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# Formation of high-carbon abrasion-resistant surface layers when high-energy heating by high-frequency currents

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**Abstract.** The paper shows the possibility of carburization of low-carbon steel surface layers using high-frequency currents. The mathematical modeling of carburization using high-energy heating by high-frequency currents (HEH HFC) has been carried out, the temperature fields formed during the given processing have been calculated, as well as the structural changes in the surface layers have been simulated. The features of the structure formation in the surface layers of low-carbon steel after carburizing via HEH HFC have been determined by optical and scanning microscopy, which is confirmed by the computational models. The rational mode of fusion via HEH HFC has also been determined (power density of the source $q_s$ = (1.5 ... 4.0) · $10^8$ W $m^{-2}$, (the relative travel speed of parts $V_p$ = 5 ... 100 mm / sec), with forming the compressive retained stresses in the surface layer ($\sigma_{RS} \approx$ -300 ... -400 MPa).

## 1. Introduction

The problem of improving the abrasion resistance of the surface layers of metallic materials for constructional purposes is relevant. This is due to the fact that a large amount of machine parts and structural elements are out of order due to their abrasion [1 - 10]. One of the most cost-effective methods for solving the problem is chemical and thermal processing of steel. The most common method today is the cementation process followed by quenching and tempering. The main disadvantage of this method is high labor intensity and duration of the process. The second problem is that in the standard processes of surface saturation of steel by reinforcing elements it is almost impossible to handle large-size items. An effective solution of the problem is the use of high-energy heating processing of the surface layer of the material for the purpose of alloying. In modern production such methods of surface hardening of materials as laser treatment [11, 12], and plasma arc welding [13 - 17], electron-beam treatment [18 - 22] are successfully used. These technologies can significantly accelerate the process of hardening of the surface layer. Such heat sources as laser beam, plasma and electron beam can be used for rapid heating or melting the surface in a short period of time during which the heat is not able to penetrate deep into the product, and therefore, will not change its properties.

There is little research devoted to surface carbon alloying of low-carbon steels when exposed to high-frequency currents [23, 24]. This is probably due to the fact that during this type of processing it is very difficult to secure the saturant (carbon) on the surface of the part. During HFC processing, when exposed to a strong magnetic field, the carbon powder "is blown" off the sample surface. To find the solution of this problem is also an urgent task.

The aim of this work was to develop a surface carbon alloying technology of low carbon steel using high-energy heating by high-frequency currents.

## 2. Materials and methods

### *2.1. Materials and methods of field experiments*

The samples used for the surface hardening were the bars with the dimensions 10 × 10 × 100 mm made of steel 20 (0.19% C, 0.47% Mn, 0.20% Si, 0.009% P, 0.042% S, 0.15% Ni, 0.15% Cu), pre-treatment of which was carried out on the machining center DMC 635 and on the surface grinder 3G71. Graphite GL-1 (GOST 5279-74) was used as a saturant.

The bar surface was coated with graphite epoxy resin, after solidification of which the surface grinding was repeated. The saturant thickness was 0.1 ... 0.2 mm. The size control was carried on profilograph-profilometer Form Talysurf Series 2.

The samples with the hardened coating were processed on the contrivance, the main drive of which has stepless speed control in the range $V_p$ = (5 ... 200) mm / sec. The energy source was the vacuum-tube generator HFG 6-60 / 0.44 with an operating frequency of the current 440 $10^3$ Hz. The heating process was carried out on the depth pattern (the thickness of the hardened layer did not exceed the penetration depth of the current into the hot metal - 0.6 ... 0.8 mm) in a continuous-sequential manner. When hardening, a loop-type inductor, equipped with a ferrite magnetic core N87, was used (Figure 1) [25 - 28]. HEH HFC of the experimental samples was carried out in the following modes: the power density of the source $q_s$ = (1.5 … 4.0)·$10^8$ W $m^{-2}$, the travel speed of parts $V_p$ = (5 ... 100) mm / sec. The active inductor wire width was $R_s$ = 2 mm, the processing was carried out with a gap Δ = 0.1 ... 0.2 mm, followed by intensive water shower cooling of the surface (heat transfer coefficient α = 30·$10^3$ W / ($m^2$ ·°C) or by air cooling.

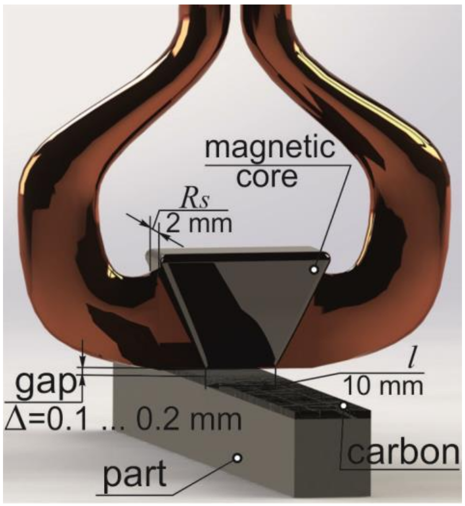


**Figure 1.** HEH HFC processing scheme

Structural studies of the samples were carried out using a light microscope Axio Observer A1m and scanning microscope EVO 50 XVP of the company «Carl Zeiss».

