Induction Hardening of External Gear

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Abstract. Problems and solution of gear induction hardening are described. Main attention is paid to the parameters of heating and cooling systems. ELTA 7.0 program has been used to obtain the required electrical parameters of inductor, power sources, resonant circuits, as well as to choose the quenching media. Comparison of experimental and calculated results of investigation is provided. In order to compare advantages and disadvantages of single- and dual-frequency heating processes, many variants of these technologies were simulated. The predicted structure and hardness of steel gears are obtained by use of the ELTA data base taken into account the Continuous Cooling Transformation diagrams.

1. Introduction

History of heat treatment shows very attractive perspective of this technology to increase the service life time of steel gears [1 – 5]. There are two main processes that influence the quality of heat treatment. Heating steel in furnace permits to form austenite at 800 – 900 °C. Quenching needs to cool the heated parts below the martensite start temperature Ms. In this case, hardness of steel reaches its maximal achievable value, which depends on steel grade.

The era of induction gear hardening started at the end of the 1920s in the USA and at the end of the 1930s in Russia with publication of the USA patents by Broun W (1926) and by Vologdin V P (1939) [5]. Theoretical and experimental investigations permitted to find the basic technological parameters of induction heating processes: an optimal frequency range, specific power of source, heating time, etc. Later studies were dedicated to refinement of technology and search of the optimum parameters of heating and cooling systems [3 – 8].

At present, fast induction heating of external small and middle size gears is the most preferable process in the comparison with heating in gas or resistance furnaces. It can significantly decrease the oxidation and improve the quality of the metal. At the same time, induction hardening of gear is a very complicated technology from many points of view.

2. Methods of investigation and feature of ELTA 7.0

2.1 Methods of calculation

The development of induction hardening technology requires the detailed experimental study or computer simulation. There are many general-purpose programs, for example Flux 3D, Ansys Multiphysics, ThermNet, Magnet, Comsol, and others that may be used to find optimal solution. These programs are mainly based on a Finite Element Method (FEM) that allows the users to describe and simulate complex geometry 3D systems. They are expensive and require well-trained operators to run...
them effectively. Due to a complex configuration of induction devices for gear hardening, it is necessary to use a 3D model that takes a lot of time for simulation (for example several hours for hardening with single frequency). To decrease this time, often only one part of the whole gear wheel is simulated and then all parameters can be calculated separately.

ELTA 7.0 (Electro-Thermal Analysis) program with Gear Application has been developed to solve electrical and thermal problems of gear hardening easily than 3D program. Special modification of a finite difference method (FDM) for the 2D internal electrothermal task and an analytical Total Flux Method (TFM), proposed by Nemkov V, for the external electromagnetic task allows one to find required decision with suitable accuracy and time. The program calculates the two-dimensional distribution of power sources and temperature in $\frac{1}{2}$ part of tooth cross-section, impedances of substitution circuit ($R$, $X$), induction current $I_{\text{ind}}$ and voltage $U_{\text{ind}}$, as shown in Figure 1.

![Figure 1. 2D calculation model of external gear (a), magnetic substitution circuit in TFM (b) and electrical substitution circuit of “inductor – workpiece” (c)](image)

The non-linear differential equations for magnetic field $H$ and temperature $T$ are described as:

$$\frac{\partial}{\partial x}(\rho \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(\rho \frac{\partial H}{\partial y}) = j\omega\mu\frac{\partial H}{\partial t},$$

$$C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + w,$$

where $\rho$ – electrical resistivity, $\omega$ – angular frequency, $\mu$ – permeability, $x$, $y$ – coordinates of workpiece cross-section, $C_v$ – volume specific heat, $\lambda$ – thermal conductivity, $w$ – heat sources density.

The boundary conditions are described as known magnetic strength $H_e$ on the surface in the air gap between inductor and gear, symmetry in central parts of face and bottom ($dH = 0$), supermagnetic ($H = 0$) or normal component of current is equal to 0 in the main body of a gear wheel ($x = 0$) and temperature dependent thermal losses on the surface of the gear. These losses are included in the data base of the program at the forced cooling stage.

