Modeling and Investigation of Hardening Processes

A. Vasiliev, I. Pozniak, V. Greshnov

Abstract

To study qualitative and quantitative characteristics of hardening process is proposed complex mathematical model. The mathematical model is based on solution of electromagnetic, thermal and structural changes problem. Some numerical and physical experiments results including high intensive hardening process are presented. The results of numerical investigation of high intensive hardening process as hardening depth via surface power density and frequency are presented too.

Introduction

Hardening process is technology based on using large temperature gradient, which is produced by means of impact induction heating and following cooling process when the heat flow is directed to outside of metal (hardening process with quenching) and inside of metal (without quenching). Approach of hardening without quenching has number of advantages, such as increase solidity of hardened case and rise of compression stress in the hardened one.

Induction heating approach for the high intensive hardening process requires using high frequency (up to 440 kHz) and surface power density (up to 10 kW/cm²) [1]. In this case to get necessary characteristics of the hardened case it needs to investigate high intensive induction heating process to define optimal frequency surface power density and design factors of the induction system. The hardening process requires investigating electromagnetic, thermal, stress and structural phenomena where mathematical modelling together with experiments allows to get well results.

1. Mathematical model

Simulation of the induction heating process includes a computation of electromagnetic and temperature fields. 2D electromagnetic phenomena is described by the following equation [2]:

\[
\frac{\partial^2 \vec{A}}{\partial x^2} + \frac{\partial^2 \vec{A}}{\partial y^2} - j \omega \sigma \vec{A} = -\mu_0 \mu \vec{J}.
\] (1)

Where \( \vec{A} \) - magnetic vector potential, \( \sigma \) - electrical conductivity of metal, \( \mu \) - relative magnetic permeability, \( \mu_0 \) - permeability of free space.

Transient heat transfer process is described by the nonlinear Fourier equation [3]:

\[
\frac{\partial}{\partial x} \left( \lambda(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda(T) \frac{\partial T}{\partial y} \right) = C_v(T) \frac{\partial T}{\partial t} + w.
\] (2)
Where $T$ - temperature, $C_v$ - volume specific heat, $\lambda$ - thermal conductivity of the metal, $w$ - heat source density. The heat source density is calculated from electromagnetic problem. All coefficients of equations (1) and (2), namely, thermal conductivity, volume specific heat and electrical resistivity of metal are functions of temperature. Moreover, relative magnetic permeability is a function of two parameters - magnetic field intensity and temperature.

Maximum surface temperature during hardening process depends on kind of steel and could be up to 1200°C, therefore, above the Curie temperature. Accurate data of relative magnetic permeability dependence are not readily available but it could be approximated as follows [3]:

$$\mu(T, H)=1+(\mu -1)\left[1-\left(T \cdot 750^{-1}\right)^n\right], \quad T < 750,$$

$$\mu(T, H)=1, \quad T \geq 750.$$ 

where $n$ - exponent.

The most reliable data, which is supported by experimental investigations, is well approximated equation (3) with $n=2$.

Boundary conditions for thermal problem is defined by the next equation:

$$p = \varepsilon \sigma_s \left(T^4 - T_c^4\right) + \alpha(T - T_c),$$

where:

$\varepsilon$ - emissivity; $\sigma_s$ - Stefan-Boltzmann constant; $\alpha$ - film coefficient; $T_c$ - ambient temperature.

Structure changes problem is based on algorithmization of structure changes diagram [4-7].

Algorithm solution is based on jointly solving a system of two differential non-linear equations of electromagnetic (1) and temperature fields (2) and provides a reliable coupling of both phenomena. The solution approach is finite element method [8]. Solution of the equation system (1 - 2) together with structure changes problem is realized by block-iteration method and its coupling is shown at Fig. 1.

2. Results and Discussion

Physical and numerical experiments were carried out for usual kind of hardening technology (with quenching) and hardening process with high intensive induction heating with surface power density up to 10 kW/cm² and frequency ratio up to 440 kHz. Transformation of excess ferrite for hypoeutectoid steel is finished at considerably high temperature for fast cooling process in comparison with slow cooling process [5], so phase transformation does not finished at usual temperature hardening process. It explains necessity to reach surface temperature 1200°C. Induction heating is carried out at high frequency to get required temperature gradient and it takes high surface power density to get fast heating process. Sketch of investigated induction system is shown at Fig. 2. Specimen which has been heat-treated with conditions

![Fig. 1. Block-scheme of the mathematical model](image-url)
$p_0=8.2\ kW/cm^2$ and $f=440\ kHz$ is shown at Fig. 3. Depth of hardening zone is defined by structure changes algorithm (Fig. 4) [4]. Second necessary condition to get hardening zone is to reach required cooling rate of the layer.

The results of investigation show that the hardening domain is beginning for surface power density no less than $5\ kW/cm^2$ and frequency no less than $100\ kHz$ (Fig. 5). In this case depth of hardening zone is reached up to 0.9 mm.

![Fig. 2. Sketch of induction system](image)

(1 – ferrite; 2 – inductor; 3 – air; 4 – steel specimen)

![Fig. 3. Specimen after heat treatment](image)

($p_0 = 8.2\ kW/cm^2, f=440kHz$)

![Fig. 4. Structure changes diagram steel 116](image)

Fig. 5. Depth of hardening layer via surface power density and frequency

Testing of mathematical model was based on comparison of results of physical and numerical experiments on the base of hardening process with high intensity heating by induction method (Tab. 1) and hardening process with water-cooling (Tab. 2).

Table 1. Experimental and calculations data of hardening process with high intensity heating by induction method

<table>
<thead>
<tr>
<th>$f$, kHz</th>
<th>$p_0$, kW/cm$^2$</th>
<th>Coordinate points, mm</th>
<th>Hardness HRC</th>
<th>$p_0$, kW/cm$^2$</th>
<th>Structure layer, mm</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>~8,5</td>
<td>0,0</td>
<td>62</td>
<td>10</td>
<td>0,39</td>
<td>Martensite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,5</td>
<td>60</td>
<td></td>
<td>6</td>
<td>0,51</td>
</tr>
<tr>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>0,85</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>0,92</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Experimental and calculations data of hardening process with water-cooling

<table>
<thead>
<tr>
<th>Structure (hardness, HRC)</th>
<th>Experiment</th>
<th>Calculation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Coordinate points, mm</td>
<td>Hardness HRC</td>
</tr>
<tr>
<td>Martensite (57-66)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bainite (47-57)</td>
<td>0.42 56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.05 58</td>
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</tr>
<tr>
<td></td>
<td>2.19 54</td>
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</tr>
<tr>
<td></td>
<td>2.59 49,5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.60 47,5</td>
<td></td>
</tr>
<tr>
<td>Troostite (40-47)</td>
<td>3,99 44</td>
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</tr>
<tr>
<td>Sorbite (33-40)</td>
<td>4,87 39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5,83 35</td>
<td></td>
</tr>
<tr>
<td>Pearlite (15-33)</td>
<td>6,93 30</td>
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<tr>
<td></td>
<td>7,90 28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9,91 28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12,50 26</td>
<td></td>
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</tbody>
</table>

Experimental and calculations data of hardening process is shown at Fig. 6. It takes to note that developed computer code as structure changes problem does not depend on geometrical dimension of problem. It is allow to use it together with other program packages including commercial software, ANSYS or other, for instance.

Fig. 6. Experimental and calculations data of hardening process
References

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