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The features of steel surface hardening with high energy heating by high frequency currents and shower cooling

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Abstract. The paper examines the process of surface hardening of steel 45 with the help of high energy heating by high frequency currents with simultaneous shower water cooling. We theoretically justified and experimentally proved a possibility of liquid phase forming in the course of heating not on the surface, but in the depth of the surface layer.

1. Introduction

Surface hardening of steel workpieces with concentrated energy sources is characterized by high rates of heating (tens of thousands of degrees a second) [1 - 7]. Under these conditions the heating of steel is carried out up to the melting temperature for the completion of the austenitizing process. While using the surface sources of heating (laser or plasma) the maximum values of temperatures are definitely observed on the surface of material proper [8, 9]. But for three-dimensional energy sources (electron beam, high frequency currents) this fact is not obvious. It is explained, first of all, by the physical nature of a three-dimensional source, i.e. by the law of energy distribution throughout the depth of a heated layer. A possibility of melted metal micro-volumes to form in the depth of material at heating with an electron beam in the atmosphere is shown in paper [10]. Ledeburite structure typical for the heat treatment of cast irons was registered in these areas during surface hardening of hypereutectoid steel.

At heating of steels in air medium by a concentrated electron beam the emitted energy distribution in material is similar to that of high energy heating by high frequency currents (HEH HFC) [11]. In this case during the surface hardening with HEH HFC one can also expect a possibility of liquid phase local volumes emergence in the depth of material.

The objective of this research is to determine the most heat-stressed layer during high energy heating of steel workpieces by high frequency currents with simultaneous shower cooling.

2. Materials and methods

HEH HFC allows implementing power density of around $3.0 \cdot 10^8$ W m^{-2} by a continuous method of heating. The processing scheme is presented in Figure 1 [12].

Typical features characteristic of HEH HFC consist in the following. For the maximum concentration of energy in the local material volume the heating is carried out at current frequency of 440000 Hz. To achieve this we used a flat loop inductor with minimum width of an active wire (b_{min} =1.2 mm) equipped by a ferrite magnet duct with high magnetic permeability. The treatment is carried out with minimum technological clearances of δ = 0.1... 0.5 mm. In order to prevent a possible break-down of an active wire and provide a reliable heat extraction the inductor wall thickness was chosen to be a = 0.12...0.15 mm [13, 14].

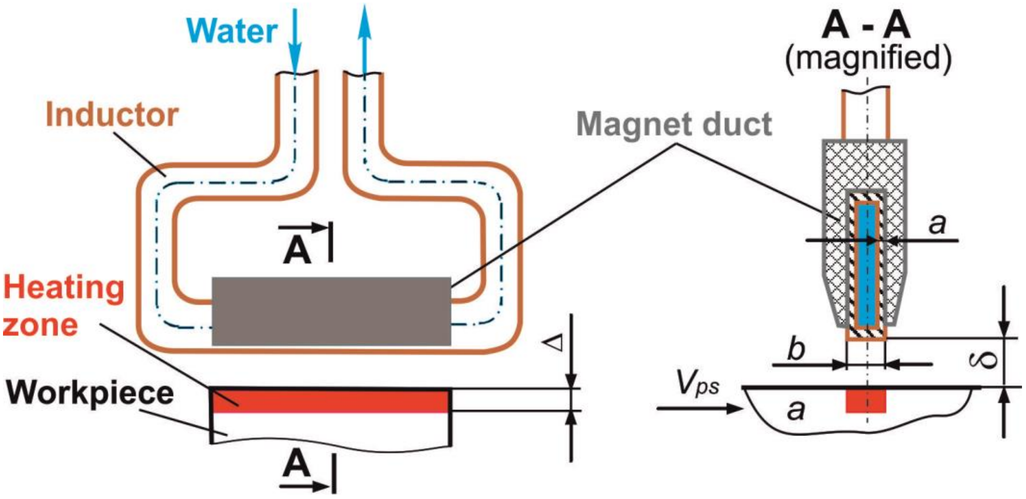


Figure 1. The scheme of processing with HEH HFC

The source of energy emission at HFC heating is the eddy currents emerging in the material under the influence of alternating magnetic and electric fields. The value of specific heating power will be defined by the density of current J, whose change in the depth of metal is described by the dependence

