INVESTIGATION OF THE HIGH-LEVEL SURFACE HARDENING OF STEEL

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ABSTRACT

High-level induction surface hardening at a power density of 3-15 kW/cm^2 is not widespread and not investigated enough due to constructive complexity of energy concentration. The work examines the principles of modeling the processes of induction hardening. Much attention is paid not only to the cooling mode but also to the heating mode.

The results of exploring the modes of high-level hardening of different steels are listed.

INTRODUCTION

A distinctive feature of induction heating of metals is the thermal energy generation being produced immediately in the heated piece that permits reaching high speeds of heating with insignificant percentage loss.

High-level surface heating of a thermo technically massive body, when the cooling of the surface to be hardened happens due to abstraction of heat into the body so that the hardening medium is not required, is of both practical and theoretical interest. Time slot for high-level induction hardening of steel varies from seconds to fractions of a second. In such a small space of time the piece has no time to get heated deep so that a forced cooling in water or oil is not needed. It makes the processing much easier. The corresponding induction surface heating is fulfilled at an increased power density of 3-15 kW/cm^2, and the forming of the hardened case is essentially different from the classical hardening technique. As a result, high-level air hardening permits to minimize the zone of phase transformations to the width of the hardened case (0.1–1.5 mm). That is why, similarly to hardening by nitriding, the after-polishing of the surface is excluded, the cyclic strength of the piece and its wear-resistance rise, a better surface hardness (60-65 HRC) is reached, and undulation is slightly increased. An efficient redistribution of temperatures gradient while cooling excludes, as the investigations have shown, the appearance of tensile stresses on the surface. The case is formed with compression after strains and other characteristics providing lesser friction and wear during the usage of the piece.

Putting the surface hardening without forced cooling into practice is restrained by a number of circumstances: at first, insufficient study and, at second, purely psychological barriers connected with changing the settled technologies.

Solving psychological problems lies in breaking yet unshakable notions of selecting the frequencies of acoustic range for induction heating, and in inevitability of subsequent surface machining. The standard current frequency range for the classical induction heating of machinery pieces lies between 1 and 10 kHz. Power density delivered with the induced current to the piece lies between 0.2-1.5 kW/cm^2. The hardening heat time varies from 1 to 10 sec. Forced cooling is fulfilled to raise the cooling rate and obtain the martensitic structure.

The selection of such parameters and modes of the heat treatment was substantially connected with the current sources existing in time of applying induction hardening. These are rotary, thyristor and tube oscillators of big weight and size. Besides, tube oscillators have lower efficiency which used to be determinative at selecting sonic frequencies for heating.

Nowadays, the advanced technologies of power sources allow using easy-controllable, high-performance transistor sources that can be easily fixed to the heated object at high power and wide frequency range from 10 to 800 kHz. At that, it is possible to increase the specific power sharply up to 20 kW/cm^2, to decrease heating time down to hundredth fractions of a second, and, in a great number of cases, to quit using forced cooling.

Resting on the previously said and considering that high-level hardening without cooling demands lower power inputs, this technology may be called energy-efficient. Besides, the performance capabilities of such type of thermo strengthening permit to use it as a final operation, and sometimes it may be used after building the construction or a machine unit. High-level hardening is recommended for strengthening by raising the hardness index (up to 65 HRC) of extensive surfaces of such massive pieces like slide ways of cutting machines, races, shafts of paper-making machines etc.

MATHEMATICAL MODELING

The modeling the hardening process is generally rather a difficult job. The model must take account of electromagnetic and thermal fields as well as structural changes, strains and deformations. The results of the modeling are the following: hardness, the phase makeup and structure of the hardened case, grain size, strains and deformations, and finding locations of probable splitting. To get a correct result we should examine structural changes not only while cooling but also while heating and, moreover, take account of the initial structure of steel.

