How Accurate is Computer Simulation of Induction Systems?

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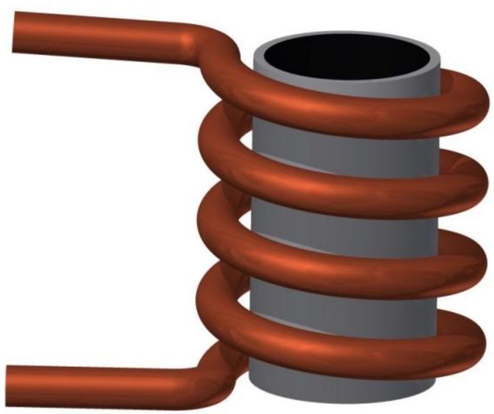
Layout

- Criteria of nearness
- Factors influencing accuracy
  - Considered processes
  - Geometry (incompleteness, variation during processing, simplification, etc.)
  - Material properties (electromagnetic, structural, thermal, mechanical)
  - Formulation of electromagnetic task
  - Simulation methods and algorithms
- Examples of simulation
- Summary

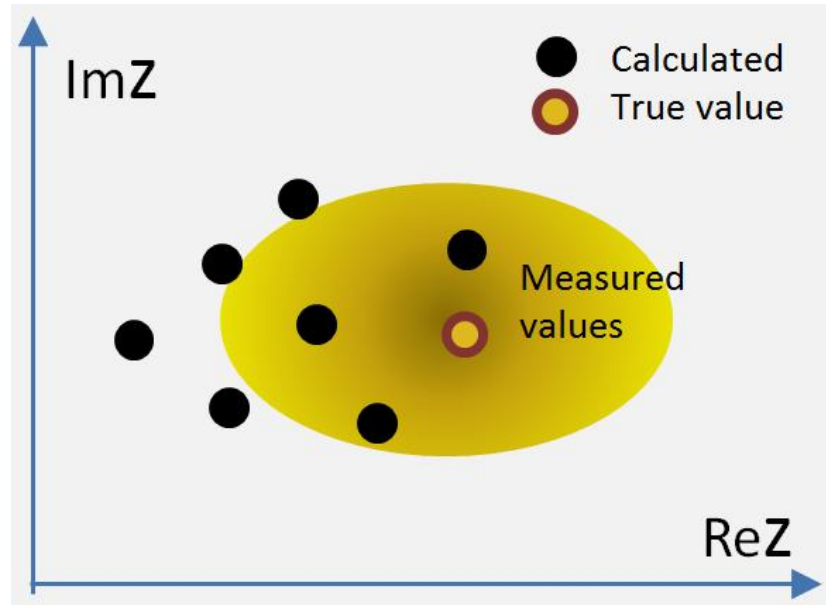
What is Accuracy?

- Accuracy is the nearness of calculated and “true” values.
- Common definition associates accuracy with systematic errors and precision with random errors.
- For each particular case and model, simulation is precise in sense of repeatability of the results but not always accurate.
- Experiments are not precise and not quite accurate but they are the most reliable “in large” providing a general picture of the situation and taking into account al the complex of phenomenae and environmental conditions.
- Evaluation of errors is extremely important for optimization of calculation process, optimal design and control. Big contribution in this field was made by experts from St. Petersburg, Hannover, Samara, Padua and other scientific schools.

Simple Case of Accuracy Analysis



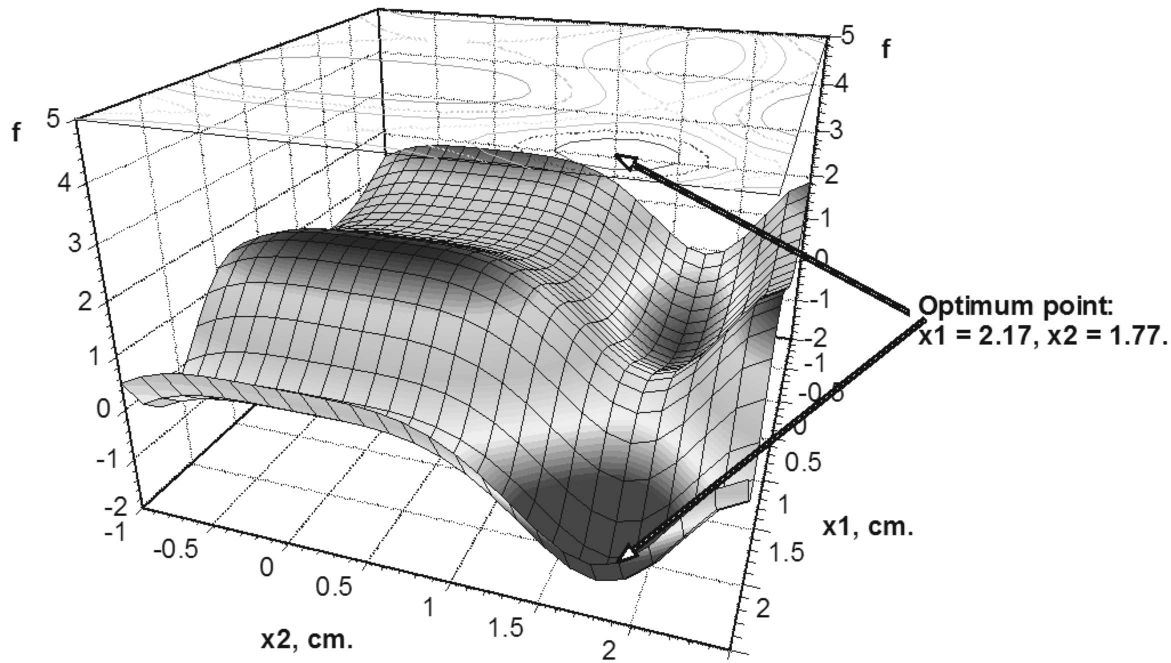
$$Zi = ReZ + j\ ImZ$$



"Concentrated" parameters (impedances, efficiency, power, currents, voltages, etc.) are very important for simulation of the whole induction system including power supplies and matching circuits.

"Distributed" parameters (power density, fields, temperatures, stresses, hardness pattern, etc.) are necessary for evaluation of quality of the process. Different criteria of nearness may be applied for evaluation of accuracy.

