Simulation of Physical Fields in Induction Hardening Technology - from Digital Twin to New Technology

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Abstract. A new technology for the final induction heat treatment of large mill rolls has been developed. When designing this technology, installation and control system, a digital twin of the system was created on the basis of combined numerical models of electromagnetic and temperature fields in cylindrical axially symmetrical systems. The final heat treatment of mill rolls consists in a two-stage, multi-frequency induction hardening of body of large rolls. The developed digital twin of the system allows one to evaluate the key features arising during induction hardening, such as temperature distribution, hardness of the hardened layer, stresses that arise during hardening. The design of induction systems through digitalization allows one to improve the design, equipment composition and heat treatment mode to achieve maximum quality and minimize energy costs.

1. Introduction

Rolls' induction hardening has been used in industry for many years, but the technological process is not always designed optimally, just like induction hardening installations are designed without taking into account key production features. Today, it is advisable to create new technological complexes that can reduce energy consumption and increase labor productivity, without reducing the quality of the product. For optimal design, it is advisable to develop a digital twin of a technological complex with numerical models embedded in it for calculating electromagnetic fields in induction block, temperature fields in a workpiece, taking into account stress fields, as well as simultaneously taking into account the levels of active and reactive power. It is also necessary to observe the mechanical vibrations of structural elements that occur during operation and the temperature characteristics of all devices within the induction system.

Digital twins are used by a very large induction heat treatment plants, such as the induction hardening plant for large mill rolls. The power level of this plant reaches the level of 3 MW, therefore, when designing, it is advisable to use computer modeling and numerical models built in specialized software packages.

2. Problem

Induction hardening of large mill rolls was first used in the 1920s in the USSR and the USA [1]. Even then, it was noticed that it was difficult to achieve a constant high quality of the hardened surface of
the rolls, the rolls did not always have a high hardness of the hardened layer, and there were also cases when the rolls cracked after hardening due to high residual stresses.

Mill rolls are made of steels with a high chromium content - 8X3SMF, 9X, 9XF, 9X2, 9X2V, 9X2SF, 9X2MF, 9X5MF, 9X2SVF, 60X2SMF, 65X5MF and others. The hardness of the work roll body is in the range of 90-102 HSD. In addition to the high hardness value, one of the important parameters of the hardened layer is uniformity. Hardness differential along the length of the roll body is no more than 2 HSD. The depth of the working layer for alloys 9X1, 9X2, 9X2MF is at least 17 mm, and for alloys 8X3SMF, 65X5MF – at least 30 and 45 mm, respectively. In this case, the mill rolls must withstand high contact pressure and, at the same time, the formation of cracks on the surface of the roll body is not allowed.

To develop the technology for the final heat treatment of mill rolls, a digital twin of the induction system was developed, which includes numerical models of technological heat treatment, two-dimensional models of electromagnetic and thermal fields, models of thermal stresses arising in the process of heating and cooling the rolls. All numerical models are required to predict hardness, grain size, stresses and other characteristics of rolls and the hardened layer [2, 3].

As a result of computer simulation, a two-stage technology for poly-frequency hardening of large mill rolls was developed. The technology consists in induction heating of the roll before hardening at the base frequency (100 Hz) at the first stage, and then there is a hardening stage, which is performed at a different frequency. The temperature distribution and parameters of the power source during the multi-frequency hardening process are shown in Figures 1 and 2. The frequency of the hardening stage is selected based on the depth of the working layer.

Developed technology takes into account the dangerous temperature and stress gradients arising during the hardening process, which allows avoiding the formation of cracks and obtaining a uniform distribution of hardness on the surface of the roll body.

Developed digital twin turned out to be extremely effective for digital control of induction heat treatment complexes (Figure 1, 2). Numerical modeling has shown that it is advisable to use modular induction systems for hardening the mill rolls.

