Applied Thermal Engineering 81 (2015) 168–176

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Temperature field detection model based on the dimensional change during the thermal forging process

Yu-cun Zhang, Xian-bin Fu*, Fu-li Zhang

Yanshan University, Qinhuangdao 066004, China

HIGHLIGHTS

- Temperature field model is established by the moving heat source method.
- The internal temperature of forgings is timely calculated by this model.
- Combining the measured dimension, the heat energy function is further improved.
- The difference of theoretical temperature and simulated temperature is between 0 and 2%.

ARTICLE INFO

Article history:
Received 18 September 2014
Accepted 9 February 2015
Available online 18 February 2015

Keywords:
Thermal forging process
Thermal forgings
Temperature field
Detection model
Heat source function

ABSTRACT

The temperature of large forgings is a critical technological parameter for improving the forming quality. In order to improve the quality of large forgings, the temperature field detection model is proposed in the paper, and the temperature field is influenced by the dimensional change of forgings. Firstly, combining the measured dimension and the measured temperature, the temperature model in the temperature-drop process is established by the two-dimensional unsteady heat conduction method. Secondly, according to the principle of energy conversion, the plastic work in the process of the dimensional change is converted into heat energy. The conversion coefficient between the plastic work and heat energy is described by a function including the dimensional change and temperature. Using the virtual heat source method in the moving coordinate system, the temperature model in the temperature-rise process is obtained. Finally, the forging temperature detection model is established by the superposition of the two temperature model functions. The feasibility of the model is verified by the experiments and the simulations. This model provides a theoretical basis for improving the quality of forgings.

1. Introduction

Large forgings are the critical components in electric power, shipbuilding, metallurgy, heavy machinery and defense industry. The dimension and temperature are crucial factors for improving the forging technology and the quality of forgings during the thermal forging process [1]. Therefore, the temperature field influenced by the dimensional change is significant.

Recently, many scholars, at home and abroad, have carried out a considerable amount of researches on the temperature field influenced by the dimensional change. With the progress of advanced measurement technique in recent years, the experimental data in the hot forming process become available. Guan et al. used the traditional test method of cycle data to obtain the temperature field, and he analyzed the temperature under the same material [2]. Caron et al. investigated variable thermal conduction coefficient based on the forging experiments of hot forgings. He solved the isotropic inverse heat conduction problems and obtained the unsteady temperature field [3]. This traditional test method could obtain a series of temperatures during the hot-forging process, but the traditional method was time-consuming and it needed the high cost of material. Then, the finite element method was used for solving the temperature field during the thermal forming process. The finite element method was applied by coupling the internal forging temperature and dimension in the small and finite unit [4,5]. James et al. utilized the thermal coupling FEM to calculate the temperature field and strain. The compensatory relation between temperature and the dimensional change was analyzed [6]. Compared with the traditional test method, the finite-element

* Corresponding author. Yanshan University, Qinhuangdao City, 066004 Hebei Province, China.
E-mail address: binxf2013@126.com (X.-b. Fu).

http://dx.doi.org/10.1016/j.applthermaleng.2015.02.015
1359-4311/

method could be timesaving. However, the finite-element method could only calculate the internal temperature field of the grid nodes.

In order to fully calculate the internal temperature field, the temperature field influenced by the dimensional change was further studied by the methods of mathematical physics. Xua et al. proposed a theoretical formula of thermal deformation during the thermal forging process. Firstly, he took the thermal performance factor into account in the temperature field of hot-forging [7]. Furthermore, the thermal performance factor was further considered as the shape factor of the larger forgings. Luo et al. improved the traditional calculated formula of thermal deformation. The relation between temperature and the shape factor was obtained through the improved calculated formula [8]. Fan et al. established the one-dimensional thermal conduct model by simplifying the structure of the complex shapes. He obtained the effective thermal conductivity of hot forgings. The transient temperature field was calculated in the forging process [9]. In order to develop the temperature field influenced by the dimensional change, the time factor was further considered. Zhang et al. proposed the multi-scale method of high-order asymptotic, and he coupled the time domain and the temperature field. The temperature field was obtained by this kind of method in the small unit [10,11]. The heat source of hot forging was used during the forging process. Zhang et al. studied the topology optimization law of thermal conductivity. The internal temperature field was further calculated during the thermal forging process, and the internal temperature field contained a heat source [12]. Lu et al. studied the periodic change of the heat source. He established the calculation model of CFD in the temperature field of the heat source. The temperature field of forgings was obtained by this model [13]. Sodoyama Barriosa et al. improved the finite volume method and the gauss integral method in thermal forming temperature field. Two methods solved the direct and inverse problem to evaluate the net heat flux in the hot forning [14]. Compared with the above several kinds of research methods, the methods of mathematical physics could be better used to analyze the temperature field. The above methods mainly researched the temperature field influenced by the internal parameters. The information of the actual measurements should be further considered. Therefore, based on the measured temperature and measured dimension, the temperature field influenced by the dimensional change should be further studied.