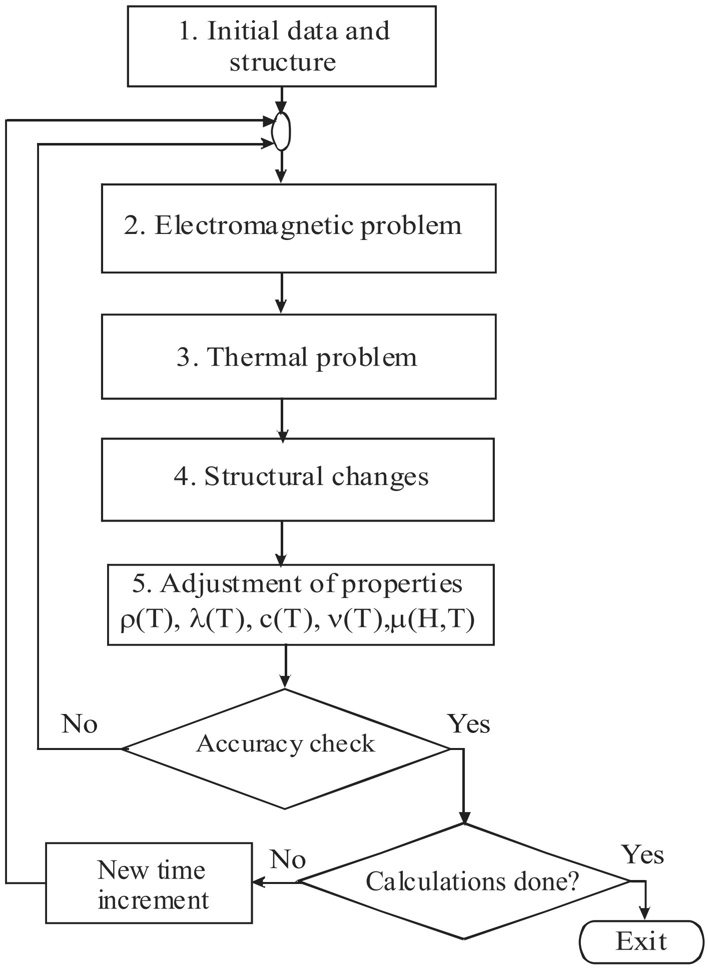

Figure 1. Modeling of the heating process algorithm.

<u>The modeling of steel heating</u>

According to [1] it is possible to assert that the degree of austenitizing, carbide dissolving, homogenizing and grain growth depends not only on the temperature but also on the heating rate and exposure time at the hardening temperature. Due to high heating rates and short exposure time the hardening temperature must be considerably higher in the process of induction heating than in case of furnacing. The austenite grain formed while fast heating turns out much smaller, its coarsening being much slower. In case of high-level hardening without forced cooling the upper limit of heating is restrained with the surface reflow only. Laser hardening permits heating with reflow.

Insufficient heating leads to insufficient austenite homogenization showing itself in rise of the critical cooling rate, emergence of troostite in the martensate structure, and unequal depth of the hardened case. In practice, they often erroneously try to eliminate the obtained low hardness of the surface layer by dint of raising the cooling rate instead of raising the hardening temperature.

The modeling of heating before hardening requires solving the three problems simultaneously: electromagnetic, thermal and structural. The algorithm of such approach is shown in figure 1.

1) *Initial structure.* The initial structure is very important for induction heating. The smaller carbides and more proportional their structural distribution before hardening, the better they dissolve and greater austenite homogenization degree is.

The most appropriate initial structure is sorbite or lamellar pearlite, and the least one is spheroidized pearlite, especially if coarse-grained [1].

The dependence of the austenitizing temperature on the initial grain size diminishes with increase in temper and, on the contrary, rises with increase in the heating rate. According to Vologdin VNIITVCh (All-Russian High Frequency Current Institute), at heating the 0.4% temper steel at a speed of 1000°C/sec the austenitizing temperature for a 0.01 mm grain amounts to 910°C, and for a 0.1 mm grain it is 960°C. The austenite homogenizing temperatures in similar conditions are 925°C and 1047°C pro tanto.

