Curie Isotherm Instability during Scanning Induction Heating of Magnetic Steel Strip

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***Abstract*—Unstable behavior during scanning induction heating of continuously moving through single-turn inductor magnetic steel strip has been studied on computer model. The instability is reflected in striped heating or “zebra-effect”, i.e. either hot strip coming from the inductor with a red glow (temperature above the Curie point) or dark strip below Curie point, alternating regularly. I.e., the Curie isotherm undergoes discontinuities on the surface in the longitudinal section of the strip. The instability is caused by power loss density localization in the non-magnetic zone heated over Curie temperature. This phenomenon was confirmed experimentally by heating magnetic steel plate, and also in the experiment with a thin-walled tube, where an edge-effect was avoided. The domain of instability occurrence and its parameters have been determined. The results can be used to ensure a uniform heating temperature when designing induction heating systems for strips of magnetic steel in a longitudinal magnetic field.**

Keywords—zebra-effect; Curie isotherm; striped induction heating; strip heating in longitudinal field

I. INTRODUCTION

Striped induction heat is originally mentioned in [1], [2], [3]. The fact of appearance of concentric “hot” and “cold” rings on a surface of a magnetic steel cylinder heating inside single shot multi-turn or rather wide single-turn inductor was established there.

Absence of an evident practical significance of this effect caused a minor attention of specialists to these messages for half a century [4], [5]. However, the phenomenon itself is interesting for the induction heating theory, and its practical significance can be found in the study of such case as spiral hardening of cylinders and strip heating of a tape by scanning inductors. These phenomena, traditionally considered as harmful, can be used to provide useful properties to workpieces. For example, a spiral hardening of a shaft may give it a torsion anisotropic tension, while alternation of hardened and unhardened regions produces better conditions for a grease retention on friction surfaces, similar to the effect of a hardened mesh applied by a scanning laser beam.

Scanning induction heating of magnetic strip to temperatures near the Curie point is widely used in practices of anticorrosion zinc galvanizing. The problem of uniform heating is very important, as it determines the quality of products. However, in known publications, the effect of striped heating of the strip in a longitudinal magnetic field is not covered widely.

In papers [2], [3], [6], [7] the fact of the striped heating effect at the surface of magnetic steel cylinder inside one-shot inductor has been presented. In the paper [1] a scanning induction heating is noted as preventing the phenomena. But in [6][5], [7] the striped heating inside scanning single-turn inductor has been observed. No external periodic influence was applied.

In an experimental part of this paper the numerical and the experimental models of induction systems with observed striped heating of steel plate and tube are described. In some cases, the effect domain is presented.

The numerical simulation was conducted with usage of experimentally determined in [7] dependency of magnetic permeability on temperature.

An edge-effect, which is reflected in more intensive heat of edges, is observed on the plate but not tube samples. In some cases, junctions of heated strips are observed on both types of samples. In certain conditions heated strips appear in the edge effect region.

II. EXPERIMENT

The numerical model for simulation of the phenomena is two-dimensional. It includes electromagnetic part consisting of inductor, heated sample and encircling air domain, described by Maxwell equations. Thermal part of the model is simplified to workpiece only and described by Fourier equation, boundary conditions for it are average convection and radiation heat losses from free surfaces. Model takes into account magnetic permeability dependency μ(T) obtained from [7] that is:

$$\mu(T) = 1 + (\mu - 1)(1 - (T/T_C)^{25}) \qquad (1)$$

$$\alpha + \beta = \chi.$$

(1) (1)

The dependency above is used for $T < T_C$, and $\mu(T) = 1$ is used for $T \geq T_C$, where T_C is the Curie point of the sample material.

The investigated effect is obtained in physical experiment on plate and tube steel samples. The inductor current is sinusoidal with frequency of about 50 kHz. It is supplied by power stabilized transistor generator.

A. Striped heating of steel strip

In this study copper inductor with outer diameter *O* encircles the steel strip with thickness *D* and air gap *G* moves along it with constant speed *V*. It moves up in Fig. 1 (experiment diagram) and Fig. 2 (numerical simulation results). Inductor is powered by sinusoidal current with amplitude *I* and frequency *f*.

To simplify the model it is simulated in 2D plane environment with infinite width and 280 mm length; inductor length is assumed infinite too. Taking into account system's symmetry along the plate centerline only a half of it is simulated. Fig. 2 represents results of simulation in four time points: (a) 5,8 s, (b) 6,9 s, (c) 7,3 s and (d) 7,7 s. System parameters are: *I* = 3,5 kA, *f* = 440 kHz, *D* = 4 mm, *G* = 8 mm, *O* = 8 mm, *V* = 50 mm/s. White colored areas have temperature 740°C or less, black - 760°C or more. It can be seen that there are alternating stripes with various temperatures close to Curie point following the inductor.

