Researches concerning the influence of high and low frequency electric currents on the solid state transformations in steels

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Abstract

By an inductor for superficial hardening with 8kHz HF currents, having three coils: one for austenitizing and two for quasi-isothermal hardening of the bar steel surface, realised by simultaneous cooling with water, was studied the influence of the induction currents on the martensitic, bainitic and pearlitico-bainitic transformations in some carbon-steels and alloyed steels. The obtained microstructures indicates that the action of HF electric currents within the solid state transformation increases the driving force of allotropic transformation: \( \gamma \rightarrow \alpha' \) by a force of temperature gradient, bigger than those generated by a classical quenching after induction heating, determining a finer structure corresponding to an increased harness. Also, the influence of low frequency electric current on the pearlitic transformation was studied to some steel wire samples, resulting the influence of the I.f. electric currents and of the internal electric field on the spatialization and the shape of the pearlitic colonies lamellae.

Indexing terms/Keywords

Keywords: Bardeen equation, pearlitic lamellae, bainitic structure, martensitic transformation, induction currents

Academic Discipline and Sub-Disciplines

Solid state transformations of steels

SUBJECT CLASSIFICATION

Pearlitic, bainitic and martensitic transformations

TYPE (METHOD/APPROACH)

Experimental approach

INTRODUCTION

There are known experiments revealing the changes in superplastic behaviour generated by electric current pulses and the changes in the phase transformation kinetics resulted from applying an external electric field, [1].

The aim of the experimental work presented in the paper was to analyse the influence of the electric currents of high frequency or low frequency upon the solid state transformations of steels: pearlitic, bainitic and martensitic.

The micro-physical way by which the high frequency induction currents acts upon the Fe-atoms network of steels subjected to high frequency (HF) currents heating, refers to the action of an electro-kinetic force \( F_e(r) \), generated by the increasing of repulsive component: \( B/r^2 \), dependent to the kinetic energy of the network electrons, from the expression of the Bardeen-type potential of interaction among the metallic network atoms:

\[
U(r) = -\frac{A \cdot e^2}{r} + \frac{B}{r^2} + \frac{C \cdot e^2}{r^3}; \quad A, B, C - \text{constants}
\]  

The force \( F_e(r) = -\nabla U(r) \) overlaps with periodical inversed sense on the driving force \( f_x(T) \) of the allotropic transformation and contributes to the CFC structure destabilization, in a favourable sense for the allotropic transformation: \( \gamma \rightarrow \alpha' \). Of practical point of view, this phenomenon presents importance for the superficial hardening with HF currents heating.

2. The method and the inductor used for hardening under the action of induction currents

For experimental and applicative purposes was studied the possibility to obtain bainitic and martensitic structures by superficial quasi-isothermal hardening under the 8kHz induction currents generated during the transformation in the surface of some carbon-steel or alloyed steel bars by a special realised inductor, [4-6].

As a solution to this issue, was proposed a method and an inductor for thermal treatment with HF currents heating of the hollow or bar-shaped steel sample pieces. The inductor used in these experiments was formed with three coils, with the first coil for heating in the austenitic domain and with the second and the third coil for quasi-
isothermal maintaining under A1 critical point, in the pearlitic, bainitic or martensitic domain, by the simultaneous action of the induction electric currents and of the cooling water which is circulated through inductor and get out through holes uniformly disposed on the interior surface of the second and the third coils, (method named in a little forced way: “quasi-isothermal hardening” [4 -6]).

The dimensions for inductor were: \( \phi = 21 \text{mm}; \ h_{\text{tot}} = 50 \text{mm}; \ h_{\text{coil}} = 10 \text{mm}; \) the space between the first and second coil: \( h_d = 10 \text{mm}. \)

The experiments were made at S.C. INDUCTRO S.A. - Bucharest, at 8kHz frequency of the induction currents and with water as cooling liquid, having as samples- bar segments of 20mm diameter\( \times \)80mm length and 55mm length Charpy samples . The used installation was of type: MSJ70, with rotative generator of a maximum power: 100kW.