In the paper, taking measured dimension and measured temperature as the background, temperature field affected by the dimensional change model is established. The dimensional change and the temperature are connected by virtual hot source method in the moving coordinate system. Combining measured dimension and measured temperature, the conversion relation of heat energy is further improved. The feasibility of the model is verified by experiment and simulation method. This model provides a theoretical basis for improving the quality of forgings.

2. Temperature field model of the temperature-drop process

Temperature during the forging process is influenced by the outside environment, and the thermal radiation, the thermal convection and the direct contact heat transfer accelerate the diffusion of the temperature. Most of the forgings are regularly shaped. This paper takes axial forgings as an example. Because the axial forgings are symmetric, the angle of axial forgings will be not considered. The two-dimensional heat transfer equation is applied to establishing the temperature field model in the temperature-drop process. Combining heat loss under the influence of the outside environment, temperature field model in the temperature-drop process is:

$$\frac{\partial T'(r,h,t)}{\partial t} = \mathrm{Nu}'\left(\frac{\partial^2 T'(r,h,t)}{\partial r^2} + \frac{1}{r}\,\frac{\partial^2 T'(r,h,t)}{\partial r} + \frac{\partial^2 T'(r,h,t)}{\partial h^2}\right) \tag{1}$$

where T' (r, h, t) is the temperature field in the temperature-drop process. Nu′ is the constant, $\mathrm{Nu}' = \lambda'/\rho' c'$. λ is the heat transfer coefficient, ρ' is the mass density, c' is the specific heat capacity.

When the strength of the heat source is zero at the beginning of hot forging, the internal temperature is the same as the surface temperature. So the measured temperature of larger forgings is regarded as the initial condition of the heat-transfer equation. The initial condition is:

$$T'(r,z,t=0) = T_0(r_0,z_0) \tag{2}$$

Boundary conditions of the heat-transfer equation are obtained, taking the environmental temperature as the reference standards. The boundary conditions are shown as follows:

$$\begin{cases} \partial T'/\partial r|_{r=R_\tau} - \varsigma_1[T_1]_\tau = 0 \\ \partial T'/\partial h|_{h=0} - \varsigma_2[T_2]_\tau = 0 \\ \partial T'/\partial h|_{h=H_\tau} + \varsigma_2[T_2]_\tau = 0 \end{cases} \tag{3}$$

where $[T_1]_\tau$ is the measurement of surface temperature in the radial direction, $[T_2]_\tau$ is the measurement of surface temperature in the axial direction. ς_1 is the ratio between the convective heat transfer coefficient and the thermal conductivity. ς_2 is the ratio between the contact heat transfer coefficient and the thermal conductivity, H_τ is the axial dimension, R_τ is the measurement of radius.

Using the separation variable method, the variable T(r, h, t) is separated into $T(r,h,t) = \varphi(h)\phi(r)T(t)$. Eqs. (4)–(6) are derived from Eq. (1). Eqs. (4)–(6) are shown as follows:

$$\partial^2 T(r,h,t)\Big/\partial t^2 + \mathrm{Nu}' s^2 T(t) = 0 \tag{4}$$

$$\phi^2(r) + \phi'(r)\Big/r + a^2\phi(r) = 0 \tag{5}$$

$$\varphi^2(h) + p^2\varphi(h) = 0 \tag{6}$$

where s^2 is the separated variable of the first division segregation; a^2 and p^2 are the separated variables of the second division segregation, and $s^2 = a^2 + p^2$.

Eq. (4) is deduced by the general solution formulas of the differential equation with the constant coefficients. The general solution is:

$$T(t) = A\exp\left(-\mathrm{Nu}' s^2 t\right) \tag{7}$$

where A is the coefficient of the solution. A is determined by a given time t.

According to the Bessel formula and the finiteness of the forging temperature, the general solution of Eq. (5) is solved. The general solution is $\phi(r) = BJ_0(ar)$. B is the coefficient of the solution. $J_0(ar)$ is the zero order Bessel function of the first kind. Using the first boundary condition of Eq. (3), the general solution is further deduced.

$$\varsigma_1 J_0(a_n R_\tau) - a_n J_1(a_n R_\tau) = 0 \tag{8}$$

where a_n is the eigenvalues of Eq. (8), n is the number of eigenvalues, $J_1(a_n R_\tau)$ is the first order Bessel function of the first kind.

Eq. (8) is expressed by normal form. The normal form of Eq. (8) is: