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SIMULATION

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SIMULATION OF INDUCTION HEAT TREATMENT OF STEEL ARTICLES WITH THE HELP OF ELTA 6.0 AND 2DELTA SOFTWARE

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Processes of induction heat treatment of steel articles are studied with the help of ELTA and 2DELTA software for electrothermal analysis. A novel process of combined hardening of extra heavy balanced drill pipes is studied as an example. The results of the computations are confirmed by experimental data.

Key words: cooling curves, induction heat treatment, alloy steel, computation programs, ELTA 6.0 and 2DELTA software.

INTRODUCTION

Induction heat treatment is a widely used method for thermal improvement of the properties of steel articles. Induction surface hardening with high-frequency currents suggested by the founder of domestic high-frequency electrothermics V. P. Vologdin has made it possible to solve the problems of hardening of rails and some automotive and tank parts before the second world war and during the war. The undeniable merits of this scientist have been acknowledged in the world [1].

The induction method of heating for hardening steel articles has features distinguishing it from the traditional direct and indirect heating in resistance or gas furnaces, where the temperature is commonly uniformly distributed over a section of the article. Due to the surface effect, when the energy is mainly concentrated in the external layer at a specific depth, this layer can be heated rapidly to the hardening temperature and then be cooled both from the surface due to the hardening environment and due to removal of heat into the internal not yet heated layers. The cooling rate may be very high, which provides a high hardness of the martensite and strong compressive stresses on the surface. To make an optimum choice of the interrelated heating parameters (frequency, power, time) responsible for the required temperature distribution, many complex engineering problems of surface induction hardening had to be solved in the second half of the twentieth century. The works of a number of research centers, the All-Union Research Institute for High-Frequency Currents in the first turn, have made it possible to determine optimum temperatures at various austenitization times for some steels subjected to surface hardening (G. F. Golovin, M. M. Zamyatin, et al.), to study the properties of cooling media, and to obtain dependences of the heat transfer coefficients, which turned out to be quite helpful for the later development of programs for electrothermal computations (G. F. Golovin, M. M. Zamyatin, N. V. Zimin, et al.) [2, 3]. Intense research of special features of induction heat treatment has been performed in many countries.

Today we possess detailed atlases of diagrams of isothermal and thermokinetic transformations of supercooled austenite for steels of various grades, which may be used for determining their properties after quenching. For this purpose, actual curves of temperature variation at individual points of cross section of the article are plotted and superimposed on the diagrams with allowance for the initially nonuniform temperature distribution after induction heating. Most studies of temperature variation temperature under induction heating and forced cooling are now performed with the help of computer simulation.

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The aim of the present work was to study processes of induction heat treatment of steel articles, i.e., extra heavy balanced drill pipes (UBTS) from steel 40KhN2MA (4340 according to ASTM-SAE), using the ELTA and 2DELTA software for electrothermal analysis developed by the authors.

METHODS OF STUDY

The variety of configurations of heat treatable steel articles used in industry can commonly be reduced to simple configurations with cross section in the form of a cylinder, flat body, rectangle, or square. The induction coils for the heating may be external cylinders enclosing the article from the outside or internal cylinders for heating the internal cavity; for articles with rectangular cross section the external coils may have an oval or rectangular shape flat above the surface of charging and capable to create a longitudinal or transverse magnetic field. The available universal software (FLUX, MAXWELL, ANSYS, ELCUT etc.) are not fully satisfactory for meeting the requirements of developers of processes of induction heat treatment for different reasons, the main of which are the complexity of simulation, the long time of computation, and in some cases the impossibility to specify the cooling conditions in various hardening environments. A detailed description of the computational methods and simulation software for induction systems for heat treatment of steels with an analysis of the results and of the advantages and disadvantages of each method can be found in [4]. It is hard to compare the recommended computational techniques for programs with alternative methods and approaches due to the large volume of the material.

In order to develop the equipment and processes we needed a universal but simple-to-apply software for easy and fast computation of the electromagnetic parameters of the heater and of the temperature fields in heating and cooling for virtually all simple configurations of available induction systems.

To meet a maximum number of needs including the possibility of simulation of hardening processes, we created the ELTA software, which is now employed successfully in Europe, Asia, America and Africa by many leading developers and users of induction facilities and processes. The possibilities of the software are described in [5]. For cylindrical articles we also suggested a two-dimensional subject-oriented 2DELTA software based on the ELTA variant [6, 7].

An advantage of the software for simulating forced cooling is employment of a database covering well-tested temperature dependences of the heat transfer coefficients of a great number of cooling media developed and applied in Russia and of temperature dependences of heat transfer coefficients supplied by specialists of other countries engaged in research of hardening processes and applying the programs mentioned. This makes it possible to simulate induction hardening with cooling by compressed air, immersion of billets into a still or forcedly stirred water, oil and polymer liquids, and sprayer water cooling with different intensities and temperatures. The software allows the user to obtain families of temperature curves, the start of which is specified by the user as well as the diagrams of isothermal and thermokinetic transformations. The thermokinetic diagrams known for various steel grades may be imposed onto the designed cooling curves by importing them from an earlier created text file. It is possible to simulate the process of induction heating of a billet immersed into water, cooled from the inside of a hollow cylindrical preform, a steel strip heated on one side, etc. The ELTA program permits simulation of the process of induction heat treatment with the use of an internal inductor located in a cavity of the article [8]. Variants of the processes studied are quite numerous.

RESULTS AND DISCUSSION

In the late 1970s specialists of the All-Union Research Institute for Electrothermal Equipment have developed facilities and processes of induction heating of extra heavy balanced drill pipes (UBTS) installed later at the Experimental Mechanical Plant of Special Equipment (Drogobych, Ukraine) [9].

Today, the demand for UBTS has grown due to the growing volume of drilling works in oil and gas prospecting and extraction in Russia; such pipes are produced from alloy steels 40KhN2MA, 38KhN3MFA (40KhGMA, AISI4145H). At the start of the XXI Century Russian producers have even returned to making a part of such pipes without heat treatment.

Threading of unhardened pipes is a simple enough process, but the endurance of such thread is low. During mechanical drilling the entire column has to be lifted to the surface after 400 h of service, and the threaded locks are reconditioned. This lowers considerably the efficiency of the drilling and is fraught with accidents.

In the general case heat treatment of such articles is conducted by three variants.

The first process consists of bulk heating of pipe ends up to 1.5 m long to the hardening temperature in a synchronous heater, sprayer cooling, repeated heating for high-temperature tempering, and cooling. This technique raises the strength of only the zone of possible threading of the pipe not involving its middle part. In accordance with the TU 51-774–77 performance specification, the length of the heat treated part of UBTS should be 0.8 – 1.2 m.

In this process, the remaining part of the pipe is not heat treated. Another process has been suggested to provide enough abrasive wear resistance of the middle part of the pipe, i.e., combination of the heat treatment of the ends of the pipe with additional surface hardening by continuous heating and cooling in an induction facility [10, 11].

Finally, the third process involves bulk heat treatment over the whole of the length of the extra heavy drill pipe in continuous induction heaters with medium-frequency currents. A line for such heat treatment has been developed at the Vologdin All-Russian Research Institute of High-Frequency Currents. The pipes are produced in accordance with the TU 3663-033-48416997–2005, TU 3 RG 200–2003, and API Spec 7-1 specifications.

The first two processes are substantially less power consuming than the third one, which makes their application expedient. The endurance of the UBTS after the heat treatment increases to 2000 – 2500 h and lowers substantially the accident rate.

In what follows we present some results of computational design of a rational process of heat treatment of UBTS with the use of cooling curves plotted with the help of the software mentioned and thermokinetic diagrams imposed on them. As an example, we will consider a novel combined process of bulk hardening and tempering of the ends of extra heavy drill pipes from steel 40KhN2MA with external diameter 0.229 m, internal diameter 0.09 m and total length 6.1 – 6.5 m which is followed by surface hardening of the remaining external part of the pipe. The preliminary computation was performed using the one-dimensional ELTA 6.0 program for estimating the structure of the steel in the middle part of a pipe end and then applying the 2DELTA program with the aim to allow for the actual sizes and edge effects of the “inductor – charge” system.