The used steels for the test samples are mentioned in the table 1, (old national standard):

<table>
<thead>
<tr>
<th>Steel</th>
<th>C%</th>
<th>Mn%</th>
<th>Si%</th>
<th>Cr%</th>
<th>Mo%</th>
<th>Ni%</th>
<th>Cu%</th>
<th>( A_1 )°C</th>
<th>( M_s )°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>35Mn16</td>
<td>0.34</td>
<td>1.56</td>
<td>0.39</td>
<td>0.14</td>
<td>0.04</td>
<td>0.11</td>
<td>0.12</td>
<td>695</td>
<td>325</td>
</tr>
<tr>
<td>OLC45</td>
<td>0.5</td>
<td>0.6</td>
<td>0.35</td>
<td>0.15</td>
<td>0.04</td>
<td>0.11</td>
<td>0.05</td>
<td>735</td>
<td>350</td>
</tr>
<tr>
<td>OLC55</td>
<td>0.57</td>
<td>0.61</td>
<td>0.35</td>
<td>0.17</td>
<td>0.04</td>
<td>0.11</td>
<td>0.05</td>
<td>723</td>
<td>290</td>
</tr>
<tr>
<td>OLC60</td>
<td>0.62</td>
<td>0.55</td>
<td>0.24</td>
<td>0.05</td>
<td>0.02</td>
<td>0.05</td>
<td>0.08</td>
<td>720</td>
<td>285</td>
</tr>
<tr>
<td>42MoCr11</td>
<td>0.45</td>
<td>0.77</td>
<td>0.37</td>
<td>1.05</td>
<td>0.07</td>
<td>0.27</td>
<td>0.2</td>
<td>730</td>
<td>310</td>
</tr>
<tr>
<td>OSC8</td>
<td>0.81</td>
<td>0.26</td>
<td>0.33</td>
<td>0.2</td>
<td>0.05</td>
<td>0.15</td>
<td>0.11</td>
<td>720</td>
<td>210</td>
</tr>
<tr>
<td>OSC10</td>
<td>0.98</td>
<td>0.25</td>
<td>0.33</td>
<td>0.4</td>
<td>0.05</td>
<td>0.15</td>
<td>0.11</td>
<td>725</td>
<td>210</td>
</tr>
</tbody>
</table>

Was studied the action of 8KHz induction currents during the following transformations of these steels:

1. Bainitic transformation : to steel samples of OLC55 and 35Mn16, (set no. 1);
2. Martensitic transformation : to steel samples of OLC45, 42MoCr11, OSC8 and OSC10, (set no. 2);
3. Pearlito- bainitic transformation: to steel samples of OLC 45, OLC60, 42MoC11 and OSC10, (set no. 3).

3. Experiments realised with high frequency currents

3.1.- The 1st Set of experiments

A first set of heat treatment experiments with quasi-isothermal transformation under the action of induction currents, was made having as samples bar segments of 20mm diameter and 80mm length, from steels: OLC55 and 35Mn16.

The steel samples were heated with HF currents until approx. 920°C with the first coil of the inductor and cooled with water under the action of induction currents, with the second and the third inductor coil, at a speed of approx. 3mm/s of the steel sample passing through inductor.

The following structures were obtained:

<table>
<thead>
<tr>
<th>Steel</th>
<th>35Mn16; (O.2.2)</th>
<th>35Mn16; (O2.3)</th>
<th>OLC55; (O2.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro-structure</td>
<td>Upper Bainite</td>
<td>Lower Bainite</td>
<td>Martens. +res.A.</td>
</tr>
<tr>
<td>Hardness</td>
<td>45 HRC</td>
<td>51 HRC</td>
<td>56 HRC</td>
</tr>
</tbody>
</table>

For comparison, with a common inductor has been realized also some classic treatment of hardening by HFC heating, with or without tempering, in the following way:
The temperature of the quasi-isothermal maintaining stage was done by controlling the cooling liquid flow, as well as by the control of the power transmitted to the inductor piece (the installation power). For visualize the samples structures has been used metallographic attack with Nital 2%, the magnification being x750.

The micro-structures corresponding to the superficial induction HF hardening heat treatment of the used samples and TTT diagrams with the specific cooling curves, are shown in the drawings: I-III.

Observations and conclusions

From the first set of experiments realized with the HF hardening inductor under the action of induction currents, the following observations raised up:

- By solid state transformation with maintaining at temperatures in the bainitic and martensitic domain, under the action of induction currents, all specific transformation structures were obtained: upper bainite, lower bainite and martensite, but was observed that:
  - the upper bainite obtained under the action of induction micro-currents of 8kHz frequency (O.2.2) presents a lamellar aspect very similar to the lower bainite;
  - the lower bainite obtained under the action of high frequency micro-currents (O.2.3) is more developed than the lower temper bainite (O1.2), with longer needles morphology;
  - the martensite obtained under induction micro-currents at a speed of approx. 3mm/s is more homogeneous than the martensite of classic hardening with HFC, with fine needles with a tendency of parallelism (O1.3., in comparison with O1.1);
  - the surface hardness of samples subjected to bainitic hardening heat treatment under the action of HF induction currents (O.2.2, O.2.3) is equivalent to those of low-temper martensite, (O.2.1).

This last experimental result can be explained by the conclusion that the bainitic morphology of steel transformation is influenced by the action of induction micro-currents during the transformation in the sense of the bainite plates sizes increasing through an increased transformation’s driving force, as a result of an increased value of the repulsive potential term of the Bardeen relation (1).

3.2.- The second Set of experiments

-In a second set of heat treatments of quasi-isothermal martensitic hardening with 8 kHz induction currents, and with water as cooling liquid, with the used method and inductor, were treated by superficial hardening the following steels: OLC45, 42MoCr11, OSC8, OSC10, as U-Charpy samples, of 55mm with a u2 notch, coupled in pairs.

A P2 subset was subjected to classic martensitic hardening (C.h.) with HF currents heating and a P1 subset was subjected to hardening with the quasi-isothermal quenching inductor, under the induction currents action, (e.c.h.), with the same parameters, except the inductor power.

The heat treatment parameters, the obtained structure, the hardness and the obtained tenacity are presented in the table 4 of below:

Table 4: The structure, the hardness and the tenacity of steel samples

<table>
<thead>
<tr>
<th>Steel</th>
<th>Sample</th>
<th>T.aust. (°C)</th>
<th>Ind.Pow. (kW)</th>
<th>S.speed (mm/s)</th>
<th>Hardness(HV30)</th>
<th>Tenacity (J)</th>
<th>Structure</th>
<th>+Ares. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: OLC45</td>
<td>P1 (e.c.h.)</td>
<td>-890°</td>
<td>45</td>
<td>4</td>
<td>798</td>
<td>90</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P2 (C.h.)</td>
<td>-890°</td>
<td>75</td>
<td>4</td>
<td>660</td>
<td>78</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td>R2: 42MoCr11</td>
<td>P1 (e.c.h.)</td>
<td>-890°</td>
<td>45</td>
<td>4</td>
<td>700</td>
<td>0.4</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P2 (C.h.)</td>
<td>-890°</td>
<td>75</td>
<td>4</td>
<td>590</td>
<td>0.8</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td>R3: OSC8</td>
<td>P1 (e.c.h.)</td>
<td>-890°</td>
<td>45</td>
<td>4</td>
<td>883</td>
<td>0.4</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P2 (C.h.)</td>
<td>-890°</td>
<td>75</td>
<td>4</td>
<td>862</td>
<td>0.3</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td>R4: OSC10</td>
<td>P1 (e.c.h.)</td>
<td>-890°</td>
<td>45</td>
<td>4</td>
<td>885</td>
<td>0.3</td>
<td>Martens.</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>P2 (C.h.)</td>
<td>-890°C</td>
<td>75</td>
<td>4</td>
<td>862</td>
<td>0.2</td>
<td>Martens.</td>
<td>15</td>
</tr>
</tbody>
</table>
The obtained microstructures are presented in the micrographs of the drawing IV.

The roentgenograms (drawings V) confirmed the obtaining a more strained martensitic structure under the action of the induction microcurrents, corresponding to less intense diffraction lines for P1 comparative with P2.