The internal electromagnetic task permits to calculate active and reactive power in the $\frac{1}{2}$ part of the tooth cross-section, these parameters are in the whole gear wheel and impedance of load $R_{\text{work}}$, $X_{\text{work}}$. Using an impedance boundary condition, geometrical and electrical parameters of induction coil and applying the analytical Total Flux Method (total magnetic flux $\Phi_i$), all integral parameters of inductor can be found. The main parameters that may be of interest for a designer of the induction system are inductor impedance, total electrical power, voltage $U_{\text{ind}}$, current, electrical efficiency, power factor, etc.

The impedance of inductor $Z_{\text{ind}}$ can be calculated as:

$$Z_{\text{ind}} = R_{\text{ind}} + cR_{\text{work}} + j(X_{\text{ind}} + c(X_{\text{work}} + X_s + \frac{(X_{\text{work}} + X_s)^2 + R_{\text{work}}^2}{X_0})), $$

where $R_{\text{ind}}$, $X_{\text{ind}}$ – resistance and reactance of coil, $R_{\text{work}}$, $X_{\text{work}}$ – resistance and reactance of the workpiece, $X_s$ and $X_0$ – reactance of the air gap between the inductor and the workpiece and outside the inductor respectively, $c = X_0^2/(R_{\text{work}}^2 + (X_0 + X_{\text{work}} + X_s)^2) – \text{coefficient}$. 
2.2 Feature of ELTA 7.0

Input of gear parameters in ELTA 7.0 is very convenient (Figure 2). There are several standard parameters of the gear wheel: the number of teeth \( N \); module \( m \) (Metric system) or pole pitch \( p \) (British system); root diameter \( D_r \); pitch diameter \( D_p \); outside diameter (tip or addendum circle) \( D_o \); face width (or Gear thickness) \( Z_g \); interior diameter \( D_i \). Using these parameters, ELTA calculates mass of gear (0.7328 kg in Figure 2) and the recommended frequency range of power source (48 – 96 kHz).

![Figure 2. Window of Gear Application](image)

The screen of Gear Parameters has the other standard parameters: circular pitch – 0.7854 cm, circular thickness – 0.3927 cm, addendum – 0.25 cm and dedendum – 0.3125 cm. Material and initial temperature of the gear can be chosen in the window **Material**, for example, 0.4% C Steel Annealed, \( T = 20 \, ^\circ\text{C} \).

The windows of Inductor and Processing have the same format as for cylindrical systems in the previous version of ELTA. The program can simulate both single- and dual-frequency heating. For example, gear is heated at the first stage in inductor 1 with low frequency (for example, 2 kHz), then it is quickly moved in inductor 2 and then it is heated with high frequency (for example, 200 kHz). At each stage (Figure 3), duration and power (or voltage, current) can be chosen by developers to find rational solution of heating technology.

![Figure 3. Window of Processing: parameters of heating stages 1 (a) and 3 (b)](image)

One of the important features of ELTA is Cooling Diagram that applies only to processes with cooling stages. This diagram shows temperature dynamics with selected radii during the process of
cooling. All cooling curves start at the time when the local temperature crosses a level specified by the user, for example 800 °C. It means that the zero point of the time scale is individual for each curve, i.e. point of the cross-section. The A_r temperature can be used as a characteristic temperature for heat-treating processes. This graph may be displayed in the logarithmic scale of time. Applying the Time-Temperature-Transformation curves (TTT, also known as Isothermal Transformation Diagram) or the Continuous Cooling Transformation diagram (CCT) to the Cooling Diagram, the user can find the structural transformations in the part cross-section including the case depth and hardness, if applicable on the CCT graph.

3. Results of investigation

3.1 Comparison of experimental and calculated results

Experimental results have been obtained in universal induction systems of FREAL Ltd for heating different steel workpieces. Results of the experiment and simulation are shown in Figure 4 and 5.

Figure 4 shows results of gear heating: m = 4 mm, N = 16, Dr = 54 mm, Dp = 64 mm, Do = 70 mm, Di = 32 mm and Zg = 39 mm, obtained in 11 turns induction coil with 78 mm ID, 108 mm length and constant power 9.8 kW of the transistor generator with variable frequency during the heating process of 62 – 64 kHz.