To define area of self-oscillations set of numerical simulations of scanning induction heating of plate was done with different *I* and *V*. Results of it are represented on Fig. 3: squares for well-defined stripes, rhombs – less defined, crosses and triangles – overheating and underheating respectively. *f* = 440 kHz, *D* = 4 mm, *G* = 8 mm, *O* = 8 mm.

Fig. 4 shows temperature plot along the plate length (x-axis) after 1 second of scan heating with same parameters. Temperature oscillations amplitude reached 100°C and occurred about the Curie point (T_{max}=800°C, T_{min}=700°C), period of maximal heated stripes was 6 mm.

The plates used in physical experiment are positioned vertically as on Fig. 1. and Fig. 2 (dimensions of first one are *D* = 6 mm and 120 mm wide, second has 4 mm and 100 mm respectively). Due to limited power available from induction heating power supply unit and an edge-effect area the striped heating is limited and difficult to register properly. So observations were done with lowest power and inductor scanning speed possible.

Fig. 5. is the photo of striped heating of steel plate with next parameters: *D* = 6 mm, *O* = 12 mm, *G* = 10 mm, *V* = 21 mm/s, *f* = 46 kHz, *I* = 6 kA, the inductor is located on top part of the photo. With same parameters junction of lines was observed as shown on Fig. 6.

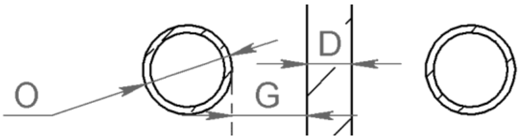

Fig. 1. Plate experiment diagram.

Fig. 2. Striped plate heating simulation results.

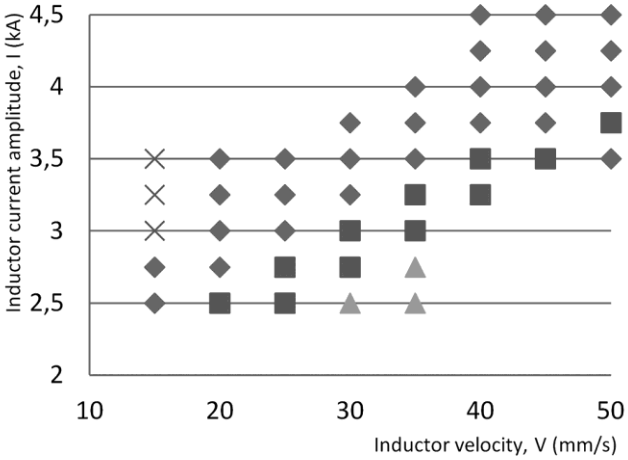

Fig. 3. Plate striped heating domain

One of experiments showed stripes forming at plate edges. Parameters for this case were: *D* = 4 mm, *O* = 12 mm, *G* = 11 mm, *V* = 37 mm/s, *f* = 46 kHz, *I* = 6 kA. Scanning speed was too fast for given current, so plate center was not heated to T_C. Edges had enough exposition for it, though, and had a striped heating effect visible for some time. After heat spreading along the plate from its edges stripes disappeared. This phenomenon can be seen on Fig. 7.