**Observations and conclusions**

From the second set of experiments realized with the superficial treatment inductor under the action of induction currents, the following observations raised up:

- It is observed that, in relation to the classic heating by HFC hardening, at the martensitic hardening under the induction currents action were obtained hardness on surface with up to 140HV, higher, to all treated steels, with the tenacity characteristic to the classic hardening with heating by HF currents or even a little higher, to OLC45, which is therefore an indicated steel for martensitic hardening under the induction currents action. It is also observed by the obtained micrographs, a higher size for the martensite needles resulted by intense cooling under the induction currents action, which could be explained by the conclusion that the maintaining of induction currents action during the martensitic transformation, increases the value of the transformation driving force by means of the repulsive component, given by the electrons kinetic energy, of the Bardeen potential (1), which increases the gradient of this potential on the radial direction from the test piece surface.

The observed supplemental induction micro-currents hardening effect presents similitude with the observed effect of an external electric field which, applied during the steel heat treatment, has accelerated the austenite transformation and has increased the hardening, [1].

The generating and the maintaining of an increased driving force proportional to the temperature gradient, at the martensitic transformation under HF current action, may be explained by the fact that, at approximate 4mm from the sample surface, the induction micro-currents maintains a high temperature, although the sample surface is intensive cooled with water and has the temperature under 150°C in the space of third inductor coil.

In this case, results a higher temperature gradient-comparative with the classical superficial hardening, when the obtained temperature gradient rapidly decreases at cooling, passing from the initial gradient (i) to lower gradients (2,3), to the value f, like in the fig. 2.

The dependence of the martensitic transformation driving force to the temperature gradient, results in the form [7]:

\[
F_b = -\text{grad}U(r,T) \approx \frac{\Delta U_{12}}{2a} = \frac{\beta \cdot b^0}{a^2} \cdot \gamma \cdot \text{grad}T
\]  

(2)

where: \(\beta\)-constant dependent of chemical potential;
\(\gamma\)- dilatation coefficient; \(a\)- the network parameter, the relation being obtained by simplifying the Bardeen potential expression (1) in the form:

\[
U(r,T) = U_a + U_r = -\frac{\alpha \cdot a^0}{r} + \frac{\beta^0 \cdot b^0}{r^2} (1 + \gamma \cdot T) \quad \text{; } \quad \beta^0 (1 + \gamma \cdot T) = \beta
\]  

(3)

by the radius dilatation expression:

\[
r_b(T) = \frac{\beta \cdot b^0}{\alpha \cdot a^0} = a_0 \cdot (1 + \gamma \cdot T) = a(T)
\]  

(4)

**3.3.- The third Set of experiments**

In two subsets of superficial hardening under the action of HF induction currents during the solid state transformation, was studied the influence of HF induction currents during the pearlitic transformation.

**3.3.1.- The first sub-set of the third Set**

In a first subset of heat treatments of quasi-isothermal hardening with 8 kHz induction currents and with water as cooling liquid, were superficially hardened steel bars of approximate 20mm diameter and 80 – 200 mm length from: OLC45, OLC60, 42MoC11 and OSC10, heated with HF currents generated by the first coil under Ac3 and cooled with
water under the action of induction currents with the second and the third coil, on a sample speed passing of ~1mm/s through the inductor coils. The obtained results are presented in the table 5.

For the samples O.5.2 and O5.3 (42MoC11 - table 5), the flow of cooling water was increased comparative to O.5.1. The steel sample O.6.2 (OSC10) has been classically hardened with HF currents heating, for comparison.

The determined hardness variation is presented in the fig. 4, in the fig. 3,a being presented the hardened area at O.5.3.

The determined hardness variation is presented in the fig. 4. For the micro-structures visualizing, the heat treated bar ends, cut with abrasive disk under water and finely smoothed, were attacked with Nital 2%.

The initial heat treatment of the samples corresponds to the properties necessary for the sample core.

