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A new modelling method for superalloy heating in resistance furnace using FLUENT

Zhenglong Fu, Xinhong Yu *, Huaili Shang, Zhenzhen Wang, Zhiyuan Zhang

Department of Material, Northwestern Polytechnical University, Xi'an, 710072 Shaanxi Province, China

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ABSTRACT

The simulation of heating process of superalloys is of great significance to predict the temperature distribution and equilibration time of workpiece. In this paper, a new method was proposed to simulate the heating process of superalloy billet in resistance furnace for all strategies of thermal schemes using commercial CFD software FLUENT. In the model, numerical analysis of natural convection and surface thermal radiation in a chamber electric furnace having heat-conducting solid walls of finite thickness with a heat source located in the side and top walls of the furnace in conditions of convective heat exchange with environment has been carried out, and such conjugate heat transfer process was solved by FLUENT solver. Furthermore, a PID methods was proposed to control the energy source of the resistance wires based on FLUENT UDF, in order to regulate the furnace temperature according thermal scheme. This model was validated through temperature measurement experiment in a small chamber resistance furnace. Compared with the measured data, the model was adequate for predicting the temperature profile and equilibration time of superalloy.

1. Introduction

In heat treatment, a workpiece is heated in a furnace to a given time and temperature. The equilibration time is defined as the time for workpiece to reach uniform temperature distribution and equal to the furnace gas temperature.

As we all know, the conductivity of superalloy is lower than steel, and it decrease with the temperature dropping. Besides, the thermal expansion is relatively large. Therefore, the workpiece with large diameter, directly heated in a high temperature furnace, is likely to crack for large thermal stress. To prevent billet cracking as well as avoiding coarse-grain and depletion of alloying elements, the heating of superalloy materials was divided into two stage, preheating stage and heating stage. The temperature under preheating section is usually 750–800 °C, while the temperature under heating stage was usually 1100–1180 °C. The temperature rising rate and equilibration time are two important operating parameters in the heat treatment of metals, which should be regulated strictly based on temperature scheme when heating. At most situations, it is not possible to measure the core temperature of the workpiece. Sometimes, a rules of thumb was used to estimate the equilibration time, namely, a linear relationship was assumed between the equilibration time and the thickness [1]. However, the rules of thumb was not always correct in theory, although it is simple to use. In heat treatment, the electric furnace became common heating equipment for its precise temperature control property and low possibility of contamination to workpieces. Thus, modelling the heating process for superalloys in the resistance furnace is of great significance to predict the temperature distribution and control the microstructure of workpiece.

In resistance furnace, the heat generated by the resistance wires was transferred to the other walls by rays. When the rays pass through the transparent or semitransparent medium, a small portion of radiation is absorbed by the medium, and much of the rest radiation is absorbed by the solid surface. The rays absorbed by the solid surface are subsequently translated into heat flux and then conducted to the whole solid zone. As a result, the temperature of solid zone as well as the medium rise. In return, the solid surface and the medium will emit rays more intensely after temperature rising. Furthermore, the convection heat transfer happens at the interface between the gas and solid wall, and varies with the temperature of the gas and surface. In general, the change of the energy source will cause the variation of the radiation, gas flow, heat convection, and heat conduction. Such heat transfer process could be classified as conjugate natural convection combined with thermal radiation and heat conduction in a three-dimensional enclosure with variable heat sources.

* Corresponding author.
E-mail address: xhyu@nwpu.edu.cn (X. Yu).

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Constant effort has been contributed to the coupling analysis of natural convection, thermal radiation, as well as heat conduction [2–5]. Colomer et al. [2] have researched the interaction of radiation and natural convection in both transparent and participating media in a three-dimensional differently heated cavity. Albanakis and Bouris [3] have investigated the three-dimensional coupled heat transfer of turbulent mixed convection, surface radiation and conduction for an asymmetrically heated cube exposed to turbulent external flow through numerical analysis. Xin et al. [4] have numerically studied coupled heat transfer including natural convection, radiation in an air-filled cubical cavity, and heat conduction in solid walls by means of DNS using spectral methods. It found that the radiation has a great effect on the natural convection. Kuznetsov and Sheremet [5] have numerically analyzed 3D conjugate natural convection and radiation on the basis of the Rosseland approximation in enclosures. Martyushev and Sheremet [6,7] researched transient coupled heat transfer of natural convection, radiation and conduction in a cubical enclosure having heat-conducting solid walls of finite thickness and a heat source with constant heat generation rate located at the bottom of the cavity in conditions of convective heat exchange with an environment.

