Manifestation of the “striped heating” effect in numerical simulation of induction heating of ferromagnetic bodies near the Curie point

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Abstract. For the first time, the effect of “striped heating” in the induction heating of ferromagnetic materials is mentioned in the works of Soviet scientists Lozinski M.G. and Babat G.I. in 1940. [1, 8]. The phenomenon is that, when ferromagnetic steel is in induction heating near the Curie point, bright rings appear on the surface of the heated cylindrical bodies. Their temperature can be different from the temperature of the blackouts by 100–200 °C (see fig. 1). In further heating “stripes” disappear and when the temperature is about 850 °C the whole surface shines evenly. There is no such an effect in non-magnetic steels.

In further works Lozinski M.G. and Babat G.I. tried to explain separately the effect of “striped heating” and its influence on the induction hardening technology [8-10]. These works give some quantitative relations, received experimentally, as well as conditions for the phenomenon appearance and some speculations done about the causes of this phenomenon.

It should be mentioned that in their last works explanations of the “stripe effect” origin was different. Lozinski M.G. believed that magnetostrictive oscillations appear under the influence of alternating field in the surface layer which change the properties of the heated steel. The areas subjected to less mechanical deformations will have smaller resistivity and will heat more intensively.
In the last work by Babat G.I., edited by his pupils, one of the most complete hypotheses is given, describing the effect of “striped heating” [9]. Babat G.I. did not consider magnetostriction as a prime cause and we think his approach is correct. To explain this hypothesis, he introduced two concepts “stimulated striped heating” and “natural striped heating”.

The main reason for “stimulated striped heating” can be a local overheating under the inductor coils, and the main reason for the “natural striped heating” in the inductor uniform field is unavoidable heterogeneity of material properties (resistivity, heat conductivity). It is one of the reasons for the local overheating above the Currie point, in overheated areas the resultant resistivity decreases and as a consequence, current flows from the metal around are forced and this further increases the local overheating. At a certain time, the effect works as a positive feedback.

It should be taken into account that Lozinski M.G. and Babat G.I. used valve generators at a frequency from 100 kHz upto mehahertz range, but in the XX century machine generators at lower frequencies were used as sources of energy in the industrial application of the induction heat hardening. Perhaps, this and narrow application of the “striped heating” were the reasons why the researchers did not pay attention to this phenomenon for a long time.

2. Materials and methods

Wide application of reliable transistor power supplies raised the interest to the “striped heating” effect: it increased working current frequency of industrial installations for induction hardening of ferromagnetic steel. In 2013 the group of professor Dzliev S. V. (SP SETU "LETT") announced that when steel parts are heated at the frequency 66-100 kHz for hardening heat there is a “striped heating” both with stationary and scanning inductors [2-5]. They tried to model this phenomenon with the software package Ansys. Perhaps, it was the first case of numerical modeling for “striped heating” phenomenon. They managed to simulate this phenomenon only with the significant and physically baseless correction of dependence of magnetic conductivity on the temperature for the heated part.

Magnetic conductivity of ferromagnetic bodies at the induction heating depends on the magnetic field strength and temperature and can be represented as follows:

\[ \mu(H, T) = 1 + (\mu(H) - 1)K(T). \]

where \( \mu(H) \) is dependence of the magnetic conductivity on the magnetic field strength, \( K(T) \) is the coefficient of the magnetic conductivity dependence on temperature. The equations [11,12] are often used for it:
or

$K(T) = (1 - e^{((T - T_K)/c)})$.

where $T_K$ is Curie temperature, $n$ and $c$ are empirically chosen parameters.

3. Heat source redistribution effect at induction heating with discrete shuffling

How can we explain the necessity of unfounded change of the magnetic conductivity dependence on temperature? It can be explained that the final element models, constructed with the modern commercial software packages for general purposes such as Ansys or Flux, cannot show natural inhomogeneity of the material. Thus, the models constructed with these packages cannot reproduce “natural striped heating”, as they do not show all physics of the happening phenomena. Increase in magnetic conductivity results in increase in “stimulated striped heating”, caused by non-uniform heating (due to the system geometry) or by simulation error at the boundary of the final elements. In both cases greater dependence of the magnetic conductivity on temperature in calculations gives greater opportunity to receive a greater gradient of magnetic conductivity at the boundary of two final elements. It will be enough for “initiating” the phenomenon of “striped heating”.

It is necessary to take into account one more factor connected with the simulation adequacy.
works [2-7, 17] the models in the complex domain were used for the research. They are not fully mathematically grounded for nonlinear problems and in the induction heating of the ferromagnetic bodies to the Currie point have poor accuracy, in terms of understating internal heat sources. It may result in the heating time increase in the model relative to the experiment more than by 10%. Calculations for ferromagnetic bodies in the time domain fit full-scale experiments better, and heat acceleration in this case would promote heavy temperatures gradient near the surface, which is one of the mechanisms triggering the phenomenon of “striped heating”.

![Calculating program window Universal2D. Induction heating of five cylindrical steel parts in the discrete type inductor is modelled.](image)

The upper graph is the temperature on the parts surface, the middle graph is average temperature, the lower graph is the temperature in the center

An interesting effect of the similar physical nature, demonstrating redistribution of the thermal sources between the work pieces, takes place at induction heating with discrete shuffling. It occurs at the junction of two workpieces, where due to the temperature difference there is a sudden drop in the magnetic conductivity. In this case the face of the “hot” workpiece heats up still more, and the face of the “cold” workpiece looses temperature which is shown in fig. 3, where there is a calculating program window Universal2D [13, 15-16] when modeling discrete heating of steel workpieces. The temperature on the right face surface of the third workpiece decreases dramatically, and the temperature at the surface of the forth workpiece close to the left face increases. The physical nature of this phenomenon corresponds to the phenomenon of “striped heating” in induction hardening. Here, as with the bright stripes, the rule of positive feedback occurs, when the hotter part of the workpiece becomes even hotter, as in this area, especially if it is higher than the Curie point, the resultant resistance grows smaller, and current lines from colder magnetic workpiece are are forced out to flow there.

It should be noted there is no practical application of this phenomenon. The discrete heating is mostly used for forging, and during the period necessary to achieve desired temperatures (higher 1000 °C), non-uniformity caused by this effect will disappear.
4. Conclusion
The article deals with problems of correct simulation of the “stripe heating” phenomenon in numerical models. To model “stripes” it is better to use the software which allows considering heterogeneity of the material properties, such as resistivity, thermal conductivity and heat capacity.

The phenomenon of heat sources redistribution at discrete heating is shown, grounded on the same physical principle as “stripe heating”. As the temperature gradient appears naturally at the junction of two work pieces, to model this phenomenon it is not necessary to change the dependence of the magnetic conductivity on temperature without grounds and assign heterogeneity of material properties.

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