**Table 5**: Structures of solid state transformation under H.F. induction currents action

<table>
<thead>
<tr>
<th>Sample</th>
<th>Steel</th>
<th>Microstructure (center)</th>
<th>Microstructure (margin)</th>
<th>( T_{\text{Aust}} ) (^\circ\text{C})</th>
<th>Initial heat treatment</th>
<th>Transformation Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3.1</td>
<td>OLC45</td>
<td>Ferrite.+ globular and lamellar Pearlite</td>
<td>Ferrite.+ globular Pearlite</td>
<td>960°</td>
<td>Harden.+ high tempering</td>
<td>Pearlitic (quasi-is.hardn.)</td>
</tr>
<tr>
<td>O4.1</td>
<td>OLC60</td>
<td>Ferrite+ globular P. and sorbite</td>
<td>globular P. + lower Bainite</td>
<td>920°</td>
<td>Harden.+ high tempering</td>
<td>Pearl.+Bain. (quasi-is.hardn.)</td>
</tr>
<tr>
<td>O5.1</td>
<td>42MoC11</td>
<td>Sorbite+ isolated F.</td>
<td>.globul.+ lamel. Pearlite + lower Bainite</td>
<td>870°</td>
<td>Harden.+high tempering</td>
<td>Pearl.+Bain. (quasi-is.hardn.)</td>
</tr>
<tr>
<td>O5.2</td>
<td>42MoC11</td>
<td>Sorbite+ insular Ferrite</td>
<td>Globular Pearl. + sorbite + v. fine Martensite</td>
<td>970°</td>
<td>Harden.+high tempering</td>
<td>Pearl.+Mart. (quasi-is.hardn.)</td>
</tr>
<tr>
<td>O5.3</td>
<td>42MoC11</td>
<td>Sorbite</td>
<td>globular Pearl. + carbides + v.fine Martensite</td>
<td>920°</td>
<td>Harden.+high tempering</td>
<td>Pearl.+Mart. (quasi-is.hardn.)</td>
</tr>
<tr>
<td>O6.2</td>
<td>OSC10</td>
<td>Inf.Bain. +sorbite+ intragranular. crack</td>
<td>Inf. Bain.+ netw. and Intragranular Cem. + v.fine Martensite</td>
<td>890°</td>
<td>Harden. +low tempering</td>
<td>Bain.+Mart. (Classical h.f.c. hardening)</td>
</tr>
</tbody>
</table>
3.3.1.1. **The analyze of the hardness curves**

From the hardness curves (fig. 4), in correlation with the obtained microstructures, (table 5 and drawings VI-VIII) , it results the following:

a) to the sample O.3.1. (OLC45) – the hardness variation has been slow, as a consequence of a relatively small structure difference between core and surface, given by a higher amount of globular pearlite in the sample surface;

b) to the sample O.4.1. (OLC60) , the hardness in surface has been sensibly higher than that in core; this result indicates that the globular pearlite formed in surface is associated with the bainite.

c) to the samples: O.5.1.; O.5.2. and O.5.3., (42MoCr11), in the superficial zone of a 2…3 mm deepness, the hardness has resulted higher than in centre, which also indicates the hardening role of the harder associated component: the lower bainite-for O.5.1. and the fine martensite for O.5.2. and O.5.3.- more intensive cooled than O.5.1., having two steps of hardness variation, corresponding to the martensite and to the lower bainite formation, resulted by a higher driving force of the allotropic transformation.

d) related to the sample O.6.1. (OSC10) it is observed that the hardness on surface, obtained by quenching in two stages, is the same with the hardness in surface to the sample O.4.1. (OLC60) with the structure identified as being of globular pearlite + very fine inferior bainite, fact that indicates a similar surface structure. The roentgenograms confirmed the obtaining of a bainitic or/and martensitic constituent in the sample surface, corresponding to less intense diffraction lines, comparative with the sample core structure.

3.3.1.2. **The transformation curves**

Correlated with the previous conclusions resulted from the analyze of the hardness curves and the micrographs obtained for surface, it has been drawn also the transformation curves of TTT diagrams (drawing. IX) by approximating and repeating the stage shape of the time : \( \Delta t_1 = \Delta t_2 = h_{sp}/v_{sp} \) given by the sample passing through the second and the third coils of inductor, with the constant speed \( v_{sp} \), after a time \( \Delta t_1 = h_{sp}v_{sp} = 10\text{sec.} \) from the austenitizing, corresponding to the interval of 10 mm between the first and the second coil.

