Computer simulation of single frequency induction surface hardening of gear wheels: analysis of selected problems

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Abstract: Induction surface hardening of gear wheels is a complex technological process making possible to obtain a thin hardened surface zone of the tooth and to keep soft their internal part. Mathematical modelling of the process is still a serious challenge. It requires triply coupled simulation of non-linear, transient physical fields mostly in 3D formulation. The paper deals with the analysis of various factors influencing on accuracy of computations including material properties, heat transfer parameters and modified values of critical temperatures. The main goal of the paper is to evaluate an influence of three material properties: electric conductivity, specific heat and thermal conductivity on the accordance between computations and measurements. Exemplary investigations are provided for the single frequency induction hardening of gear wheels made of steel 41Cr4.

Keywords: induction surface hardening; material properties; coupled problems; modified upper critical temperatures; austenitisation.


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1 General idea of induction surface hardening of gear wheels and formulation of the problem

Induction surface hardening is defined as a such kind of heat treatment where a steel body or any of its parts is heated inductively to a requested hardening temperature and then quenched practically without any austenitisation stage (Rudnev, 2017). The result is hard, brittle microstructure. The idea of the surface induction hardening of gear wheels is dependent on requested hardness pattern. Exemplary hardness pattern is shown in Figure 1. Such a pattern means full hardening of thin tooth zone only, transition zones hardened partly and keeping soft the internal part (Figure 1).

Figure 1  Tooth hardness pattern

1: fully hardened surface zone, 2: partly hardened transition zone, 3: soft internal zone.

There are different induction surface hardening methods for gear wheels accordingly to requested hardening patterns (Rudnev and Totten, 2014). They are divided into two kinds:

- spin induction hardening,
- continual induction hardening.
Spin induction hardening means simultaneous heating of the gear by encircled inductor and then immediate cooling. Continual hardening means heating of the several teeth or the single tooth only, their (its) immediate cooling and then removing of the inductor-sprayer system to the next position etc. A kind of method is selected based upon size of gear and its modulus $m$ defined as

$$m = \frac{D_r}{n}$$

where

$D_r$: reference diameter

$n$: number of teeth.

For gear wheels with the modulus smaller than 6 ($m < 6$ mm) the spin induction hardening method is mostly applied. It is realised in a different arrangements and supply systems (Figure 2(a))

- single frequency induction hardening (SFIH)
- consecutive dual frequency induction hardening (CDFIH)
- simultaneous dual frequency induction hardening (SDFIH).

The continual induction hardening could be realised in different arrangements. Two of them are more often applied (Figure 2(b)):

- tooth-by-tooth induction hardening (TTIH)
- part-by-part induction hardening (PPIH).

For gear wheels with the modulus bigger than 6 ($m > 6$ mm) the TTIH is mostly applied. The PPIH is used for instance for the hardening of big circular saws applied in continuous casting of steel lines (Barglik, 2015).

Figure 2 Classification of induction surface hardening of gear wheels (description in the text)

In the paper, we concentrate on the SFIH process of gear wheels supplied from the high frequency MOSFET generator. Mathematical modelling of such the process requires analysis of coupled, non-linear electromagnetic, temperature and hardness fields mostly in 3D formulation. It makes possible to simplify designing of the appropriate devices and consequently to minimise a time of experiments provided in industry. However the advantage of such a mathematical modelling is dependent on a formulation of the
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mathematical model with reasonable simplifications. The paper presents analysis of selected problems connected with numerical simulation of the SFIH spin process of gear wheels. As the example of hardened body gear wheels made of steel 41Cr4 are applied. The knowledge about material properties of the steel and their changes with temperature, heat transfer parameters during heating and cooling and critical temperatures $A_{c1}$ and $A_{c3}$ dependent on velocity of heating plays important role. Inaccuracy of these data may cause serious errors (Barglik, 2016). The paper concentrates on evaluation of the electric conductivity, thermal conductivity, specific heat and their temperature dependences on inaccuracy of mathematical modelling of the process.

