j,\min}, \eta_j - \sum_{i} \eta_i \cdot \left( 1 - \exp\left( b(T)^{n(T)} \right) \right) \right\}
\]

where \( \eta_i \) denotes volumetric participation of the austenite, \( \eta_j \) is volumetric participation of the phases created during cooling process, \( \eta_{j,\min} \) is final participation of the ith-phase estimated from the TTT diagram, \( b(T) \) and \( n(T) \) are coefficients depend on the temperature and time \( (t_{in}, t_{of}) \) of the beginning and end of phase transformation.

\[
n(T) = 6.12735 \ln \left( \frac{t_i(T)}{t_{in}} \right), \quad b(T) = \frac{0.01005}{t_{in}^{0.18}}
\]
Participation of created martensite is evaluated on the base of empiric Koistinen-Marburger equation [1,9]:

\[ \eta_i(T,t) = \left( \bar{\eta}_i - \sum_{\eta_{j}} \right) \left( 1 - \exp (-k(M_s - T)) \right), \]

\[ k = -\ln \left( \sum_{\eta_{j}} \right) \left( \frac{M_s - M_f}{M_s - M_f} \right) \]

where: \( M_s \) denotes initial temperature of the martensitic transformation estimated on the base of TTT diagram.

From the method of calculation of phase fractions by using TTT diagrams follows that timeline in the diagram does not represent the actual time of continuous transformation. Real time transformation is determined from the equation [1]

\[ t = \sum \Delta t + \sum \Delta t_{corr} \]

where correction time is defined as follow

\[ t_{corr} = t_{i-1} - \left( \frac{-\ln(\eta_i)}{b(T)} \right) \]

The kinetics of the phase transformations during cooling strongly depend on austenisation temperature, therefore model, which exploits two TTT diagrams for C45 steel (880 [°C] and 1050 [°C] austenisation temperature) was developed [10,11]. The constructed application uses a pairs of corresponding points of both TTT diagrams. Each of the points located at the curve determining the end of transformation must have the maximum value of transformation.

Increment of the temperature and phase transformations dependent strain \( \Delta e^{T,\phi} = \Delta e^{T} + \Delta e^{\phi} \) is obtained from following relation:

\[ \Delta e^T = \sum \alpha_i(T) \eta_i dT, \quad \Delta e^{\phi} = \sum \gamma_i(T) d\eta_i \]

where: \( \alpha_i \) is linear thermal expansion coefficient of the ith-phase, \( \gamma_i = \delta V_i/(3V) \) denotes coefficient of volume change during ith-phase transformation.

5. Examples

In the paper the calculation for the cooling axisymmetric element was presented. The dimensions of the steel element are \( r=0.04 \) [m], \( h=0.06 \) [m], the radius of the container with the coolant is 0.12 [m], height is 0.12 [m]. The effect of coolant motion on distribution of bainite, martensite, thermal and structural strains was investigated. In the presented examples only natural convection is taken into account. Material properties of steel element taken as for C45 steel and for coolant assumed as for liquid sodium. Following initial conditions were assumed: initial temperature of cooled element \( T_{i}=1200 \) [K], initial temperature of coolant \( T_{c}=300 \) [K], ideal contact between element and coolant. Sample results obtained from calculations are shown in figures 2 and 3.

6. Conclusions

Presented model may be used to estimate of kinetics and distribution of phases in the solid state, after solidification process for axisymmetric medium-carbon steel element. The results from this model may be used to prediction of technological conditions for casting process. The solutions of the numerical model of phase transformations, temperature and coolant flow are in good conformity with the reference results (analytical solution, numerical benchmarks and experimental researches).
Fig. 3. The fields of a) ferrite, b) pearlite, c) bainite, d) martensite, e) structural and thermal strain after cooling

References