Due to the necessity for bulk heat treatment of UBTS the first process may be implemented using commercial-frequency current (50 Hz). Our experience of solution of problems of uniform heating over the length of a pipe, and hence of the heat treatment quality, connected with the edge effect of the charging, allowed us to create an induction system based on a patented facility for induction heating with additional end coils [10].

Preliminary design of the required variant of induction heater with the help of ELTA 6.0 takes several minutes. The computation gives the integral parameters of the inductor coil, the mains power, the power coefficient, the efficiency, and other characteristics that will permit passing to a detailed design of the induction system. The heating and cooling curves (Fig. 1) required for analysis of the structure of the hardened steel are obtained in several seconds.

It can be seen from Fig. 1, which presents the temperature dependences at various points of cross section of a pipe on the time and the curves describing the thermokinetic transformations of the steel, that a martensitic structure forms at a distance of up to 10 mm from the external surface and up to 5 mm from the internal surface (the temperature curves intersect the line M_s); a bainitic structure (a fine ferrite-carbide mixture) possessing high toughness and strength forms in the middle layers (the upper temperature curves intersect the line A → Bainite). Using another type of diagrams of thermokinetic transformations with imposed hardness values we can find that the hardness may attain up to 650 *HB* in external and internal surface layers and up to 350 – 450 *HB* in deep layers. Such a structure can be obtained by simultaneous combined cooling of the external and internal surfaces of the pipe end.

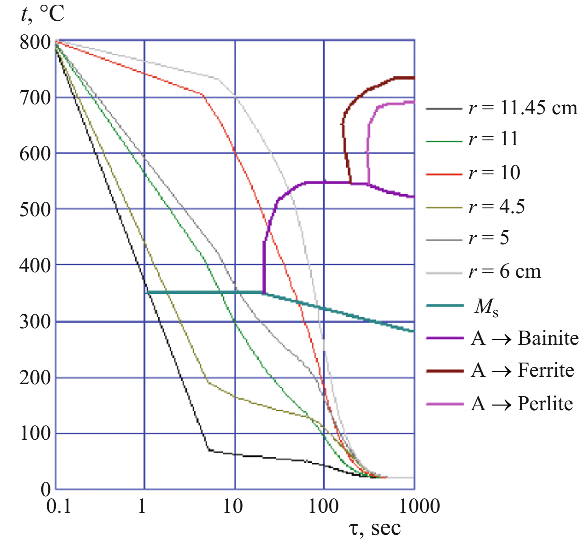

Fig. 1. Distribution of temperature over cross section of a pipe (r) under sprayer cooling from the outside of the pipe with intensity 0.8 $m^3/(m^2 \cdot sec)$ and from the inside with running water after bulk heating from the initial temperature of 870 – 860°C.

The specified hardness of heat treated steel 40KhN2MA is 255 *HB*, whereas the initial (without heat treatment) steel having a structure of coarse-plate pearlite with inclusions of structurally free ferrite has a hardness of about 160 *HB*. The desired hardness at which mechanical treatment and threading is still possible is 300 *HB*. Therefore, the quenching is followed by high-temperature tempering at 570 – 620°C and then by sprayer cooling. This toughening yields a fine ferrite-carbide mixture with a hardness of 300 – 350 *HB*.

To check the computed data, we performed a detailed experimental study of the distribution of temperature over the length of pipes in a laboratory and mechanical tests of a test pipe batch for determining the strength, ductility and impact toughness over cross section of their end regions [12].

The distribution of hardness over the length of the pipes was studied in order to determine the sizes of the heat treated zones and the uniformity of properties over the length. The hardness of the heat treated semiproducts was measured by the Poldi method (see Table 1).

