International Journal of Engineering Science 117 (2017) 34–50

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

Rational approaches to high temperature induction heating

Bogdan Drobenko[a], Petro Vankevych[b], Yevhen Ryzhov[b,*], Maksym Yakovlev[b]

[a] *Institute for Applied Problems of Mechanics and Mathematics named after Ya. Pidstryhach, National Academy of Sciences of Ukraine, 3-B Naukova St., 79060 Lviv, Ukraine*

[b] *National Army Academy named after Hetman Sahaidachny, 32 Heroes of Maidan St., 79012 Lviv, Ukraine*

ARTICLE INFO

Article history:
Received 5 December 2016
Revised 28 April 2017
Accepted 4 May 2017

Keywords:
Thermo-mechanics
Thermal stresses
High temperature inductive heating
Finite elements
Processes coupling

ABSTRACT

Taking advantage of the developed earlier approach to the modeling of thermo-mechanical processes in electro-conductive solids subjected to high temperature induction heating the investigation were carried out to study the effect of electric current frequency on residual stresses in a cylinder. The process of induction treatment includes heating a solid to certain temperature followed by cooling. The effect of cooling conditions on residual stresses is also investigated. It is shown that appropriate selection of cooling conditions and electric current frequency could essentially affect both a level and special features of residual stresses distributions in the cylinder. In doing so, a range of stresses spreads from compressing to tensile neighboring plasticity region. Such selection thus allows for development of rational approaches to inductive heating whose goal could be desired level of residual stresses or minimized duration of induction heating (with the desired level of residual stresses). It is shown that the model, in which the heat exchange coefficients are substituted by their averaged values over cooling interval, might lead to incorrect prediction of residual stresses in the cylinder. Specifically, the difference in values of axial residual stresses calculated using averaged heat exchange coefficients and using their real (varied with the temperature) values may be as high as 40%.

1. Introduction

Electromagnetic fields are widely used in modern thermal processing technologies. Contactless energy delivery to a body, high heating rate, possibility to produce local effect are the principal advantages of electromagnetic thermal processing. In particular, the electro-magnetic field is used for welding, rectifying, outgassing, drying, doping, deposition of strengthening coatings, etc. Because of the well-known skin effect the inductive treatment is an effective method for strengthening boundary level of a product. In particular, induction treatment is used for improvement of the mechanical characteristics of carbon steels. Local induction heating is also used for high temperature annealing of constructive elements in order to remove completely or, at least, to reduce a level of residual stresses and strains, which thereby enhances strength characteristics of a product.

Generally, the electromagnetic field causes coupled electromagnetic, thermal and mechanical processes in electro-conductive solids. These processes substantially influence constructive parameters of a solid and its strength. The correct

* Corresponding author.

E-mail addresses: drobenko@ukr.net (B. Drobenko), dedykto@ukr.net (P. Vankevych), zheka1203@ukr.net (Y. Ryzhov), myyg2015@gmail.com (M. Yakovlev).

http://dx.doi.org/10.1016/j.ijengsci.2017.05.001

and adequate description of the above listed processes requires development of appropriate mathematical models with taking into account differences in such material properties as electric conductivity, polarization and magnetization.

Because the problem of the modeling of coupled physical processes is rather complicated if considered in a general form, several simplified assumptions are usually used in the model development. These assumptions concern mainly temperature dependencies of material properties, relations between induction and strength for both: electric and magnetic fields, etc. However, such assumptions might lead to substantial errors in estimation of thermo-mechanical behavior of electro-conductive solids (Drobenko & Hachkevych, 2014; Drobenko, Hachkevych, & Kournyts'kyi, 2008). Let us consider this in more details. Generally, the properties of electro-conductive solids at elevated temperature are different from those at room temperature. For example, at temperatures 550–600 °C carbon steels deform mainly plastically. Magnitude of electric conductivity of steel may change by an order of magnitude in the temperature range of 20–1000 °C, whereas ferromagnetic materials completely lose their ferromagnetic properties at Curie temperature. Therefore, the models capturing processes taking place in ferromagnetic materials subjected to high temperature induction heating should account for temperature dependencies of material properties, elastic-plastic deformation as well as nonlinear dependencies of field inductions on strengths and temperature.

