ELECTRICAL EFFICIENCY OF INDUCTION CONTOUR HARDENING SYSTEMS

Jerzy Barglik
Silesian University of Technology
Katowice, Poland
jerzy.barglik@polsl.pl
ORCID: 0000-0002-1994-3266

Adrian Smagór
Silesian University of Technology
Katowice, Poland
adrian.smagor@polsl.pl
ORCID: 0000-0001-7667-6697

Albert Smalcerz
Silesian University of Technology
Katowice, Poland
albert.smalcerz@polsl.pl
ORCID: 0000-0003-0957-1291

***Abstract*— The paper deals with the mathematical modeling of induction contour hardening of gear wheels. Uniformity criteria of obtained contour profile are discussed. In order to determine the electrical efficiency of the process its first stage: induction heating is considered. Numerical modelling of coupled non-linear electromagnetic and temperature fields are described. In order to evaluate accuracy of the proposed approach exemplary computations of the full process are provided. Results are compared with measurements and satisfactory accordance is achieved.**

Keywords— induction heating, contour hardening, coupled problems, critical temperatures

I. INDUCTION CONTOUR HARDENING (ICH)

The ICH process makes possible to obtain a thin hardened zone along the working surface of treated elements. The process is effective: short in time and energy-saving in opposite to a long-term, energy consuming, classical surface heat treatment like for instance carbonizing and consequent hardening [1]. In many advanced industrial applications the crucial quality condition is connected not only with thickness but also with the uniformity of the hardened contour zone. Its thickness is described by the Surface Depth Hardening (SDH) [2] defined as the distance perpendicular to any surface point to a such inside point where the hardness decreases to the 80 % of the maximal value. Uniform shape of profile is especially important in a case of gear wheels used in automobile and aerospace industries. For the ICH process of gear wheels with modulus m > 6 mm satisfactory results could be achieved by means of the Tooth-by-Tooth Induction Hardening (TTIH) method [3]. For smaller gear wheels mostly the Dual Frequency Induction Hardening (DFIH) method is applied [4], but anyway it is not easy to obtain the uniform thickness of the hardened contour zone [5]. Uniformity of the contour profile could be represented by the coefficient K (see Fig.1):

$$K = \frac{h + h_1 - h_2}{h} \tag{1}$$

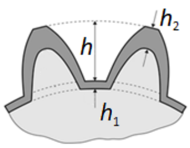

Fig.1 Definition of uniformity coefficient K. h – height of the tooth, h_1 – SDH coefficient on the axis of the root, h_2 – SDH coefficient on the axis of the top

The paper concentrates on mathematical modelling of induction heating as the first stage of the ICH process, which makes possible to determine electrical efficiency of the process and also to analyse which parameters of the system influenced on it. As the example the Consecutive Dual Frequency Induction Hardening (CDFIH) for small gear wheels is considered.

II. MATHEMATICAL MODELLING

The ISH process consists of two consecutive stages: rapid induction heating and intensive cooling. A break between these two stages (austenitization) is very short and it could be neglected. In order to calculate the electrical efficiency of the ICH process we should concentrate on the induction heating stage only. The electrical efficiency η_e is defined

$$\eta_e = \frac{1}{P_t} \cdot \int_V p_V \cdot \mathrm{d}V \tag{2}$$

where: P_t – total active power delivered to the system from the generator calculated by means of Poynting theorem [6], p_V – volumetric density representing the sum of MF and HF power released in the element.

The block scheme of the applied algorithm is presented in Fig. 2

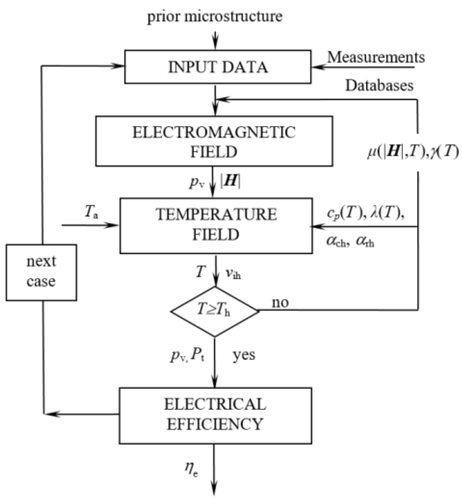

Fig.2 Block scheme of the heating stage of the ICH process

Input data are completed based upon measurements or taken from proper databases. A kind of prior microstructure influencing on critical temperature is taken into account as well [7]. Computations are provided by means of the Flux 3D software for coupled electromagnetic and temperature fields [8]. Based upon electromagnetic computations volumetric density of active power p_v, absolute value of the magnetic field intensity and velocity of induction heating v_{ih}. Non-linear dependence of electric conductivity γ on temperature is

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

noticed. The magnetic permeability changes rapidly because of magnetic transformation at the Curie point Ac_2. It is determined by measurements and considered as dependent on the absolute value of the magnetic field intensity and on the temperature [9]. Other material properties (specific heat c_p, thermal conductivity λ) as well as convection heat transfer α_{ch} and radiation heat transfer α_{rh} are considered as temperature dependent. It is assumed that temperature of convection and radiation environments are the same

$$T_{ac} \approx T_{ar} = T_a \tag{3}$$

Multiple reflection phenomena are neglected [10]. Computations of induction heating terminate when the average temperature exceeds the hardening temperature T_h

$$T_h \geq Ac_3(v_{ih}) = Ac_{3m} + \Delta T \tag{4}$$

where: Ac_3 – upper critical temperature guaranteed termination of austenite transformation, Ac_{3m} – modified value of the upper critical temperature dependent on heating rate, ΔT – increase of temperature, $\Delta T = 15 – 30$ K.