3.3.1.3. **Observations and conclusions**

- Regarding the microstructure from the test piece, superficially treated with cooling under the action of induction micro-currents, it is observed as general characteristic of the used steels O3, O4 and O5, the formation, besides the fine hard component – bainite or fine martensite, of exclusively globular pearlite at OLC45 and OLC60, associated with a small amount of lamellar pearlite or sorbite, at 42MoCr11. This globular pearlite structure is characteristic to the heat treatment of incomplete annealing and was formed because that the used austenitizing temperature was not higher than the Ac3 critical point temperature specific for the used heating rate, (=100°C/sec.). In consequence, it was realized a new set of heat treatments under the H.F.C. action with the same sample speed in the inductor space but with an austenitizing temperature higher than Ac3, for observe also the influence of H.F.C. on the pearlitic lamellae formation mechanism.

3.3.2. **The second sub-set of the third Set**

In a second subset of heat treatments of quasi-isothermal hardening with 8 kHz induction currents and with water as cooling liquid, with the same inductor and method, were superficial treated steel bars from OLC60 – for pearlitic-bainitic transformation under the induction currents action with austenitizing at a temperature \( T_a \) higher than Ac3, (to \( \sim 1150^\circ C \)).

There were used steel samples of 80mm length and 20mm diameter, with pearlitic initial structure.

The heat treatment parameters, structure and hardness are presented in the table 6 and the obtained micro-structures, visualized at 1000x and 2000x magnification, are presented in the drawing X.

**Table 6: The structure and the surface hardness to O4` steel samples**

<table>
<thead>
<tr>
<th>Steel sample O4` - OLC60</th>
<th>Temp. of aust. (°C)</th>
<th>Power on inductor (kW)</th>
<th>Pas. speed (mm/s)</th>
<th>Structure</th>
<th>Surf.Hardn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>O4<code>P1</code></td>
<td>1150</td>
<td>15</td>
<td>-1</td>
<td>Pearl.+( fine mart.)</td>
<td>630 HV</td>
</tr>
<tr>
<td>O4<code>P2</code></td>
<td>1150</td>
<td>10</td>
<td>-1,7</td>
<td>Pearl.+(fine mart.)</td>
<td>530 HV</td>
</tr>
<tr>
<td>O4<code>P3</code></td>
<td>1150</td>
<td>10</td>
<td>-1,7</td>
<td>Pearl.+(fine mart.)</td>
<td>450 HV</td>
</tr>
</tbody>
</table>

**Observations and conclusions:**

From the obtained micrographs (drawing X) has been found that in the steel test pieces’ surface with initial pearlitic structure, passed with low speed through the inductor under the action of induction currents also in the cooling stage, after austenitizing at \( \sim 1150^\circ C \), it results in association with very fine martensite, the formation of troostite in
rosette—found especially at the hereditary austenitic grains limits, where the driving force of the transformation was higher, and a small amount of parallel fine sorbitic lamellae, perpendicularly grown on the grain limit.

This experimental result shows that the action of 8 kHz induction currents during the pearlitic transformation not impede the formation of the pearlitic lamellas, but the preponderant troostitic and very little sorbitic structure formed in the sample surface, suggests the conclusion that the induction currents could have a role of finishing the pearlitic structure, in the sense of favouring the troostite formation. The fact that the HC currents not impede the growth of pearlitic lamellas may be explained by the conclusion that— for a intense disturbance of the pearlitic lamellae growth, it is necessary a period of induction HF currents close to the necessary time for the carbon diffusion between two cementitic lamellae of the pearlite, i.e.—a frequency of the induction currents of 100-400 MHz, according to a theoretical result of the author, [4], [7].

3.4. Another method and inductor for the bainitic hardening

An alternative method of superficial hardening transformation control to the steel pieces hardened with the presented method and inductor of quasi-isothermal superficial hardening, consists in electrically supplying the inductor with high frequency electric currents, but in low frequency pulses, of 5-50 Hz—depending to the piece passing speed through the inductor coils or/and the specific supply power and of the cooling water flow. In this way, after austenitization, the cooling speed between the HF current impulses results according to the martensitic hardening and the method is equivalent with a martensitic superficial hardening with repeated low tempering and quenching.

This alternative may be recommended for example for the superficial hardening of tools made of OSC.

The installation modifying, needed to apply this alternative of hardening by HF currents heating, is minimal, involving only an electronic switch of low frequency.

