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Perspective of using electrothermal software programs in investigation of forge heating by induction

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ABSTRACT

A lot of problems to be investigated for forge heating such as high efficiency; uniform temperature distribution; low oxidation, etc. requires the industrial user-oriented programs to predict these parameters. ELTA and 2DELTA are the programs, which may be used in the first step of projecting process before the detailed construction of induction system. Description of the computer assisted design of induction lines is illustrated by several examples

Key words — induction heating, hot forging, computer simulation, ELTA programs.

1. INTRODUCTION

In the production of steel goods, induction heating is used in the whole chain of manufacturing processes [1]. It can be easy integrated into the forging process near the hammers, presses or forging machines. Hot forging of steel, i.e. A process of working metal to the desired shape by impact or pressure, usually requires pre-heating billets up to 950 – 1250 °C by induction installations. It is unique technology of rapid heating, achieved by internal induced currents. Induction installations can effectively heat the products of square, rectangular or round cross section and obtain uniform temperature prior to deformation.

A lot of problems to be investigated for forge heating by induction such as high efficiency; uniform temperature distribution; low oxidation, etc. requires the electrothermal programs to predict these parameters. Care must be taken in choosing frequency of power source, parameters of induction coils and so on to meet the necessary requirements of heating technology.

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Induction process and coil design involve more complicated phenomena than other heating techniques and are more knowledge demanding than traditional methods. Extensive work is being carried out in the field of numerical methods of electromagnetic and thermal calculation and computer simulation programs to meet necessary requirement of induction process designers. Electromagnetic and thermal processes in induction installations are mutually related (coupled) and must be simulated as tightly coupled. Many groups and individuals are working on the development of induction heating simulation methods and tools. In our days many programs, created on the base of Maxwell and Fourier equations by different groups of developers, may be used for induction heating simulation. Among the commercial programs that are being used or may be used for these simulation tasks, there are Flux 2D and 3D from Cedrat, Maxwell from Ansoft, Ansys Multiphysics, ThermNet and Magnet from Infolytica, Sysweld from ESI Group, Opera and Electra from VectorField, Inducto from Integrated Engineering, QuickField from TOR, products from Cosmos, and programs from other companies. They are expensive and require well-trained operator to run them effectively. The coil and part geometry in induction lines for forge heating is simple but the number of stages and the overall space is very big that creates difficulties in using general-purpose finite element programs. The ideology of ELTA (ELectro Thermal Analysis) and 2DELTA (Two Dimensional variant of ELTA for cylindrical systems) programs is different [2]. They are the engineering programs which do not require special knowledge in computer simulation due to simple self-explanatory interface and preinstalled design options and database.

The main problems to be investigated for forge heating by induction can be divided on three types: technological, technical and economical (Figure 1).

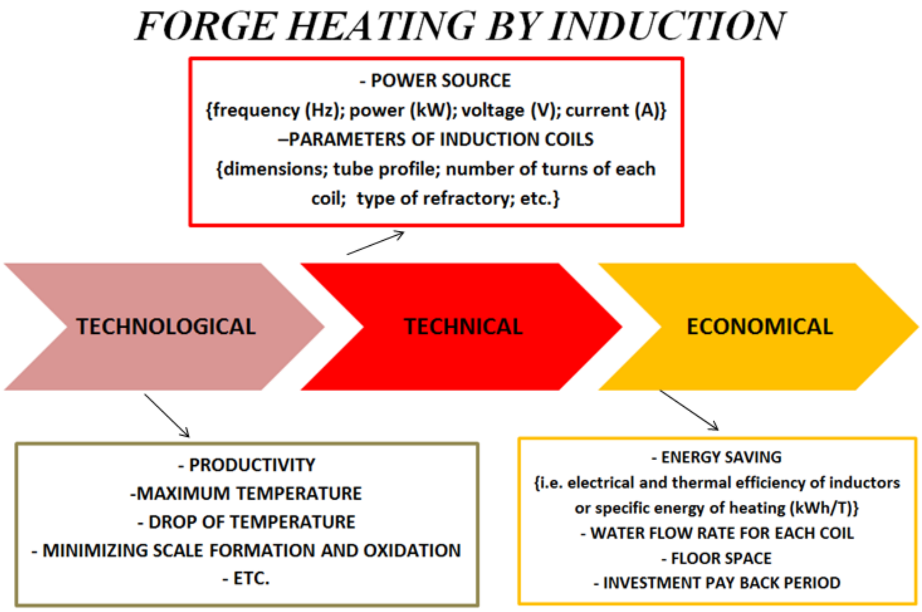

Figure 1: Approach phases for a best practice design

Technological problems are productivity, maximal temperature of overheating, drop of temperature, minimizing scale formation and oxidation of metal, etc. *Technical problems* are parameters of power source (frequency, power, voltage, etc.), parameters of induction coils (dimensions, tube profile and number of turns, number of coils in the heating line, etc.). *Economical problems* are energy saving, i.e. electrical and thermal efficiency of inductors or specific energy of heating, water flow rate for cooling of coils, floor space, pay-back period of investment, etc.

Technological problems can be solved at the beginning of development for new technology and induction system or during the deep modernization of old technological process and equipment. If productivity of line must be increased new induction coils and power supply can be required. Several steps of fast calculation and analysis in ELTA may give necessary information about temperature behavior in the cross-section after reaching of the final temperature and can help to choose one or rational variant of system to meet the technological specifications.

Induction process and coil design are two main technical problems directly connected with solving of technological and economical problems. The solution to these technical problems may be advanced step-by-step by first determining the optimal frequency and power supply, then designing the induction coils.

