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Striation effect in induction heating: myths and reality

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Abstract

Purpose – Effect of unstable "wavy" temperature distribution on the part surface during the process of induction heating of ferromagnetic materials was observed and reported by two Russian scientists in 1940 (Babat and Lozinskii, 1940). They reported that under certain conditions, one can observe periodical or quasi-periodical bright stripes on the part surface when its temperature passes through the Curie point. In time, these stripes expand and merge, forming a normal temperature pattern. They called this phenomenon "polosatiy nagrev" (striation heating). Let us call it the "zebra effect" for simplicity. It can exist for a relatively long time, from several seconds to several tens of seconds. Several explanations of the zebra effect were
AQ: 1 proposed with not very convincing arguments.

Design/methodology/approach – Wider spreading of induction technology and use of computer simulation of induction processes create a demand and open new possibilities for study of the zebra effect. This study provides an overview of the available information about the zebra effect and gives new explanation of this phenomenon based on existing experimental data and new results of simulation. Conditions for zebra occurrence and its technological importance or limitations are discussed.

Findings – Computer simulation using the Flux 2D program allows to demonstrate the striation (zebra) effect that can appear in the process of heating magnetic materials and reproduce main experimental findings related to this effect. Simulation provides a great opportunity to investigate the zebra phenomenon in virtual reality, providing qualitatively correct results. Results of simulation show that the zebra effect can appear in a relatively narrow range of material properties and operating conditions. The main factor is a big enough gradient of permeability near the Curie point. At present, it is difficult to expect high quantitative accuracy of simulation due to multiple assumptions in simulation algorithms and insufficient or inaccurate information about the material properties near the Curie point.

Originality/value – Several explanations of the zebra effect were proposed with not very convincing arguments. There were concerns that the zebra effect could set significant limits on the use of induction heating for surface hardening due to non-uniform temperature distribution along the part (Babat and Lozinskii, 1940; Babat, 1965; Lozinskii, 1949, 1969). However, it did not happen. There were no complaints from scientists or practitioners regarding any negative effect of the zebra phenomenon. Moreover, the authors of this paper did not find any original publications on this issue for more than half a century. Only few old induction experts confirm that they observed the zebra effect or something similar, whereas a great majority of induction community members never heard about it.

Keywords Computer simulation, Induction heating, Electromagnetic induction, Curie point

Paper type Technical paper

Introduction

Effect of striation was observed by professors G.I. Babat and M.G. Lozinskii, and their findings were published in 1940 (Babat and Lozinskii, 1940). They worked at a large radio tube factory Svetlana in St. Petersburg and were doing a big research on induction technique
AQ: 2 and technology using ~~HF~~ tube generators. This fact is very important for further discussion. At that time, in the Union of Soviet Socialist Republics (USSR), there was a very tough discussion about the optimal selection of frequency for induction heating, especially for surface hardening. There were no good power sources in the middle frequency range (10-100 kHz), and the selection had to be between tube generators and machines (alternators).

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When Babat and Lozinskii observed the striation effect, they started a detailed study trying to explain why and when it appears and what might be its influence on the emerging induction surface hardening technology. One of the first explanations was that due to the magnetostriction effect, the standing waves of mechanical (acoustic) oscillations take place in the part surface. Stresses change the electromagnetic properties of the material (resistivity in the regions between striations declines), and power in the striation regions will be higher, resulting in a higher temperature. This description allowed explaining the fact that the distance between the temperature stripes drops with frequency increase and supported some other observations. However, this description alone could not explain the whole process dynamics, and in the latest publication, professor Lozinskii (1969) writes the following: AQ: 3

> Currents from the neighboring zones (having a width of about one to one half of the depth of penetration into hot steel) which have not yet been heated to the Curie point of the steel attempt to enter those annular sections which are the first to lose their permeability.

This increases the current density in the "annular sections" and leads to further fast heating of these zones. It means that mechanical oscillations were considered as an effect that triggered striation. All attention in the further development of striation was paid to redistribution of induced current, and nothing was said about distribution of the magnetic field, which generates eddy currents. Babat wrote "maybe the process dynamics is more complicated than I described it" (Babat, 1965).

In spite of the absence of proved theoretical explanations, we need to be grateful to these scientists for their extensive experimental study. The results of these studies contain a group of observed facts about the striation effect and attempt to create experimental dependences for conditions for appearance of stripes, distance between the temperature "nodes", specific power, frequency and duration of the effect.

It is important to keep in mind that both Babat and Lozinskii used tube generators with frequency from several hundred kilohertz to several megahertz and tried to keep constant voltage on the inductor, considering this regime as "natural" for HF heating.