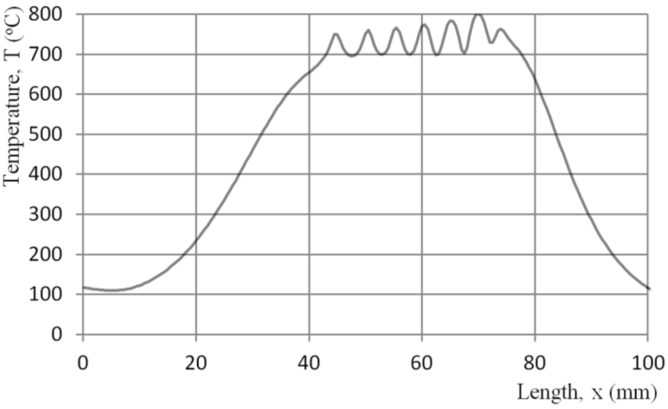

Fig. 4. Temperature along plate surface

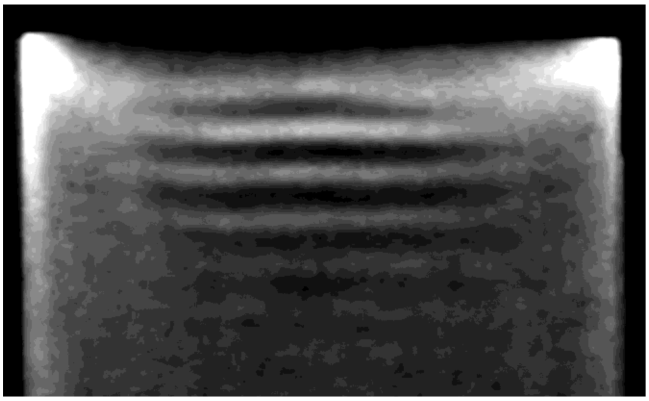

Fig. 5. Plate heating experiment

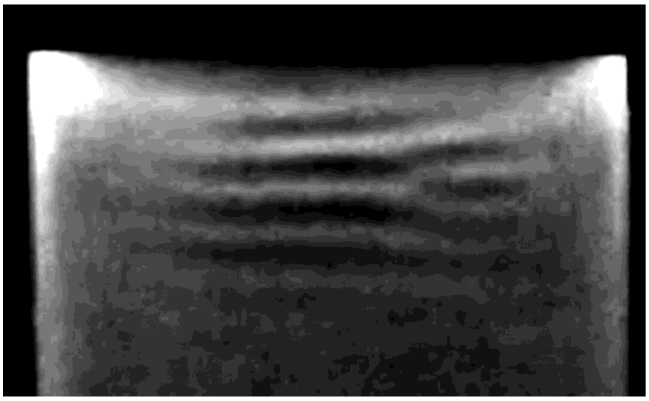

Fig. 6. Hot stripes junction

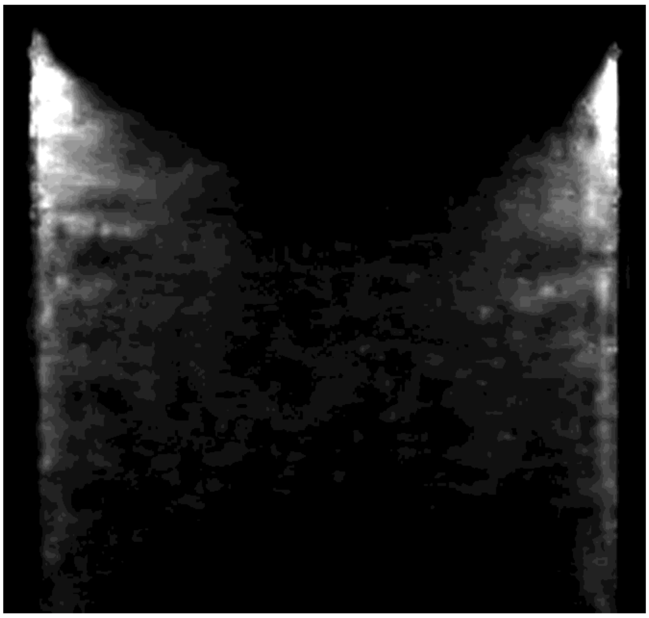

Fig. 7. Striped heating of plate in edge-effect area

B. *Striped tube*

In the Fig. 8 the diagram of experimental setup for the tube sample is presented. Embracing inductor with centerline diameter *D* of 150 mm made from 10 mm copper tube is positioned at the variable height *Hi* from bottom of the sample. It moves up along the sample with constant speed 6 mm/s. The inductor current amplitude is 4.5 kA. The sample is a magnetic steel tube 500 mm long with outer diameter of 107 mm and the wall 6 mm thick.

In physical experiment the temperature of heated sample surface is measured by pyrometer located at the distance 800 mm from the surface at the variable height *Hp*. The pyrometer is cyclically moving along the surface to register the area temperature. It moves up to the middle of the inductor with speed of 67mm/s, then down with 50mm/s, and then cycle starts again. So it scans hot area temperature distribution twice for about 2.3 seconds.

In the Fig. 9, Fig. 10 and Fig. 11 the photos of the striped heating of the tube are presented. According to Fig. 9 the period of the striped heating is 11 mm. In the top of the pictures there is the inductor which is dark. At the bottom there is a light point of laser pointer of the pyrometer.

