Influence of the chemical composition of cast iron on the temperature of loss of magnetic properties when heating by high-frequency currents

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Abstract. One of the important tasks of modern materials science concerning technical issues is the need to ensure the surface properties of hardened products. An increase in the resource of machines and an increase in reliability are limited by the wear resistance of their components and assemblies: the less wear of the main rubbing pairs, the longer the service life [1]. For example, according to [1], a piston internal combustion engine accounts for 36-52% of the total number of machine failures. Modern technologies have a large number of hardening methods that can increase almost any characteristic of the structural strength of the material. Surface hardening of parts can be carried out in two ways - by changing (modifying) the state of the surface layer or by coating.

Introduction

The cylinder liner is one of the main most loaded engine parts. Widespread in automotive and tractor internal combustion engines of domestic and foreign designs received sleeves of gray cast iron with surface hardening of the working mirror.

The cast-iron cylinder liner of the engines is a thin-walled cylinder with a variable thickness along the height. Working together with pistons and rings, it forms a volume in which the thermal energy of the fuel combustion process is converted into mechanical energy [1]. Under operating conditions, the liner experiences high heating temperatures, tremendous pressure from the combustion of a mixture of fuel and gases, the effects of wear and tear friction [2].

Abrasive wear resistance [3] and macrogeometry conservation of the sleeve mirror during operation [2, 4] are taken as the main indicator determining the durability of the liner, especially diesel engines. The issue of obtaining cast iron sleeves with high macrogeometry stability during operation and at the same time with high wear resistance of the working mirror is still relevant.

The practice has shown that the best results on hardening cast-iron cylinder liners of engines are obtained by surface hardening with heating by high-frequency currents (HFC). It was shown in [5, 6] that with such hardening, a sufficient depth of the layer allows reshaping of the sleeve to repair dimensions, which increases the resource of its operation. However, during hardening of the high-frequency part of the working surface of the liners, significant stresses, deformation of the mirror geometry and insufficient hardness can occur. These factors cause increased wear on the cylinder liners. Therefore, to prevent these defects, it is necessary to select the optimal hardening conditions for HFC of each chemical composition of cast iron.

Main part

Heating using high frequency currents is a complex thermal process. The result of induction heating depends on a large number of factors and is associated with the properties of the electromagnetic sys-
tem, the basis of which is the heated object. The part is placed in an inductor connected to a high-frequency current generator [7]. An alternating magnetic field creates eddy currents in a thin surface layer of the metal, and heating is carried out due to the resistance of the metal to the flow of these currents. Immediately after heating, which lasts seconds, the part is placed in a sprayer for cooling.

The essence of the surface hardening of HFC is that the surface layers of cast iron parts quickly heat up to hardening temperatures, and then cool at a speed greater than critical. In the work [7] on the kinetics of induction heating, I.N. Khidin showed that a large power per unit of the heated volume at low temperatures decreased sharply when the surface of the product reached a temperature loss of magnetic properties, and the heating of the layer surface slowed down because of this. A diagram of the changes in the rates of high-frequency surface heating of steels and cast irons is presented in Figure 1.

![Figure 1](image)

**Figure 1.** The scheme of the kinetics of induction heating:
- a – eutectoid and hypereutectoid steels;
- b – pearlite cast irons

As can be seen from Figure 1, the surface is heated in 2 stages. At the first stage, heating is carried out to a temperature of loss of magnetic properties of 768 °C, while the heating rate is an order of magnitude higher than at the second stage. The second stage is characterized by heating from the temperature of loss of magnetic properties to the temperature of hardening. The total heating time for hardening is equal to the sum of the duration of the first and second stages. The temperature of the loss of magnetic properties in steels is located above the equilibrium temperature range of the eutectoid transformation $\Delta a_{1n} - \Delta a_{1k}$ (Fig. 1, a). The heating time for hardening is short; therefore, stress and deformation after hardening are also insignificant.

Due to the high content of carbon and manganese, cast irons have a wider eutectoid transformation interval located at higher temperatures than steel (Fig. 1, b). In this case, the temperature of the loss of magnetic properties may be lower than the temperature at which the perlite to austenite begins to transform. Therefore, in cast irons, an increase in the duration of the second stage is observed, which practically determines the time of high-frequency heating of cast irons to reach the hardening temperature. Long-term heating of cast iron products gives greater deformations and lower surface layer quality, including lower hardness than expected.

As can be seen, the reduction in the time of heating cast irons during surface hardening with heating by HFC requires a temperature loss of magnetic properties above the temperature values of the critical interval of the eutectoid transformation. This will reduce the total heating time, which has a positive impact on the results of hardening.
Optimization of the hardening mode of cast iron cylinder liners of engines is possible due to changes in the chemical composition of cast irons. The optimal chemical composition should provide a state in which the temperature of the loss of magnetic properties would be higher than the temperatures of the critical interval of the eutectoid transformation. We studied 30 melts of the following chemical composition: 2.8-3.8 % C; 0.5-2.3 % Si; 0-1.2 % Al; 0.5-1.2% Mn; 1.5-4.5 % Co. Comparison was made with serial sleeves of gray cast iron type SCh22, the chemical composition of which is 3.3 % C; 2.2 % Si; 0.6% Mn; 0.2 % P.