The results may be summarized shortly as follows (Babat, 1965; Lozinskii, 1949, 1969):

- The zebra effect can be observed when heating magnetic bodies to a temperature approaching to the Curie point. The effect is well pronounced for pure iron (dynamo iron) than for carbon steels and less for alloyed steels.
- Number of stripes depends on frequency, and the distance between nodes is larger when frequency is lower (Figure 1). F1
- Stripes can appear when heating in multi-turn and in single-turn inductors (Figure 2). F2
- There are minimal levels of power at which the zebra effect exists:

$$Pi > 1{,}000/\delta \tag{1}$$

where P_i is the power density with units in W/cm^2 and δ is the penetration (reference) depth for hot steel (above the Curie point) with units in mm.

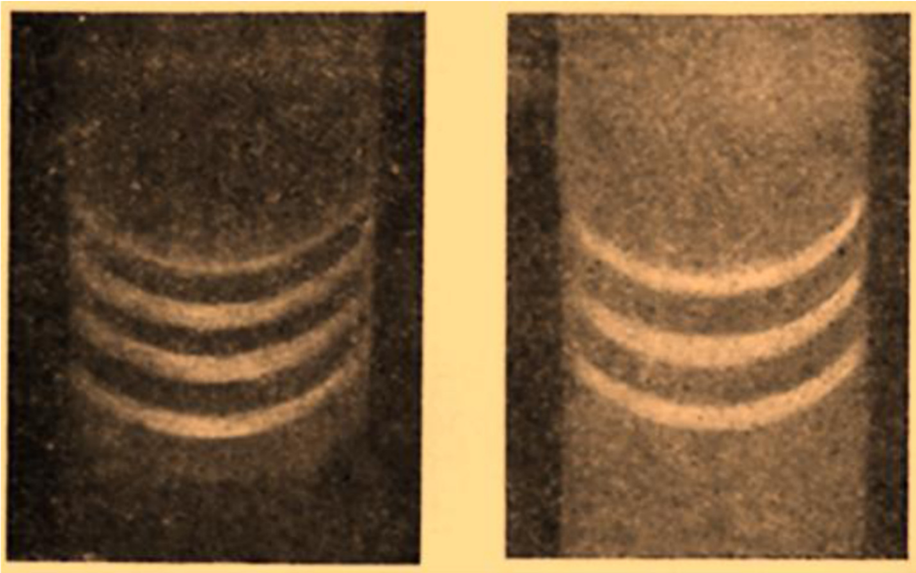
The distance x between temperature maxima is approximately:

$$x = 2{,}000/\sqrt{f} \tag{2}$$

where x is in mm and f is in hertz.

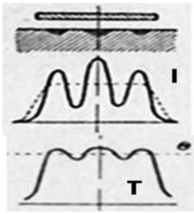
It means that for $f = 1$ MHz, $x = 2$ mm, whereas for 10 kHz, $x = 20$ mm.

Period of zebra's existence:



Source: Photos of M. Divilkovsky [2]

Figure 1. Striation effect at different frequencies



Notes: T – example of temperature distribution; I – evaluation for linear current density distribution

Figure 2. Striation effect for a single-turn inductor

$$\tau = 3\delta^2 \qquad (3)$$

where τ is in seconds (approximately 0.9 s at 1 MHz and 90 s at 10 kHz) and δ is in mm.

The stripe pattern can change during heating. Stripes become wider and finally merge, forming a normal "smooth" temperature distribution on the surface.

One of the main statements of both authors was: "It isn't possible to obtain uniform hardened layer with a thickness less than δ, in a zone wider than 5δ". However, it was also said that a wider zone may be achieved at a lower frequency and fast heating with high power (Lozinskii, 1949, 1969). No experimental data on the zebra effect for heating at any "low" frequency (let us say less than 50 kHz) were found in available literature.

Since the last publication of professor Lozinskii (1969), the zebra effect was not mentioned in any publication on induction heating (to our knowledge) for more than half a century. We can propose the following explanation for such a strange situation: regimes, corresponding to the zebra effect, are out of the mainstream of studies and practical applications. Plus, some users observed some periodical variations in temperature distribution in the process of heating but did not attribute them to zebra instability. For scanning heating in a single-turn coil, it might be attributed to the well-known "barber pole effect", caused by lower heating of some portions of rotating parts passing the zone of weaker field in the zone of the coil's leads. For multi-turn coils, such an attribution may be to local non-uniformities under individual coil turns. In simulation, we can assume that the zebra effect was missed mainly due to insufficient knowledge on (and attention to) the behavior of magnetic permeability near the Curie point, Tc. For example, in a well-known program Elta (2017), permeability is approximated by equation (4) with initially default value of $n = 2$. However, any other value of n can be selected by the user:

$$\mu(T,H) = 1 + (\mu(H) - 1)(1 - (T/T_C)^n) \tag{4}$$

Here, $\mu(H)$ is dependence of μ from field strength H at room temperature. Temperature dependence is described by parabola. Initially, the value $n = 2$ was selected according to some data for surface hardening of machinery parts at relatively low frequencies and high power densities (up to 10 kW/cm^2) (Slukhotskiy and Ryskin, 1974). In other widely used program Flux 2D/3D, approximation is exponential (Manual of Flux2D/3D, 2017). In both programs, it is the user who must select values of n or Ct:

$$\begin{aligned} \mu(T,H) &= \mu(H)K(T);\ K(T) = \left(1 - \exp\left(\frac{T - Tc}{Ct}\right)\right); \\ \mu(H) &= \mu_0 H + J_s \frac{H_a + 1 - \sqrt{(H_a + 1)^2 - 4H(1 - a)}}{2(1 - a)}; \end{aligned} \tag{5}$$

where $H_a = \mu_0 H \mu_i - 1/J_s, J_s$ is the saturation flux density and μ_i is the initial permeability.