In case of a special quality kind of steel having as a prior microstructure the tempered martensite (like for instance steel AISI 4340 or other similar) the temperature increase $\Delta T = 100$ K in order to exceed the critical temperature $Ac_m(v_{ih})$ guaranteed the uniform austenite microstructure. Exemplary dependences of the critical temperatures for investigated steel on heating rate are determined from the Time-Temperature-Austenitization (TTA) diagram taken from specialized measurements. Final step of computations is determination of the electric efficiency and its comparison with classical hardening methods.

III. ILLUSTRATIVE EXAMPLE

Exemplary computations are provided for small gear wheels with modulus m = 2 mm and number of teeth n = 16, made of steel AISI4340 by the Consecutive Dual Frequency Induction Hardening (CDFIH). Configuration of the inductors-sprayer system is shown in Fig. 3

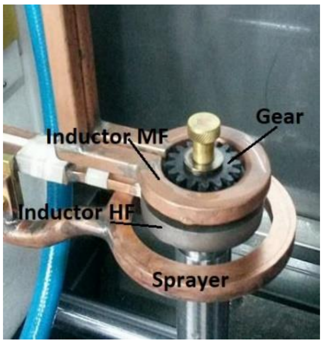

Fig.3 Configuration of the inductors-sprayer system during CDFIH process [11]

Dimensions and parameters of the analysed CDFIH system are listed in details in [11]. Modified upper critical temperature Ac_{3m} for real induction heating conditions with the heating rate of 230 K/s is equal to 840°C, It means that the hardening temperature reaches value of about 940°C. In order to evaluate the accuracy of the proposed modelling it is necessary to compare distribution of calculated and measured hardness. It means that we calculate the full process of induction hardening. For the cooling stage also the Flux 3D software for temperature field coupled with the modified QT steel software supported by several own numerical procedures for calculation of hardness and microstructure fields are applied.

Comparison of obtained results are collected in Table 1

TABLE 1 COMPUTED (HVc) AND MEASURED (HVm) HARDNESS DISTRIBUTION

Distance, mm	0	0.25	0.5	0.75	1	1.5	2
HVc	690	686	682	676	660	590	490
HVm	684	680	672	666	650	571	480

Quite reasonable accordance between calculations and measurements are achieved.

CONCLUSIONS

The paper deals with the mathematical modelling of induction contour hardening of gear wheels. In order to optimize the process two main evaluation criteria should be taken into account. The first of them is the criterion of uniformity of the hardened profile. But in this paper a special emphasis is put on the second criterion: the electrical efficiency of the process in comparison with classical hardening systems. In order to determine the electrical efficiency of the process: induction heating stage is considered. Numerical modelling of coupled non-linear electromagnetic and temperature fields is provided and described. In order to evaluate accuracy of the proposed approach exemplary computations are provided. Computed hardness is compared with measurements and satisfactory accordance is achieved.

REFERENCES

[1] X. Wang, B. Li, "A carburizing-quenching Jominy curve hardness model, " Materials Letters, vol 265, pp. 1-4, April 2020.

[2] V. Rudnev, G. Totten, Induction Heating and Heat Treatment, ASM International, 4C 2014.

[3] R. D. Yadav, A. K. Singh, "A novel magnetorheological gear profile finishing with high shape accuracy", International Journal of Machine Tools and Manufacture, vol. 139, pp. 75-90, April 2019.

[4] J. Barglik, "Mathematical modelling of induction surface hardening", COMPEL- The international journal for computation and mathematics in electrical and electronic engineering, vol. 35, no. 4, pp. 1403 – 1417, 2016.

[5] J. Barglik, K Ducki, D. Kukla, J. Mizera, G. Mrówka-Nowotnik, J. Sieniawski and A Smalcerz, "Comparison of single and consecutive dual frequency induction surface hardening of gear wheels", IOP Conference Series: Materials Science and Engineering, 2018

[6] J. Barglik, Induction Heating in Technological Processes. .Issues of the Silesian University of Technology. Gliwice 2015.

[7] T. Shinozaki, Y. Tomota, T. Fukino and T. Suzuki, "Microstructure evolution during reverse transformation of austenite from tempered martensite in low alloy steel", ISIJ International, vol. 57, no. 3, pp. 740 -743, 2017.

[8] www.altair.com/flux/ February5/2020

[9] J. Barglik and A. Smalcerz, "Influence of the magnetic permeability on modelling of induction surface hardening", COMPEL-The international journal for computation and mathematics in electrical and electronic engineering, vol. 36, Issue 2, pp. 555-564, 2017.

[10] J. Barglik, M. Czerwiński, M. Hering, M. Wesołowski, "Radiation in modelling of induction heating systems," IOS Press Amsterdam, Berlin, Oxford, Tokyo, Washington DC, pp. 202-211, 2008.

[11] Barglik, A. Smalcerz, A. Smagór and G. Kopeć, "Experimental Stand for Investigation of Induction Hardening of Steel Elements", Metalurgija, vol. 57, no. 4, pp. 341-344, 2018