USO DO SOFTWARE ELTA PARA ESTUDO DO PROCESSO TÉRMICO E ENERGÉTICO EM LINHAS DE AQUECIMENTO POR INDUÇÃO PARA FORJAMENTO À QUENTE

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RESUMO *- Este trabalho tem como objetivo apresentar técnicas de simulação para validação e revalidação do aquecimento por indução para conformação a quente com os focos no processo térmico e na otimização energética através do software 2DELTA* ***- EL****ectro****T****hermal* ***A****nalysis.*

Serão apresentados os conceitos de aquecimento por indução aplicado aos aços de engenharia, princípios do aquecimento por indução, curvas características dos materiais, definição e seleção da frequência em função da geometria do billet a ser forjado e estudo de caso. Este software permite, de forma sistemática, implementar simulações para as aplicações de aquecimento por indução para geometrias mais comumente utilizadas na indústria. É utilizado por empresas fabricantes e usuários de sistemas de aquecimento por indução para dimensionamento térmico e elétrico da linha de aquecimento.

No chão de fábrica é uma ferramenta importante na investigação dos processos existentes, no desenvolvimento e solução de problemas nas linhas de produção conduzindo ao uso das melhores práticas térmicas e energéticas na produção de forjados.

Palavras-chave: ELTA - **EL**ectro**T**thermal **A**nalysis, forjamento a quente, aços de engenharia, aquecimento indutivo, corrente induzida, equações de Maxwell e o aquecimento por indução, seleção frequência do forno.

USE OF THE ELTA SOFTWARE FOR STUDY OF ELETROMAGNETIC AND THERMAL PROCESSES IN INDUCTION HEATING STEEL FORGING LINES

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ABSTRACT: This work aims to present simulation techniques for validation and revalidation of induction heating forging lines with approach on the thermal process and focuses on energy optimization through the use of the software 2DELTA-**EL**ectro**T**hermal **A**nalysis.

Presentation contains information of induction heating of steel products, material characteristics, electromagnetic and thermal process in inductors, and simulation technique for optimal design of induction heating lines. 2DELTA is also an effective tool for learning induction heating.

2DELTA software allows users to systematically implement simulations for the induction heating applications for the most commonly geometries used in the forging shops. It is used by manufacturers and users of induction heating systems for thermal and electrical design of the induction heating forging line.

General considerations about use of simulation for validation and optimal design of heating lines are supported with an example of validation of one multi-stage line for heating billets for forging purposes.

Keywords: ELTA-ELectroTthermal Analysis, hot forging, engineering steels, induction heating, induced current, Maxwell's equations and frequency selection, induction heating forging lines.

A process approach to investigate an induction heating before forging:

The principle of forging is to obtain, using hot deformation of a metal, by shock or pressure, the approximate or definitive required shape and dimensions of a work piece, while improving its mechanical characteristics.

Induction heating lines are widely used in steel industry for heat treatment and hot deformation (extrusion, rolling, forging) of billets, slabs, tubes and others products. Multi-zone lines of high productivity are the most effective equipment for this purpose. Simulation of such lines using traditional software package requires multi-stage processing with transfer of heating results from one stage to the next. This presentation will use 2D **EL**ectro**T**hermal **A**nalysis software (2D ELTA) to investigate the electromagnetic and thermal process of an existing induction heating line comparing calculation with field results.

The 2DELTA program contains a database of materials, which can be easily adapted by the end users to their specific needs. It is mainly self-explanatory with very user friendly graphic interface and does not require special knowledge in computer simulation.

By definition a billet induction heating line must deliver work pieces at the right temperature profile and right production rate, defined by the forging process, using the best economical and technical practices to determine the type of material to be forged.

The design or optimization of any induction system must balance the use of power and time against the required thermal profile in the load. Simulation with 2DELTA reveals the relationship between power, time and thermal profile during heating, transportation and cooling, allowing induction equipment users to balance and optimize complex induction processes.

To enter the simulation into ELTA it is necessary the billet mechanical characteristics and an understanding of the billet heated specification prior to forge. Based on this it is possible to select the proper coil and a preliminary start point for initial calculation to achieve the required thermal specs and adequate coupling to the induction heating power supply.

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2DELTA calculation approach:

2DELTA (Two Dimensional ELectroThermal Analysis) is a subject oriented program developed to design of induction heating processes and equipment for a cylindrical system [1].

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 1.