Recently, professor S. V. Dzliev and his group from the university LETI, St. Petersburg, Russia, reported that they observed heat pattern, typical for the zebra effect, when heating steel rods stationary or by scanning (Dzliev *et al.*, 2013a, 2013b). They made an attempt to simulate the process using the 2D FEA software and were able to reproduce it by varying the curve of temperature dependence of the magnetic permeability. This investigation paid attention to a forgotten effect and resulted in several important findings. One of them is an influence of permeability from temperature. They showed that, when using in simulation formula (4), there was no zebra effect for low value of n ($n = 2$). It appeared for $n = 25$, which they used for further simulation cases. An example of a 3D graph of the surface temperature for a rod with a length of 150 mm is presented in Figure 3. It is clear that in the time period of F3 approximately 10-20 s, there are oscillations typical for the zebra effect (Figure 3). Unfortunately, both articles do not contain enough information for reproducing either experiments or simulation. The authors noted that the zebra effect is caused by "instability of permeability" near the Curie point, which results in "auto-oscillations". However, this statement does not explain the mechanism of striation.

Study

A review of available information showed that a study of the zebra effect is a very difficult task due to the multiple factors involved, uncertainty in effect evaluation criteria and insufficient information about the material properties, especially about permeability near the

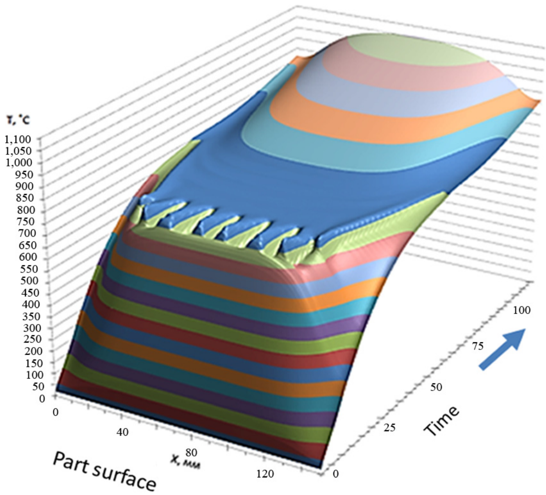


Figure 3. Temperature distribution on the part surface with a period of the zebra effect

Curie point. To our opinion, the factors that influence the zebra effect are as follows: current frequency, power supply mode (fixed or varying in time coil voltage, current or power), system geometry (cylindrical or flat system, coil and part dimensions, single or multi-turn coil, etc.), part material (permeability, specific heat and electrical and thermal conductivities) and mode of operation (static or scanning).

This study concentrated on finding conditions of zebra effect existence, dynamics of its development and attempts to explain physics of this effect. The 2D simulation program Flux 2D is the main tool for the study. The Elta program was also used for comparison of the results of simulation with and without account for the zebra effect's influence on the heating process and system parameters. The traditional frequency domain approach (Slukhotskiy and Ryskin, 1964; Neuman, 1948) is used in both the above-mentioned programs. For the studies contained in this paper, the same temperature dependent volumetric heat capacity, electrical resistivity and thermal conductivity (Figure 4) are used to limit the variables to the thermal dependence of magnetic permeability, frequency, source field distribution and source magnitude on the striation effect, which are believed to be the more influential factors by the authors.

F4

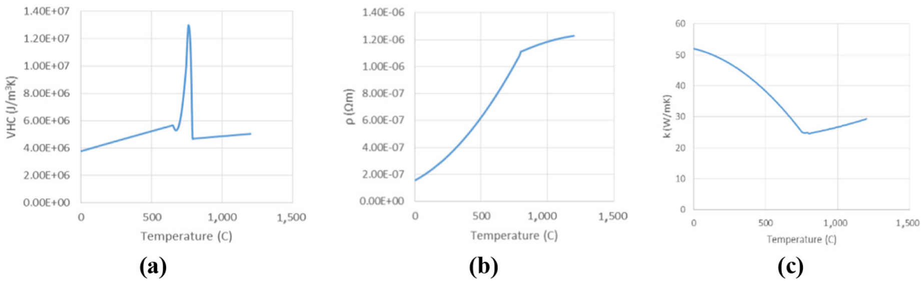


Figure 4. Temperature-dependent volumetric heat capacity (a), resistivity (b) and thermal conductivity (c) used in the studies with Flux 2D