Figure 5 shows results of gear heating: m = 2 mm, N = 26, Dr = 47.5 mm, Dp = 52 mm, Do = 56 mm, Di = 37 mm and Zg = 23 mm in 2 turns induction coil with 60 mm ID, 18 mm length and constant power 22 kW of the transistor generator with single constant frequency 74 kHz.

Figure 4. View of first induction system (a), 2D graph (b) and color map of temperature (c)

Figure 5. View of second induction system (a), 2D graph (b) and color map of temperature (c)
Many other variants of single- and dual-frequency heating processes, which are described in the conference proceedings, were simulated to check the correlation between the experiment, 3D programs and ELTA 7.0 (Table 1) [6 – 8].

**Table 1. Comparison of results for single- and dual-frequency induction hardening**

| Parameter                    | Source [6] | Source [7] | Source [8] | Source [7] |
|------------------------------|------------|------------|------------|------------|
| **Gear**                     |            |            |            |            |
| Module, mm                   | 2.5        | 1.06       | 1.64       | 1.06       |
| Pitch diameter, mm           | 140        | 43.5       | 100        | 43.5       |
| Number of teeth              | 56         | 41         | 61         | 41         |
| Face width, mm               | 14         | 13.8       | 15         | 13.8       |
| **Inductor**                 |            |            |            |            |
| Internal diameter, mm        | 150        | 47.92      | 108        | 47.92      |
| Length, mm                   | 14         | 13.8       | 16         | 13.8       |
| Turns                        | 1          | 1          | 1          | 1          |
| **Processing**               |            |            |            |            |
| Frequency (MF/single), kHz   | 10         | 10         | 200        | 36         |
| Coil current (MF/single), A  | 600        | 1275       | -          | 2660       |
| Coil power (MF/single), kW   | -          | 100        | -          | -          |
| Heating time (MF/single), s  | 10         | 10         | 8          | 6          |
| Dwell time, s                | 0.2        | 0.2        | 0.7        | 0.1        |
| Frequency (HF), kHz          | 185        | 200        | -          | -          |
| Coil current (HF), A         | 1700       | 1300       | -          | -          |
| Heating time, s              | 0.23       | 1          | -          | -          |
| **Calculation**              |            |            |            |            |
| CAE software                 | Flux 3D    | Flux 3D    | MSC Mark   | Flux 3D    |
| $T_{aver.}$ preheating, ºC   | 280        | 290        | -          | -          |
| $T_{aver.}$ preheating (ELTA), ºC | 272 | 390 | - | - |
| $T_{aver.}$ post heating, ºC  | 850        | 870        | 900        | 925        |
| $T_{aver.}$ post heating (ELTA), ºC | 860 | 800 | 900 | 905 |

Experimental and calculated results of electrical parameters and temperature are very close taking into account the uncertainty of presented data. The accuracy of calculated temperature at the tip, bottom and pitch points of the gear and integral parameters of the induction heating installations permits to use ELTA 7.0 for preliminary investigation and optimization of complex induction hardening technology. When the rational variant of the heating system and the process is found, the obtained parameters should be refined by the experiment or 3D simulations.

### 3.2 Investigation of single- and dual-frequency hardening processes

Induction hardening of external gear is a very critical technological process and needs the skills in many fields of knowledge. Close cooperation of the induction specialists and the technologists is required in order to ensure the desired mechanical properties of the gear.

There are several problems to be solved. From the viewpoint of developers of the induction system, they are: the type of power sources and required power, the frequency range for single-frequency or initial and final frequency for a dual-frequency process, parameters of the heat station (induction coil, the type of resonant circuit, transformer and leads), etc.

From the viewpoint of developers of technology, they are: methods of hardening (through or surface), the type of quenchant (water, oil, polymer, etc.), quenching conditions (showers of different intensities, dipping in still or agitated water or oil), etc.