2) *Electromagnetic problem.* Depending on the geometry of the heated piece, one-dimensional, two-dimensional and three-dimensional problems may be of use. In case of the high-level hardening without cooling, a one-dimensional statement is only possible for the continuous operating mode as it does not take account of heat conduction lengthwise the piece. Two-dimensional statement is good for cylinder-shaped bodies but in case of flat extensive systems it neglects the edge effect of the piece and the inductor. Since due to dependence $\mu(H)$ the field spreading in the loading is not sinusoidal, it is necessary to solve the problem in the time depending wave what creates considerable difficulties. Some of the widespread programs are either incapable of computing the electromagnetic field in the time depending wave or spend exceedingly much time on computing. We may firmly assert that in the immediate future three-dimensional problems in the time depending wave for each step of the thermal problem will not be computed for an acceptable space of time. The alternative is the solution by fundamental, and instead of a true curve $B(H)$ the adjusted one should be used, energy conservation being taken into account [2].

3) *Thermal problem*. Solution to the thermal problem may be considered the easiest in this algorithm. Due to a high heating rate and short exposure, in many cases we may neglect the surface losses.

4) *Structural changes*. In case of increased temper, time needed for pearlite to change into austenite reduces. The alloying elements that do not form carbides accelerate the process of changing while carbide formers raise the stability of carbides thus slowing down the process [1].

Examining structural changes we may solve either the diffusive problem of an austenitizing process immediately [3] or use the thermokinetic diagrams of austenite forming. The second approach is the most convenient but, as a rule, there are no thermokinetic diagrams for the heating rates at 1500°C/sec and higher.

5) *Adjustment of material properties*. The material properties, such as heat conductivity, heat capacity, density, specific resistance depend on temperature, magnetic conductivity also depending on magnetic intensity. It explains why each time step demands simultaneous iterative computation. One cannot solve the electrical and thermal problems separately. Besides, it is possible to make use of a solution to the structural problem and keep track of phase transformations heat more precisely, and to use other property dependences for the zone of obtained austenite.

The modeling of the cooling of steel

To decide a question of a type of emerging structures and their properties, it is necessary to determine the cooling rates in each micro volume that are to be derived from a solution to the thermal problem. In the general case, when modeling cooling for the hardening process one needs to solve the thermal, structural and deformation problems simultaneously. An algorithm of such solution is shown in figure 2.

1) *The structure of the heated metal*. Austenite distribution is derived from a solution to the heating problem. As a rule, FEM is used for modeling but at this stage of computing machinery development the finite element is not commensurable with the grain so we should use a notion of percentage infill.

2) *Thermal problem*. A correct selection of cooling medium heat transfer coefficient is the most difficult part of the classical induction hardening since it depends not only on the refrigerant used but also on the shape of the heated piece. In some cases an averaged heat transfer coefficient turns out preferable.

3) *Structural changes*. The result of the solved structural problem must be the percentage distribution and the grain size of the austenite dissociation constituents, the account of phase transformation heat, and volume change caused by the austenite dissociation.