Coefficient of thermal dependence of permeability

Variation of magnetic permeability with temperature is a very complicated problem, and information about it is quite insufficient, especially for "industrial" steels typically used in induction heating processes, such as carbon and low alloyed steels. Demand for more accurate simulation (Nemkov, 2015) led to several newer studies in this area (Zedler *et al.*, 2008; Vladimirov *et al.*, 2008). Analysis of literature shows that in low magnetic fields, the permeability drops with temperature much slower than in the strong fields (Figure 5). F5
Figure 6 shows curves of temperature coefficient K_t for different values of n and Ct in formulas (4 and 5). These curves allow us to see permeability variation with temperature and correlate simulations results when using Flux 2D and Elta. Temperature-dependent values of electrical resistivity, heat capacity and thermal conductivity are used in simulation. F6

System description

Two system geometries have been used. In the first case, a single-turn 127-mm long cylindrical coil with internal and external diameters of 42 and 46 mm, respectively, was used

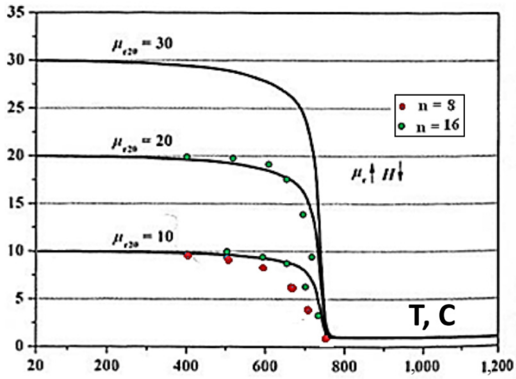


Figure 5.
Permeability variation versus temperature and its approximation

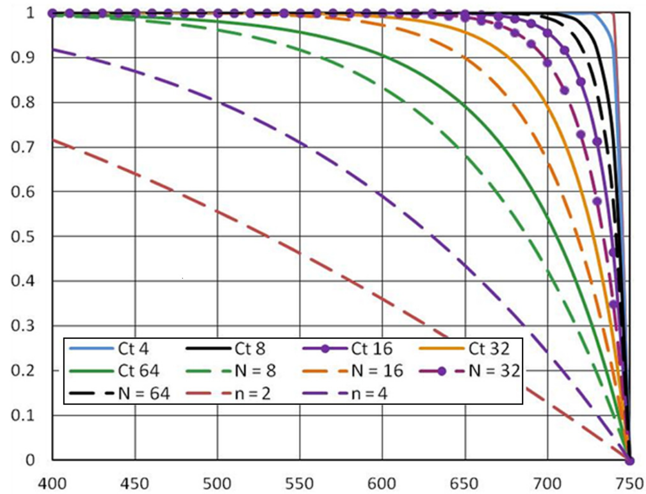


Figure 6.
Approximation of permeability variation with temperature for Elta and Flux 2D

for heating a rod with a diameter of 31.8 mm and length of 200 mm. Rod material is steel 1,040 (0.4 per cent of carbon) [$\mu_i = 500$, $a = 0.3$ and $J_s = 1.8$ in equation (5)]. The induction coil was presented as a current layer (Litz coil) or impermeable for field layer (solid copper sheet)
F7 (Figure 7). The second case was for a 127-mm long piece of an infinitely long system, in which there must be no "external" factors for a non-uniform field distribution in length that could trigger the zebra effect. The part diameter and properties are the same as in Case 1. One quarter of the system was simulated. The coil was energized by constant current or constant voltage at frequencies 20 and 40 kHz.

Results of simulation

Case of finite length of the coil

F8 Color maps of temperature and magnetic field lines are presented in Figure 8 for the coil current 2,000 A (in half of the system length), different values of *Ct* and two frequencies 20 and 40 kHz. For *Ct* = 64, the process of heating was traditional, without the zebra effect. A non-magnetic layer with uniform thickness was in the central zone of the coil. For *Ct* = 32 at 20 kHz, three hot stripes started to appear after approximately 16 s, reached maximum at approximately 22 s and merged at t = 26-28 s, forming a traditional heat pattern.

At *Ct* =16, the process was approximately the same as for *Ct* = 32.

Times of start and end of the zebra effect were approximately the same for both values of *Ct*. There are three hot zones in the whole length of the system with a pattern similar to that in Figure 3. Distance between the temperature maxima is approximately 23 mm, which is about 1.5 times greater than that from the formula 2,000/√f [equation (2)].

