Induction contour hardening of gear wheels made of steel 300M

Jerzy Barglik
Silesian University of Technology, ul. Krasińskiego 8, 40-019 Katowice, Poland

Corresponding author: jerzy.barglik@polsl.pl

Abstract
The paper deals with induction contour hardening of small gear wheels with modulus of 2 mm made of the special quality steel AISI 300 M. Numerical model of coupled electromagnetic, temperature and hardness fields is shortly analyzed. Obtained hardness distribution is compared with measurements provided at the experimental set-up. Quite reasonable accordance being a level of 20 HV is achieved.

Key words: induction contour hardening, austenitization, coupled problem, dual frequency induction heating

Introduction
Induction surface hardening (ISH) is a such kind of the electromagnetic processing of materials which is realized by means of electromagnetic induction phenomenon. It causes local changes in the crystalline microstructure of surface layers of steel bodies only resulting in their higher hardness [1]. The internal part of the body remains soft with unchanged, prior microstructure. The ISH methods are divided into two main groups: the continual induction surface hardening (CISH) and the spin induction surface hardening (SISH). In a case of gear wheels both methods could be applied. For gear wheels with modulus \( m \) bigger than 6 mm the continual Tooth-by-Tooth methods are typically used, however for gear wheels with the modulus smaller than 6 mm various SISH methods are applied. Accordingly to requested hardening patterns and depth of the hardened zone the ISF process could be realized in different arrangements and supply systems: the single frequency process (SFIH), the consecutive dual frequency process (CDFIH) and the simultaneous dual frequency process (SDFIH). In order to obtain a contour shape of hardened zone along the whole tooth dual frequency methods are typically applied [2]. The paper deals with a mathematical modelling and experimental validation of the CDFIH process applied to small gear wheels made of steel AISI 300M with the modulus \( m = 2 \) mm. The gear wheel is heated first by the medium frequency (MF) inductor, then immediately by the high frequency (HF) inductor and finally intensively cooled by spraying. For mathematical modelling of coupled electromagnetic and temperature fields during induction heating as well as for a computation of temperature field during cooling the Flux 3D software and some own numerical procedures are applied. Dependence of critical temperatures for investigated steel and its hardening temperature on velocity of induction heating is taken into account. Non-linear dependences of material properties (electric conductivity, thermal conductivity, density and specific heat) on temperature as well as magnetic permeability on magnetic field intensity and temperature are considered. QT steel software and some own numerical procedures elaborated at the Silesian University of Technology are used for determination of hardness and microstructure distributions. Illustrative example is presented and discussed. Experiments are provided on the laboratory stand located at the Silesian University of Technology [3]. Expected contour shape of hardened zone is achieved. Good accordance between computed and measured hardness distributions is obtained.

Idea of Induction Contour Hardening Process
In general the ISH process consists of three consecutive stages: rapid induction heating, extremely short austenitization and cooling. In order to simplify the analysis the austenitization could be often neglected. However as it was mentioned in the introduction of the paper, for the case of induction contour hardening (ICH) the heating stage could be realized mostly in one or two cycles. One cycle heating means simultaneous heating in the MF and HF electromagnetic fields (SDFIH process). However the paper concentrates on the consecutive dual frequency process (CDFIH). First the MF induction heating (time \( t_{\text{MF}} \)) to the temperature lower than the modified lower critical temperature \( \text{Ac}_{1m} \) is provided

\[
T \bigg|_{t=t_{\text{MF}}} \leq \text{Ac}_{1m}(v_{\text{in}})
\]

The break between two steps of heating is used for a shifting the body between two inductors. The next step is the HF induction heating. If we heat up the body to the temperature higher than the modified critical temperature \( \text{Ac}_{1m} \)
the uniform austenite microstructure is obtained. If we have smaller final temperature after heating

\[ T|_{t=t_{MF}+t_{IF}+t_{IH}} \geq AC_{m}(v_{ih}) \]  

(2)

austenite microstructure could not be fully uniform. All three critical temperatures depend on velocity of induction heating \( v_{ih} \). Dependences of the critical temperatures on heating rate \( v_{ih} \) determined from the Time-Temperature-Austenitization (TTA) diagram for the investigated steel are presented in Fig.1.