A template 0.5 m long was cut from each heat treated end; its end faces were ground and labeled, and their Brinell hardness was measured using a TSh-2 hardness meter (D = 10 mm, P = 30,000 kN). The results of the measurements showed that the hardness over the length and over the cross section to a depth of 50 mm exceeded the minimum values specified by TU 51-774–77 with probability 99.99%. The insubstantial variation of the hardness over cross section indicates insubstantial changes in the mechanical properties. The mechanical properties of all the pipes exceeded the values required by the domestic specification and by the 7ANI

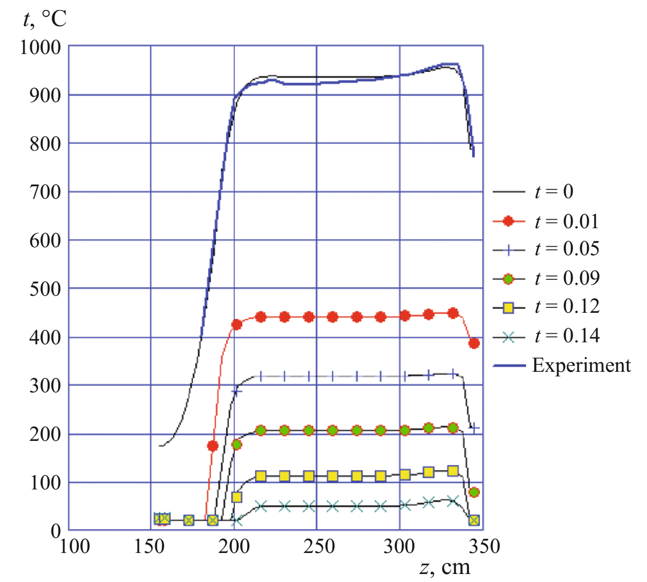

Fig. 2. Distribution of temperature over the length of the surface of a pipe during cooling after induction heating.

American standard. The production process provides the mentioned excess with probability 99.99%.

By the data of the metallographic analysis the structure of the heat treated part of the pipe is represented by a fine ferrite-carbide mixture; the structure of the middle not heat-treated part is represented by coarse-plate pearlite with inclusions of free ferrite. The structure of the ends of the UBTS heat treated with the use of induction heating is finer than after furnace heating, which confirms the expedience of induction heat treatment and sprayer cooling. Thus, the developed process implements virtually fully the possibility of raising of the quality of pipes.

In the example described, the outside surface of the pipes was cooled by water spraying at a specific flow rate of $0.8\ m^3/(m^2 \cdot sec)$. To choose a rational variant of sprayer cooling with another water flow rate, for example, 0.28, 1.2 or 3 m/sec, for a polymer solution or an oil cooling spray with intensity 0.3 and 0.7 m/sec, we can model the temperature-dependent curves of the heat transfer coefficients with the help of the software.

TABLE 1. Distribution of Hardness over the Length of a Pipe

Distance from the end, mm	*HB*, kgf/mm^2	ΔHB
0.05	320	14.8
0.10	319	10.8
0.20	311	12.2
0.90	309	13.5

Note. We present the mean values of the hardness (ΔHB is the standard deviation).

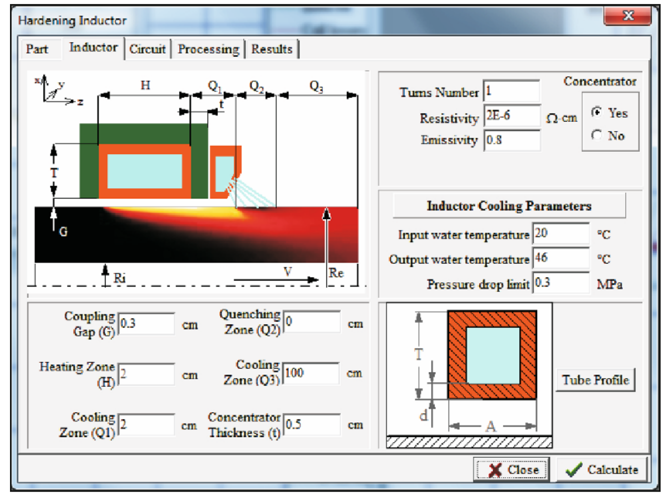

Fig. 3. Design plan of the system of surface hardening in the ELTA program.

The 2DELTA program has been used for amended computation of temperature-time dependences over the whole of the volume of the end of a pipe. Figure 2 presents the computed curves of variation of the temperature over the length on the surface of the pipe at the first cooling moments. We also present in the figure an experimental temperature curve for an actual hardening mode obtained under laboratory conditions when testing the heat treatment process.