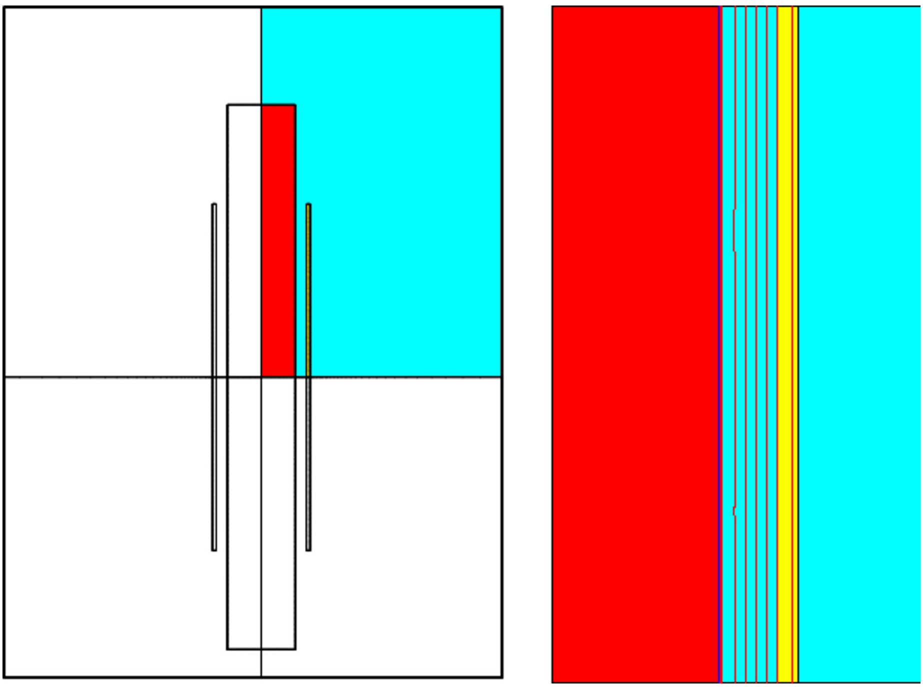


Figure 7. Geometry of induction system (left) and magnetic lines for simulation of a piece of infinitely long system (right)

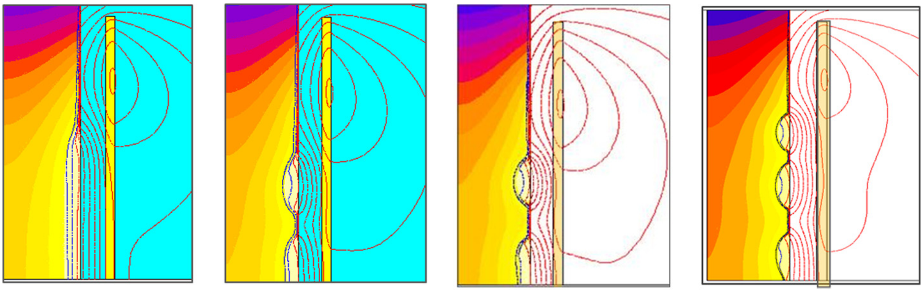


Figure 8. Color maps of temperature for different values of coefficient

Notes: For A-C, *Ct* = 64, 32, 16, respectively, *f* = 20 kHz and time 22 s; for D, *Ct* = 16, *f* = 40 kHz and time 16 s

At frequency 40 kHz, there are five or six stripes on the whole length of the system (depending upon the time), and heating time was much shorter with the maximum zebra effect at 16 s.

Case of an infinitely long system

Most of the study was made from a piece of an infinitely long system (total length of this system equals to 63.5 mm). Dynamics of zebra development and decay are presented in Figure 9. The Litz coil carries a current of 2,000 A, frequency is 20 kHz and *Ct* = 16. Uniform heating continues for the first 12 s. At 16 s, two shallow hot zones appear, which become deeper and slightly wider, and during 26-28 s, these zones merge and all the part surface becomes non-magnetic. It is interesting that the lower zone is wider than the upper one without any visible reasons. Temperature in the middle of the lower zone is slightly less than near its sides. This feature was observed by Lozinskii. F9

3D graphs of power density and temperature along the part surface are presented in Figures 10 and 11, respectively. They are similar to pictures in the article in Dzliev *et al.* (2013a). F10-11

Other results are as follows:

- The zebra effect exists at the coil current 2,500 and 3,000 A but disappears at 4,000 A. We can explain it by lower values of permeability for a given *Ct* = 16.