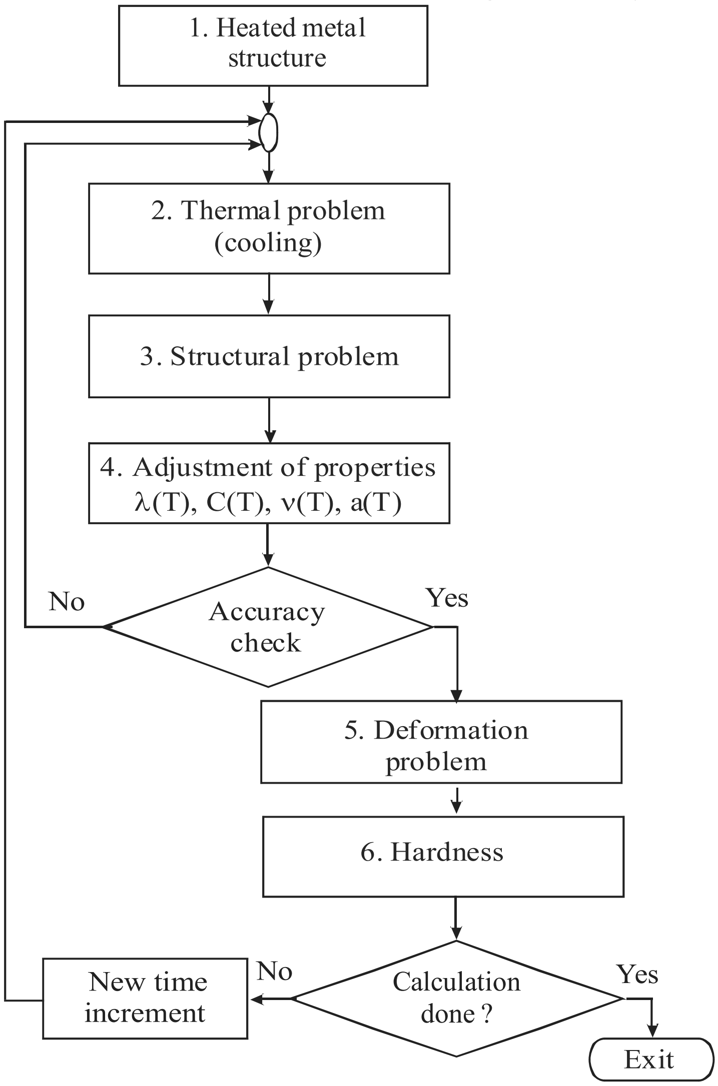

Figure 2. Modeling of the cooling process algorithm.

Thermokinetical diagrams represent the easiest way of determining the austenite dissociation kinetics at modeling. It is to be immediately mentioned that the position and shape of thermokinetic diagrams depend on the austenitizing temperature rate and the grain size. The higher temperature and bigger grain, the more curves are shifted to the right and down. It follows that one should have a large number of diagrams for one steel specimen.

As a rule, most thermokinetic diagrams are found for furnace heating and do not fit induction surface hardening well. They do not take account of the obtained structure grain. Besides, they do not give us all the information needed. Dissociation structures are given in a general way. There are no such notions as troostite, sorbite, upper and lower bainite given. They are to be traced taking into consideration the current dissociation temperature.

4) *Adjustment of material properties*. To obtain a correct result, it is advisable to use physical properties, such as heat conductivity, heat capacity, density and linear expansion coefficient, for each austenite dissociation constituent.

5) *Deformation problem*. The computing of the deflected mode must be held with phase transformations and stress relaxations due to plastic deformations and crack formation being taken into account.

Deformation of the layer in which phase transformations are registered has an undoubted influence upon austenite dissociation process. But the possibility of allowing for this influence seems to be rather difficult.

6) *Hardness determination*. It is possible to derive hardness immediately from a thermokinetic diagram but it would be too inaccurate. One of the approaches is using a percentage proportion of austenite dissociation structures at each point of the hardened case [4]. But it is necessary to examine pearlite, sorbite, troostite, upper and lower bainite, martensite, retained austenite separately. It should be considered that upper bainite may be even softer than troostite formed at higher temperatures. As a consequence, they often carry out hardening with the object of obtaining troostite.

To verify the results experimental data may be used. For instance, at VNIITVCh all data of numerous experiments is brought to special nomographic charts providing comprehensive information of structure and hardness for steels with temper rate at 0.2-0.8 % depending on the heating and cooling rates.

EXPERIMENTAL INVESTIGATIONS

Experimental investigations were carried out by means of high-level transistored oscillator powered at 40 kW developed at the Modern electrotechnics laboratory attached to Saint-Petersburg State Electrotechnical University. The frequency range of the oscillator is 50-100 kHz. A specialized matching device and a number of specially configured inductors were created for the adjustment of the high-level hardening of steel pieces (figure 3). The magnetic circuit was lifted 0.5 mm up and the edges of the work surface were rounded so that the inductor could operate in both pulsed and continuous modes (figure 4).

The main difficulty of high-level hardening is a correct energy batching. It is necessary to provide power density at no less than 3-15 kW/cm^2, temporary arrangements being precisely sustained. The developed microcontroller system permitting to assign the heat time accurate to 1 msec meets these requirements completely. The embodied computer coupling permits to register data from the working oscillator at a time step of 10 msec.