Choice of power source frequency is the most important stage of engineering design. Both a consumption of electric energy and quality of heating depends on it. For example, for through heating in forging process it is essential that electrical efficiency should be close to the maximum value and time of heating should be minimal.

2. INVESTIGATION OF CYLINDRICAL SYSTEM USING ELTA

ELTA is based on a combination of one-dimensional numerical (Finite Difference) approach and analytical account for finite lengths of the part and induction coil. Because of that simulation is very fast while providing good accuracy for systems of simple geometry typical for induction lines. One-dimensional equations describing electromagnetic field and temperature in cylindrical bodies are:

$$\frac{1}{R}\frac{\partial}{\partial R}\left(\rho R\frac{\partial \dot{H}}{\partial R}\right) = -j\omega\mu\mu_0\dot{H}, \qquad C_V\frac{\partial T}{\partial t} - \frac{1}{R}\frac{\partial}{\partial R}\left(\lambda R\frac{\partial T}{\partial R}\right) = w, \qquad (1)$$

where R – radius, ρ – electrical resistivity, $\dot{H}$ – magnetic field strength, ω – angular frequency, $\mu\mu_0$ – magnetic permeability, C_V – specific heat, T – temperature, t – time, λ – thermal conductivity, w – volumetric power density.

Final length of the system is taken into account using analytical procedure, called Total Flux method [1]. It is based on composing the magnetic substitution circuit for a system “inductor – workpiece”. Magnetic flux Φ_I created by ampere-winding of the coil I_1W_1 may be calculated directly from magnetic circuit (right part of Figure 2a). However more comfortable way is to convert the magnetic scheme in electrical substitution circuit with impedance R and X (Figure 2b).

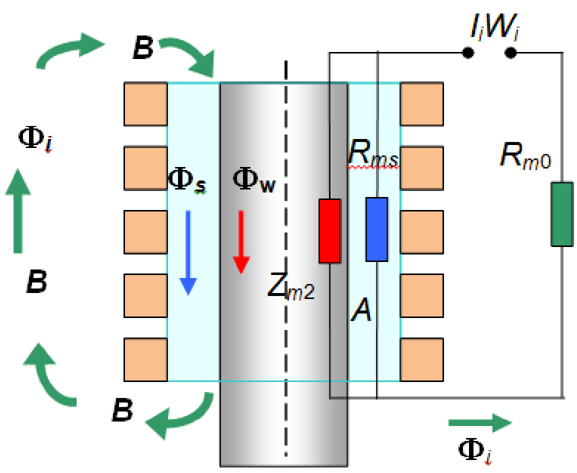

Figure 2 a: Scheme of magnetic flux, magnetic subtitution circuit of “inductor – workpiece”

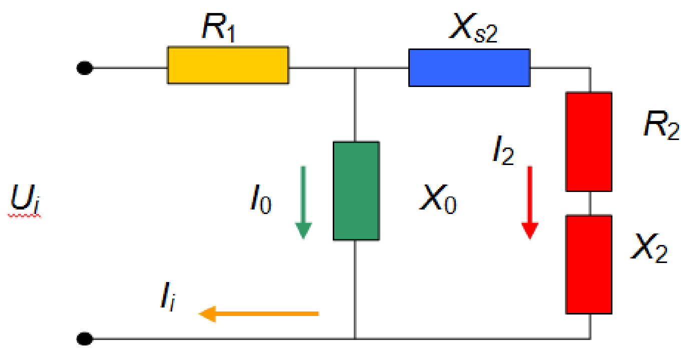

Figure 2 b: Electrical substitution circuit

Knowing impedance, voltage U_i, current I_i and other integral values of inductor can be found.

ELTA calculates effective penetration depth δ, i.e. depth from the boundary surface, where the total power absorbed by a workpiece decreases e^2 times and 86 % of total power is absorbed (Figure 3), and the threshold value of electrical efficiency η_{lim} for current geometrical parameters of cross-section (diameters or perimeters of inductor and workpiece) and electrical parameters: resistivity of inductor tube, variable during the heating process resistivity and permeability of work piece materials taken into account infinitely long induction system by using Formula (2).

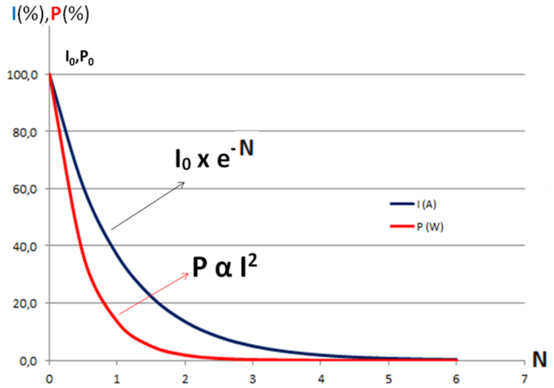

Figure 3: I (%) and P (%) as a function of δ

$$\eta_{lim} = \frac{1}{\left(1 + \frac{R_1}{(R_2 W^2)}\right)}$$

Where: R_1 – minimal resistance of induction coil

R_2 – real resistance of workpiece

W – turn number

Formula (2): Electrical efficiency

It is very convenient to see how real and ideal efficiencies change during the time. If you will see that this parameter is not good and energy consumption is very high you should:

a) Increase its space factor *g* (ideal variant for multi turn coil is *g* = 1);

b) Increase the wall thickness *d* of inductor copper tube up to penetration depth δ or more (ideal variant is *d* = 1.6δ);

c) Increase the length of system or use external magnet concentrator (controller).

Investigation of an existing forging application:

The strategy of investigation is described below as one of case study for one Forging Company that has an induction heater for continuous heating of SAE1045 steel bar 40 mm diameter (Figure 4).