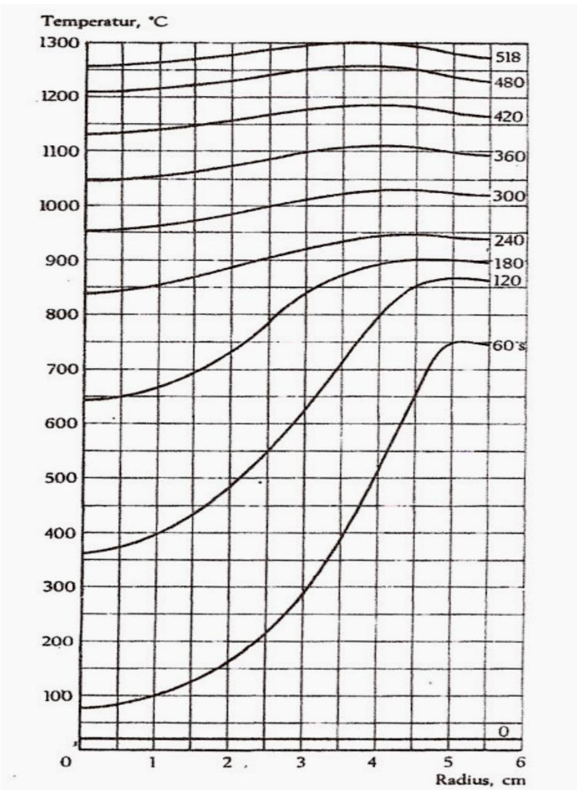
Example: Temperature Distribution during Transverse Heating of Strip



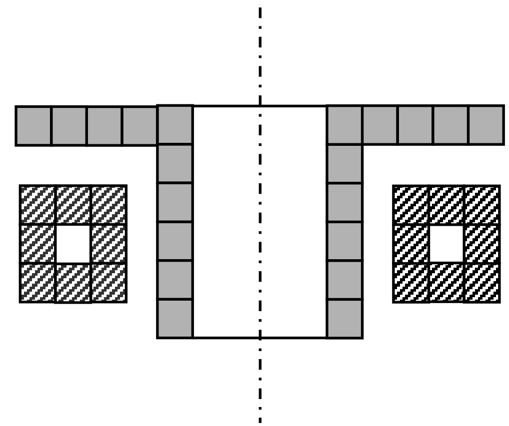
Is this field “near” to a required one? Is it optimal? Is it correctly calculated?

Nikanorov, A., Schulbe, H., Galunin, S.: *From expert solution to optimal design of electrothermal installations*, J. Elektrowarme Int., Heft 4, 2004

First publications on Numerical Simulation of Induction Systems



Temperature distribution in the ingot radius, 1D **FDM** EM+T computer simulation, Holmsdahl and Sundberg, ASEA, 1963



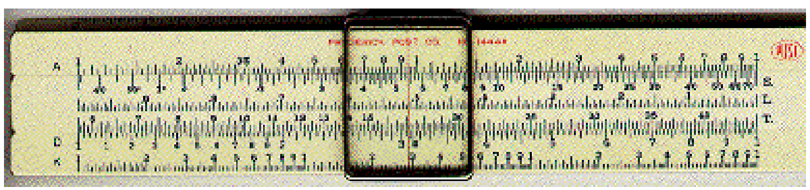
2D EM computer simulation of induction systems by Inductively Coupled Circuits method, E. Kolbe and W. Reiss, 1963

This was the simplest method of integral equations.

FEM (FEA) was used for simulation of induction systems approximately 10 years later.

Because of low speed and memory of hardware, many simplifications were required resulting in inaccuracy of simulation.

Evolution of “Hardware”

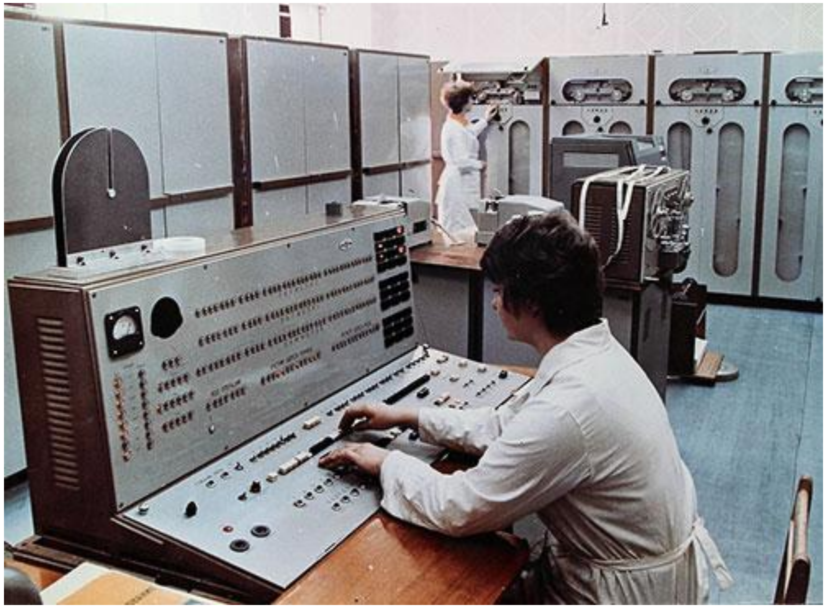


Logarithmic ruler, before 1965..
…. and later

Mechanical calculator, before 1970s

Programmable electronic calculator Casio, 1970s and later

Evolution of Hardware



Big Electronic Machines 1965 – 1990s; limited access for induction system simulation

Modern personal computer, since 2000

Powerful computers and huge improvement in software allow us to solve multiphysic problems. Sources of simulation inaccuracy are shifted to the problem formulation, properties of materials and other user-related issues.

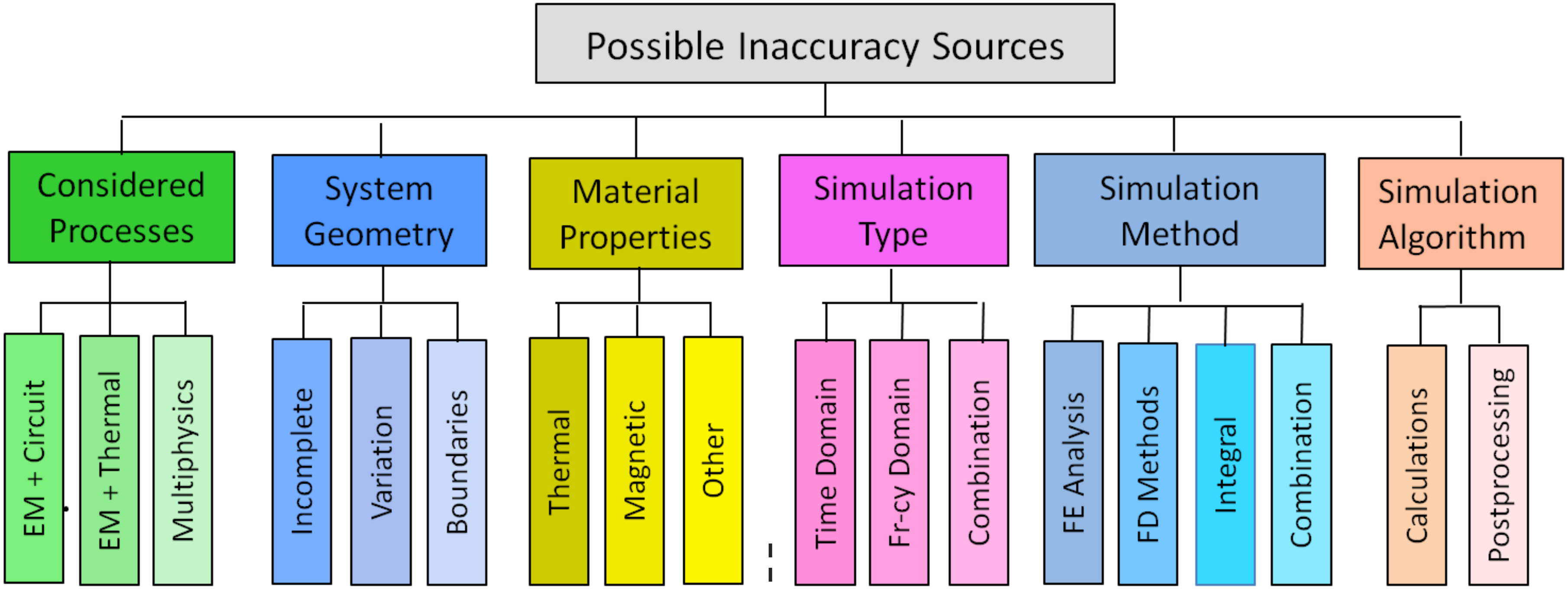
Computer Revolution in Induction Heating Technology