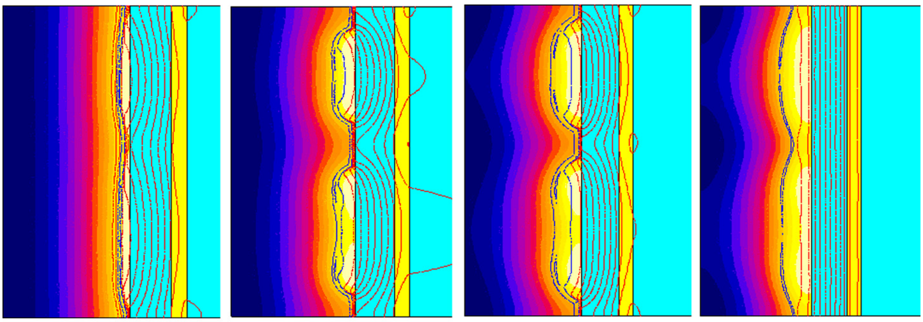
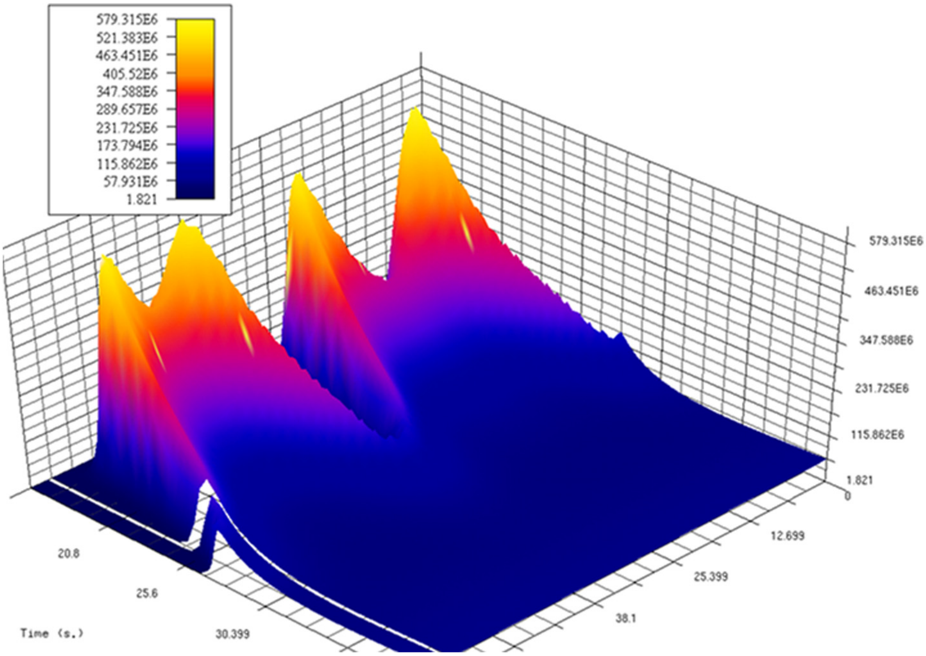


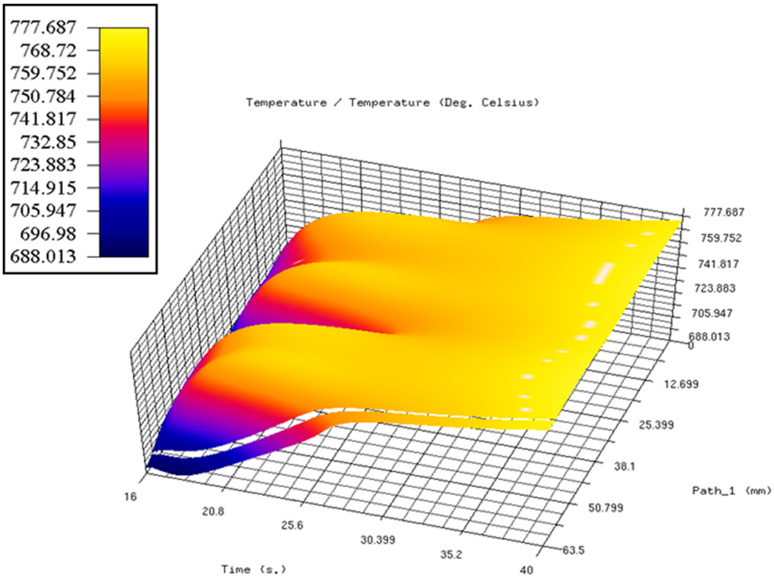
Figure 9. Dynamics of the zebra effect

Note: Heating times are 16, 20, 24 and 28 s (left to right)



Note: *Ct* = 16

Figure 10. Power density variation at a depth of 1.8 mm under the surface



Note: *Ct* = 16, time range 16-40 s

Figure 11. Color map of temperature on the part surface

- The zebra effect exists when the coil is supplied by a constant voltage corresponding to "cold" conditions.
- Two or three more hot stripes appeared at the frequency of 40 kHz.

Analysis of results

One can see that in all studied cases, the transient zones (TZs) from hot (non-magnetic) areas to magnetic areas are almost the same in spite of system geometry and currents. Additional simulation of a system with a coil made of copper sheet (Figure 12, left) gave not exactly the same but very similar results. Figure 12, right, repeats a color map of Figure 9, time 20 s with separated TZs. Magnetic field in the areas between TZ correspond to plane-parallel field and power distribution. This feature allows us to compare TZs with the end effects of cylindrical body, well studied for the ends of magnetic and non-magnetic cylinder in contact with air (Nemkov and Demidovich, 1989). In our case, there is a contact of magnetic and two-layer bodies. A special electromagnetic only study was made for a system shown in Figure 13. F12 F13

Magnetic permeability of steel in all magnetic portions corresponds to steel 1,040 at approximately 600°C. Resistivity is 77 $\mu\Omega$cm. Non-magnetic layer has resistivity 100 $\mu\Omega$cm.