\[ AC_{3m}(v_{ih}) \geq T|_{t=t_{MF}+t_{1}+t_{IH}} \geq AC_{m}(v_{ih}) \]  

(3)

For the low heating rate \( v_{ih} = 0.1 \) K/s the modified critical temperature \( AC_{m}' = 882.5^\circ C \) and it is almost the same value as for the conventional heating in furnaces. If the heating rate is distinctly bigger \( (v_{ih} = 900 \) K/s) the modified critical temperature \( AC_{m}'' = 1045^\circ C \) and it is 162.5 K higher than \( AC_{m}' \). In the same conditions as previously the modified upper critical temperature \( AC_{3m}' = 842^\circ C \) and \( AC_{3m}'' = 920^\circ C \) and it is 78 K of difference between them. For the modified lower critical temperature \( AC_{1}' = 725.5^\circ C \) and \( AC_{1m2} = 830^\circ C \) and it is 104.5 K of difference between them. The CDFIH process is terminated with the intensive cooling to the temperature guaranteed termination of martensite transformation \( (Ms_f – martensite finish temperature) \). Exemplary temperature dependence of gear wheel in the surface zone on time for the CDFIH process is presented in Fig. 2.

\[ T_{h} = T|_{t=t_{MF}+t_{1}+t_{IH}} + \Delta T \]  

(4)

where \( \Delta T = 20…40^\circ C \).
For the hardening process important influence have several parameters which should recognized by numerical simulation and experiments. The first of them is influence of the prior microstructure [1]. The second one is the magnetic permeability of steel which changes rapidly because of magnetic transformation at the temperature of Curie point \( \text{Ac}_C \) [4]. The third one is inaccuracy of temperature characteristics of material properties and heat transfer coefficients [5, 6]. An incorrect value of such properties like electric conductivity, density, thermal conductivity and specific heat could cause differences of calculated final temperature of about 100 K [5]. And finally a way of cooling and the cooling rate. The uniform martensitic microstructure at the surface zone is obtained if the cooling rate is big enough and the final temperature \( T_f \) in the whole hardened zone is smaller than the Ms temperature [1, 7].

**Illustrative Example**

Let us consider an example of the CDFIH process provided for the small gear wheel made of steel AISI 300M. Main parameters and dimensions of the gear are as follow: teeth number \( n = 16 \), width of the tooth ring \( b = 6 \) mm, root diameter \( d_r = 35.6 \) mm, tip diameter \( d_t = 26.9 \) mm, hole diameter \( d_h = 0.016 \) m. The arrangement of the CDFIH system, location of sensor points on working surface and view of prior microstructure are presented in Fig.3.

![Fig. 3: Arrangement of CDFIH system (a) 1 – MF inductor, 2 – HF inductor with flux concentrator, 3 – gear wheel, 4 – sprayer, 5 – cylinder, 6 – MF bus-bars, 7 – HF bus-bars. Location of points A…G on the working surface (b). Prior microstructure of steel AISI 300M. Tempered martensite with some tempered bainite. Mag. x1000.](image)