Old approach, old people: huge practical experience, low trust in computer simulation

New approach, new people: low practical experience, absolute trust in computer simulation

Best practice: **synergy of practical experience, theory and simulation!**

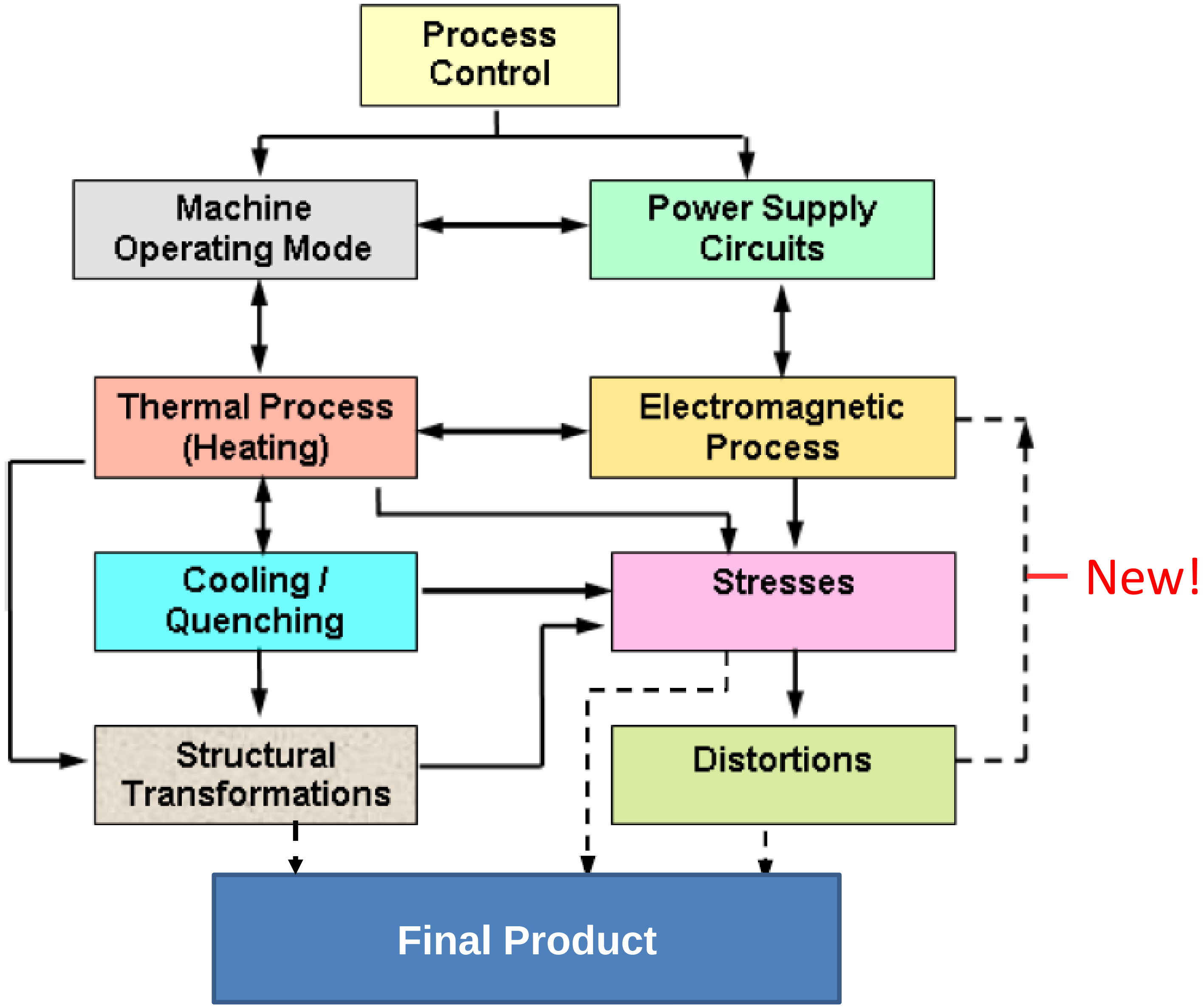
Factors that Influence Accuracy of Simulation



Problem Formulation and Description | Problem Solution and Presentation

Problem Description and Solution are mutually dependent;
effectiveness and accuracy of simulation depends on proper choice at each stage

Scheme of Processes in Induction Heat Treating

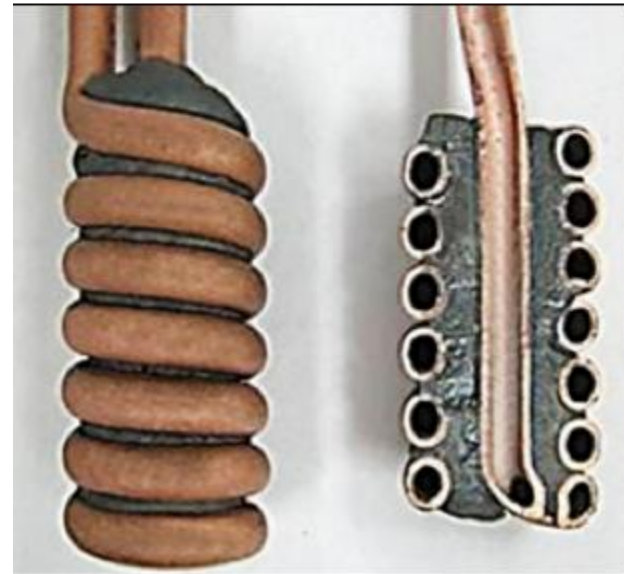


System Description

- Majority of practical simulations are being made now in 1D or 2D approaches
- Structure and geometry of real induction systems are often very simplified
- In reality a majority of induction systems are 3D
- Interference of induction device and source of power must be considered in many cases
- One of the problems – frequency variation during the process.