Color maps of power density in the part for different thicknesses of non-magnetic layer are presented in Figures 14 and 15. F14-15

The older version of Flux 2D (which was used for this study) does not conveniently allow calculation of linear power density P_0 on the part surface, and we had to export the curves of volumetric power density Pv vs radius (Figure 16) in the most interesting cross-sections and integrate them: F16

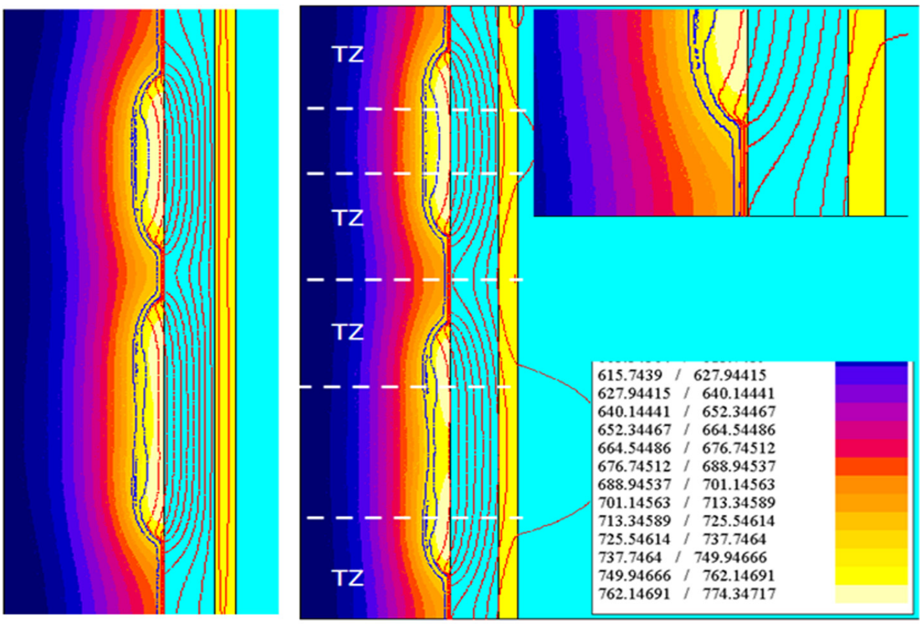


Figure 12. Color map of temperature for a solid inductor (left) and for Litz inductor (right)

Note: $Ct = 16$, time instant 20 s

$$Po = 1/Re \int_0^{Re} R dR$$

Values of P_O are shown on a graph of Figure 15 in the form of red bars. Power values are calibrated to P_O in the regular magnetic zone (bottom of Figure 15). Linear power in a system

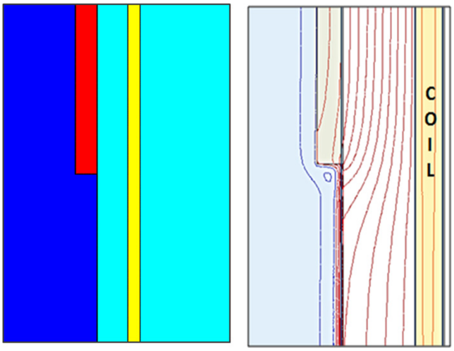


Figure 13. Layout of a system for study of the end effect (left) and magnetic lines for a non-magnetic layer that is 0.2 δ thick (right)