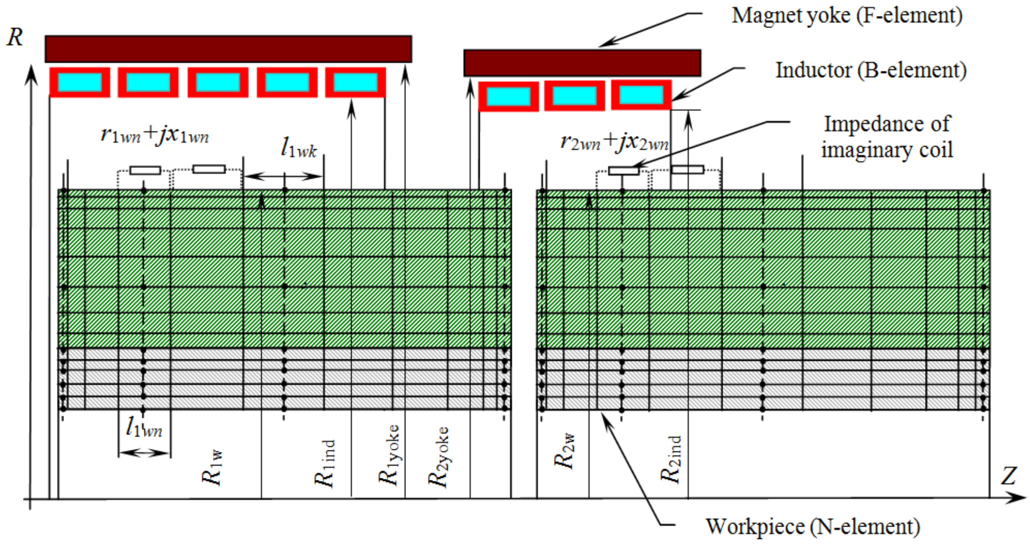


Figure 1. Sketch of calculated induction heating system

The MMF for simulation of external electromagnetic fields

The integral method takes into account magnetization currents and received the name Method of Magnetization Forces (MMF). This method is very effective for calculation of inductor parameters in combination with differential numerical calculation of electromagnetic field inside the work piece. 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 [2]:

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

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

Matrix form of equation is described as:

$$\begin{vmatrix} \dot{Z}_{\mathrm{B}} & j(x_{Bk}) & j(x_{Bf}) & j(x_{BF}) \\ j(x_{kB}) & (\dot{Z}_{kk} + jx_{kk}) & j(x_{kf}) & j(x_{kF}) \\ (N_{fB}W_B) & (N_{fk}) & (N_{1ff}) & (N_{fF}) \\ (N_{FB}W_{B1}) & (N_{Fk}) & (N_{Ff}) & ((N_{FF} - (S)) \end{vmatrix} \times \begin{vmatrix} \dot{I}_B \\ \dot{I}_k \\ \dot{I}_f \\ \dot{I}_F \end{vmatrix} = \begin{vmatrix} \dot{U}_B \\ 0 \\ 0 \\ 0 \end{vmatrix}.$$

Impedance of elements $\dot{Z}_{Ni} = \dfrac{2\pi R_{Nie}}{l_{ni}} \dot{Z}_{0Ni}$, where $\dot{Z}_{0Ni} = \dfrac{\dot{E}_i}{\dot{H}_{ti}}$, $\dot{E}_i$ – electric field strength and $\dot{H}_{ti} = \dot{I}_{wn}/l_{wn}$ – magnetic field strength, created by the n imaginary coil on the surface of work piece.

Coefficient $S_Q = \dfrac{\mu_{Qe}}{\mu_{Qi} - \mu_{Qe}} = \dfrac{\mu_Q}{1-\mu_Q}$, where μ_{Qe}, μ_{Qi} – magnetic permeability of external and internal media (for example, magnet yoke and air).

Coefficient of Magnetization Forces $N^i_{QQ} = \dfrac{1{,}32\alpha + 0{,}5}{1{,}32\alpha + 1{,}0}$ for internal part of the imaginary coil (N_k-elements), replacing the workpiece, i.e. $N_{wnwn} = \dfrac{1{,}32\alpha_{wn} + 0{,}5}{1{,}32\alpha_{wn} + 1{,}0}$, and $N^e_{QQ} = N^i_{QQ} - 1 = \dfrac{-0{,}5}{1{,}32\alpha + 1{,}0}$ for imaginary ideal magnet yoke (N_f-elements), replacing the workpiece, i. e. $N_{mm} = N_{1wn1wn} - 1 = \dfrac{-0{,}5}{1{,}32\alpha_{wn} + 1{,}0}$. ($\alpha = \dfrac{l_Q}{2R_Q} = \alpha_{wn} = \dfrac{l_{wn}}{2R_{wn}}$).

Coefficient of Magnetization Forces:

$$N_{QP} = \frac{l_Q}{2\pi\mu_0 R_Q^{med} W_Q W_P} \frac{dM_{QP}}{dn_{QP}} = \frac{l_Q}{\pi\mu_0\omega W_Q W_P (R_{Q^{add}} + R_Q)} \frac{x_{Q^{add}P} - x_{QP}}{R_{Q^{add}} - R_Q}.$$

The combination of FDM for simulation of coupled electromagnetic and thermal fields inside the part (workpiece)

Differential method is based on solution of a system of differential equations for components of electromagnetic and temperature fields. Method of Finite Differences (FDM) is relatively simple for understanding and realization. It may be used for any media, magnetic or non-magnetic.