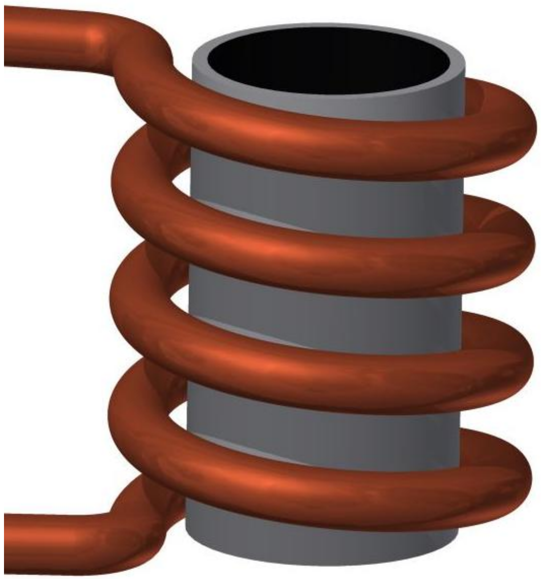
3D Effects in Cylindrical Coils

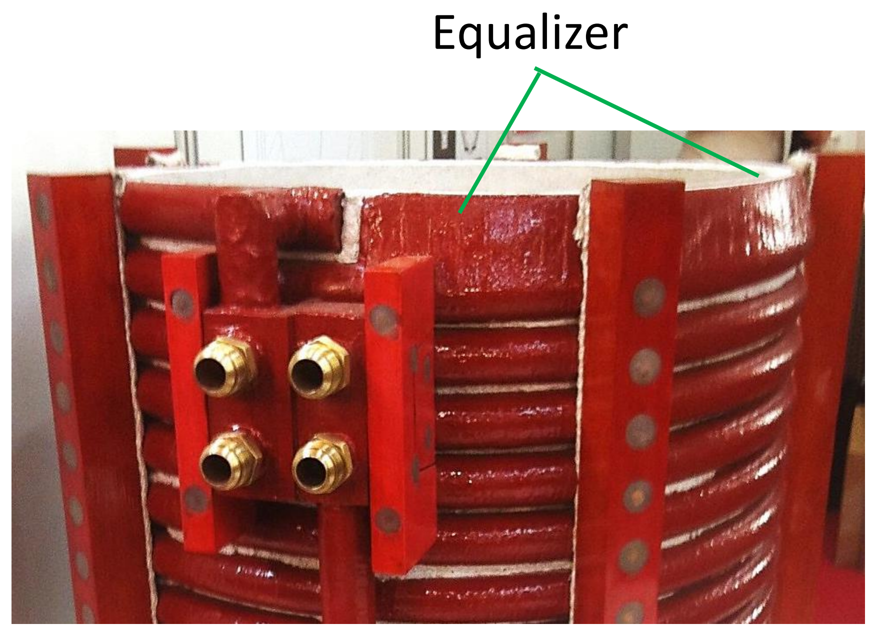
Is this coil 2D?



Multi-turn internal coil looks like axisymmetrical but must be considered as 3D due to 3 components of magnetic field

3D Effects in Multi-turn Cylindrical Coils



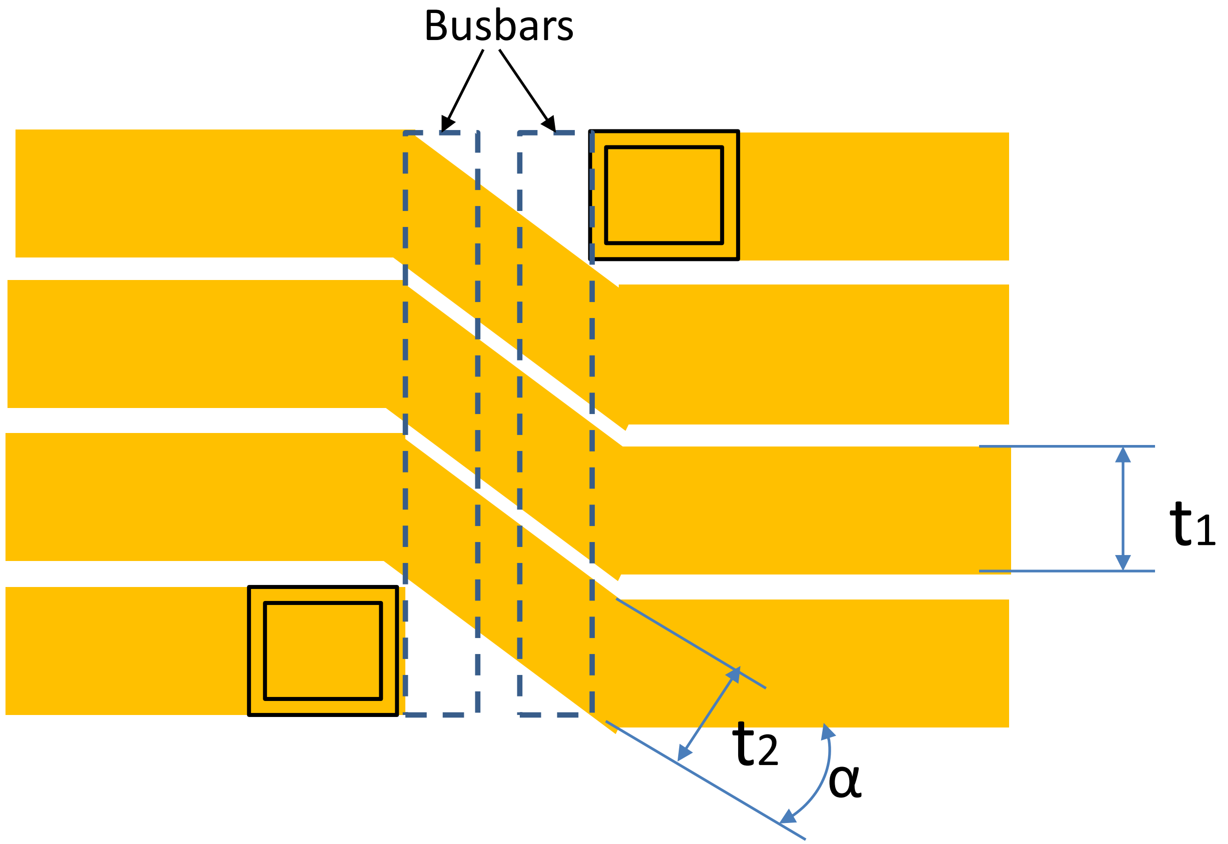


Using copper wedges (equalizers) in attempt to made the coil field 2D

3D Effects in Multi-turn Cylindrical Coils

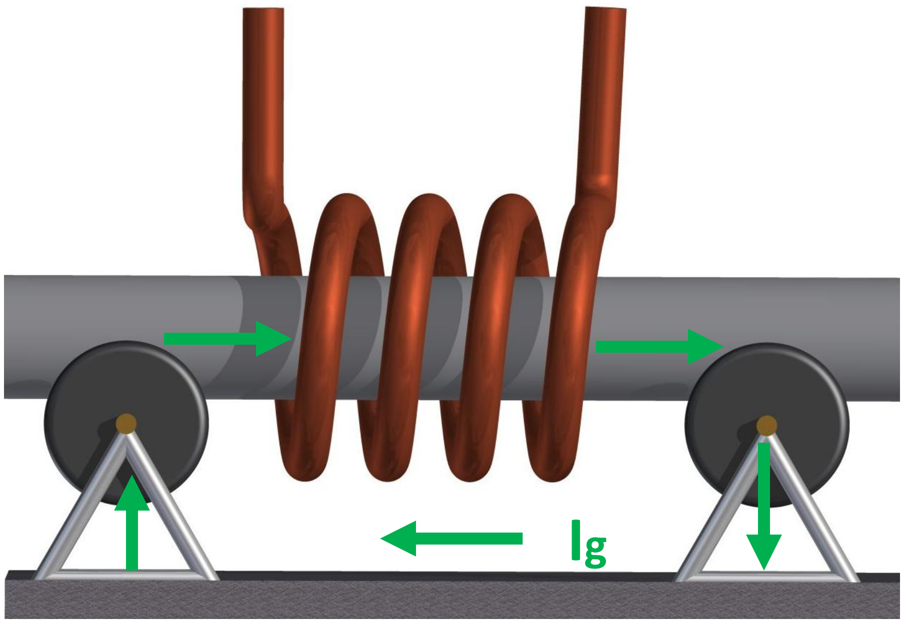
"Dog Leg" connection of plane-parallel turns can result in big distance between leads