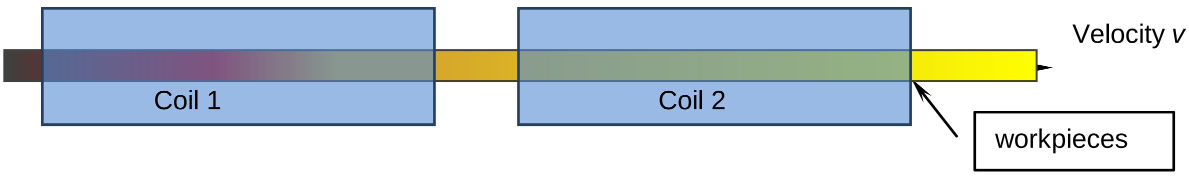

Figure 4: Sketch of induction installation

Heater has two coils connected in parallel. Each coil has length of 1200 mm with 96 turns made of rectangular tubing *A*×*T*×*d* = 8×12×1.5 mm. Coil ID = 86 mm, ceramics refractory cylinder ID = 60 mm. Coil voltage is approximately 800 V at frequency 1000 Hz. Coils have 12 branches for water cooling each; total water flow rate is around 300 lt. /min.

Calculations in ELTA are related to a certain cross-section of the load, which passes through the processing steps in function of time. This algorithm allows the user to simulate multi-step heating processes in one “shot” and is very convenient for simulation of the induction lines with any number of stages describing heating in individual inductors, cooling in the gaps between them and even heating or holding in a flame or electric furnace. Calculations are designed "in series steps", i.e. power and temperature is being calculated for each heating stage (inside the induction coils) and "cooling" stages (spaces between coils and holding zones). It make possible to simulate systems with very large number of steps, which is typical for forge induction lines.

***Variant A. Existing system*:** (Figure 5)

A set of calculation showed that with coil voltage 800 V, the 40 mm bar could reach final temperature of 1250±50 °C when its speed is 44.5 mm/sec or 1560 kg/h. It means that heating time in each coil is 27 sec. and with a space between the coils of 130 mm a “cooling” stage time in the gap is 3 sec. Bar surface temperature is approximately 1000 °C at the exit from the first coil, drops to 980 °C during transportation between the coils and raises to 1260 °C in the second coil. Heating in the second coil is low efficient (electrical efficiency is 0.35 compared to 0.64 for the first coil). Thermal efficiency is also lower (0.85 and 0.95 respectively) due to higher surface temperature. Temperature gradient in radius is rather small and temperature equalizes in 3-4 sec.