2 Model of the process

The block diagram (Figure 3) presents the general computational procedure for the SFIH process.

Figure 3 Block diagram of the SFIH process

It is based upon solving of coupled, non-linear, transient electromagnetic and temperature fields during induction heating and temperature and hardness fields during intensive cooling accordingly to requirements in 2D or 3D arrangements. Volumetric power
density released in the hardened gear \( p_v \) determined from the electromagnetic field computations consists of two components. The induction component \( p_i \) is calculated as:

\[
p_i = \frac{|\mathbf{J}_\text{ind}|^2}{\gamma}
\]

where

- \( \mathbf{J}_\text{ind} \): induced current density
- \( \gamma \): electric conductivity.

The hysteresis component \( p_H \) is calculated as:

\[
p_H = \mu_0 \cdot \mu_r \cdot f \cdot |H|^2
\]

where

- \( \mu_0 \): magnetic permeability of vacuum
- \( \mu_r \): relative magnetic permeability
- \( f \): frequency
- \( H \): intensity of the magnetic field.

But, even for the applied high frequencies the hysteresis losses could be neglected (Lupi et al., 2015). Non-linear dependences of the electric conductivity \( \gamma \), the specific heat \( c_p \) and the thermal conductivity \( \lambda \) on temperature are measured (Schubotz and Nacke, 2017).

If we could assume equality of temperatures of convection \( T_{ac} \) and radiation \( T_{ar} \) environments

\[
T_{ac} = T_{ar} = T_a
\]

we could introduce the generalised heat transfer coefficient \( \alpha_g \) having different values on the different surfaces \( S \) of the gear wheel

\[
\alpha_g(S) = \frac{\alpha_{\text{ch}}(S)(T - T_a) + \sigma_0 \varepsilon(S)(T^4 - T_a^4)}{T - T_a}
\]

where

- \( \alpha_{\text{ch}}(S) \): convection heat transfer coefficient
- \( \sigma_0 \): Stefan-Boltzmann constant
- \( \varepsilon \): total emissivity.

In order to simplify the computations dependence of the generalised heat transfer coefficient \( \alpha_g \) on temperature is neglected. Exemplary values of the generalised heat transfer coefficient in different surfaces of the gear wheel and the heat conduction in the contact surface between gear and cylinder are depicted in Table 1.

The induction heating stage is terminated when the average temperature at the surface zone of the tooth exceeds the modified upper critical temperature \( A_{c3u} \). In the same time internal parts of the tooth exceed the lower critical temperature \( A_{c1m} \) only.
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\[ Ac_{1m}(v_h) = Ac_1 + \Delta T_1(v_h) \]
\[ Ac_{3m}(v_h) = Ac_1 + \Delta T_3(v_h) \]  \hspace{1cm} (6)

where \( Ac_1, Ac_3 \) denote the lower critical temperature and upper critical temperature for a conventional hardening respectively, \( v_h \) means a calculated velocity of the induction heating.

The dependences (6) determined from the time-temperature-austenitisation (TTA) diagram for the investigated alloy special steel 41Cr4 for quenching and tempering (Q&T) are shown in Figure 4.

Table 1  Generalised heat transfer coefficient on different surfaces of the tooth

<table>
<thead>
<tr>
<th>Part of the tooth</th>
<th>Top</th>
<th>Working surface</th>
<th>Upper plane</th>
<th>Contact gear-cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_s(S) ) W/(m^2\cdot K)</td>
<td>25</td>
<td>15</td>
<td>20</td>
<td>2000</td>
</tr>
</tbody>
</table>

Figure 4  Dependence of critical temperatures \( Ac_{1m} \) and \( Ac_{3m} \) for Q&T steel 41Cr4 on velocity of induction heating

Exceeding of the modified upper critical temperature secures a completion of the austenite transformation, however exceeding of lower critical temperature causes beginning of the austenite transformation only. Then the nonstationary, nonlinear temperature field for cooling is calculated. Radiation is neglected (Barglik et al., 2008). Convection heat transfer coefficient \( \alpha_c(p, Q) \) being a function of pressure \( p \) and flow-rate \( Q \) of the quenchant is determined by measurements (Barglik, 2015):

\[-\lambda \cdot \frac{\partial T}{\partial n} = \alpha_c(p, Q) \cdot (T - T_q) \]  \hspace{1cm} (7)

where \( n \) denotes onward normal and \( T_q \) temperature of quenchant.