For hardening followed by low tempering, the same type of inductor can be used, with a quasi-isothermal maintaining of simultaneous heating and cooling stage, but with the first coil, for austenitizing, provided with holes (i) obliquely disposed for quenching, and the coils (2), (3) realised as for the inductor of quasi-isothermal bainitic hardening, but placed at a distance of 2...3 coils from the first coil, (figure 6).

1. Experiments realised with low frequency currents

The influence of the electric current of low frequency on the pearlitic transformation of some 3 mm diameter and ~1 m length wires of carbon-steel OLC 75 was studied by an experimental heating installation using 50 Hz AC electric current generated by a 48 V and up to 180 A output welding transformer with continuous adjustment. The obtained microstructures, showing sinuous pearlitic lamellae with variations of the interlamellary distances, indicates the influence of the electric current.

The experimental installation was shown schematically in figure 7a and figure 7b is a top view of the installation. The wire “s” was fastened between two bronze electric contactors 2 fixed to the wooden stand 1 and connected to the output of the electric transformer Tr.
In parallel with the wire "s", another thinner wire, 3, with a cursor rheostat, was fitted between the contactor 2 and a switching plate of a switch K through which the wire 3 was alternatively included in the electric circuit after the wire "s" to be treated has reached the austenitizing temperature, with the aim to reduce the electric current through the wire "s" and to lower its temperature until the pearlite transformation domain, where it was maintained by alternative actuation of the K-switch.

The micrographs of the obtained pearlite structures are presented in drawing XI in which S1 is the micrograph of a wire sample austenitized by electric current and slowly cooled in air and S2, S3, S4 are micrographs of the pearlitic structure obtained to the wire samples under the action of low frequency electric current.

Comments and conclusions:
-From the micrographs of pearlitic structure obtained for the S1-S4 wire samples, (drawing XI), it results a relatively normal pearlitic structure with relatively large hereditic austenitic grains and parallel pearlite lamellae of the S1 wire, cooled in air. To the S2 and S3 wire samples pearlitized under the action of the low-frequency electric current and high intensity, applied pulsatorily, is observed a granulation of a finer structure and in the S4 wire- a high degree of the irregularity of the granulation as well as of the formation of pearlite colony, phenomenon probably caused by the pulsating application of the electric current during the perlite transformation.

With regard to the lamellary structure of the pearlitic colonies, 'it is observed from the micrographs that – in contrast to the relatively normal pearlite structure, with the relatively parallel parallel perlite lamellae, of the S1 wire sample- cooled in air, the spatialization and the shape of the pearlitic colonies lamellae are slightly disturbed to the S2 wire in report with the right increasing of the normal pearlitic lamellae, the pearlitic lamellae growned under the low frequency electric currents action presenting sinuosities and interlamellary distances with large variations on the S3 wire sample and especially on the S4 wire sample, caused by the action of the electron flow of the high intensity electric current but also by the internal electric field, E, generating the electrical force F = qE at the applying of the alternately electric voltage.

The much larger distances between the pearlitic lamellae of the central area of the S4 wire sample ($x2000$ micrograph) in report to the pearlitic lamellae of the lower adjacent zone, corresponds logically to the action of the low frequency electric current I and the electric field E in the sense of the $F = qE$-driving force increasing, force which acts on the diffusion of C- atoms (which are non-ionic in steels [8]), during the lateral growth of the pearlitic colony.

In conclusion, the electric currents applied during the solid state transformation may increase the transformation's driving force, determining a more complete transformation of the austenite. The method may be applied to the quasi-isothermal hardening of steels by heating with induction currents. An supplementary advantage is given by the fact that it results- after quenching, an finely oxidized surface of the treated steel bar, as consequence of a browning effect, which protect the steel against oxidation.

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REFERENCES

O1.1. martensite, 62HRC, classic hardening

O1.2. inf. bainite, 42 HRC, harden.+low tempering

O1.3. martensite+res.austenite, 56HRC-quasi-isothermal harden. under HF currents

O2.1. temper martensite+carbides; 45HRC, superf. hardening+low tempering
O.2.2- upper bainite, 45 HRC, quasi-isoth. harden.  
O.2.3.- lower bainite, 51 HRC, quasi-isoth. hardening

O2.2-35Mn16/ x2000 –upper bainite  
O2.3-35Mn16/ x2000 –lower bainite

DRAWING III- TTT diagrams with the transformation curves (OLC55 and 35Mn16)
DRAWING IV-R1-R4, (OLC45, 42MoCr11, OSC8, OSC10) ; martensitic hardening ; (x500)