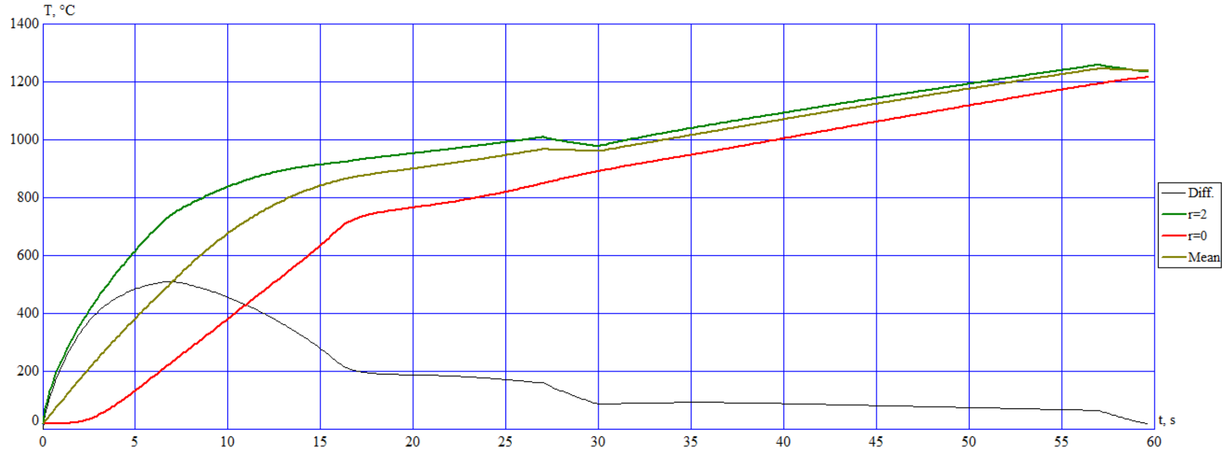

Figure 5a: Temperature versus heating time

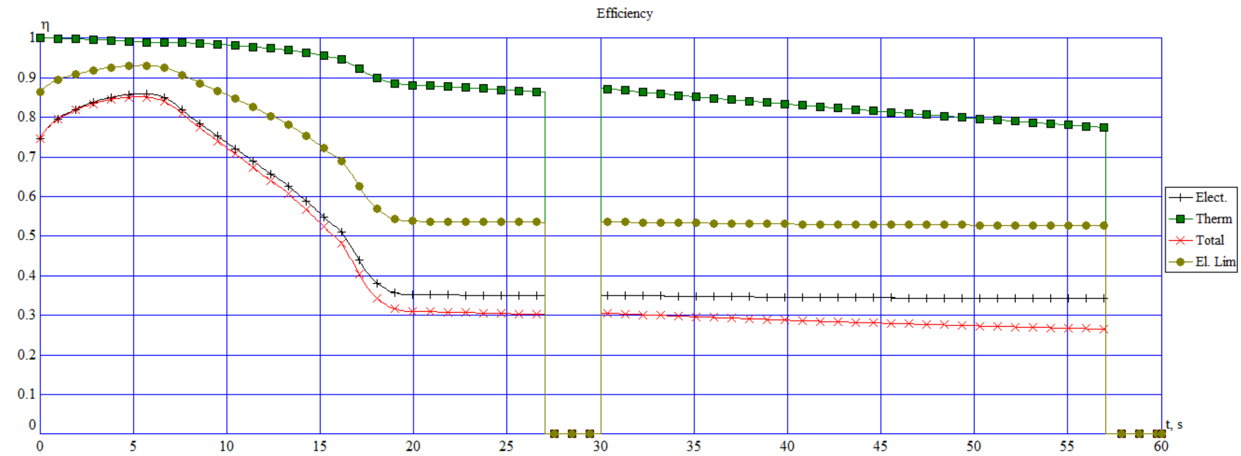

Figure 5b: Electrical, thermal, electrical limit and total efficiency

Results of analysis**:** Results of simulation are very close to measured parameters of the existing installation. Specific energy for heating bar is around 494 kWh/t, which is more than 2 times higher than minimum required energy (enthalpy) for heating to 1250 °C (243 kWh/t). In existing installation number of water cooling branches may be reduces to 7. However for higher input water temperature (e.g. 30 °C) number of branches must be at least 10 - 12 as it is at present.

Variant B. Modified heater: *(Figure 6)*

Because two coils are too long for heating at 1000 Hz, it is a good approach to remove the second coil and modify the first coil.

With several iterations it was found that the coil winding must be made of 68 turns of tubing 16×16×1.6 mm in order to have minimum power demand for the same production rate.

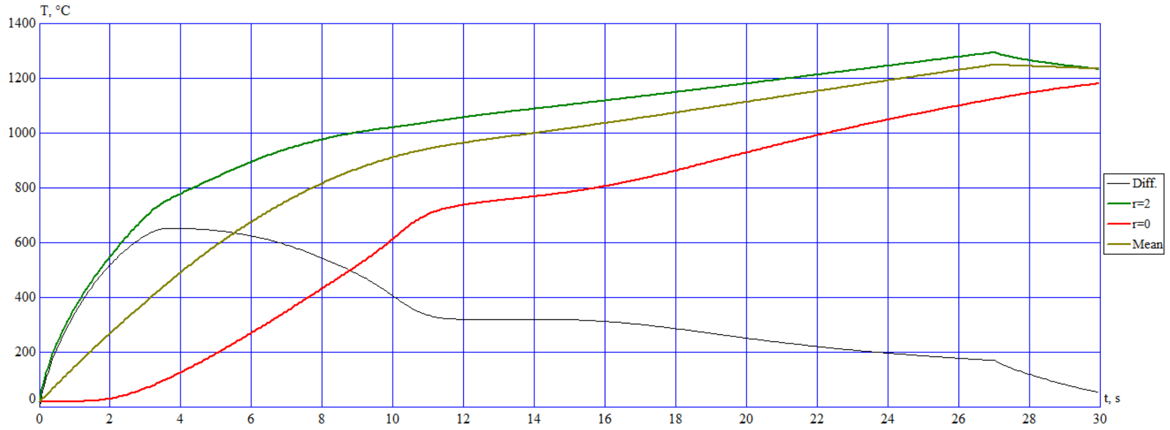

Figure 6a: Temperature versus heating time

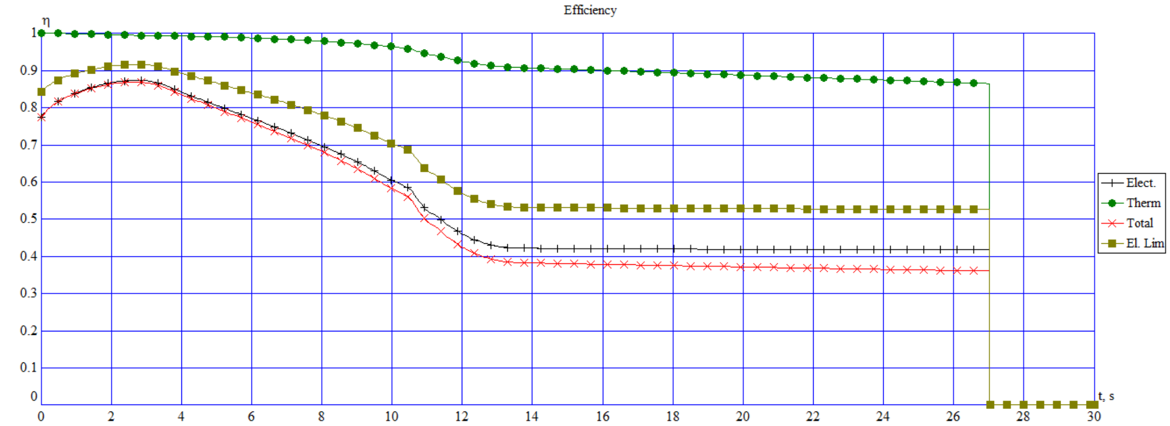

Figure 6b: Electrical, thermal, electrical limit and total efficiency

Improvements: Shorter heater length and lower price (one coil instead of two); Higher efficiency (electrical efficiency 0.56, total 0.53); Lower water demand (188 lt./min instead of 300 lt./min); Smaller and cheaper capacitor battery; Total required power is 632 kW compared to initial 772 kW, i.e. reduced by 18%.

Further improvements may be achieved if we increase frequency.

Variant C. Heating at frequency 1500 Hz: *(Figure7)*

Reference depth for hot steel at 1000 Hz is 16 mm, i.e. only 1.25 times smaller than the bar radius. It means that coefficient of power absorption *G* equals to 0.3 and is far from a threshold value which equals to 1 at high frequency. Optimal frequency for a bar with diameter 40 mm must be 3 – 4 kHz; in this range an absorption coefficient is about 0.8.