In the Fig. 12 the plot of the experimentally obtained domain of the striped heating of tube. The region is not closed, because the induction system power is limited. The continuous line mark the boundaries of domain of the effect

Plot of an example of the pyrometer data for the inductor diameter of 150 mm is presented in Fig. 13.

The numerical model was created similarly to the plate case according to the Fig. 8 diagram.

III. RESULTS

To compare results of numerical and physical experiments, we need to find the period of the striped heating.

Using set of surface temperature versus length distribution curves, as on the Fig. 4, we have built three-dimensional plot of temperature versus length and time, $T(x,t)$, Fig. 14. Then we have found maximum surface temperature for every x: $T_{max}(x)$, Fig. 15. After that we've extracted its regular part. The Fig. 15 presents $T_{max}(x)$ for next parameters: D = 6, O = 12 mm, G = 10 mm, V = 16 mm/s, f = 66 kHz, I = 3.5 kA. In this case the period is about 8.5 mm

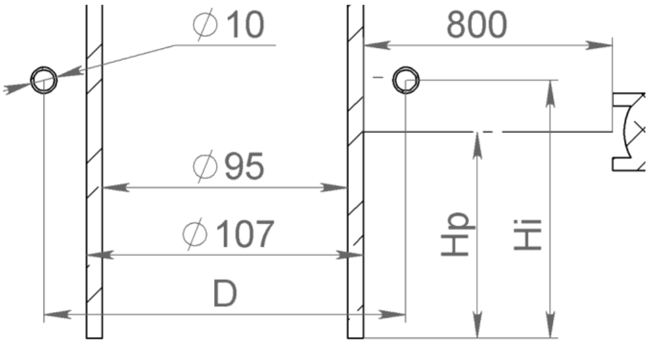

Fig. 8. Tube experimental setup diagram

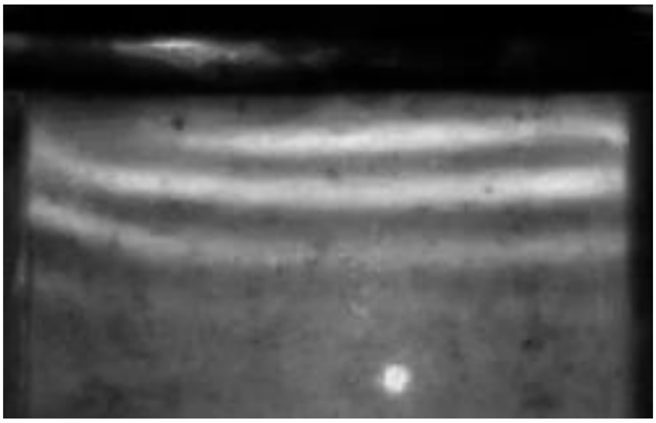

Fig. 9.   Striped heating of tube

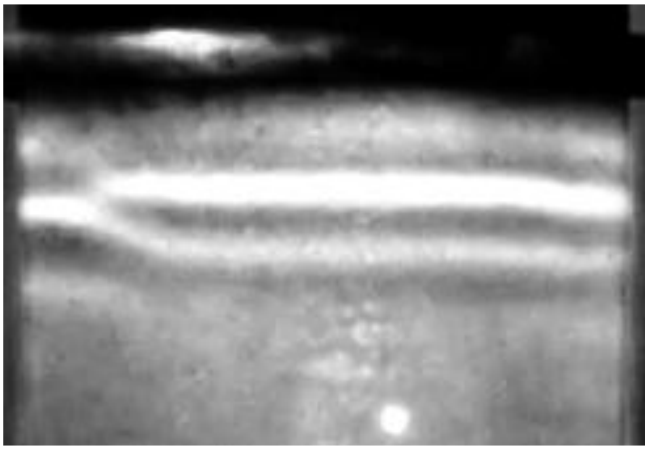

Fig. 10. Hot stripes junction on tube

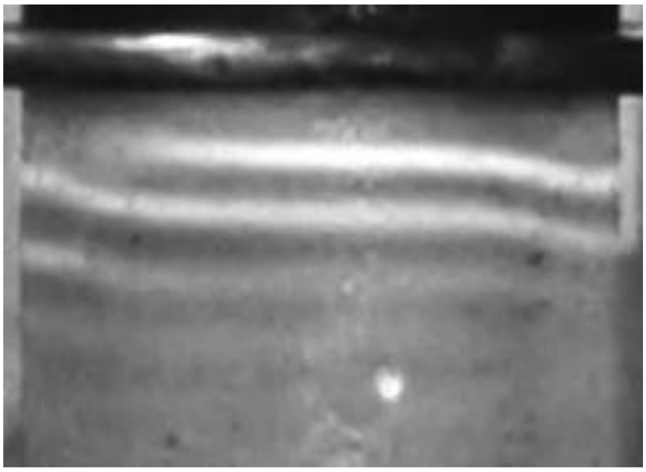

Fig. 11. Helical hot stripes on tube

Using the Fig. 5 one may derive the striped effect period – it is 9 mm. You can see, that overheat in the edge effect area near the plate edges is merging hot strips, so its observation is possible in the center of the plate. The plate width there is 120 mm, and 50-70 of it is occupied by the edge effect.

