



Theoretical and experimental analysis of electric contact surface hardening of ductile iron



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ABSTRACT

Electric contact surface hardening was based on the application of contact resistance heating between the electrode and work piece, which makes use of the rapid and cooling cycles produced on metals surface without affecting the bulk of the work piece. Surface performance can be enhanced through the phase transformations that take place during the mentioned thermal cycles. In this work, the temperature field of strengthened layer on electric contact strengthening was simulated using ANSYS software; the depth and width of strengthened layer were calculated. Moreover, the effect of main processing parameters on strengthened layer was simulated. Finally, some experiments have been carried out to harden the surface of ductile iron by self-developed electric contact surface strengthening device to verify the simulated results. It is found that the error was controlled in 15% reposefully, which represents the simulated result and experimental results to a certain degree are in good agreement.

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1. Introduction

Ductile irons have advantages for casting manufacture and have good machinability, which are widely used in the manufacture of machine tool beds, cams, pistons, cylinders, etc. [1,2]. However, under severe service conditions their performance and reliability can be limited by various forms of wear [3]. Surface hardening by lasers and electron beams have been used in the modification of surface characteristics. Both of them are the two processes that could achieve localized heating satisfied the industrial requirement. But there are a number of drawbacks of these high power systems that a coating should be prepared to enhance the absorption problems of surface for certain materials on laser hardening and a high vacuum chamber should be required by electron beams [4]. Although high frequency induction hardening was cheaper than lasers and electron beams, but has a lower heating rate, which would result in the formation of coarse microstructure. In this work, localized high intensity electric resistive heating has been studied as a mean of solving these problems. This technology was based on the application of contact resistance heating between the electrode and work piece to form a wear resistant layer on ductile iron. When the rotating work piece is made to pass by an electrode, the surface on the work piece is subjected to a short pulse of sufficient electric current heating, so a rapid technology of surface hardening, surface alloying or coating deposition may be obtained. Tests with steel on

steel showed that this technique can generate a surface layer with a martensitic or quenched microstructure according to the investigation of Batchelor et al. [5,6], and the researchers also studied surface cladding of iron-based powders on steel revealed that a continuous and strongly adhering coating was formed, which Wiemer [7] have got the same conclusion that resistance cladding is an inexpensive, versatile process for achieving low dilution clad layers from a range of material including unusual mixtures. In recent years, the application of electric contact surface strengthening on thermal sprayed coating has been studied by Donghua University's research team [8]. In the meanwhile, Zhu et al. [9] have studied the application of electric contact surface hardening on ductile iron, which rolling contact fatigue performance of surface enhanced. At room temperature, typical ductile iron with 3.84 wt% of carbon consists of ferrite, pearlite and nodular graphite. In electric contact surface transformation hardening, materials are heated and melted in a desired thin layer at the material surface using contact resistance heating followed by a quenching process to make changes in grain structure. Compared to conventional techniques, electric contact surface hardening prevents the heating up of the bulk of work piece, only the surface layer is heated and the cooling down takes place by self-quenching of the bulk material. A higher temperature gradient is available to heat the surface in a short time and the improved mechanical properties can be achieved by a fine tuning of the processing parameters [10]. The microstructure and properties of electric contact hardened layer depend on the solidification mechanism and solid transformation. But it is difficult to achieve experimentally since the experiments would be excessively and time-spending. So it is necessary to use mathematical simulation

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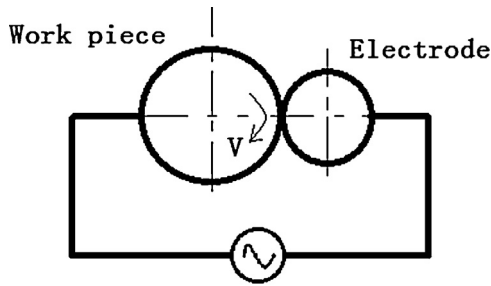


Fig. 1. The principle of electric contact strengthening process.

methods to simulate the experimental environment and analysis the temperature distribution of electric contact strengthening process.

ANSYS software has been widely used to simulate the processing of laser hardening [10,11], spot welding [12,13] and so on, by means of finite elements theoretical analysis. This report is a presentation of ANSYS FE models for the thermal simulation of electric contact surface hardening. In this work, the temperature field was concluded from the theoretical analysis by finite elements and the effect of parameters on hardened layer was also studied. The phase transformation surface was used to evaluate the temperature field. Then, the microstructure observation and microhardness measurements were carried out to corroborate this behavior.