Based upon the determined velocity of cooling \( v_c \) the hardness distribution within the body is determined (Schlesselmann et al., 2014; Spezzapria et al., 2016). The Continuous Cooling Temperature (CCT) diagram for real heat treatment condition is determined by measurements. At the end the calculated hardness distribution \( HV_c \) is compared with the value from experiments \( HV_m \) and if the absolute value of their differences tends to expected value final results are exported. In contrary the next case with a new input data begins to compute.
3 Illustrative example

As the illustrative example the SFIH spin process of small gear wheels is analysed. Arrangement of the system is shown in Figure 5. The gear wheel is located at the rotating cylinder 2. It is heated by the coil 3 connected to the MOSFET generator by bus-bars 4. Then it is cooled by the sprayer 5. As a quenchant polymer solution Aqua Quench 6 is applied.

Figure 5 Arrangement of the SFIH system (see online version for colours)


Main parameters and dimensions of the SFIH system are as follow:

**Gear wheel:** Teeth number $n = 21$, module $m = 2$ mm, pressure angle $\beta = 20^\circ$, external diameter $d_e = 0.046$ m, internal diameter $d_i = 0.037$ m, reference diameter $d_r = 0.041$ m, diameter of the hole $d_h = 0.02$ m, width of the tooth ring $b = 0.01$ m,

Inductor and supply parameters: external diameter $d_e = 0.072$ m, internal diameter $d_w = 0.052$ m, height $h_c = 0.01$ m, number of coils $n = 1$, profile $0.01 \times 0.01$ m, nominal power of the generator $P_{ih} = 120$ kW, time of heating $t_{ih} = 0.7$ s, frequency $f = 178–181$ kHz.

**Material properties:** Dependence of material properties on temperature is given in Figures 6–8. Chemical composition of steel 41Cr4 is shown in Table 2.

Table 2 Chemical composition of steel 41Cr4

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.4</td>
<td>1.05</td>
<td>0.24</td>
<td>0.73</td>
<td>0.16</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Sprayer: Copper tube of diameter $d = 0.009$ m, external diameter $d_{se} = 0.082$ m, internal diameter $d_{si} = 0.070$ m,

**Heat transfer parameters:** The generalised heat transfer coefficient during heating is presented in Table 1, quenchant: polymer solution Aqua Quench 140, its temperature $T_q = 30^\circ$C, flow-rate $Q = 2 \cdot 10^{-5}$ m$^3$/s, pressure $p = 1.2 \cdot 10^{5}$ Pa, convection heat transfer coefficient during cooling $\alpha_{ce} = 2800$ W/(m$^2$·K).
Critical temperatures: Heating velocity $v_{ih} = 1100 \text{ K/s}$, modified lower critical temperature $A_{c1m} = 805^\circ \text{C}$, modified upper critical temperature $A_{c3m} = 970^\circ \text{C}$, temperature of Curie point $T_{c1,2} = 775^\circ \text{C}$, martensite start temperature $M_s = 350^\circ \text{C}$, martensite finish temperature $M_pf = 150^\circ \text{C}$, hardening temperature $T_h = 1000^\circ \text{C}$.