### *2.2. Mathematical modeling*

Preparation of the finite element of the model was carried out in the program complex ANSYS. ANSYS Meshing Generator formed the hexahedral mesh using the following types of finite elements: Solid bodies - solids were simulated by the 8-node tetrahedrons SOLID 45; Surface bodies - surface bodies were simulated by the 4-node 4- carbon shell elements - SHELL 63; Line bodies - linear bodies were simulated by the 2-node linear elements LINK 8. The size of finite elements was 0.01 ... 1 mm. The total number of elements (Elements) was 108800.

The modeling of the HEH HFC process was carried out in SYSWELD system allowing by using the model of elastic and viscoplastic response of the material and the modern mathematical apparatus to calculate the temperature fields, distribution of the structural components, hardness, internal stress and strain [28 - 30].

The advantage of the mathematical apparatus of the heat conductivity theory can be taken only when describing the heat source at the point of action properly. [23]

The adequacy of the mathematical model was tested indirectly via the structural studies carried out beforehand and the determination of micro-hardness of the hardened layer.

## 3. Results and discussion

The calculations have shown that when HEH HFC heating we can achieve sufficiently high heating rates $V_{hr}$ = 5 ... 50 · $10^3$ °C/sec and quenching rates (in the temperature range (700 ... 500) °C – $V_{qr\_700-500}$ = 3 ... 33 · $10^3$ °C/sec, in the temperature range (400 ... 150) °C – $V_{qr\_400-150}$ = 200 ... 4100 °C/sec). When the maximum surface temperature is 1700 ... 1750 °C, the formation of high-carbon layer is realized simultaneously with the surface fusion.

Such dynamics of the distribution of the thermal field in the cross section of the plate causes non-uniform structural and phase transformations in the material and occurrence of residual strains and stresses, the level of which on the surface may reach σ = -300 ... -400 MPa. When checking the adequacy of the mathematical model, the maximum error did not exceed 4 ... 8%.

Figure 2 shows the results of optical microscopy and modeling of structural and phase transformations for steel 20 with high-carbon surface layer formed after the air quenching. When HEH HFC processing the gradient material structure is formed: the structure of hypoeutectic cast iron is formed, and then the zone typical for hypereutectoid steel can be observed, which lengthens into the zone of the base metal (Figure 2). In this case the depth of the hardened layer was h = 0.23 mm, and the size of the transition zone was 0.04 mm. The microhardness of the surface layer was 6000 MPa, while the maximum compression residual stress on the surface σ = -340 MPa (calculated σ = -384 MPa). The feature of the transition zone in this case is the precipitation of excess cementite of widemanstatten type, indicating high heating temperatures and high quenching rate in that area (Figure 3a).

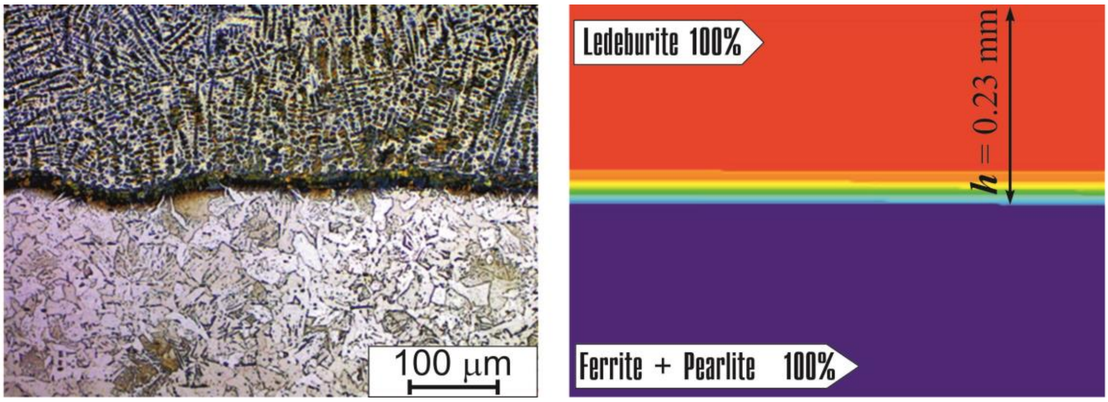


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**Figure 2.** Distribution of structural components of steel 20 with high-carbon surface layer: a) optical microscopy; b) the results of the simulation of structural and phase transformations.