Taking into account the results of [8], graphitizer - aluminum was introduced as a substitute for silicon in low-silicon cast iron to obtain lamellar graphite.

In all melts, a structure with uniformly distributed rectilinear plate graphite with a metal base consisting of plate perlite P-P96 was obtained [11].

To record temperature changes, an N041UN.2 light-beam oscilloscope with M001-IA type galvanic inserts was used, which records instantaneous values of current and voltage. The presence in the oscilloscope of six speeds of motion of the film made it possible to obtain a scan of the fast-moving process of high-frequency heating of the surface.

The calibration of thermocouple and the oscilloscope were calibrated using the reference platinum rhodium – platinum thermocouple and the secondary fixed point of the international practical temperature scale (antimony solidification temperature) according to the procedure [9] with five repetitions. The comparison of the results showed good reproducibility.

When repeating the experiments, a chromel-alumel thermocouple with a diameter of thermo electrodes of 0.17 ∙ 10⁻³ m was used. The wires were fastened, the thermocouple was homogeneous, the circuit resistance was prepared to a predetermined value, the wires were shielded, and the filters were turned on according to the method proposed in [7]. The thermal inertia of the thermocouple was checked using acceleration curves [10], which reflect the reaction of the thermocouple to step disturbances.

The result of checking the selected thermocouples showed that with a step perturbation from 0 °C (water + snow) to 100 0 °C (boiling water), the delay of the thermocouple readings occurs in just 0.014 seconds. The duration of the entire disturbance at the selected heating rate of HFC at the first stage to the inflection point (Curie point) for cast iron of experimental melts is 1.2-1.3 sec (Fig. 2). Therefore, the inertia of the thermocouple can be neglected, since the delay time is small compared with the perturbation time. The temperature on the kinetic curves can be considered true at any time.

![Figure 2. Influence of the heating rate of HFC on the character cast iron kinetic curves:](image)

The average temperature of the inflection point on the kinetic heating curve (Curie point) for serial cast iron of the SCh 22 type was determined with a 15-fold repetition of the experiment and corresponds to a temperature of 751±2 °C (Fig. 2) with a confidence probability of P=0.95.
Table 1 presents the chemical composition of several melts for a series of experiments presented in Figure 3.

Table 1: The chemical composition of cast iron melts

| Melt number | Chemical composition, % | C  | Si | Al | Mn | Co |
|-------------|-------------------------|----|----|----|----|----|
| Etalon      | 3.3                     | 2.2| -  | 0.6| -  | -  |
| 4           | 3.8                     | 0.8| 0.6| 1.2| -  | -  |
| 7           | 3.3                     | 1.4| 0.6| 1.1| -  | -  |
| 23          | 3.2                     | 0.8| 0.6| 0.6| -  | -  |
| 28          | 3.0                     | 0.5| 1.2| 1.0| 1.5|    |
| 30          | 3.0                     | 0.5| 1.2| 0.9| 4.5|    |

Figure 3 shows a series of kinetic heating curves for high-frequency samples for cast irons of various chemical compositions.

When processing the experimental data by the least squares method in Mathcad, an equation is obtained expressing the dependence of the temperature of loss of magnetic properties (TQ) in cast iron on the content of alloying elements

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TQ = 747 + 1.6[C] - 1.0[Si] + 1.0[Mn] - 6.6[Al] + 14.6[Co]. \tag{1}
\]

As can be seen, the main elements of carbon, silicon, manganese do not have an impact on the temperature loss of magnetic properties in cast irons. The effect of aluminum at its low content, apparently, can be associated with an increase in the dispersion of perlite, which, as shown in [7], slightly decrease-
es the Curie point. Cobalt has a positive effect on increasing the temperature of the loss of magnetic properties, but negatively affects the quality of hardening and the efficiency of the manufacturing process.

**Conclusion**

The experiments showed that when induction heating with high-frequency currents in the same mode, corresponding to the capabilities of the production facility for hardening by HFC, the value of the loss of the point of magnetic properties in cast iron of experimental melts and serial case cast iron is approximately the same and corresponds to a temperature of 750 °C. Therefore, it is not practical to change the relationship between the temperature of the point of loss of magnetic properties and the temperature interval of the eutectoid transformation in gray pearlite cast irons by increasing the Curie point.

To reduce the heating time by high frequency currents during surface hardening of cast iron products, it is necessary to select the chemical composition of cast iron in such a way as to lower the temperature of the interval of critical transformations relative to the Curie point. In turn, this leads to an increase in the hardness of the surface layer and the dimensional stability of the finished products.

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