2. Finite element modeling

A 3D finite element model is developed to simulate the electric contact surface hardening process using the commercial FE code ANSYS. The major schematic of electric contact strengthening apparatus was shown in Fig. 1. Localization of resistive heating was obtained by passing electric current through the contact between the rotating work piece and electrode, the small area of the contact imposed a severe constriction on the electric current causing intense resistive heating close to the contact, and the heating energy could achieve above the austenitization temperature, even above the melting-point temperature, a three phase state, i.e. solid, liquid and solid-liquid is formed. The physical statement of the problem is specified as follows. The electric current that was applied to the level of heating for the temperature that the surface will reach; the rotating speed of work piece directly controls the level of heat penetration of the contact region, and the contact force applied would affect the surface finish and residual stress of the surface. The mathematical model here illustrates the state equations of the applied heat flux, the heat generation, temperature distributions and thermal effects in the material due to the absorbed heat [14].

The developed model is used to predict the temperature distribution for the electric contact surface hardening process of a 60 mm diameter, 130 mm length ductile iron cylinder. The geometry and finite element mesh used in the model are shown in Fig. 2. As shown in this figure, a graded mesh technology is proposed. The surface has been modeled with a finer mesh while the internal work piece has been modeled with a coarser one, which occupies less memory space and improves the calculation accuracy. The mesh is formed by 252,746 rectangular elements and 48,123 nodes. The type of element used in the conducting the thermal analysis is eight-node quadratic three-dimensional solid elements "Solid70". In the heat transfer analysis, the transient temperature field of the cylinder work piece is a function of time t and the spatial coordinates (r, φ, z) and is determined by the non-linear heat transfer equation:

$$k \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \varphi^2} + \frac{\partial^2}{\partial z^2} \right) + H = c_p \rho \frac{\partial T}{\partial t} \quad (1)$$

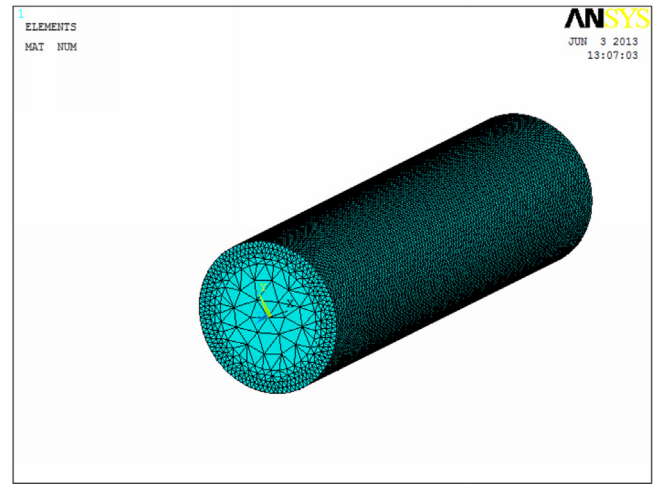


Fig. 2. The schematic diagram of meshing.

where k is the thermal conductivity, C_p is the specific heat, ρ is density. Three of thermo-physical properties of this material are temperature dependent and are taken (Fig. 3a–c) according to the metals handbook [15]. H is enthalpy. During the electric contact surface hardening process, the maximum temperature reached is above the melting point of the base material, and hence, the phase transformation is to be considered while performing the finite element simulation. The enthalpy H is calculated by the equation [16] as shown below:

$$H = \int \rho \cdot c(T) dT. \quad (2)$$

Fig. 2d shows the enthalpy value of ductile iron with the temperature.

The problem in performing the finite element analysis of electric contact strengthening is the modeling of the strengthening heat source [17]. To precisely simulate the temperature field of electric contact strengthening process, the contact resistance heating is modeled as a plane heat source model. On electric contact surface strengthening process, the uneven distribution of heat flux adapted for the contact resistance heating assumes the Gaussian distribution. The equation developed by Siva Shanmugam [17] shown in Eq. (3) is coupled with FE thermal model to calculate the heat flux of contact resistance between the electrode and work piece:

$$q(r) = \frac{3P}{\pi R^2} \exp \left(\frac{-3r^2}{R^2} \right) \quad (3)$$

where R is the effective heating radius which is equal to the contact force over yield stress of materials, r is the distance from the surface point to the heating center; P is the maximum heat intensity and relates to electric current and contact resistance, so the heat generated by electrodes current can be calculated by the equation [18] shown as below:

$$P = \eta I^2 R_c \quad (4)$$

where η is heat efficiency, I is the electric current of strengthening processing, R_c is the contact resistance between the electrode and work piece, which was related to the temperature, contact force and resistivity. In this paper, the value of contact resistance was calculated by the equation below:

$$R_c = \rho_c(T_0) \cdot \sqrt{\frac{H(T)}{H(T_0)}} \sqrt{\frac{\sigma_b}{\pi P_N}} \quad (5)$$

where $H(T)$ is the hardness of ductile iron under different temperature, ρ_c is the electric contact resistivity, σ_b is the yield stress of

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