Non linear 1D differential equation for magnetic field $\dot{H}$ [2]:

$$\frac{1}{R}\frac{\partial}{\partial R}(\rho R\frac{\partial \dot{H}}{\partial R}) = -j\omega\mu\mu_0\dot{H} ,$$

where R – radius.

Non linear 2D differential equation for temperature T:

$$C_v\frac{\partial T}{\partial t} - \frac{1}{R}\frac{\partial T}{\partial R}(\lambda R\frac{\partial T}{\partial R}) - \frac{\partial T}{\partial Z}(\lambda\frac{\partial T}{\partial Z}) = w ,$$

where Z – axial coordinate, $w = \rho\left|\frac{\partial \dot{H}}{\partial R}\right|^2$ – power sources.

$$\dot{H} = u + jv .$$

$$\left.\begin{aligned} &\frac{1}{R}\frac{\partial}{\partial R}(\rho R\frac{\partial u}{\partial R}) = -\omega\mu\mu_0 v; \\ &\frac{1}{R}\frac{\partial}{\partial R}(\rho R\frac{\partial v}{\partial R}) = \omega\mu\mu_0 u; \\ &c_v\frac{\partial T}{\partial t} - \frac{1}{R}\frac{\partial}{\partial R}(\lambda R\frac{\partial T}{\partial R}) = \rho\left[\left(\frac{\partial u}{\partial R}\right)^2 + \left(\frac{\partial v}{\partial R}\right)^2\right]. \end{aligned}\right\} .$$

Boundary and initial conditions for electromagnetic field and temperature:

$$\frac{\partial}{\partial R}u(R_0) = -\omega\mu_0 R_0 v/(2\rho);\ \frac{\partial}{\partial R}v(R_0) = \omega\mu_0 R_0 u/(2\rho);\ -\lambda\frac{\partial}{\partial R}T(R_0) = P_0,\ -\lambda\frac{\partial}{\partial Z}T(Z_0) = P_0 ,$$

$$T(R,0) = T_{\text{in}}(R) .$$

Main interface and some features from 2DELTA are: (Figure 2 and Figure 3)

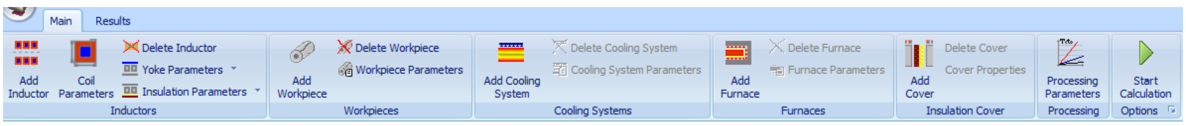


Figure 2. Main form of 2DELTA to define input parameters

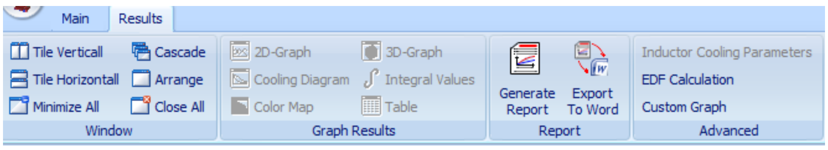


Figure 3. Form of results presentation

- 2DELTA allows simulation of many typical technological heating lines with simultaneous, non-stationary semi-continuous and continuous processes from start to stationary finish;

- Program can simulate the heating process with one, two or three layer induction coils;

- It is possible to select from many variants of resonant circuits with different schemes of compensation: series, parallel; series-parallel; parallel-series; series with transformer; parallel with transformer; series-parallel with transformer; parallel-series with transformer, etc.;

- 2DELTA can take into account circuits with series connected induction coils and simultaneously multi frequency power sources for circuits;

- Program has a special block EDF for calculation of electrodynamic forces acting on the workpieces, induction coils and magnetic concentrators.

Real technological process on the forging and pressing plant

Specification depends on the final forged piece and related technology being used. This must be taken in consideration when designing / setting up the induction heating line.

For the purpose of this work, a round billet will be investigated in a fully operational induction heating line before forging. The induction heating line for hot forging of steel work pieces consist of two parallel connected coils (Figure 4).