Frequency change from 1 to 3 or 4 kHz may demand purchase of a new power supply. It will require also longer coil in order to provide uniform heating. We can assume that the existing thyristor power supply for 1000 Hz may be turned to 1500 Hz.

Simulation below shows that even this simple change can result in significant improvement of efficiency.

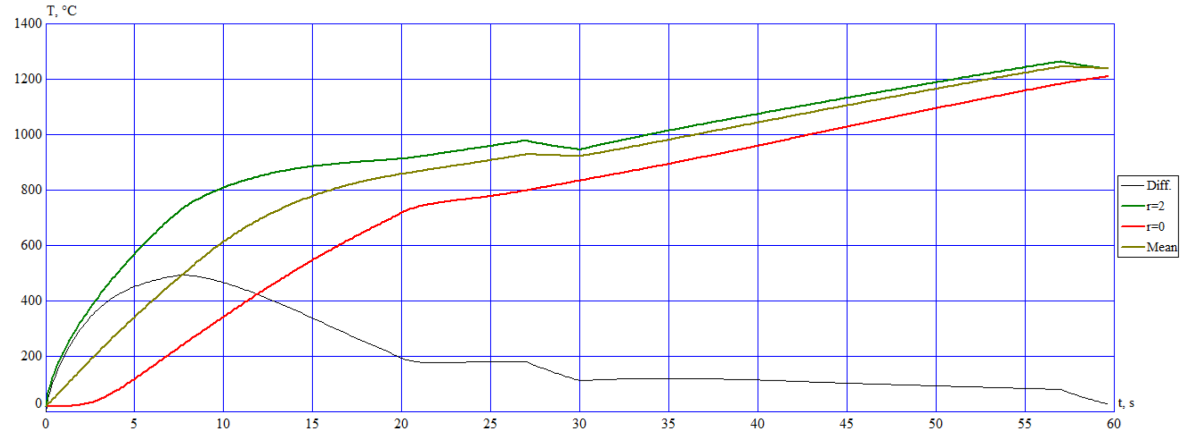

Figure 7a: Temperature versus heating time

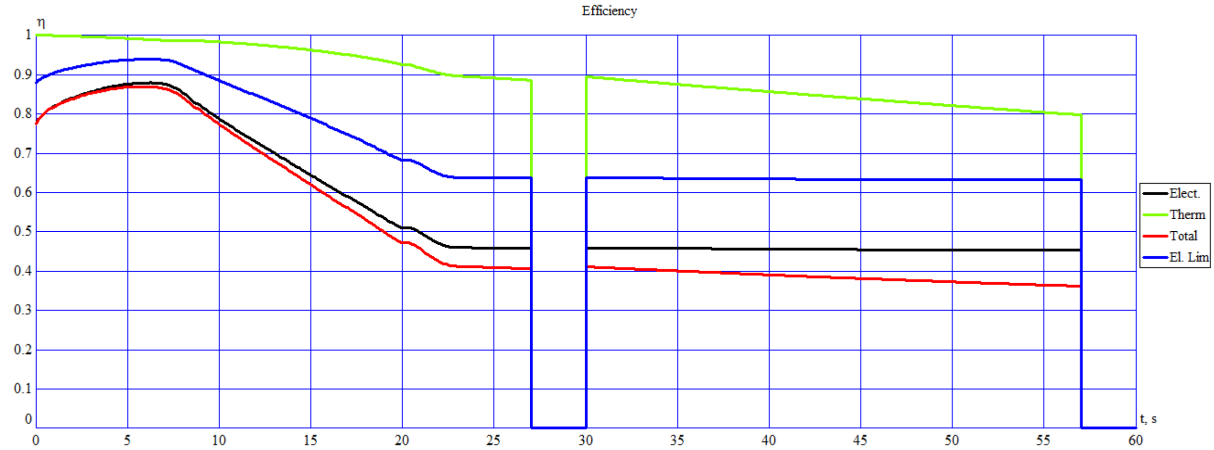

Figure 7b: Electrical, thermal, electrical limit and total efficiency

Results of simulation at 1500 Hz and improvements:

Using two modified coils same as in case ***A*** but with turn number 85, it is possible to heat bar with the same production rate using only 668 kW instead of 772 for initial design. Maximum surface temperature is 1266 °C. Lower need in water (222 lt. /min instead of 300 lt. /min) with 9 branches of cooling.

Variant D. Heating at frequency 4000 Hz: *(Figure 8)*

We can use two coils 1000 mm long with 51 turns to heat bar with required uniformity. Coils may be fed in parallel from one power supply.