Each gear has its special features, which must be considered when the technological process is
developed. One of the examples is described below. It was necessary to develop the equipment and the technological process for the surface contour hardening of the gear from steel AISI 1040, module – m=3.5 mm, number of teeth – N = 58, pitch diameter – Dp = 160 mm and face width Zg = 22 mm for special industrial application. This steel can be heat treated at 800 to 900 °C followed by quenching in the polymer sprayer and tempering. The hardened layer in the tip, flank and root of the teeth must be the same and continuous. Surface hardening is the heat method which produces a case depth that depends on hardenability of the steel. The expected hardness of steel AISI 1040 in the layer of about 2 – 7 mm can be 50 – 55 HRC.

Heating is the first most critical operation in the whole technology. The design or optimization of any induction system must balance the use of power and time against the required thermal profile in the load. ELTA shows the optimal frequency range of 24.5 – 49 kHz. Preliminary calculations have permitted to find the rational values for the single-frequency heating process: inductor power – 35 kW and time – 6 s. The transistor generator of 20 – 100 kHz may be used as power source. For optimal performance of the transistor inverters, an optimal angle of the inverter electrical load must be inductive (+10 - +15 degrees). When the main geometry of the induction coil and electrical parameters are chosen, one can simulate the heating process and find a rational decision of single-frequency. The results of simulation for three variants of heating in the induction coil of 2 turns, ID – 7.6 cm, length – 3 cm without thermal insulation are shown in Figure 6.

Both 22 and 44 kHz single-frequencies may be used to heat the gear up to 800 °C and obtain the 2 mm layer of the gear root (Figure 6 a and 6 b). Frequency 100 kHz sufficiently overheats the tip of the tooth (Figure 6 c).

The main parameters of the heat station for optimal frequency 44 kHz are: the high frequency transformer with trafo ratio of \( K_t = 7 \); capacity of the series connected tank is 1.05 mkF, inductor voltage is \( U_i = 70 – 100 \) V.

Series of preliminary calculations of the dual-frequency heating process have permitted to find the rational variant and values: first frequency – \( f_1 = 10 \) kHz, inductor power – \( P = 20 \) kW and time – \( t_1 = 5 \) s, dwell time – \( t_2 = 0.5 \) s, second frequency – \( f_2 = 200 \) kHz, \( P = 90 \) kW and \( t_3 = 0.5 \) s.

The results of simulation for this variant of heating in the same induction coil are shown in Figure 7.
Maximal thickness of the gear that can be hardened from temperature higher than 800 °C is equal to 1 mm and about 3 mm for the root and the tip zones respectively.

Quenching is the second critical operation in the hardening technology. ELTA 7.0 can save the final temperature distribution after each calculation of heating stages. It is very convenient and simulation may be continued after heating without new calculation for the heating and dwell stages. In this case, many quenchants can be investigated to obtain a martensitic structure of steel. Temperature dynamics at selected radii for top and bottom zones of the gear during the quenching in Polymer 12% Shower at 35 °C are shown in Figures 8 and 9.

Figure 8 shows a cooling process after heating at 44 kHz single-frequency and the CCT diagram for carbon steel AISI 1040.

Figure 7. Color map (a) and temperature dynamics: $f_1 = 10$ kHz, $f_2 = 200$ kHz (b)

Figure 8. Cooling and CCT diagrams in tip zone (a) and root zone (b)
Series of temperature curves intersect martensite start point Ms and the steel is completely hardened. Expected hardness of the 4 – 9 mm layer from the top surface and the 1 – 2.3 mm layer from the root surface is about 56 – 45 HRC.

Figure 9 shows temperature dynamics during the process of cooling after the dual-frequency heating process.

The layers of steel at a distance of 3.75 mm from top and 1.1 mm from bottom of the gear surface are completely hardened. Other parts of the gear do not reach the tempering temperature of 800 °C and are soft.

4. Conclusion

Fast simulation is the most delicate and complex problem in the development of new induction technology and equipment for hardening of the gear. This process can be executed with the use of ELTA 7.0 Gear Application. For example, the study of single- and dual-frequency induction hardening one external gear wheel was performed only in one working day. Obtained electrical and thermal parameters permitted to select a generator, an induction heat station, the time of each processing stage and to predict the hardness in the cross-section of the gear. The other more complicated electromagnetic and thermal problems such as edge effect of the inductor and load, the structure and hardness of steel, residual stress in whole volume, etc. may be simulated in the 3D program taken into account the preliminary results of the rational variant.

References

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