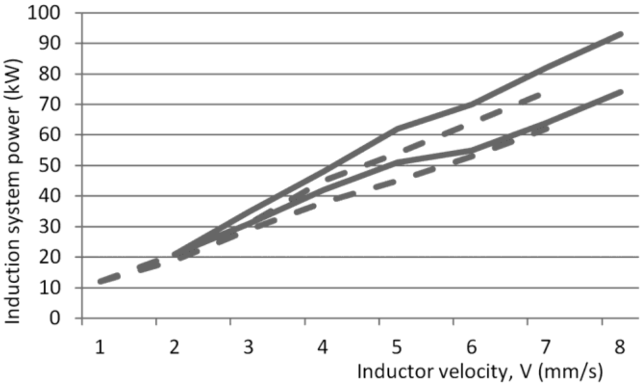

Fig. 12. Tube striped heating domain

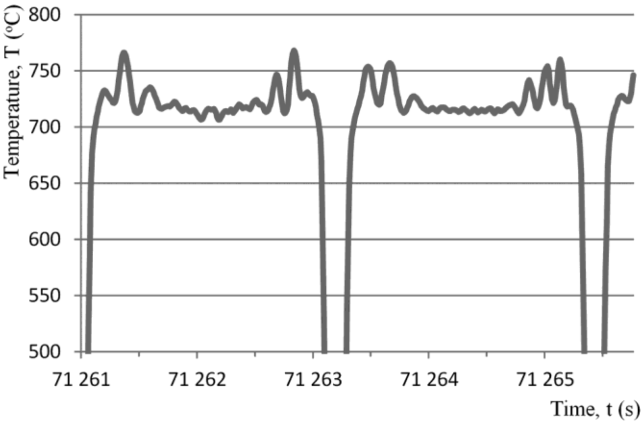

Fig. 13. Pyrometer data

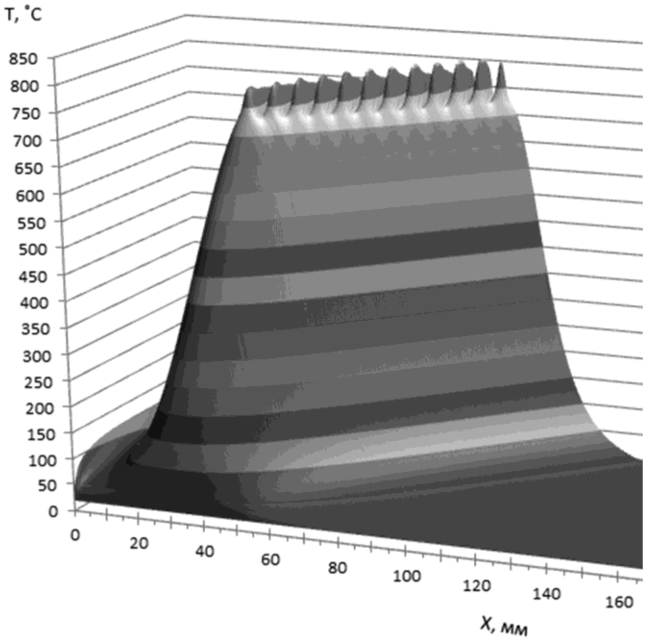

Fig. 14. Temperature of plate versus time and length

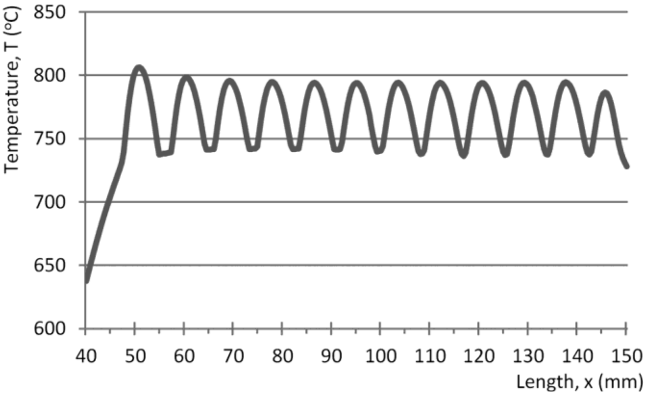

Fig. 15. Maximum surface temperature over time along the plate

So the striped effect period in case of 120 mm wide 6 mm thick steel plate is 8.5 mm and 9 mm in numerical and physical experiments respectively. Inductor velocity is 16 versus 21 mm/s, current amplitude is 3.5 vs. 6 kA and current frequency is 66 vs. 50 kHz.

