Comparison of single and consecutive dual frequency induction surface hardening of gear wheels

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Abstract. Mathematical modelling of single and consecutive dual - frequency induction surface hardening systems are presented and compared. The both models are solved by the 3D FEM-based professional software supported by a number of own numerical procedures. The methodology is illustrated with some examples of surface induction hardening of a gear wheel made of steel 41Cr4. The computations are in a good accordance with experiments provided on the laboratory stand.

1. Introduction

Induction hardening is a kind of heat treatment where a steel body or its selected part is heated by induction to an appropriate temperature and then immediately quenched [1]. The surface induction hardening is connected with hardening of a thin surface layer only and keeping soft the internal part of the treated material. In general, the induction surface hardening consists of two consecutive stages with a short austenitisation break between them. The time evolutions of the process are presented in Fig.1 for the single frequency induction hardening (SFIH) (on left) and for the consecutive dual frequency induction hardening (CDFIH) (on right).

![Figure 1. Time evolution of temperature during single (left) and dual frequency induction surface hardening (right).](image-url)
The first stage of the SFIH process is the fast induction heating. In a thin surface layer the treated material reaches the hardening temperature $T_h$ being bigger than the modified upper critical temperature $Ac_{3m}$ [2].

$$T_{|l=l_h} \geq Ac_{3m}$$  \hspace{1cm} (1)

For deeper layers the hardened body reaches temperatures bigger than the modified lower critical temperature $Ac_{1m}$, but smaller than the modified upper critical temperature $Ac_{3m}$ and the microstructure contains not only austenite, but also pearlite and carbides.

$$Ac_{3m} \geq T_{|l=l_h} \geq Ac_{1m}$$  \hspace{1cm} (2)

Finally, for the internal part of the body the material does not contain austenite at all.

$$T_{|l=l_h} \leq Ac_{1m}$$  \hspace{1cm} (3)

For the dual-frequency process, the induction heating could be realized as simultaneous or consecutive. In the latter case the heating is realized in two consecutive time steps $t_{MF}$ and $t_{HF}$ respectively with a short break between them. The first step is the medium frequency (MF) induction heating. Then almost immediately (short break time $t_{BH}$) the high frequency (HF) induction heating is realized. The heating terminates when the average temperature in the hardened zone exceeds $Ac_{3m}$. However it depends on velocity of heating. In order to determine it the Time-Temperature-Austenitisation (TTA) diagram for the investigated steel 41Cr4 is measured (Fig. 2).

Curve 1 in Fig. 2 represents dependence of $Ac_{3m}$ on velocity of induction heating $v_{ih}$. For slow heating $Ac_3 = 801^\circ C$ (point A at the curve 1). For very fast heating the modified upper criterional temperature $Ac_{3m}$ is distinctly bigger. For velocity of heating $v_{ih} = 3000 \text{ K/s}$ $Ac_{3m} = 1075^\circ C$ (point B at the curve 1). Curve 2 in Fig. 2 represents dependence of $Ac_{1m}$ on velocity of induction heating $v_{ih}$. For slow heating $Ac_1 = 736^\circ C$ (point C at the curve 2). For very fast heating the modified lower criterional temperature $Ac_{1m}$ is bigger. For $v_{ih} = 3000 \text{ K/s}$ $Ac_{1m} = 815^\circ C$ (point D at the curve 2). The second
stage – quenching – makes it possible to achieve the requested martensitic microstructure [3]. The resultant hardness depends on the speed of cooling. The real character of this dependence can be determined from the Continuous-Cooling-Transformation (CCT) diagram. For steel 41Cr4, in order to obtain uniform martensitic microstructure, the velocity of cooling should be bigger than 500 K/s and the final temperature lower than the martensite finish temperature \( M_{sf} \). During a short break between both stages the temperature of the body decreases, but at the surface layer it is still higher than \( A_{C3m} \).

2. Mathematical modelling
In the paper we focus our attention on the spin induction hardening, where the material is heated simultaneously by a ring inductor [4]. We use single and dual-frequency hardening systems which allows obtaining the prescribed hardness profile. From the physical viewpoint, induction heating is a strongly nonlinear multi-physic process (Fig. 3). The interaction between fields are connected mostly by means of temperature dependences of material properties.