Induction heating is well suited for automation. The process as such can be controlled by appropriate selection of electric current magnitude and strength, cooling conditions, geometric parameters of current sources, etc.

Majority of researches dedicated to the optimization of inductive heating (Barba, Savini, Dughiero, & Lupi, 2003; Bay, Labbe, & Favennec, 2007a; Bodart, Boureau, & Touzani, 2001; Dominguez-Tortajada, Plaza-Gonzalez, Diaz-Morcillo, & Balbastre, 2007; Favennec, Labbe, & Bay, 2003a,b; Kurek & Dolega, 2007; Masserey, Rappaz, Rozsnyo, & Touzani, 2004; Pham & Hooles, 1995) is focused on electromagnetic and temperature fields. At the same time, there are only a few works where mechanical processes are taken in account together with the electromagnetic and thermal ones. In particular, in Bay, Labbe, Favennec and Chenot (2003), Grygoliuk, Podstrigach and Burak (1979) deformation of inductively heated solid is studied. The problem on determination of the characteristics of high temperature induction heating with given constraints for thermal and residual stresses is considered in Grum (2007a, p. 9, 2007b, p. 211), Bay, Labbe and Favennec (2007b). One of the reasons why a number of such investigations are so limited could be the complexity of the problem as well as high level of interrelation between the processes taking place at inductive heating.

In this paper we develop rational approaches to high temperature inductive heating of thermo-sensitive ferromagnetic solids while assuring both residual stresses level close to predefined and minimized duration of treatment with desired permissible stress level during treatment.

2. Problem formulation and assumptions

For investigation of thermo-mechanical processes in thermo-sensitive electro-conductive solids subjected to external electromagnetic field we use recently developed mathematical model and numerical approach (Drobenko & Hachkevych, 2014; Drobenko et al., 2008). The field is generated by a set of electric currents in a finite domain of external (with respect to the studied solid) medium

$$\mathbf{j}^{(0)} = j_t^{(0)}(t)\mathbf{j}_r^{(0)}(\mathbf{r})\cos(2\pi\nu_\omega t), \quad \left|\frac{dj_t^{(0)}(t)}{dt}\right| \ll \nu_\omega \left|j_t^{(0)}(t)\right|, \quad t > 0, \tag{1}$$

where $j_t^{(0)}(t)\mathbf{j}_r^{(0)}(\mathbf{r})$ is the modulated amplitude, t is the time, $\mathbf{r}$ is the radius-vector, ν_ω is the electric current frequency.

Mathematical model is based on the general theory of electromagnetic field-matter interaction where an effect of electromagnetic field on thermal conductivity and deformation is taken into account by ponderomotive forces and heat sources. Nonlinear material relations, thermal conductivity equations as well as equations of non-isothermal elastic-plastic flow complete a set of model equations. Numerical calculations are based on finite elements method and a unified set of single step algorithms.

Suppose that the frequency of external electromagnetic field is beyond the vicinity of resonance frequency; in this case dynamic effects in the mechanical behavior of electro-conductive solid can be neglected, as shown in Hachkevych (1992), Podstryhach, Burak, Gachkevich and Cherniavskaya (1984). Deformation of a solid can then be considered within quasi-static approach. Suppose also that magnitudes of electromagnetic field, displacement and strains are such that relations between deformations and strains are linear. The effect of structural mobility of a medium on electromagnetic characteristics as well as thermoelectric and striction effects are also neglected. The effect of external electromagnetic field on thermal and mechanical processes in a solid is taken into account by ponderomotive forces and heat sources. A material of a solid is polarizable and magnetizable. Relations between inductions and strengths of both electric and magnetic fields are nonlinear with the induction and strength vectors being parallel. All electric, thermal and mechanical characteristics of a solid material are considered as being temperature dependent.

With the above taken assumptions, the problem of determination of stress-strain state of electro-conductive solid subjected to quasi-steady electromagnetic field is formulated in two stages. At the first stage the coupled non-stationary Maxwell and thermal conductivity equations, as well as expressions for ponderomotive forces are obtained for parameters of electromagnetic and temperature fields. At the second stage non-isothermal thermo-elasto-plasticity theory is used for formulation of equations for displacement, stresses and strains in the solid.