We have derived the period in case of tube heating by inductor of 150 mm diameter. For the simulation it is obtained from maximum surface temperature plot in Fig. 16 – it is 18 mm. For the physical experiments there are two ways: from the photo of the experiment in Fig. 9 – it is 11 mm – or from the pyrometer data. The plot of tube surface temperature scanned by pyrometer is derived from the pyrometer data and is presented in the Fig. 17. From this plot it is also possible to obtain the maximum surface temperature, get the regular part of it and at last – the period of striped heating is 12 mm.

Using the pyrometer one can catch more hot stripes than by photo. But because of the pyrometer large measurement spot the temperature deviation in striped heating area is averaged. From the Fig. 16 for the simulation the temperature deviation in striped effect area is about 70 °C, and from the Fig. 17 for physical experiment it should be not less than 50 °C.

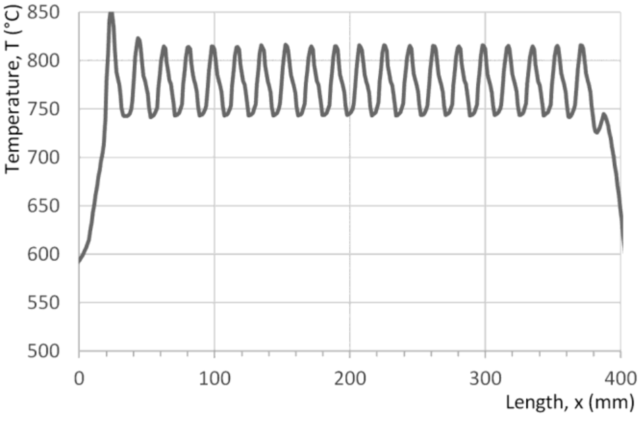

Fig. 16. Maximum surface temperature over time along the pipe

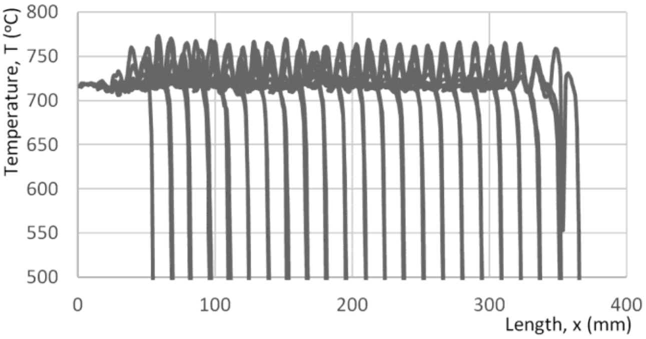

Fig. 17. Tube surface temperature obtained from pyrometer

IV. DISCUSSION

The striped effect period for plate both in experiment and simulation is about 9 mm, but other parameters of both systems are not completely equal and the edge-effect is significant. To reduce edge-effect influence another power supply should be used to develop nature experiments to allow the use of wider plate. Alternatively, one can run a simulation in 3D environment to get similar edge-effect in induction system, but such approach will demand higher computational power.

For the tube the striped effect periods are 11-12 and 18 mm in physical experiment and numerical simulation respectively. Certainly the experiments should be done more accurately. But probably the difference is caused with the tendency of the hot stripes to develop helically, which can’t be included in two-dimensional numerical simulation model.

The junctions of the stripes probably are associated with random positions of starting points of the hot stripes. In the striped heating of a plate the stripes are starting near the edges and, developing to the center, may joint without alignment.

V. CONCLUSION

Striped heating The scanning inductor striped effect is observed in either numerical or natural experiments. Its appearance is likely in heat to about the Curie temperature.

Deeper comparison of the experimental observations and numerical simulations should help to clarify the induction heating phenomena understanding and to develop the computer simulation models, especially in 3D, the induction systems technique and practice of the induction treatment

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