Almost 2D Multi-turn Coil

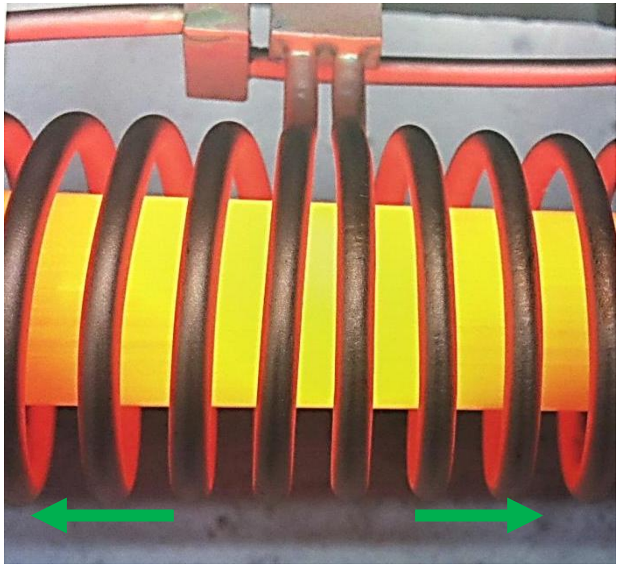


$t_2 = t_1 \cos \alpha$; for $\alpha = 45^0$ $t_2 = 0.707 t_1$

“Ground” Current



Effect of “ground” current is often observed in systems with multi-turn coils for heat treating and forging, as well as HF welding



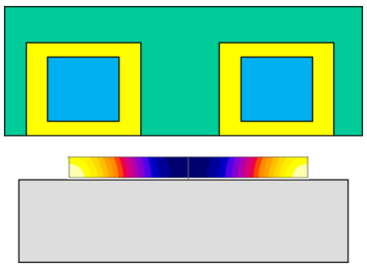
Special connection of coils is often used for elimination of ground current but it reduces efficiency and power factor

No publications on simulation of ground currents are familiar to the author.
Usually these currents are detrimental, causing damage of contact bodies, roll bearing, etc. However they may be used for benefits….

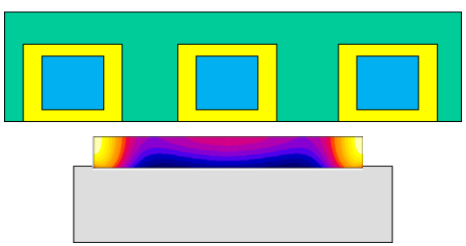
Trico Beam Hardening Using “Ground” Current

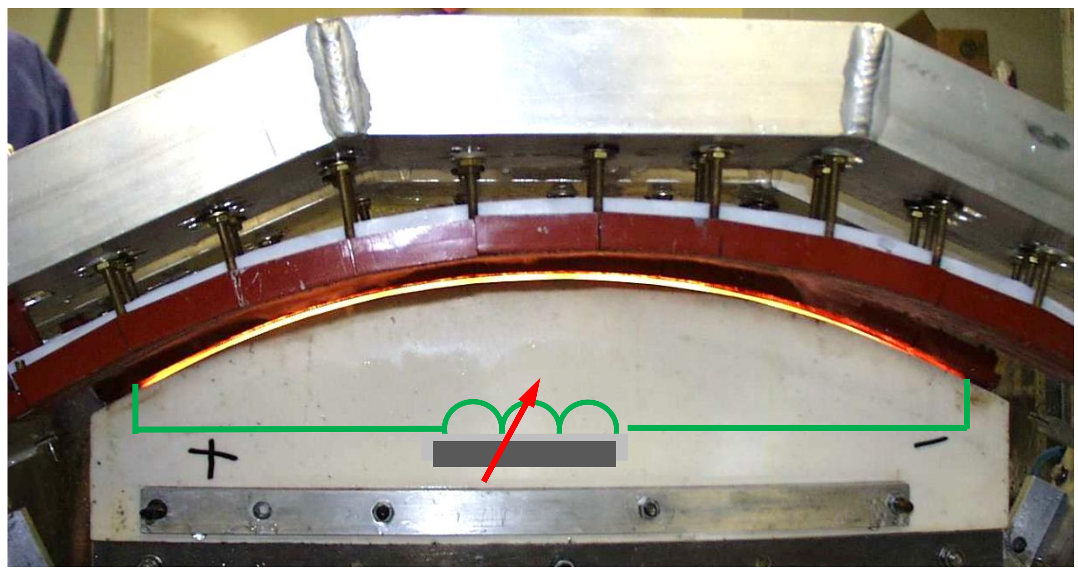
Temperature distribution

Hair-pin coil



Split-n-Return coil





Split-n-Return coil with a reactor in the external circuit

Material Properties

Properties for simulation of electromagnetic and thermal problems:

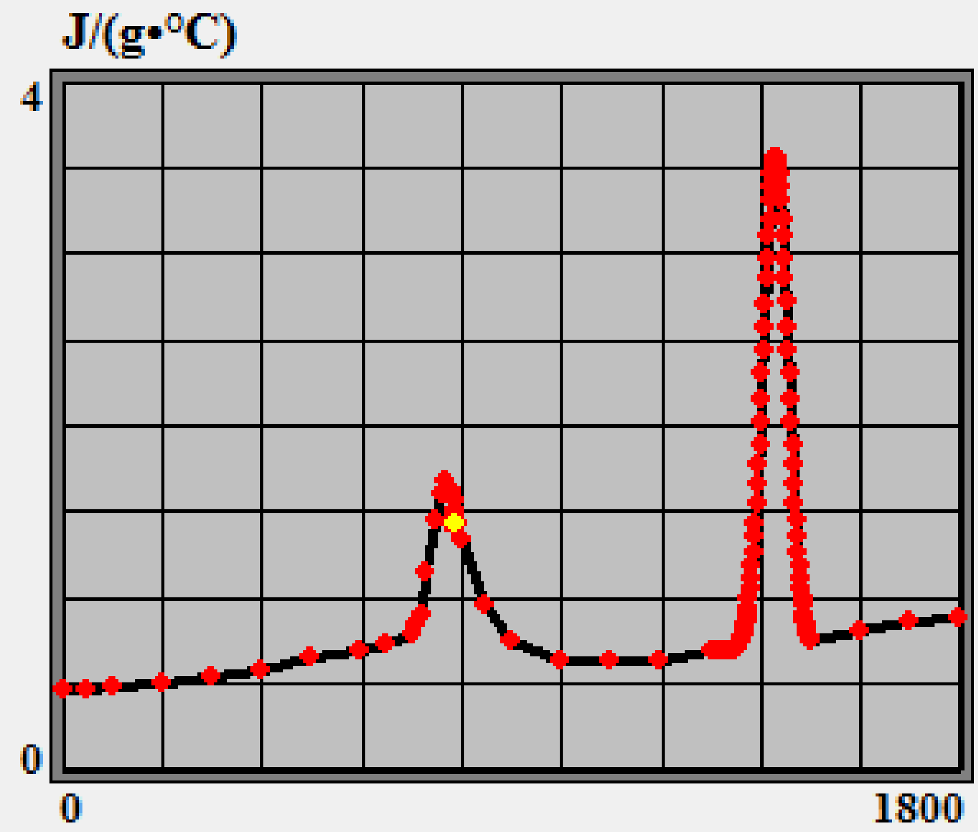
- Density d(T)
- Specific heat c(T)
- Electrical resistivity ρ(T)
- Magnetic permeability μ(H, T).