Electromagnetic and temperature fields were analyzed by means of FEM-based software. The total volumetric power density \( p_v \) consists of two components, but the hysteresis losses are neglected:
\[ p_v = p_{hi} + p_i \] 
\[ p_{hi} = p_{hi}(|H|, f) \] 
\[ p_v \approx p_i = \frac{|J_{ind}|^2}{\gamma} \]

where \( H \) denotes the magnetic strength, \( f \) the frequency, \( J_{ind} \) eddy current density and \( \gamma \) electric conductivity.

Dependences of the specific heat \( c_p \), the thermal conductivity \( \lambda \) and the electric conductivity \( \gamma \) on temperature are shown in Fig. 4 – 6. Dependence (7) of the relative magnetic permeability \( \mu_r \) on temperature for \( |H| = \text{const} \) was shown in Fig. 7 [5].

\[ \mu_r = f(|H|, T) \] 

The heat transfer was given by (8). Radiation was taken into account, however multiple reflection phenomena were neglected [6].

\[ -\lambda \frac{\partial T}{\partial n} = \alpha_c (T - T_{ac}) + \sigma_0 \varepsilon (T^4 - T_{ar}^4) \]

where \( \alpha_c \) denotes convection heat transfer coefficient, \( T_{ac} \) temperature of convection environment, \( \sigma_0 \) Stefan constant, \( \varepsilon \) emissivity, \( T_{ar} \) temperature of radiation environment.

**Figure 4.** Dependence of the specific heat on temperature.

**Figure 5.** Dependence of the thermal conductivity of temperature.

**Figure 6.** Dependence of electric conductivity on temperature.

**Figure 7.** Dependence of the relative magnetic permeability on temperature.
The computation of temperature field for induction heating terminates when the average temperature of the thin surface zone exceeds $A_{C3m}$. Then temperature field for cooling by spraying was calculated. Dependences of the specific heat $c_p$, the thermal conductivity $\lambda$ and convection heat transfer $\alpha_{cc}$ on temperature were taken into account. The computation of temperature field for cooling terminates when the inequality (9) was satisfied.

$$T_{t_c} \leq M_{S_f}$$ (9)

where $t_c$ denotes the time when cooling terminates and $M_{S_f}$ means the temperature when the martensitic transformation is completed.

And finally hardness and microstructure distribution were determined and compared with measurements.

3. Illustrative Example

The numerical solution of the induction hardening of gear wheels was provided by the Flux3D software with some own procedures. An attention was paid to the convergence of results in the dependence on the density of discretization meshes for the electromagnetic and temperature fields and on the position of the external artificial boundary.

Basic parameters and dimensions of the system are as follows:

**Gear wheel**: teeth number $n = 16$, width of the tooth ring $b = 0.006$ m, external diameter $d_e = 0.0356$ m, internal diameter $d_i = 0.0269$ m, diameter of the hole $d_h = 0.016$ m, material: steel 41Cr4 (its chemical composition is presented in Tab. 1).

**Table 1. Chemical composition of steel 41Cr4.**

| Element | C   | Cr   | Si   | Mn   | Ni   | Cu   | P   |
|---------|-----|------|------|------|------|------|-----|
| %       | 0.4 | 1.05 | 0.24 | 0.73 | 0.16 | 0.16 | 0.025 |

**Figure 8.** MF inductor (left) and HF inductor – sprayer system (right).

**MF inductor** (left part of Fig. 8): number of turns $n = 1$, external diameter $d_e = 0.054$ m, internal diameter $d_i = 0.0395$ m, height $h = 0.007$ m, length of bus-bars $h_b = 0.363$ m, distance between them $\Delta l = 0.003$ m

**HF inductor** (right part of Fig. 8): number of turns $n = 1$, external diameter $d_e = 0.061$ m, internal diameter $d_i = 0.0395$ m, height of coil $h = 0.007$ m total height (coil + concentrator) $h_t = 0.021$ m, Flux concentrator: external diameter $d_e = 0.0815$ m, internal diameter $d_i = 0.039$ m, thickness of upper and lower layer $b = 0.005$ m.