Conjointly with one of the largest Saint-Petersburg factories Electrosila Public Company a number of experiments were carried out in order to determine the capabilities of high-level hardening without cooling and outline the ways of its manufacturing application. The results of investigations for the pieces of 40X (EN 37 Cr 4; B.S. 530 M 40) steel follow in figure 5-7.

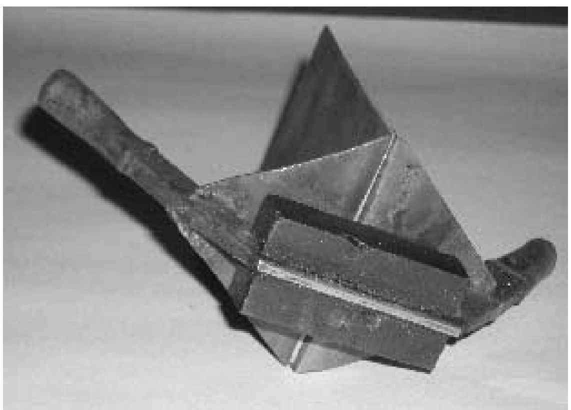

Figure 3. High-level hardening inductor, length 53 mm, width 3 mm.

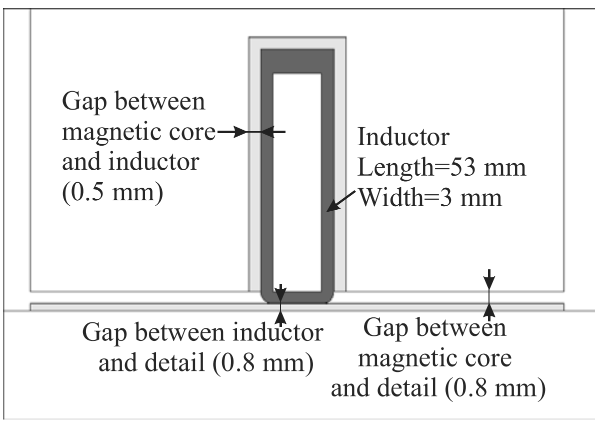

Figure 4. Induction system cross-section scheme.

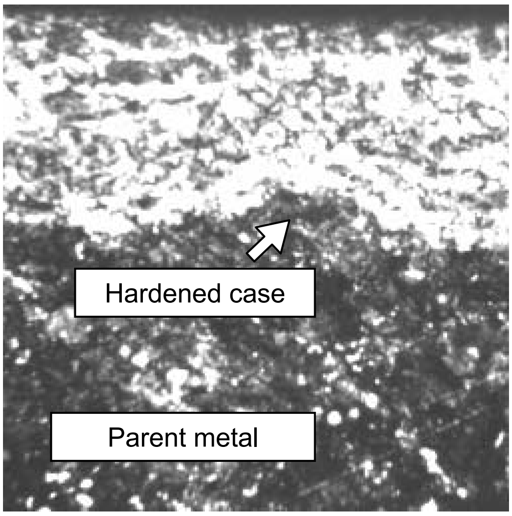

Figure 5. Cross-cut section microstructure. Magnified x50.

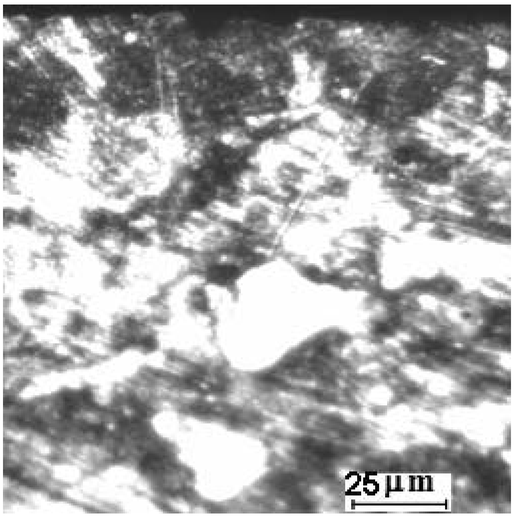

Figure 6. Hardened case. Magnified x200.