Main problems are with specific heat and especially with magnetic permeability.

Problems with specific heat:

- Data availability for different structures of materials
- Approximation of data in zones of structural transformation
- No account for chemical reaction (e.g. oxidation in forge heating)
- A set of calculations showed that an error in temperature can reach 10%.

Specific Heat of Steel 1040



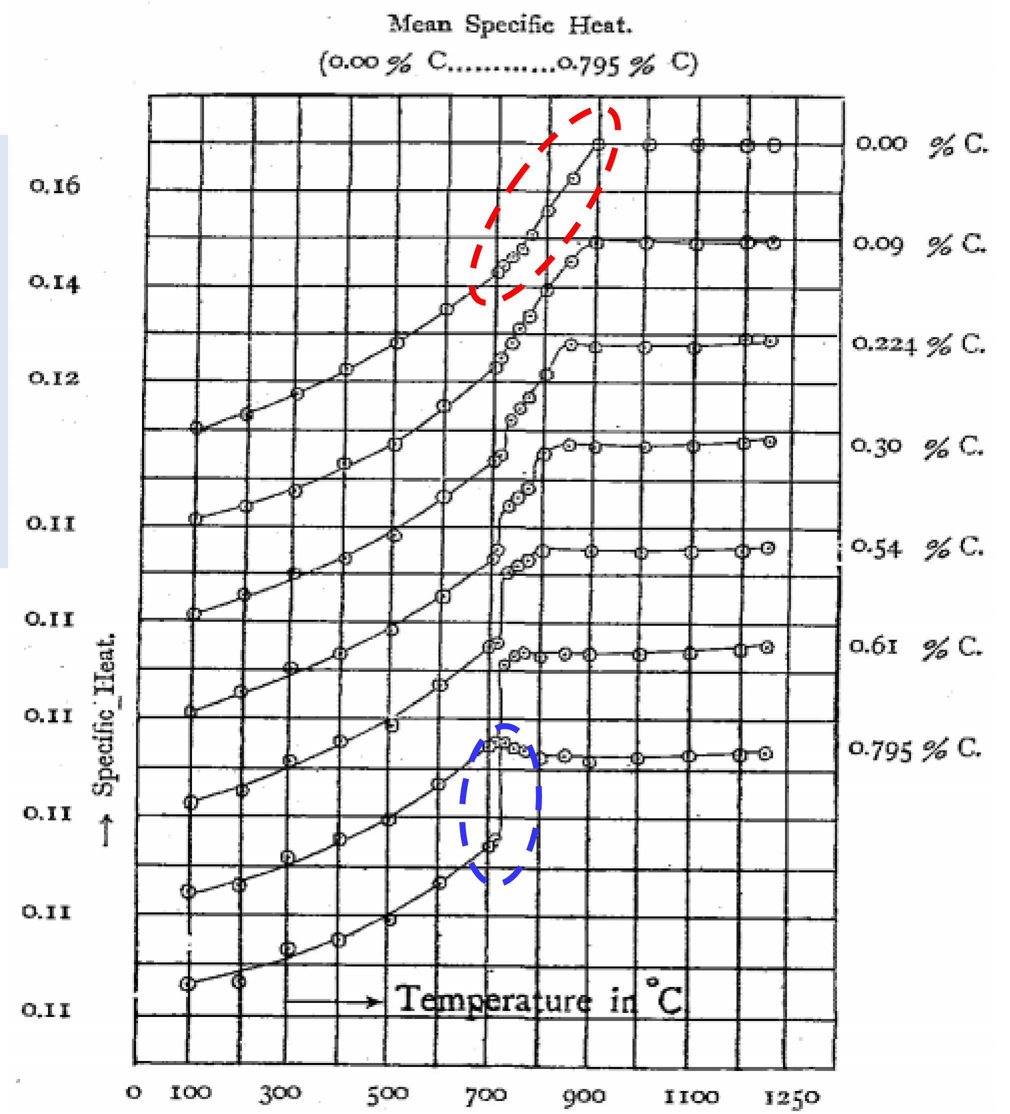
747	1.4699
760	1.6202
770	1.6998
775	1.6602
780	1.6307
785	1.5897
787	1.5207
790	1.4597
800	1.353
850	0.9794

Source: database of program Elta 6.0

Specific Heat of Steels

On The Specific Heat of Carbon Steels

by Saburo' Umino
The science reports of the Tohoku University,
Sendai university, 1926
Sci. Rep. Vol. XV. No.3, p.331



Pure Iron, 0%C

Nearly pearlitic steel, 0.8%C

Magnetic Permeability Mu of Steels

Mu is sensitive to material composition, structure, field strength and temperature. In many cases it is anisotropic.

Main questions:

1. How to characterize Mu at alternating fields?

Time domain approach was published by M. Kogan in 1966.

However more simple approach based on ideas of L. Neiman (1940s) and Slukhotsky (1950s) were commonly used. It uses a certain "equivalent" value of Mu during the whole period of field.