In this paper, a new method was proposed to simulate the heating process of superalloy workpiece in resistance furnace for all strategies of thermal schemes using commercial CFD software FLUENT. In the model, numerical analysis of natural convection and surface thermal radiation in a chamber electric furnace having heat-conducting solid walls of finite thickness with a heat source with variable heat generation rate located in the side and top walls of the furnace in conditions of convective heat exchange with environment has been carried out. Such complex conjugate heat transfer model was solved by FLUENT solver. Instead of paying attention to the interactions of each heat transfer mechanism and solution method of the governing equations, this model mainly focus on heat generation rate of energy source as well as the transient heat conduction inside the workpiece. In order to regulate the furnace temperature according thermal scheme, a PID methods was proposed to control the heat generation rate of the resistance wires based on FLUENT UDF—user defined function in FLUENT. During calculating process, the calculation results of the three latest time steps are sampled to control the input power according to PID feedback principle adopted by resistance furnace.

2. Heat transfer theory

In resistance furnace, heat conduction happens in the solid zone. The fluid flow happens in the furnace gas, while the radiation and convection heat transfer happen at the interface of the solid surface and the gas. The heat transfer process was shown in Fig. 1. In the solid zone, the temperature field is solved by transient heat conduction equation. While in fluid zone, the temperature field, velocity field is solved by continuity equation, N-S equations, as well as energy equation. The radiation transfer equation was defined by DTRM radiation model. As we know, fluid density is related to its pressure and temperature. However, the fluid density mainly depends on its temperature, ignoring the effect of pressure, when it at a relatively low velocity. To make the governing equations easier to converge, Boussinesq model was used to define the gas density. Namely, $\rho = \rho_0(1 - \beta\Delta T)g$. The density ρ of buoyancy term in N-S equations is eliminated by such definition. The buoyancy term in N-S equations finally turns into $(\rho - \rho_0)g \approx -\rho_0\beta(T - T_0)g$, while the density in other equations was regarded as constant. Significantly, such assumption is suitable when density change is small.

In the coupling relations, the interfaces between different zones (solid and fluid) are regarded as the interior face of the whole computational domain. By keeping the heat flux or temperature continuous at the interface, the coupling heat transfer equations are solved, details being found in Ref. [8].

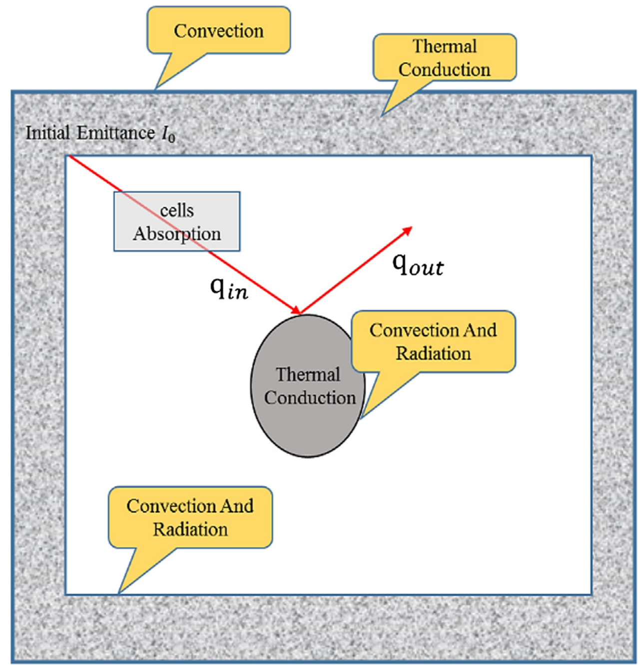

Fig. 1. The diagrammatic sketch of energy transfer process in resistance furnace.

2.1. Heat conduction

The heat conduction mainly happened inside the solid material, and transient heat conduction was govern by:

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + S_h \tag{1}$$

where $h = \int_{T_{ref}}^{T} C_p dT$, ρ are mass density, , λ, C_p are thermal conductivity, and specific heat of the solid material (e.g. the furnace wall, resistance wire, the superalloy) respectively. These thermal properties were defined as functions of temperature. S_h is volume energy source, which was used to define the heat generate rate inside the solid. In the resistance wires, S_h was defined by own developed PID method introduced subsequently.

2.2. Flow and convection

The solution of natural convection heat transfer was a complex process, while the quantity of heat transferred by convection usually makes up only a very small proportion of all. To solve the temperature field of the fluid zone, the flow equations of the furnace gas must be solved in advance. Thus, the continuity equation, N-S equations, and energy equation of furnace gas were needed.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} = 0 \tag{2}$$

N-S equations:

$$\frac{\partial}{\partial t}(\rho v_x) + \nabla(v_x\vec{u}) = \nabla(\mu\nabla v_x) + S'_x \tag{3}$$

$$\frac{\partial}{\partial t}(\rho v_y) + \nabla(v_y\vec{u}) = \nabla(\mu\nabla v_y) + S'_y \tag{4}$$