For the studied heater variant, hardening develops over the length of about 1.4 m of the pipe end [10]. An inconsiderable part over a length of about 30 mm of the end has a temperature below 800°C and therefore remains unhardened. The cooling diagrams in the sections where hardening may occur are similar to those given in Fig. 1.

The second part of the process of heat treatment, i.e., surface hardening of the tube with exception of the hardened ends, presents much higher interest. The task of the developer is to determine the design of the induction heater and of the cooling system. From the standpoint of technology and economy it is expedient to conduct the surface hardening to a low depth. This may be provided by a medium-frequency current or a high-frequency current and continuous process in a short inductor.

Figure 3 presents a variant of the system in question for the process of surface heat treatment of UBTS-229. Figure 4*a* and *b* present the cooling diagrams for the cases of sprayer cooling and cooling without sprayer, respectively.

The main parameters of continuous induction heating are as follows: power 136 kW, frequency 250 kHz, scanning rate 0.65 cm/sec. The heat treatment of one pipe 6.6 m long takes about 9.5 min.

It can be seen from Fig. 4 that the hardening for martensite occurs in a surface layer about 1.5 mm thick (the temperature curves intersect the line M_s). After sprayer cooling, low-temperature tempering develops from internal layers (the temperature grows to 100°C). The internal layers of the

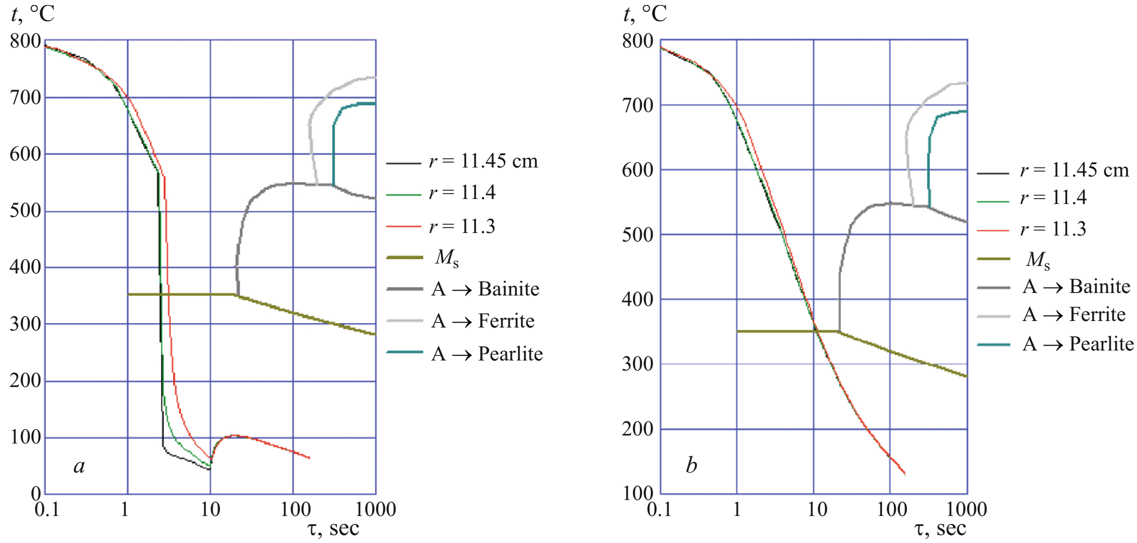

Fig. 4. Distribution of temperature over cross section of a pipe (*r*) after induction heating for the cases of sprayer cooling (*a*) and cooling without sprayer (*b*).

pipe do not heat to a temperature of possible hardening and are not given in the plots.

CONCLUSIONS

1. Subject-oriented ELTA and 2DELTA programs are convenient tools for designing processes of induction heat treatment for steel pipes and give rational solutions on the design of installations and on the modes of heating and cooling.

2. The computational and experimental data match well, which allows us to recommend the programs for designing heat treatment modes.

3. The design solution implemented for a novel process of heat treatment of UBTS has proved the possibility and expediency of commercial application of the software to pipes with elevated mechanical properties.

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