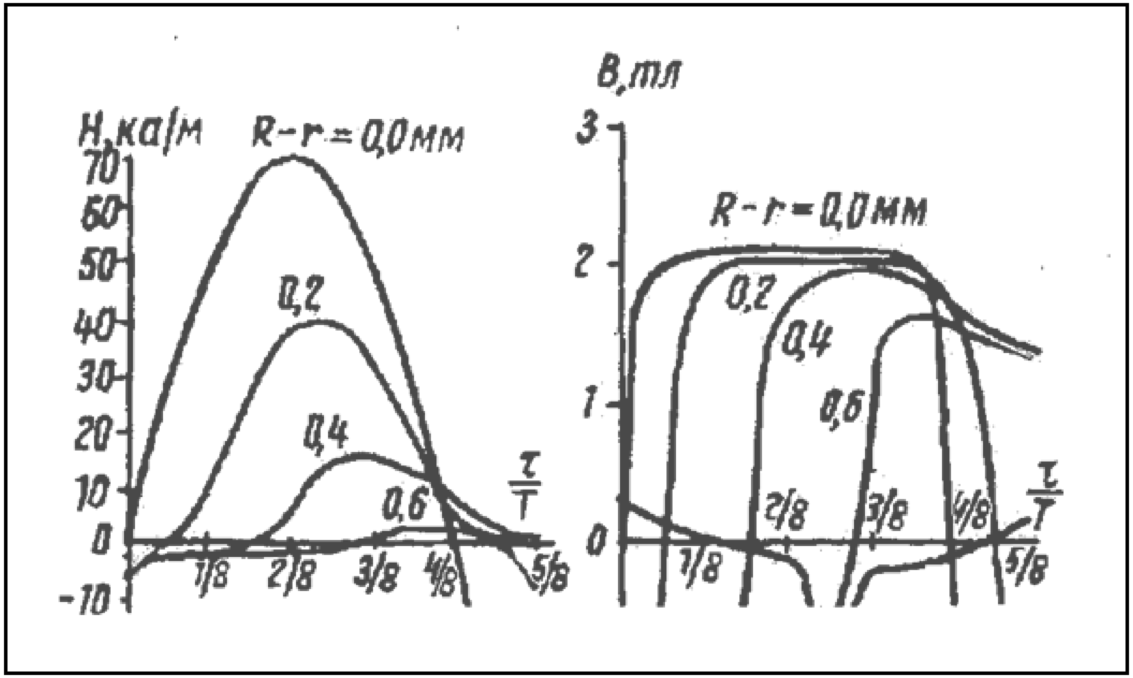
Our knowledge about accuracy of this approach in induction heating conditions is insufficient. Only recently some attempts were made for simulation of EM field in Time Domain in induction heating.

2. Calculation of hysteresis losses. Majority of programs neglect them compared to eddy-currents. It becomes quite incorrect in heating of particulated materials.

3. Some programs consider Mu constant in depth. It is well known that this assumption reduces absorbed power up to 30%.

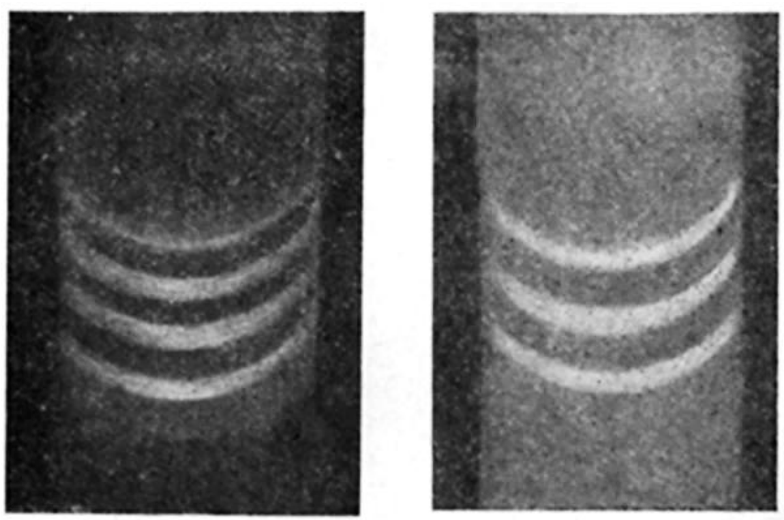
4. Behavior of magnetic materials at temperatures close to Curie point.

No.1 Time-Domain Solution of 1D EM Problem

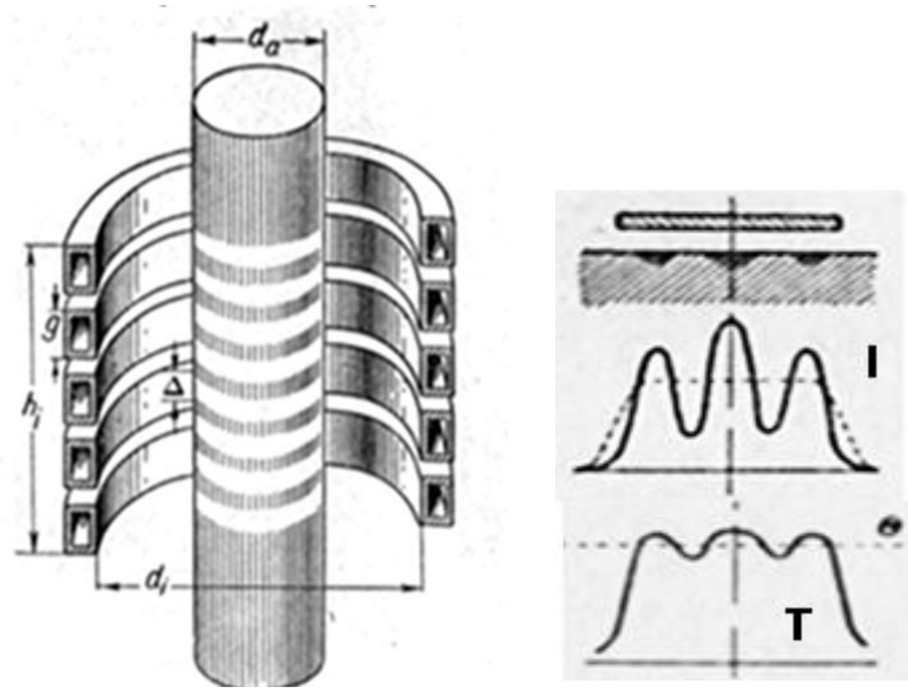


Waveforms of H and B in magnetic cylinder for sinusoidal external field strength, Time Domain simulation by M. Kogan, 1966