![Figure 1](image_url)

**Figure 1.** The process of induction heating and hardening of large-sized rolls of the rolling mill.

The use induction heaters modular structure has a significant advantages in induction heating technology, since it allows to optimize the operation modes of equipment in relation to: energy consumption; scale formation; ability to maintain a constant final temperature [4, 5, 6].

The advanced digital control allows to effectively process possible disturbances, such as: changes of speed, diameter and initial temperature of the workpiece, and, therefore, to minimize the
amount of defects during heating. Digital program control based on modern intelligent systems is the key to the quality of hardening of large-sized rolls of rolling mills.

Figure 1 shows the process of induction heating and hardening of the roll of the rolling mill. In the first heat treatment pass, the induction heating is performed at the base frequency (100 Hz), and a quenching pass is performed at a different frequency (70 Hz). The frequency of quenching should be determined from the technical requirements for the depth of the working layer, the frequency of heating is selected from the mass and size parameters of the equipment.

\[
\sigma_e = \left(\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}\right)^{1/2}
\]

where \(\sigma_e\) – equivalent von Mises stress, \(\sigma_1, \sigma_2, \sigma_3\) – principal stresses. Principal stresses are normal stresses on three mutual perpendicular planes of elemental parallelepiped; planes are chosen so that tangential stresses on them equals zero.

The stress with biggest value defines \(\sigma_1\), smallest defines \(\sigma_3\) and \(\sigma_2\) lies between them. During mill rolls quenching they experience three-dimensional, volumetric stresses. Complex three-dimensional state of tension defines single positive value of equivalent stress, which can be used to predict yield development in plastic material. Von Mises criteria is independent from third deviatory stress invariant [3] (according to Mises criteria for each stressed state of deformable body, both tension and compression, three principal stresses defines single positive value of equivalent stress, which can be used to predict development of dangerous deformations).

\[\text{Figure 2. The parameters of the induction system during hardening.}\]

When calculating mechanical stresses developing during quenching of large-dimensioned mill rolls using finite element analysis equivalent stress can be calculated for each element of the model. So one can find places of stress concentration and based on stress distribution quenching setting can be corrected [7, 8, 9].

Obviously, that whole heat treatment process time (pre-heating, heating up to quenching temperature, quenching and cooling) all of the roll material should be in elastic zone of stress-strain curve for roll steels, so for estimation of stress-strain behavior based on the equivalent von Mises stress assurance coefficient should be used to guarantee quenching without specimen destruction (hardened layer delamination, surface cracking) [10, 11, 12].

Figure 3 represent distribution of temperature and equivalent von Mises stress along the roll radius with and without pre-heating. One can see that mill roll pre-heating to 500°C before quenching reduces maximal equivalent stress greatly, so the roll will not deformed critically or fractured with such quenching setting.
3.1200 mm mill roll quenching (a) single-shot without pre-heating, (b) with 500°C pre-heating. Marked: 1 – temperature distribution behind the inductor vs. roll radius, 2 – equivalent von Mises stress distribution.

Special program should be developed to keep quality level high during large-dimensioned mill rolls quenching. This program should digitally control the quenching process in real-time environment (Figure 4). This digital software should define induction system parameters during pre-heating and quenching. The input for it are the temperature needed behind the inductor, on the roll surface and on the depth defined by technical specification, the output, generated by the program, are values of voltage and current, power level and inductor scanning rate. The software should be able generate the setting of quenching process, ensuring that roll temperature after pre-heating is 500°C, and on the second, quenching inductor run, temperature after inductor on the roll surface and 100 mm deep is exactly 950°C [13, 14, 15].

3. Conclusions
New technologies for induction heat treatment of large diameter rolls of rolling mills with a barrel diameter of up to 65” are developed. It was found that the digital model of the induction system must necessarily include the calculation of electromagnetic and thermal fields, the calculation of stress and strain fields, as
well as the calculation of power source parameters. This digital model can be used to create an intelligent control system for the installation of induction heat treatment of large-sized rolls of rolling mills, which provide high-quality heat treatment and minimize residual stresses [16, 17, 18, 19, 20].

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