Figure 4 shows the results of metallographic analysis and modeling of structural and phase transformations for steel 20 with high-carbon surface layer formed after water quenching. The formation of martensite is observed both in austenite forming a part of ledeburite fused layer (Figure 4a) and in the transition zone (Figure 3b). The formed structure has raised microhardness up to 7000-7500 MPa.

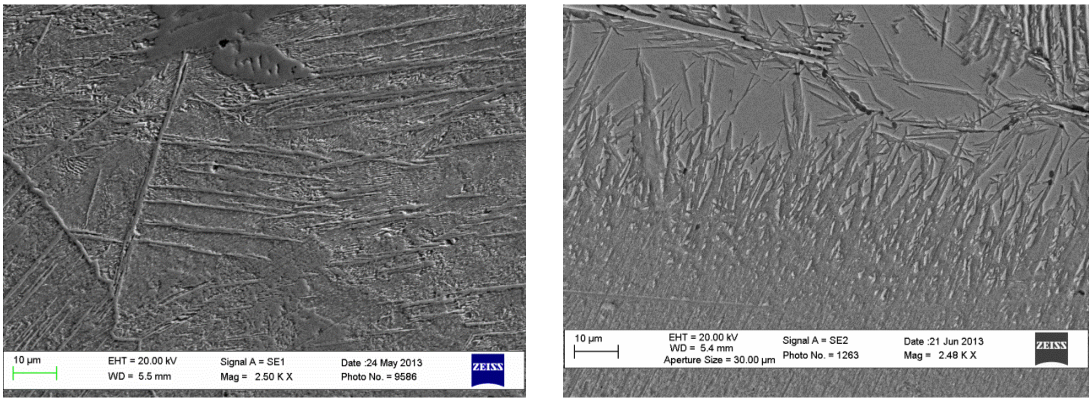


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**Figure 3.** The structural features of the transition zone: a) in air cooled samples; b) in water cooled samples

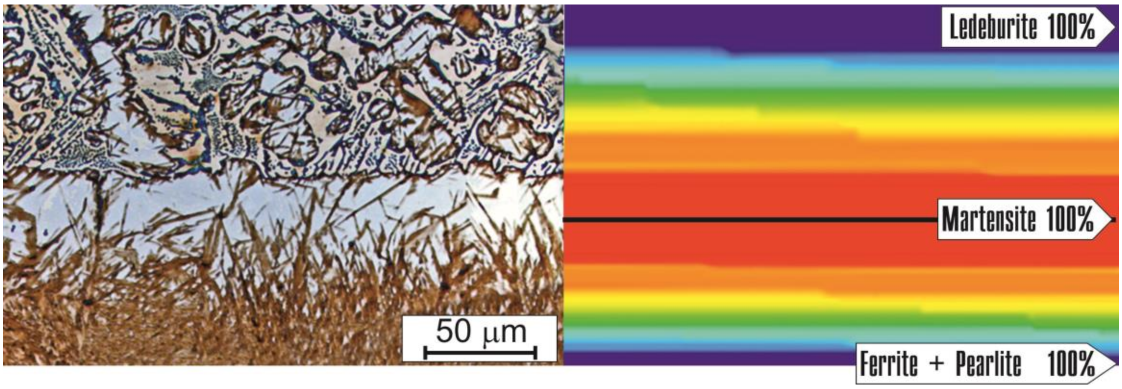


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**Figure 4.** Distribution of structural components of steel 20 with high-carbon surface layer near the transition zone: a) optical microscopy; b) the results of the simulation of structural and phase transformations.

## 4. Conclusions

1. The proposed technology of high-energy heating by high-frequency currents for producing high-carbon layers with increased hardness can compete with classic carburizing of the low-carbon steel. Due to instantaneous heating of the surface the carburizing layer is melted, mixed with the base and in the process of fast cooling the material forms a complex structure.

2. Via the optical and scanning microscopy it has been shown that in the process of HEH HFC heating followed by air quenching the hypoeutectic cast iron with high microhardness (6000-6500 MPa), and therefore high abrasion-resistance, is formed. If the processing finishes in water quenching, it will lead to the formation of the martensitic phase and, consequently, to an increase in the microhardness (7000-7500 MPa) and wear resistance.

3. By applying finite element method we have computationally solved the problem of modeling the stress and strain state of the material when surface high-energy hardening by high-frequency currents. It is shown that when high-energy heating by high-frequency currents the heating and quenching rates are, respectively: $V_{hr} = 5 \ldots 50 \cdot 10^3$ °C/sec and $V_{qr\_700\text{-}500} = 3 \ldots 33 \cdot 10^3$ °C/sec (in the temperature range 700 ... 500 °C). The level of residual compressive stresses on the surface of the sample is $\sigma_{max}$ -300… -400 MPa. The developed mathematical model is recommended for optimization of technological

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modes of processing, while ensuring large-sized hardened layers, comparable to the thickness of carburized layers produced by methods of classical carburizing technology (1-1.5 mm).

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