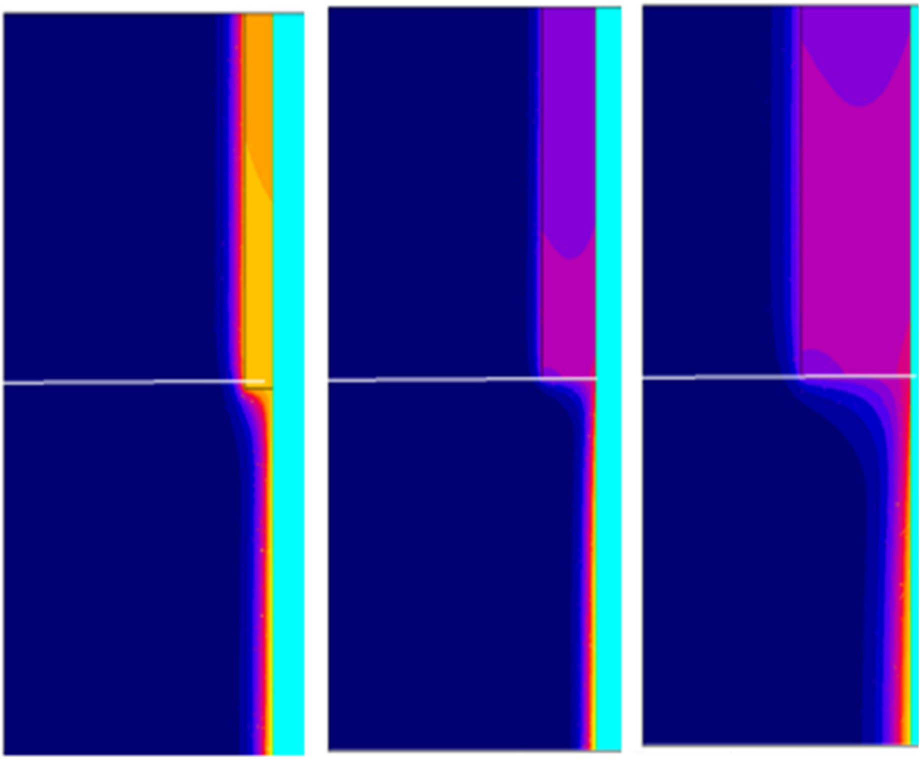


Figure 14. Color maps of power density for different thicknesses of non-magnetic layers: 0.2 δ, 0.5 δ and 1 δ

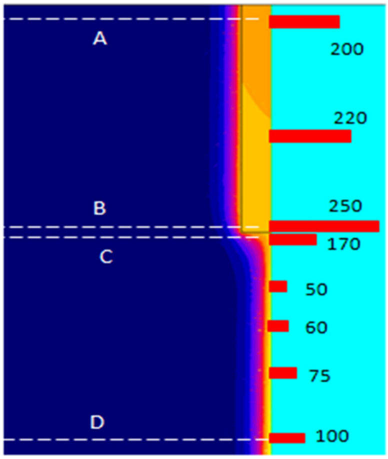
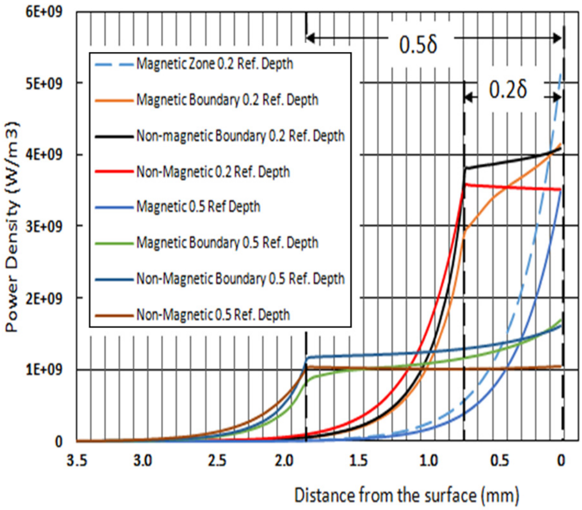


Figure 15.
Color map of power density distribution in the boundary zones of magnetic and partially magnetic (0.2 δ) zones



Note: Dashed and solid blue lines are for a section D in Figure 14

Figure 16.
Power density Pv distribution in depth for non-magnetic layers of 0.2 δ and 0.5 δ

without a non-magnetic layer would be equal to 200 units (for a given current and calibration).

A non-magnetic layer that is 0.2 δ thick strongly reduces power in the magnetic portion of the part, especially near the border with insert. Linear power has a maximum value beyond the border and slowly drops with a distance from the magnetic portion. This power distribution completely corresponds to what we observe with the zebra effect in simulation and in experiments.

These findings allow us to state that the zebra effect is caused by redistribution of the magnetic field and induced power density in the system due to a special kind of end effect in the border areas of magnetic and partially non-magnetic portions of the part. Increase of frequency reduces width of these TZs and diminishes the distance between the striation zones.

Conclusions

The conclusions of this study are as follows:

- Computer simulation using the Flux 2D program allows us to demonstrate the striation (zebra) effect that can appear in the process of heating magnetic materials and reproduce main experimental findings related to this effect.
- Simulation provides us a great opportunity to investigate the zebra phenomenon in virtual reality, providing qualitatively correct results.
- Results of the simulation show that the zebra effect can appear in a relatively narrow range of material properties and operating conditions. The main factor is a big enough gradient of permeability near the Curie point.
- At present, it is difficult to expect high quantitative accuracy of simulation due to multiple assumptions in simulation algorithms and insufficient or inaccurate information about the material properties near the Curie point.
- A basic source of inaccuracy can be a frequency domain approach, which is not tested for big gradients of permeability and temperature. Time domain simulation can be a more reliable method.
- More information is necessary about the magnetic properties of steels near Curie points.
- Further simulation and experimental studies with no doubts will discover many new facts about the "mysterious" zebra effect.

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AQ2— Please provide the spelled-out form of the following abbreviation: HF.

AQ3— Please check the edits made in the following sentence, and correct if necessary: Original: When Babat and Lozinskii met the striation effect, they started a detailed study trying to explain why and when it appears and what might be its influence on the emerging induction surface hardening technology.Revised: When Babat and Lozinskii observed the striation effect, they started a detailed study trying to explain why and when it appears and what might be its influence on the emerging induction surface hardening technology.

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AQ5— Please provide all the authors' names for references Dzliev *et al*. (2013a) and Dzliev *et al*. (2013b).

AQ6— Please provide significance of "[2]" in legend of Figure 1.