$$J_Z \big/ J_O = e^{-Z\cdot\sqrt{\frac{\pi\mu_0\mu f}{\rho_e}}}.$$

Here J_Z is the current density at the depth of Z; J_0 is current density on the surface; ρ_e is specific electric resistance; f is current frequency; μ_0 is the absolute magnetic permeability of vacuum, μ is a relative magnetic permeability of the material.

Specific electric resistance and magnetic permeability of steel change while heating, with specific resistance increasing up to the point of magnetic transformation, after which its growth slows. Magnetic permeability is hardly dependent on temperature up to approximately 650…700 °*C*, after which it rapidly decreases and approximately equals to the magnetic permeability of vacuum. Consequently, the energy distribution in the depth of the material is not constant.

The kinetic curves of workpiece surface heating by HFC have a bend in the interval of temperatures of 700…800 °*C*. The heating process is subdividing into the initial stage with great nearly constant speed of temperature increase and the stage of slower heating above temperature at which steel loses its magnetic properties. The redistribution of energy along section of a workpiece is the key reason of heating slowdown at the point of magnetic transformation. Indeed, there is always a temperature gradient during the heating on the section of a processed workpiece. The ρ_e and μ values depend on the temperature of the material. The spread of an electromagnetic process is thus occurring in an environment with ρ_e and μ variables. The paper [15] considers a case when material seemingly consists of two layers having different ρ_e and μ. If the first layer is heated above the temperature of 800 °C, and the second is not exposed to heating (20 °C), the distribution of eddy current would exactly correspond to a dependence presented in Figure 2. Therefore, under the condition that the top layer of material has lost ferromagnetic properties and the underlying layer is heated to temperature

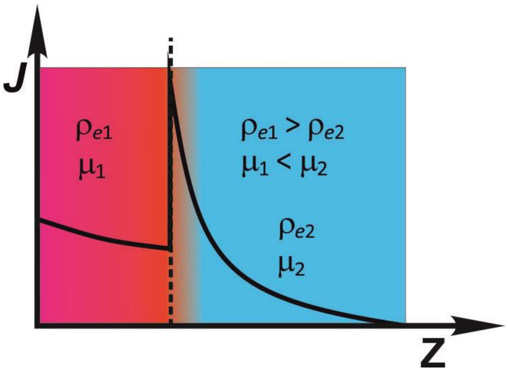


Figure 2. Current density distribution in the depth in a two-layer medium

not exceeding Curie temperature, there is a redistribution of current density. The maximum of energy emission shifts from the surface to the layer which did not lose ferromagnetic properties.

During modeling of temperature fields in steels under HEH HFC according to the algorithm presented in [11] we determined that at a certain combination of heating modes the temperature of the underlying layer could reach higher values than those on the surface (Figure 3). Thus temperature of the layer at the depth of Z = 0.2 mm from the surface reaches values of melting temperature of material while temperature of the surface layer is below this value. It occurs due to the fact that at the heating of the surface layer to Curie T_{k} temperature, when steel loses ferromagnetic properties, a large part of energy is emitted to the underlying layer. Simultaneously, intensive heat removal takes place in the surface layer by cooling liquid being fed directly to the heating zone, while in the underlying layer heat removal is regulated by the material heat conductivity. Under these conditions the formation of liquid phase not on the surface, but in deeper layers of heated metal becomes possible.