No.3 Striation Effect



M. Divilkovsky, f= 477 kHz (left) and 242 kHz (right). Armco iron

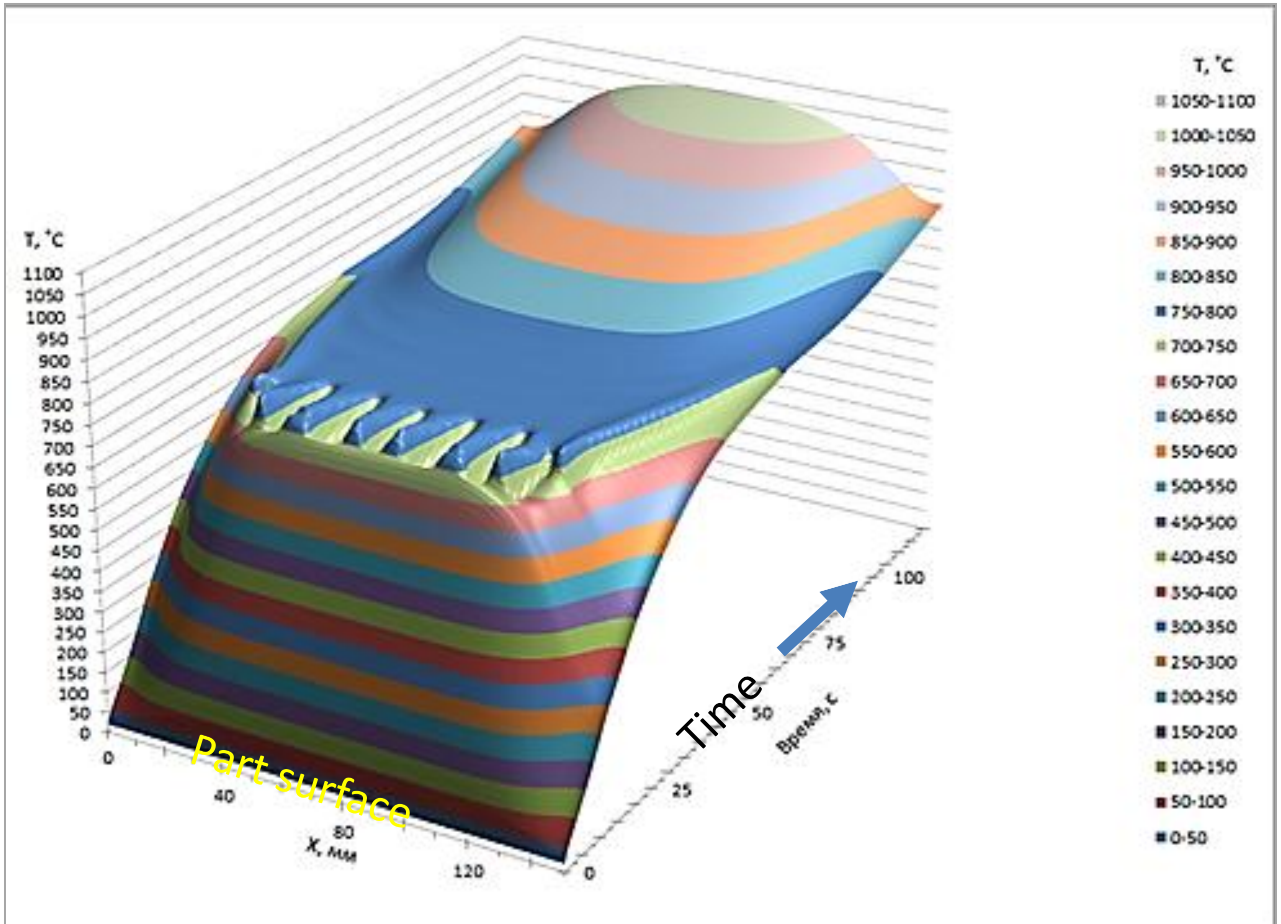


G.I. Babat, Induction Heating of Metals and its Industrial Applications.
2nd edition, Energia, 1965, 552 p.

Striation or Zebra Effect

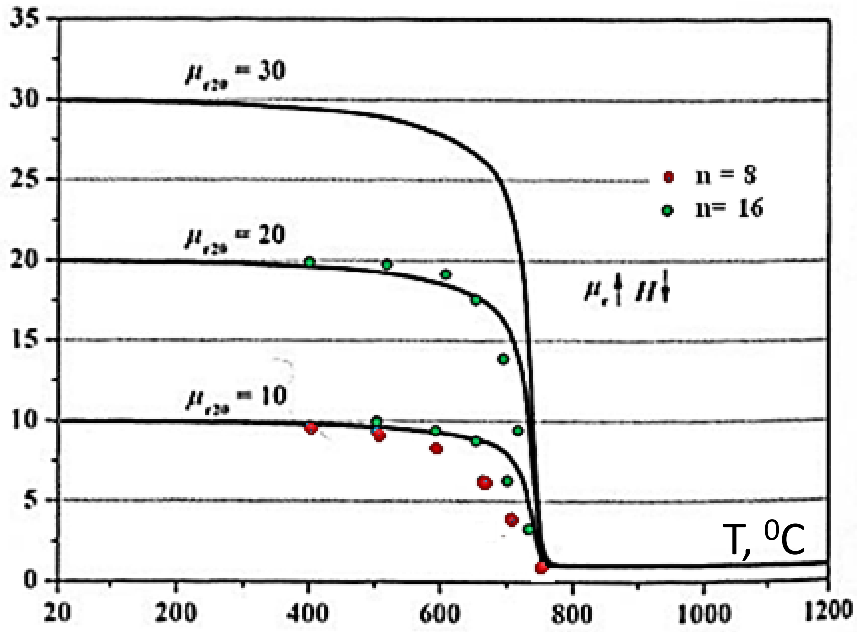
Zebra effect should not be mistaken for a “Barber's pole" effect, well known in induction. Barber’s pole effect demonstrate helical stripes, caused by slow part rotation/feed ratio in scanning processes

Surface Temperature Distribution vs. Time



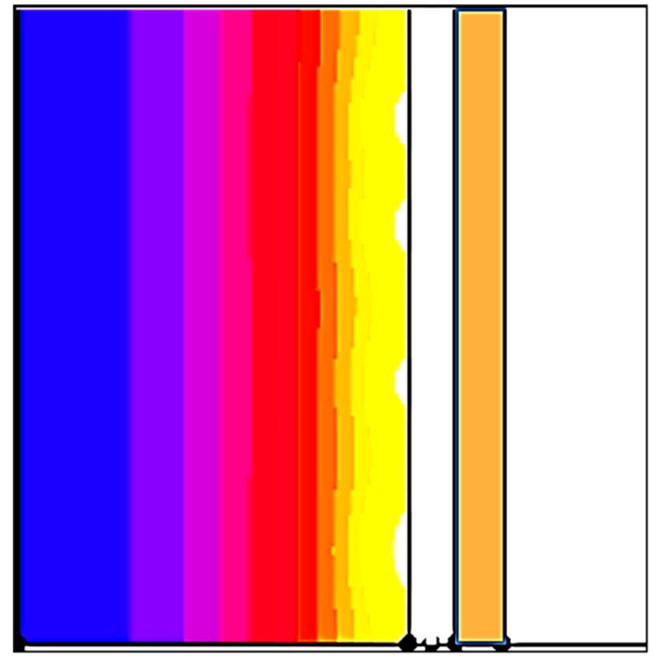
Source: S.V. Dzliev et al. Instability in induction heating of magnetic steel. J. of Induction Heating, no. 23, 2013, in Russian

Temperature Dependence of Mu and Simulation of Zebra Effect



Dependence of permeability vs. temperature for a carbon steel for different field intensities; marks show permeability value calculated with a formula below

$$\mu(T) = 1 + (\mu - 1)\left(1 - \left({}^{T}/_{T_k}\right)^{n}\right)$$



Temperature distribution on the surface of a part heated in a long single-turn inductor. n = 16

Approximation of μ = f(T)
Source: program Elta 6.0

Summary

- Computer simulation is a great tool for research, development, learning and teaching
- It can be very accurate when the task is correctly formulated and proper simulation technique selected
- The user of simulation must be a good expert in induction technique; it is vital
- Modern computer allows us to solve difficult problems of induction heating; the cutting edge is “non-linear coupled 3D EM+Thermal+XXX” problems
- There are many programs for simulation of induction heating but their ability and limitations (causing inaccuracies) are not well investigated and described
- Material characterization and databases are the key problems in achievement of high accuracy
- International collaboration is required for further advancement of simulation technique.

FLUXTROL Inc. Centre for Induction Technology

EPM 2015 October 12-16, 2015 8th International Conference on Electromagnetic Processing of Materials Hôtel Majestic - Barrière, Cannes sur Mer • France

THANK YOU FOR ATTENTION!

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