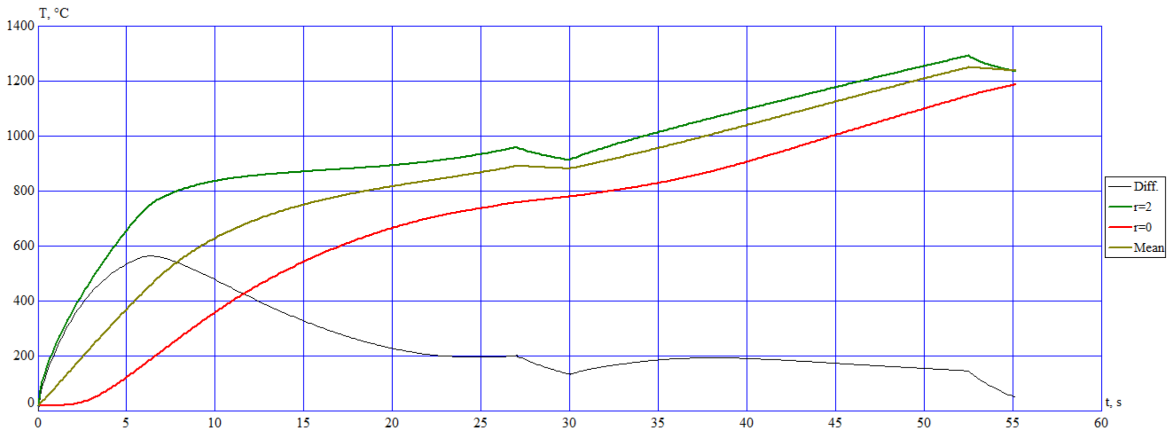

Figure 8a: Temperature versus heating time

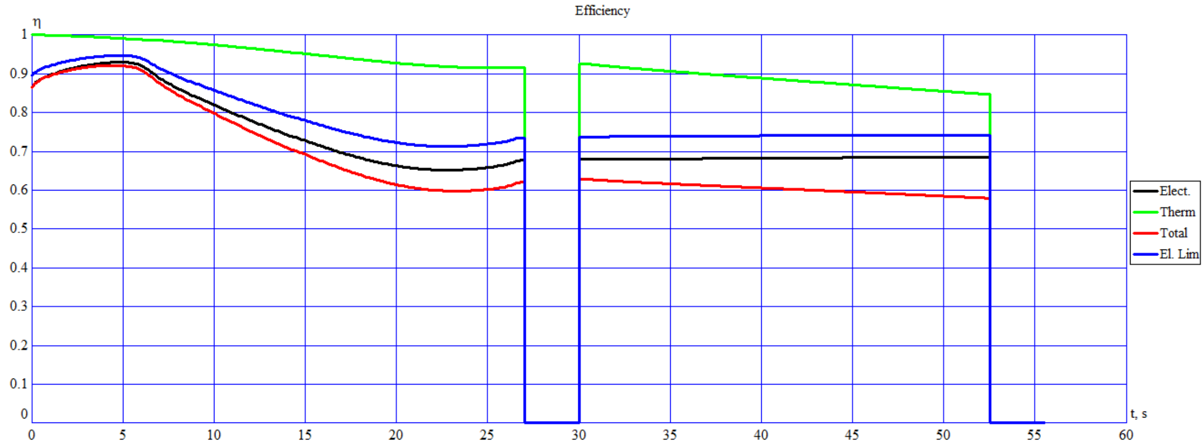

Figure 8b: Electrical, thermal, electrical limit and total efficiency

***Improvements*:** Total required power is only 478 kW, i.e. 1.61 times lower than in the existing installation. Lower water demand (116 lt. /min instead of 300 lt. /min in existing installation) with only 2 branches of cooling for each coil. Capacitor battery is smaller and cheaper.

***Overall conclusions*:**

Installation parameters for the same production rate of 1.56 t/hr are shown in Table 1.

Table 1: Results of simulation

Variant	Number of coils	Frequency, kHz	Power, kW			Water, lt. /min	Reactive power, kVAr
			Coil 1	Coil 2	Total		
A	2	1.0	479	293	772	300	3488
B	1	1.0	632	-	632	188	3056
C	2	1.5	419	249	668	222	3054
D	2	4.0	282	175	457	110	3163

Simulation of the existing system (**Variant A**) showed results very close to measured in practice both for electrical and cooling parameters. Using ELTA it is possible to simulate different heating regimes and heater designs including multi-stage processes. The second phase (coil design) may be performed by the same program or with 2DELTA. If more detailed analysis of the coil parameters is required such as calculation of losses in individual turns, turn spacing variation, etc. as ELTA has no automatic optimization procedure, an operator can effectively optimize the process and system in several iterations with account for multiple restrictions and several goal functions.

Operator-guided design can provide big savings in capital investments, energy and cooling water demand by optimizing the overall function { technological; technical; economical } based on the existing restrictions or supplying the best practice recommendations to improve the existing process through a retrofitting or by replacing the existing system.

3. INVESTIGATION OF SYSTEM WITH SQUARE CROSS-SECTION

ELTA 6.0 program has an option for 2D FD simulation of heating bodies with rectangular cross-section and coordinates *x, y*. Two-dimensional non-linear differential equations for magnetic field $\dot{H}$ and temperature *T* are described by Equation (3):

$$\frac{\partial}{\partial x}(\rho\frac{\partial \dot{H}}{\partial x})+\frac{\partial}{\partial y}(\rho\frac{\partial \dot{H}}{\partial y})=j\omega\mu\mu_0\dot{H},\ C_V\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})+w. \quad (3)$$

This important 2D option for heating of bodies in the longitudinal magnetic field permits to replace the frequently utilized method of replacing the square to the equivalent related to mass circle.

This variant of calculation gives more accuracy results and can obtain not only surface temperature but its distribution in the cross-section, including problem corner zones. The strategy of preliminary study of forge heating line by induction, or in combination with furnace, may be performed using 2D option of ELTA 6.0 as described below.

The parts are usually moving continuously or in small steps along the rails of being supported by driving rolls. These lines can contain many induction coils. The coils typically have the same length but their window dimensions, thermal insulation and turn numbers may be different. Induction coils are often connected in series and parallel group supplied from individual power sources with the same or different frequencies. Depending on techno-economical situation gas furnace may be installed before the induction line for energy savings or electrical resistance furnace may be installed at the end of the line for temperature equalization or for holding and flexibility.

Design of such lines is a rather challenging task. It may be divided in two phases. The first phase is determination of the line length, power distribution along the line and optimal frequencies for different parts of the line, which should grand required technological specifications and good techno-economical results. This first stage may be called "the process design". The second phase is a detailed determination of individual coil parameters and their optimization as well as proper selection of the power supply and matching circuitry.