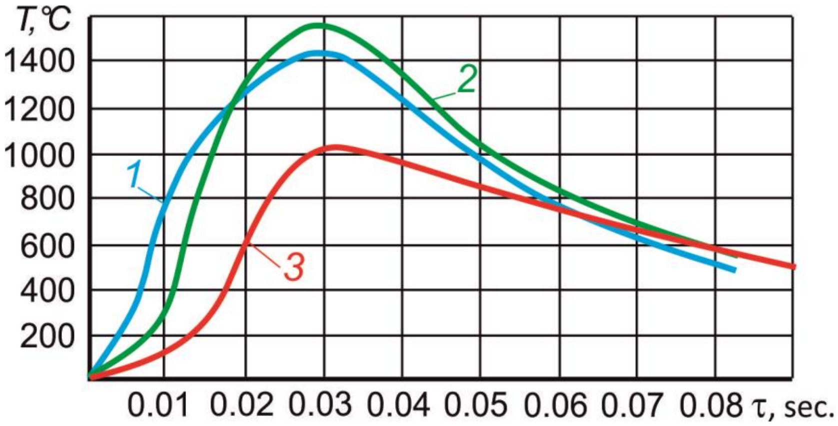


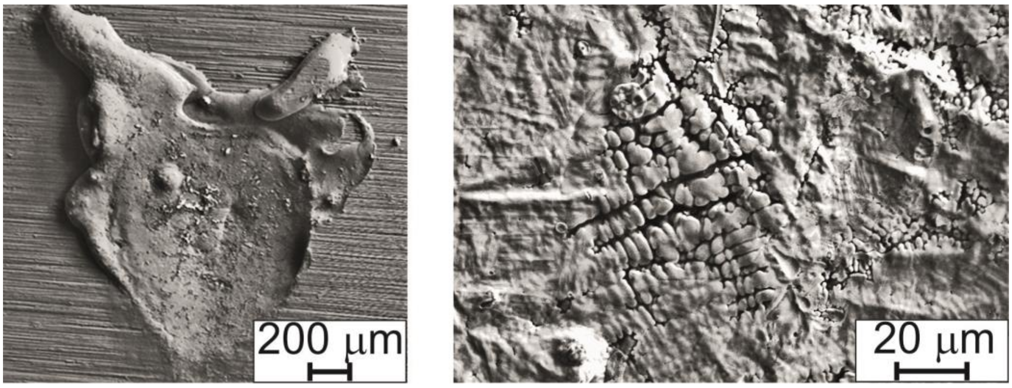
Figure 3. The heat cycles implemented on different depths of the surface layer with HEH HFC: the material is steel 45; specific heating power q = 200 MW/m^2, the part speed movement V_{ps} = 60 mm/s, b = 1.2 mm; *1* – Z = 0; *2* – Z = 0.2 mm; *3* – Z = 0.8 mm

Figure 4. The traces of meltdown on the hardened samples

We carried out the experiment in order to confirm the received modeling results of temperature fields with specific heating modes presented in Figure 3. While processing a cylindrical sample we registered the appearance of auto-oscillations of the inductor caused by periodic ejections of the melted metal to the surface (Figure 4).

3. Results and discussion

This phenomenon can be explained as follows. In these conditions the energy source is slowly moving, in other words, heat transfer speed is higher than the speed of a source motion. Therefore at the initial moment of heating no melting of metal is observed (Figure 3). At a certain moment of time the temperature at the depth of around 0.2 mm reaches the values of metal melting temperature (the curve 2, Figure 3). In this case a confined volume of melted metal forms in the near-surface layer in the zone located directly under the inductor. Thermal expansion of melt leads to the increase of pressure of this volume. The surface metal layer heated up to high temperatures (curve 1, Figure 3) turns plastic. It leads to dagger-shaped melting, in other words, melted metal is being thrown out of the underlying layer, leaving a crater (hole) on the surface of a sample, as well as beadings and drops of melted metal (Figure 5).



a b

Figure 5. The hole on the sample surface after the meltdown ejection (*a*) and a fragment inside the hole (*b)*