**Sprayer**: distance between inductor and sprayer 0.02 m, external diameter $d_e = 0.085$ m, internal diameter $d_i = 0.061$ m, quenchant: 10 % of Aqua Quench 140, 90 % of water.

**Heat transfer parameters**: radiation for heating only, the temperature of convection and radiation environment $T_{ac} = T_{ar} = 20^\circ C$, the heat transfer coefficient during heating $\alpha_{cc} = 20$ W/(m²K),
temperature of quenchant $T_q = 30^\circ$C, convection heat transfer coefficient during cooling $\alpha_{cc} = 1200$ W/(m$^2$K),

Modified criterial temperatures for real heating conditions: heating velocity $v_{ih} = 200 – 400$ K/s, $A_{c3m} = 920 – 950^\circ$C, $A_{c1m} = 770 – 780^\circ$C.

Parameters of the induction heating for various cases: medium frequency: power of the generator: $P_{MF} = 60$ kW, current $I_{MF} = 1385$ A, heating time $\Delta t_{MF} = 4 – 7$ s, frequency $f = 36$ kHz, high frequency: $P_{HF} = 20$ kW, current $I_{HF} = 500$ A, frequency $f = 280$ kHz, $\Delta t_{HF} = 0.7 – 1.5$ s, rotation velocity $v_r = 2$ r/s.

Below three examples of the induction hardening are presented. First the CDFIH process was analyzed for following parameters: MF heating: $t_{MF} = 4$ s, $I_{MF} = 1385$ A, $f_{MF} = 36$ kHz, Break: $\Delta t_{B1} = 0.2$ s, HF heating: $t_{HF} = 0.7$ s, $I_{HF} = 500$ A, $f_{HF} = 240$ kHz.

Temperature distribution within the tooth after MF heating is presented on left part of Fig. 9. For $\Delta t_{MF} = 4$ s average temperature within the tooth $T_{av1} = 475^\circ$C, which is sufficiently lower than $A_{c1m}$. After HF heating the average temperature in the thin hardened zone along the working surface of the tooth $T_{av2} = 923^\circ$C.

![Figure 9. CDFIH process. Temperature distribution: MF heating (left) and HF heating (right).](image)

And the second and the third case the SFIH process were analyzed for the same current and frequency ($I_{MF} = 1385$ A, $f_{MF} = 36$ kHz; $I_{HF} = 500$ A, $f_{HF} = 240$ kHz) and for the longer time of heating $t_{MF} = 6.6$ s, $t_{HF} = 1.5$ s. Temperature distribution after SFIH heating was presented in left side (MF) and right side of Fig. 10.

![Figure 10. SFIH process. Temperature distribution MF heating (left) and HF heating (right).](image)
For $t_{MF} = 6.6$ s the average temperature within the tooth is $T_{av} = 935^\circ$C. Taking into account calculated velocity of heating $v_{th} = 140$ K/s the final temperature was sufficiently higher than $A_{C_{3m}}$. But the non-uniform temperature distribution was characteristic. At the top of the tooth the average temperature is $T_{av\text{top}} = 820^\circ$C only. For $t_{HF} = 1.5$ s the average temperature in the thin hardened zone along the working surface of the tooth is $T_{av} = 953^\circ$C. Taking into account that for the case calculated velocity of heating $v_{th} = 620$ K/s the final temperature was still higher than $A_{C_{3m}}$. The temperature distribution in the hardened zone was more uniform in comparison with the previous case. Based upon results (Fig. 9 – 10) hardness distribution was calculated. Computations were compared with the measurements and quite reasonable accordance between them was noticed.

4. Summary
The paper presents the SFIH and CDFIH methods applied for induction hardening of small gear wheels made of steel 41Cr4. Computations were compared with measurements of hardness distribution and the reasonable accordance was achieved, however the expected hardness distribution characterized by thin fully hardened surface zone was obtained for the CDFIH method only. Next research in the area will be aimed on improvement of numerical model in order to shorten time of computations.

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