**Figure 6** Dependence of the electric conductivity of temperature

**Figure 7** Dependence of the specific heat on temperature

**Figure 8** Dependence of thermal conductivity on temperature
4 Results

Values of material properties exhibit some uncertainty due to possible differences in the chemical composition of steel and inaccuracy of measurements. That is the reason that computations are provided for various temperature characteristics. As a software the Flux 3D (User guide Flux12, 2015) for coupled electromagnetic and temperature fields, the QT Steel (http://www.ita-tech.cz/en, 2017) and/or own numerical procedures for the hardness distribution are applied. Due to symmetry of the system and because of a numerical condition of periodicity (User guide Flux12, 2015, p.102) the calculation area is limited to ½ part of the whole tooth (Lupi et al., 2015). In order to evaluate the influence of the selected material properties on inaccuracy of the modelling several computations are provided. Electric conductivity, specific heat and thermal conductivity, are shifted by 10% down and up. Influence of the magnetic permeability was discussed in (Barglik and Smalcerz, 2017) and it is not considered in the paper. Totally 48 different cases are analysed. Exemplary temperature distribution within the volume of the tooth after $t = 0.65$ s (total time of the heating $t_{\text{ih}} = 0.7$ s) for the case No 4 ($\chi(T), 1.1\lambda(T), c_p(T)$, $f = 178$ kHz, $P_J = 21.5$ kW) during induction heating of gear wheel made of steel 41Cr4 is presented in Figure 9. Average temperature within the hardened zone with average thickness of 0.5 mm is equal to 1002.4°C.

Figure 9  Exemplary temperature distribution within the ½ part of the tooth (see online version for colours)

It sufficiently exceeds the hardening temperature $T_h$. Calculated temperature distribution in point B located at the working surface near the root of the gear wheel (see Figure 10) for different cases are shown in Figures 11–13 respectively.
**Figure 10** Location of points A – F on the working surface of the tooth (see online version for colours)

**Figure 11** Temperature dependence on time for the electric conductivity $\gamma \pm 10\%$ (see online version for colours)

**Figure 12** Temperature dependence on time for the specific heat $c_p \pm 10\%$ (see online version for colours)

**Figure 13** Temperature dependence on time for the thermal conductivity $\lambda \pm 10\%$ (see online version for colours)
Figure 11 presents the time dependence of temperature during induction heating for three various electric conductivities. Inaccuracy in the values of electric conductivity $\gamma$ of ±10% order causes rather big final temperature differences of about $\Delta T = +110$ K. In contrary 10% increasing of the specific heat causes decreasing of the final temperature ($\Delta T = -75$ K) (Figure 12). The same tendency is for the thermal conductivity. If $\lambda$ increases of 10% the final temperature decreases ($\Delta T = -80$ K) (Figure 13).

In order to validate the computations the hardness distribution for the case 1 with measured material properties (as in Figures 6–8) is calculated along the line A – F situated at the working surface of the tooth (Figure 10). Computations are validated by experiments provided at the industrial stand located in the ELKON company in Rybnik. The hardness in points A – F was measured at the symmetry plane of the gear. In order to avoid decreasing of the hardness investigated gear wheels were not tempered. Hardness distribution is measured by means of the Rockwell hardness tester FM 700. Comparison of the results is presented in Figure 14.

A reasonable accordance (average 6%) between calculated and measured hardness distribution is achieved.

5 Conclusions

The paper deals with the analysis of the SFIH process of gear wheels made of steel 41Cr4. A special emphasis was put on the influence of different temperature dependences of electric conductivity, thermal conductivity and specific heat on final temperature distribution and on the hardness patterns. The authors investigated the influence of uncertainties of these properties in a range of ±10%. Computations confirm a distinct influence of these inaccuracies. Depending on combination of cases final temperature differences could reach even a value of about $\Delta T = \pm 110$ K, however in some cases the errors compensate each other. Similar computations were presented in (Barglik et al., 2014) for induction hardening of gear wheels from the alloy special steel 50CrMo4, however they were not checked by experiments. In this paper, in order to validate the computations the hardness distribution along the line AF located on teeth working surface were measured. Quite reasonable accordance between computations and measurements not exceeding 6% is noticed. Next research in the area should be aimed at improvement of the numerical model in order to shorten the computation time.
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References