The program can simulate the process of heating using an option "power density on the part surface" without accurate description of the coil design, which is very convenient for the first stage of development (Process Design). In detailed coil design (phase two), the program allows to make simulation of selected coils with different preinstalled power supplying circuits at different regimes (generator or coil power, current or voltage, preinstalled or variable frequency, etc.).

The results of study for forge heating of ferromagnetic billets in the system of identical inductors are presented in Table 2 and Figure 5. Parameters of system to be investigated: *Workpiece dimensions:* thickness 16 cm, width 16 cm, length 60 cm (in this case for continuous heating a selected part length must be equal to the coil length of simultaneous heating). Material – carbon steel 1040. *Inductor dimensions:* “the window” of inductor - 38×38 cm, the length 60 cm, the number of turns 12, copper tube 4.7×2.5×0.2 cm. Heat insulation Refractory Concrete with a thickness of 1.5 cm. *Processing parameters:* frequency 500 and 1000 Hz, the time of heating (inside the inductor with the continuous process of heating) 90 s, the time of cooling in the air space between the inductors 20 s.

Table 2: Results of calculation

N	f, Hz	I_i, A	P_i, kW	U_i, V	cos φ_i	Z, Ohm	η	η_{lim}	T_{max}, °C
1	500	7746	800	762	0.144	0.099	0.713	0.866	1011
2	500	10461	800	993	0.077	0.095	0.492	0.716	1276
1	1000	5903	650	1138	0.108	0.195	0.783	0.876	964
2	1000	8383	650	1571	0.049	0.187	0.582	0.727	1303

It is evident that the real electrical efficiency for frequency 500 Hz is far from maximum value. Relationship of efficiencies η/η_{lim}. = 0.87 for the first inductor and 0.72 for the second one, i.e. less than 0.9. The specific energy consumption is 331 kWhr/t and final average temperature of the line heating is 969 °C. Maximum temperature on the surface is 1276 °C and in the angular zone 1144 °C (Figure 9, left). It can be seen that electrical efficiency for frequency 1000 Hz is increased; specific energy consumption is decreased to 269 kWhr/t. Maximum temperature on the surface is 1303 °C and in the angular zone 1231 °C (Figure 9, right). Final average temperature of the line heating is 912 °C.

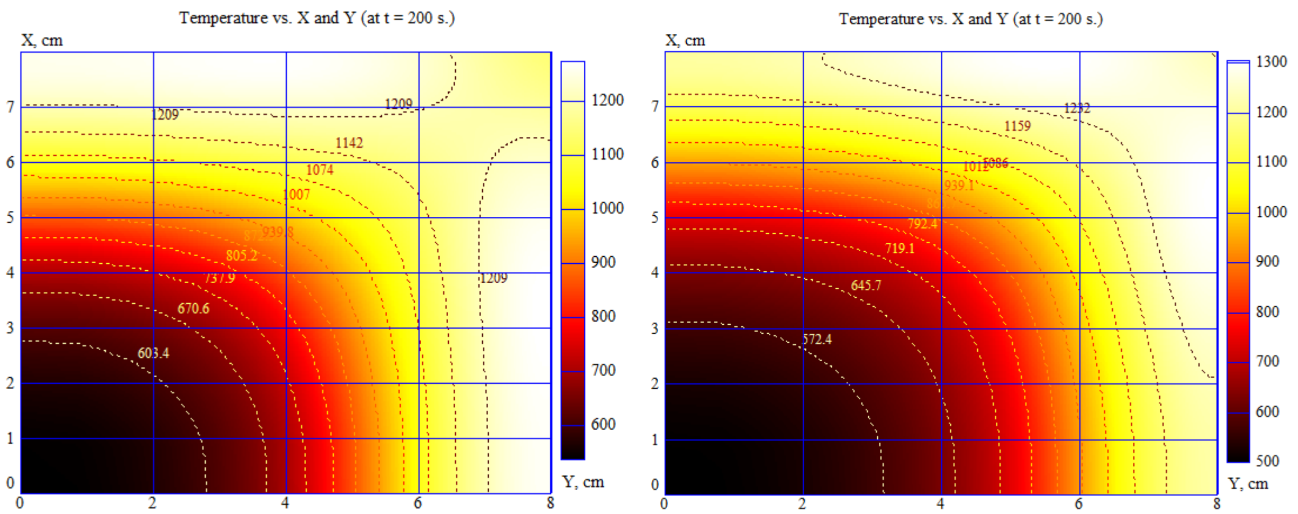

Figure 9: Color map of temperature at frequency 500 Hz (left) and 1000 Hz (right)

The results of two calculations show that choose of frequency and power is very critical stage in the design of induction heating technology of workpieces with square cross section. It is necessary to take into account both specific energy consumption, and quality of heating especially overheating of corner parts of billet.

4. INVESTIGATION OF CYLINDRICAL SYSTEM USING 2DELTA

2DELTA program provides a two dimensional simulation of electromagnetic and thermal fields in cylindrical induction heating using both integral and differential numerical methods. A sketch of 2D induction heating system is shown in Figure 10.

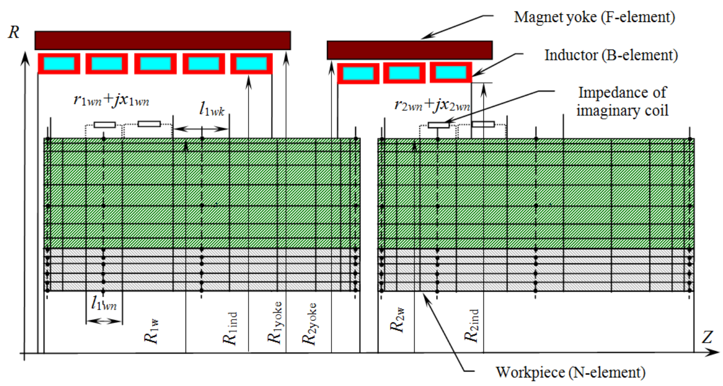

Figure 10: Sketch of calculated induction heating system

The Method of Magnetization Forces (MMF) used in this case is very effective for calculation of inductor parameters in combination with differential numerical calculation of electromagnetic field inside the workpiece. Results of calculation of internal field are used as impedance boundary conditions for solution of external part of calculations.