It is noteworthy that at certain combinations of surface hardening modes the melting of material can start on the surface layer. But, as can be seen in Figure 5, no traces of metal melting are observed up to the hole. The absence of melting traces after the hole is explained by the fact that there is a reduction of the clearance between the active inductor wire and processed surface in the course of an ejection of the melted metal, which leads to the increase of intensity of magnetic field between the inductor and the heated sample. This, in turn, increases a repellent specific mechanical effort between the inductor and the workpiece resulting in elastic deformation of conducting copper tubes and, as a consequence, the increase of the clearance and reduction of the specific heating density. After the passage of the melting zone, the value of the clearance is restored due to the inductor elasticity and the cycle of the workpiece surface heating repeats. The periodic formation of the metal meltdowns (Figure 4) is caused by this cyclic process. One important point is that there was no closure of the inductor active wire and the processed surface that could have led to the short circuit and melting of the copper in the inductor active wire and, as a result, its destruction. The X-ray microanalysis of the melted layer demonstrated no traces of copper in the meltdown (Figure 6), further supporting this idea.

As Figure 4 demonstrates, the ejection of the meltdown does not occur along the full width of the sample; instead it takes place in two locations. This is caused by the relatively labor consuming technology of the HEH HFC inductor production. The absolute linearity of the inductor active wire is difficult to provide. Its profile has linearity departures of about 0.02...0.04 mm that, undoubtedly, affect the level of specific heating density. The deepest meltdown occurs exactly in the two zones with minimum clearance between the inductor and the processed surface.

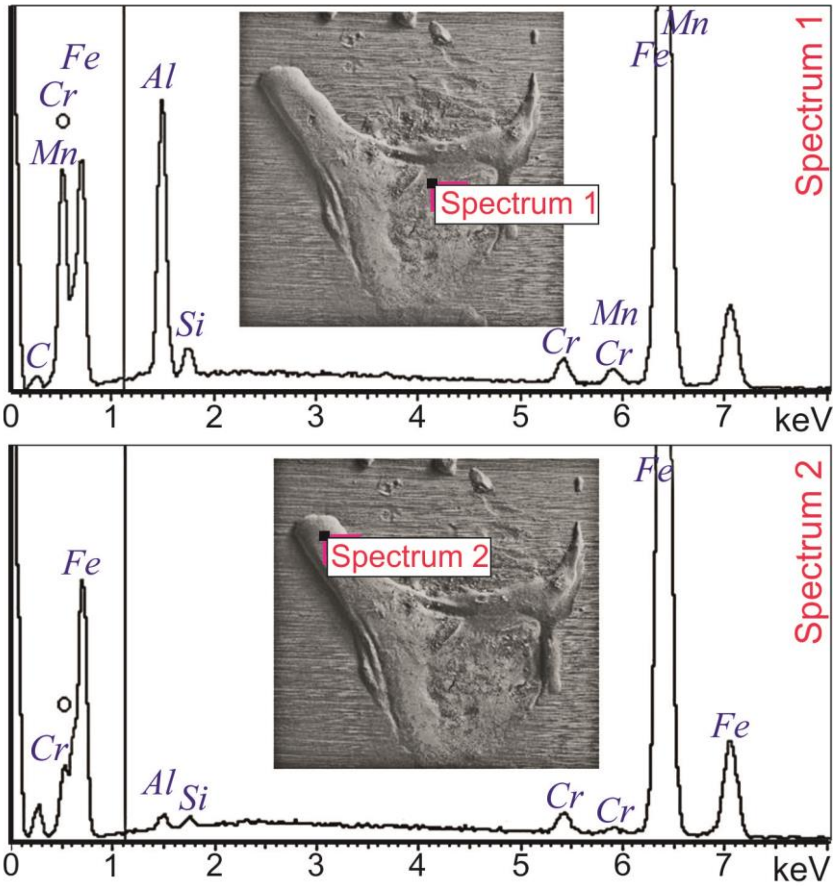


Figure 6. Diffraction patterns shot in two areas of local metal melting

Figure 7 demonstrates the surface fragments in the vicinity of the hole. The initial stage of metal melting is clearly visible here. In this zone metal melt formed at a smaller depth directly in the near-surface layer of the material. On the sample surface there are places of metal plastic deformation (swelling), as well as separate micro-craters of melted metal ejection.