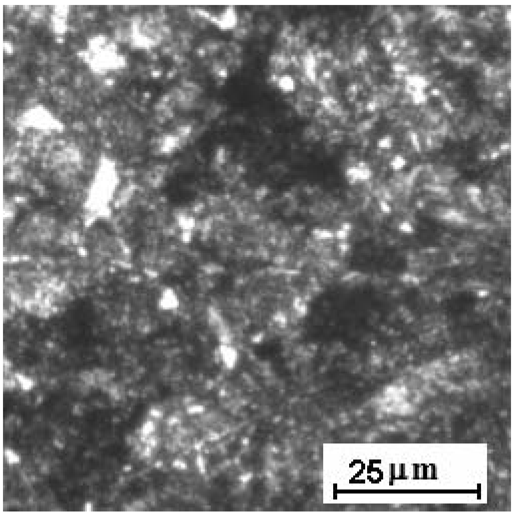

Figure 7. Parent metal zone. Magnified x200.

The heating was accomplished at 80 kHz, surface power density at 10 kW/cm^2, during 100 msec. The section microhardness gauging was made with "Micromet-II" unit. The end shape is a tetrahedral pyramid with a square base, loaded 100 and 200 gram, its endurance under the loading being 10 sec. Hardness gauging shows the following. Surface layer hardness is 58 – 60 HRC remaining to 0.1 mm depth. On a depth of 0.2 mm the hardness makes 46 HRC. The parent metal hardness is 20 HRC.

By sight the hardened case structure does not look like the classical martensite structure. Martensite acicularity is not clearly revealed due to too a small size of martensite plate (amorphous martensite).

The crossing of the hardening lines and acute edges does not lead to the microsplitting of the edges and other effects of this kind. In the zone of crossing there are no fundamental distinctions in structure and hardness as compared to remaining hardened case.

The obtained experimental results do not match the data from [5] well. This may be explained by the fact that these works used a one-dimensional model for computations which does not fit the pulsed mode. Besides, the austenitizing process in the subsequent hardening was absolutely ignored.

It is necessary to mention that by raising the heating rate in this experiment we could significantly increase the hardening depth.

Table 1 illustrates it by giving the experimental results of the high-level hardening of Х12МФ (DIN X 165 CrMoV 12; AISI D2) steel. The structure of the steel consists of carbides and grained carbide. The parent metal hardness is 20 HRC. The current rate at hardening was 80 kHz. It is easy to trace the way the heating rate influences the resulting hardness and the hardened case depth.

In the immediate future it is planned to carry out more than a hundred experiments with various steel pieces containing 0.4-1.65 % carbon at the heating rates from 1000°C/sec to 15000°C/sec. This will help to create a sufficient database for verification and correction of the developed models. Without carrying out a sufficient number of experiments, the development of a precise model is impossible. Electrosila Public Corporation renders assistance in realizing this project. Saint-Petersburg Administration and the Russian Federation Ministry of Education gives a financial support by way of grants.

Elaboration, testing and verification of models are planned to be carried out conjointly with Byelorussia State University of Information and Radio Electronics which has successfully developed a three-dimensional program for modeling the properties of the pieces exposed to ThermoSim heat treatment [6].

Table 1.

				Hardness, HRC		
№	Heating rate, msec	Surface power density, kW/cm^2	Maximum layer thickness, mm	on the surface of the hardened case	at a range of ½ layer thickness from the surface	near the border of the conversion of the parent metal into the hardened case
1	100	10	0.5	54	45	41
2	150	10	0.7	54	45	43
3	250	5	0.8	55	45	43
4	350	5	1	58	43	42
5	200	10	1.1	59	46	42
6	250	10	1.2	60	47	42
7	990	3.33	1.4	60	50	46

CONCLUSIONS

The major thesis of this article lies is the following: the modelling of phase transformations in the process of induction surface hardening should be carried out not only for the cooling process but also for the heating one. The higher heating rate is, the more correct the thesis is. To carry out the experiments confirming the computation, one needs to use certificated steels and be informed either of the prehistory or of the structure and the size of the grain. Pieces of the same steel but with different microstructure would be hardened in different ways. The higher heating rate, the bigger the difference in hardening will be.

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