At beginning the gear wheel 3 is located inside the MF inductor 1 and heated to the temperature of about the lower critical temperature \( \text{Ac}_{1m} \). Then it is quickly removed to the next position inside the HF inductor 2. When the temperature exceeds the modified critical temperature \( \text{Ac}_{m} \) gear is removed to the final position inside sprayer 4. As a quenchant the polymer solution is applied. In order to obtain expected hardness distribution along external diameter of the element the gear mounted on cylinder 5 rotates with velocity of about 2….5 r/s. In order to minimize electrical losses lengths and distances between MF bus-bars 6 and HF bus-bars 7 are as minimal as possible. Computations are provided by means of the Flux 3D software for coupled electromagnetic and temperature field during induction heating and cooling and QT steel software supported by several own procedures for hardness and microstructure fields. Let us choose points A….G located at the working surface of the tooth (Fig.3b). Prior microstructure of the material is presented in Fig. 3c. Several computations make possible to recognize correct parameters and shorten a time necessary to find optimal parameters during experiments are provided on the specialized laboratory stand located in the Silesian University of Technology in Katowice [3]. After computations following parameters of the process are selected: \( \text{MF induction heating} \): current \( I_{MF} = 1450 \) A, time of heating \( t_{MF} = 4 \) s, its frequency \( f = 36 \) kHz, austenitization \( t_a = 0.1 \) s, \( \text{HF induction heating} \): current \( I_{HF} = 520 \) A, time \( t_{HF} = 0.4 \) s, frequency \( f = 242 \) kHz. Modified critical temperatures and hardening temperature: lower critical temperature \( \text{Ac}_{1m} = 700^\circ \text{C} \), upper critical temperature \( \text{Ac}_{3m} = 700^\circ \text{C} \), critical temperature \( \text{Ac}_{in} = 700^\circ \text{C} \), hardening temperature \( T_h = 1030^\circ \text{C} \), rotation velocity: 5 r/s, quenchant: Aqua Quench 140, its concentration – 10 %, Tempering: time \( t = 3600 \) s, temperature \( T_f = 160^\circ \text{C} \). Results of computations and measurements as well as their comparison are presented in Figs. 4-5. Oscillograms of MF and HF inductor currents are presented in Fig. 4a. Distribution of hardness along the line A…G located at the working surface is presented in Fig. 4b. It is not fully uniform, but differences between points A located at the root of the tooth and G placed in the top is equal to 20 HV and it matches general requirements. Hardness along the line AG is not fully uniform, but difference between points A and G is equal to 20 HV and it matches requirements. In order to control a shape of contour pattern the Surface Depth Hardening (SDH) coefficient is calculated along the line A…G. Let us calculate the SDH coefficient defined as the distance perpendicular to the surface point to a point where the hardness decreases to the 80 % of its maximal value at the surface (Fig.5a). Corresponding microstructures are presented in Figs. 5b, c.
Fig. 4: Oscillograms of inductor currents MF current in blue, HF current in yellow (a). Hardness distribution along the surface line A…..G. (b) 1 – induction hardening (computations), 2 – induction hardening (measurements), 3 – induction hardening and tempering (measurements).

Fig. 5: Surface Depth Hardening (SDH) distribution along the surface line A…..G (a), Microstructure of steel AISI 300M. Contour zone with martensitic microstructure Mag. x1000 (b) Transient zone Mixed microstructure with martensite, bainite and ferrite mag. x1000 (c).

Summary
The induction contour hardening (ICH) process for gear wheels made of steel AISI 300 M is analyzed in the paper. The CDFIH method is applied. Prior microstructure of the material consists of the tempered martensite. Numerical model of the process dealing with coupled electromagnetic, temperature and hardness fields is elaborated. Illustrative example is presented. Calculated and measured hardness distribution are compared and acceptable accordance is achieved. A shape of contour zone is not uniform and the SDH coefficient changes between 0.5 mm at the root of the gear to 1.8 mm at the top of the tooth. Next research activities should be aimed at obtaining of more uniform shape of the contour zone.

Acknowledgment
The paper was prepared within the NCBiR project PBS2/A5/41/2014

References
1. V. Rudnev, G. Totten, Induction Heating and Heat Treatment, *ASM International*, 4C (2014).
2. J. Barglik, Mathematical modelling of induction surface hardening, *COMPEL* 35 (2016), pp. 1403 - 1417.
3. J. Barglik, A. Smalcerz, A. Smagór, G. Kopec, Experimental Stand for Investigation of Induction Hardening of Steel Elements. *Metalurgija* 57 (2018) Vol. 4 pp. 341 - 344.
4. J. Barglik, A. Smalcerz. Influence of the magnetic permeability on modelling of induction surface hardening. *COMPEL* 36, (2017), 555 - 564
5. J. Barglik, A. Smalcerz, A. Smagór, Induction hardening of gear wheels of steel 41Cr4, International Journal for Applied Electromagnetics and Mechanics, 57, (2018), S3 - S12.
6. S. Schubotz, B. Nacke, Modeling and verification of convective heat transfer coefficient for induction applications, International Journal for Electromagnetics and Mechanics, 53, (2017), 79 - 88.
7. S. Lupi, Fundamentals of Electroheat, Electrical Technologies for Process Heating, Springer, (2017).