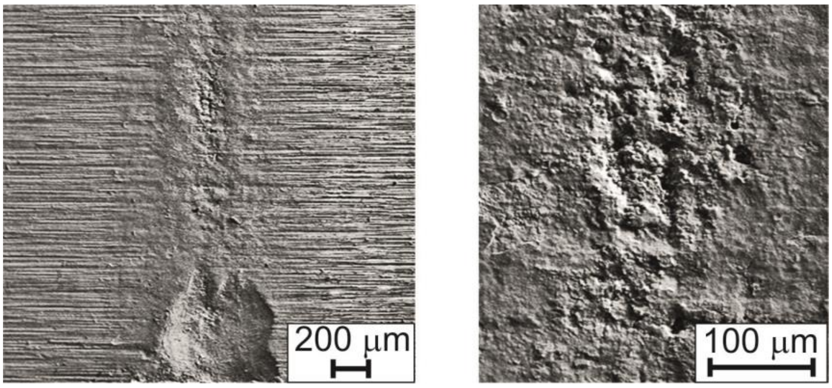


Figure 7. The fragments of the zone corresponding to the initial stage of metal melting

The images of different areas of the metal melting zone recorded on a raster *Carl Zeiss EVO50 XVP* electron microscope are presented in Figure 8. The presence of metal liquid phase, intensive cooling from the surface by feeding cooling liquid directly into the heating zone and intensive heat removal deep into the metal due to material conductivity lead to the conclusion about a possible receiving of an overcooled melt. The images demonstrate that dendrite structures form on the surface of the holes in the material. Metal crystallization occurred under the conditions of rapid cooling resulting in the emergence of significant magnitude gradients of stresses and, as a consequence, in the emergence of micro-cracks.

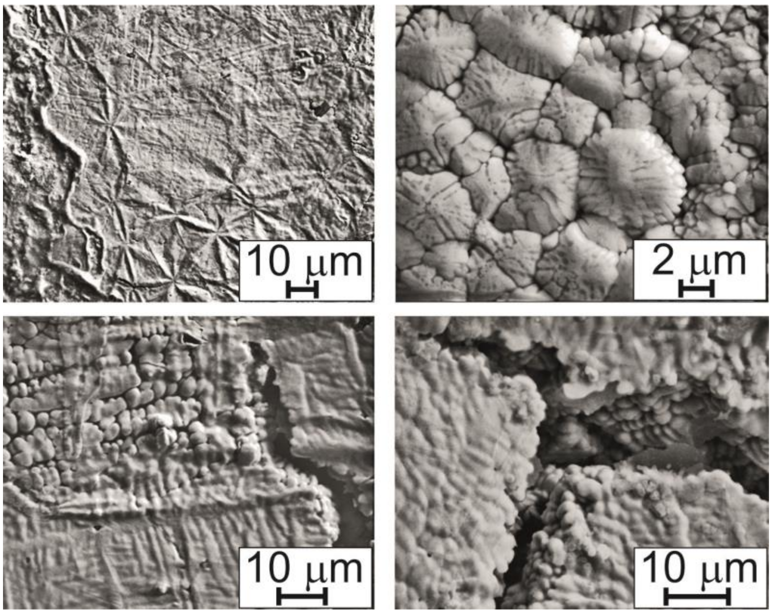


Figure 8. Fragments of the metal melting zone

4. Conclusions

During surface hardening of steels the presence of material melting is, as a rule, inadmissible. Thus, on the ground of the conducted research we came to the conclusion that the modes of surface hardening with HEH HFC and simultaneous shower cooling should be assigned on the basis of the most heat-stressed layer. For instance, for the steel 45 maximum temperature values are implemented at the depth of 0.15... 0.2 mm.

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