R1P1/x500 (OLC45) –under HF currents
R1P2/x500 (OLC45)-classic sup. hardening

R2P1/x500 (42MoC11) –under HF currents
R2P2/x500 (42MoC11)-classic sup. hardening

R3P1/x500 (OSC8) –under HF currents
R3P2/x500 (OSC8)- classic sup. hardening
DRAWING IV-continuation

R4P1/x500 (OSC10) – under HF currents

R4P2/x500 (OSC10) – classic sup. hardening

DRAWING V-Roentgenograms of the samples: O1P1 and O1P2; O4P1 and O4P2 (on surface)
**DRAWING VI-Microstructures (OLC45; OLC 60; 42 MoC11) at 1000 x; (aust. at Ac3)**

- **O3.1**-middle; (x1000)-ferrite+globular and lamellar pearlite

- **O3.1**-margin; (x1000)-ferrite+globular pearlite

- **O4.1**-middle, (x1000)-ferrite+globular pearlite and sorbite

- **O4.1**-margin, (x1000)-lower fine bainite + globular pearlite

- **O5.1**-middle, (x1000)-sorbite+isolated ferrite

- **O5.1**-margin, (x1000)-globular and lamellar pearlite+lower fine bainite
DRAWING VII-Microstructures: 42MoCr11; OSC10 at 1000 x; (aust. at Ac3)

O5.2-middle (x1000); - sorbite; insular ferrite

O5.2- margin (x1000); globular pearlite and sorbite + very fine martensite

O5.3- middle (x1000); - sorbite

O5.3- margin (x1000); globular pearlite + carbides + very fine martensite

O6.1- middle (x1000); lower bainite; cementite network

O6.1- margin (x1000); microcracks; lower bainite and sorbite; cementite network
DRAWING VIII –Microstructures: OSC 10 at x1000 and OLC60+42MoCr11 at x2000; x3000

O6.2. (OSC10) -middle (x1000); intragranular microcrack, lower bainite and sorbite

O6.2- margin (x1000); - intragranular network of tertiary cem. and lower bainite+fine martensite

O4.1. (OLC60) -margin, - globular pearlite + lower bainite; (x2000) and (x3000)

O5.1. (42MoCr11) -margin, - globular pearlite + lower bainite; (x2000)

O5.2. (42MoCr11) -margin, - globular pearlite + very fine martensite; (x3000)
DRAWING IX- TTT diagrams and the quenching curves (OLC45; OLC60; 42MoCr11; OSC10)

<table>
<thead>
<tr>
<th>Sample</th>
<th>C%</th>
<th>Mn%</th>
<th>Si%</th>
<th>Cr%</th>
<th>Mo%</th>
<th>A1°C</th>
<th>Ms°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.35</td>
<td>0.15</td>
<td>0.04</td>
<td>735°</td>
<td>350°</td>
</tr>
<tr>
<td>O4</td>
<td>0.62</td>
<td>0.55</td>
<td>0.24</td>
<td>0.05</td>
<td>0.02</td>
<td>720°</td>
<td>285°</td>
</tr>
<tr>
<td>O5</td>
<td>0.45</td>
<td>0.77</td>
<td>0.37</td>
<td>1.05</td>
<td>0.07</td>
<td>930°</td>
<td>310°</td>
</tr>
<tr>
<td>O6</td>
<td>0.98</td>
<td>0.25</td>
<td>0.33</td>
<td>0.4</td>
<td>Ni-0.15</td>
<td>725°</td>
<td>210°</td>
</tr>
</tbody>
</table>

DRAWING X- O4'-OLC60, microstructures at x1000; x2000; (austenitizing at $T_A > Ac3$)

O4'P1'-middle (x1000); ferrite+glob.and lam.pearlite; --margin (x2000); troostite and fine martensite
O4‘P2’—margin: troostite and lamelary pearlite + fine martensite; (x1000); (x2000);

**DRAWING XI**- wire samples S1-S4 (OLC75); pearlitizing under low frequency electric currents action

S1/x500

S2/x500

S3/x500

S4/x500