A system of equations describes voltage balance for each circuit with account of circuit resistance, self-and mutual inductances as in (4):

$$\left.\begin{aligned} &Q \in B, && \dot{Z}_Q \dot{I}_Q + j\sum_P x_{QP}\dot{I}_P = \dot{U}_Q; \\ &Q \in N_k, && \dot{Z}_Q \dot{I}_Q + j\sum_P x_{QP}\dot{I}_P = 0; \\ &Q \in N_f, && \dot{I}_Q - \sum_P N_{QP} W_P \dot{I}_P = 0; \\ &Q \in F, && S_Q \dot{I}_Q - \sum_P N_{QP} W_P \dot{I}_P = 0 \end{aligned}\right\}, \tag{4}$$

where Q, P – elements of system, $\dot{Z}_Q$ – impedance of coil, $\dot{I}$ – current of element, $\dot{U}$ – coil voltage, N_{QP} – coefficient of Magnetization Forces, W – number of turn, $S_Q = \mu_Q/(1-\mu_Q)$ – coefficient.

Variant of induction line to be investigated consists of 2 parallel connected coils (Figure 11).

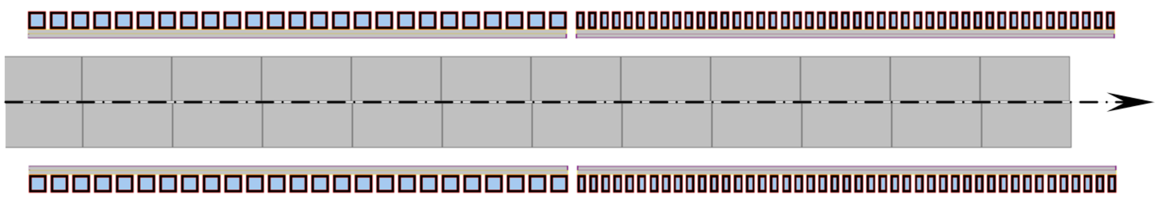

Figure 11: View of investigated induction system

Parameters of system to be investigated: *Workpiece parameters:* material – carbon steel 1040, diameter 10 cm, length 10 cm. *Inductor parameters: Coil No 1*: Internal diameter (ID) 16 cm, length 60 cm, turns number 25. Profile of copper tube 2×2×0.3 cm. Thermal insulation: Portland cement concrete, thickness 0.5 cm, magnesite 0.5 cm. *Coil No 2*: *ID* 16 cm, length 60 cm, turns number 45. Profile of tube 1×2×0.3 cm. Thermal insulation: Portland cement concrete, thickness 0.5 cm, magnesite 0.5 cm. *Processing parameters:* final temperature of heating is 1220±50 °C, frequency of thyristor inverter in stationary stage of heating is 1100 Hz, constant coil voltage is 430 V (coils are connected in parallel) and production rate is 1.11 t/hr. Rate of push 20 sec and calculation time are found knowing production rate (calculations are made in time, which is related to position of the test point on the part surface in a real process of heating $t = T \times n$, with T – rate of push and n – number of workpieces in the coil, i.e. time in each coil is 120 sec).

Results of 1D simulation in ELTA and 2D simulation in 2DELTA are shown in Figure 12.

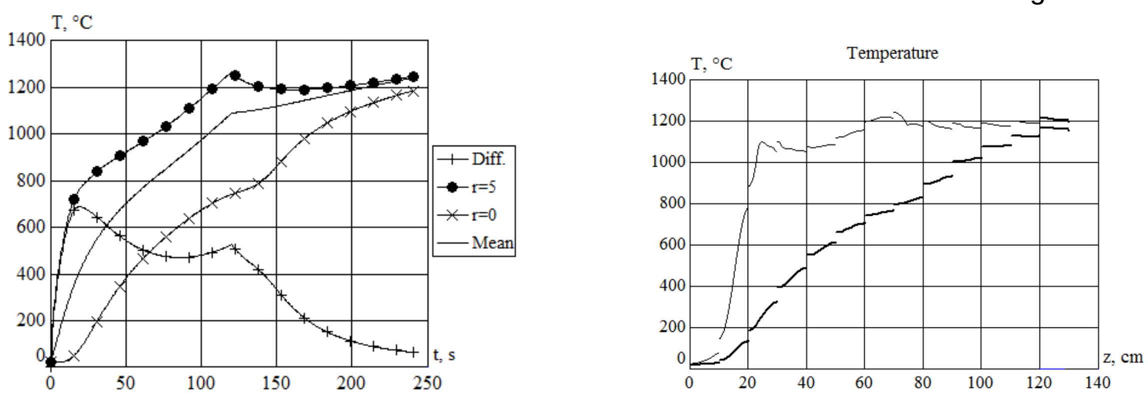

Figure 12: Temperature dynamics along the induction line: ELTA – left, 2DELTA - right

As can be seen from Figure 12, 2DELTA program can simulate more exact temperature distribution taken into account the real length of billet. 2D program may be used to find distribution of temperature along the length and radius of workpieces, mainly at the last one on the exit from inductor and comparison to technological requirements (quality of heating), investigation of “end” effects, e.g. how the displacement of inductor and workpiece end parts can influence on power sources and temperature taking into account the heat losses.

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