Coupling thermal, electrical and metallurgical problems in modelling of induction surface hardening of steels

Krzysztof Bzowski[1], Tadeusz Wieczorek[2], Jerzy Barglik[2], Łukasz Rauch[1] and Maciej Pietrzyk[1]

[1]AGH University of Science and Technology, Mickiewicza 30, 30-059 Krakow, Poland
e-mail: kbzowski; lrauch; maciej.pietrzyk@agh.edu.pl
web page: http://www.isim.agh.edu.pl
[2]Silesian University of Technology, Krasińskiego 8, 40-001 Katowice, Poland
e-mail: Tadeusz.Wieczorek; Jerzy.Barglik@polsl.pl;
web page: https://www.polsl.pl/Wydzialy/RM/Strony/Katedra_RM4.aspx

ABSTRACT

Induction surface hardening is a complex process, which involves thermal, electrical and metallurgical phenomena. Numerical modelling of this process is described in the paper. The model takes into consideration coupled electromagnetic, temperature, heat stress and metallurgical fields. Electromagnetic field was simulated by solution of the equation describing electromagnetic vector potential. Temperature field was determined by the solution of Kirchhoff-Fourier equation with additional terms accounting for heat generation rate due to electromagnetic field and for the recalescence during phase transformations. Description of this part of the model can be found in [1].

Modelling of phase transformations during induction surface hardening has to account for specific features of this process. Various areas of the specimen are subjected to different complex thermal cycles. In some areas of the specimen transformation of pearlitic-ferritic microstructure into austenite is not completed and simulation of cooling has to begin from the two-phase microstructure. Using JMAK (Johnson-Mehl-Avrami-Kolmogorov) equation for such complex thermal cycles encounters several numerical problems. Therefore, the idea of Leblond [2] was used. The main assumption in [2] is that rate of the transformation is proportional to the distance from the equilibrium. Original Leblond model is based on the first order differential equation, which does not allow to account for the delay due to nucleation. In the present work extension of the Leblond model was based on the control theory. The second order inertia term with two time constants was introduced. The first time constant was responsible for the delay due to nucleation [3]. In consequence effective simulations of phase transformations in varying temperature during cooling were possible.

In the present paper the model of [3] was extended by accounting for complex thermal cycles of heating and cooling. This extension required introduction of different time constants responsible for nucleation during heating and cooling. The distinction was made on the basis of the sign of difference between current and equilibrium volume fractions of phases. Coefficients in equations describing time constants were determined inverse analysis of dilatometric tests performed for various heating and cooling rates.

As an illustrative example induction surface hardening of a gear wheel made from steel was taken. Full coupling between thermal, electromagnetic and metallurgical models was used. Results of simulation of the cycle of thermomechanical treatment recapitulate the paper. These results include distributions of phase composition in the final product after induction surface hardening.

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