Parameters of system:

Workpiece: diameter 84 mm, length 250 mm Material: 44MnSiVS6

Induction system: first coil – internal diameter 162 mm, length 2340 mm, turn number 128, refractory thickness 15 mm; second coil – internal diameter 180 mm, length 2340 mm, turn number 128, refractory thickness 16 mm;

Production rate: 2910 kg/h @ 1230 ^{o}C +/-30 ^{o}C @ Rate of push: 13.50 s

Forging coil line length: 5m Machine type: pusher

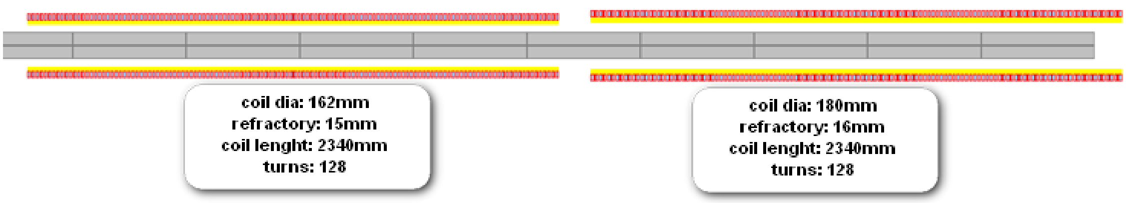


Figure 4. View of investigated induction system in 2DELTA program (100mm displacement)

The main problems that must be solved in the first step of design are:

a) find geometrical parameters of induction system (number and length of coils, number of turns and copper tube profile, internal diameter of coils, parameters of thermal insulation, etc.);
b) parameters of power source (power, frequency, output voltage, etc.);
c) parameters of resonant circuit (series or parallel compensation, length and profile of leads, capacity of capacitor bank, etc.).

As our approach to this work is to check an existing line with 2DELTA we will run calculation at the same frequency (275 Hz) for the actual process and coils characteristics as above. Figure 5 shows evolution of the temperature along the induction heating coil line.

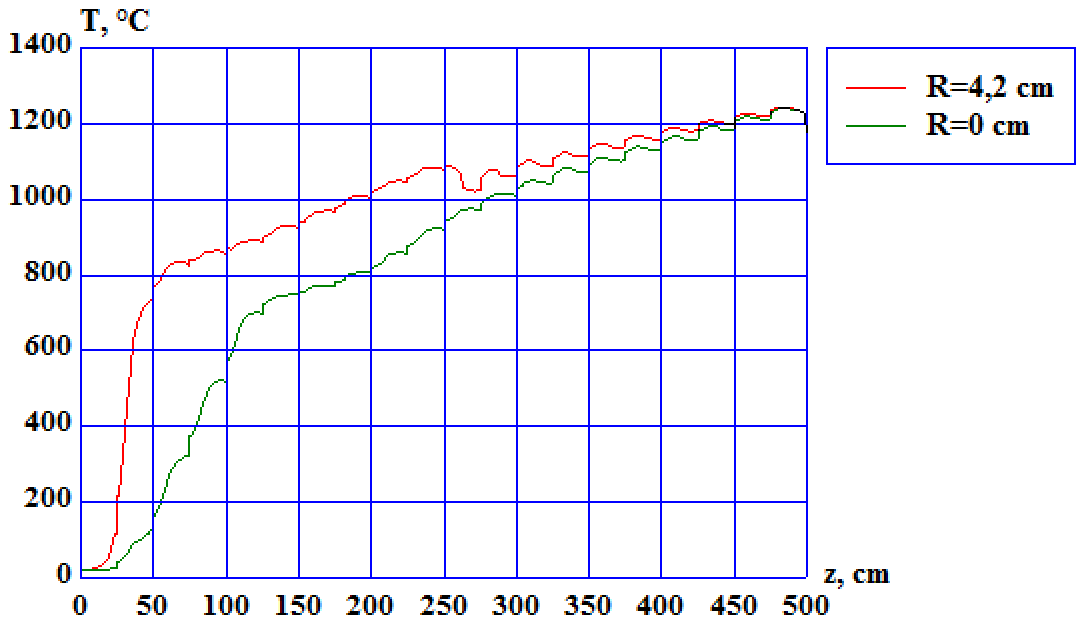


Figure 5. Temperature along the induction heating line in 2DELTA program

One of difficult simulation problems is to set the frequency range of generator to match to the load characteristics because of its values can change in starting regime in very wide ranges when workpieces heat from 20 to 1200 °C.

It is very difficult to select the correct value of capacitance in both regimes. In starting regime capacitance must be less than in stationary one, but often the control system of the power generator in some cases doesn't allow to start the heating process.

At cold start of induction heating line the only possible way to overpass this situation is to heat in stationary the whole work pieces line until generator goes to the set point (out of limit) before starting the pusher mechanism.

Figure 6A and Figure 6B shows that for stationary regime set point (1060 V) initial power should be approx. 1400kW + 900 kW = 2300 kW what is not possible from a 1500 kW (nominal) power converter. Power supply sees a load that is greater than nominal and goes to current limit. In fact the challenge is to balance the high coil power factor of the load at the starting regime to the nominal coil power factor in stationary regime.

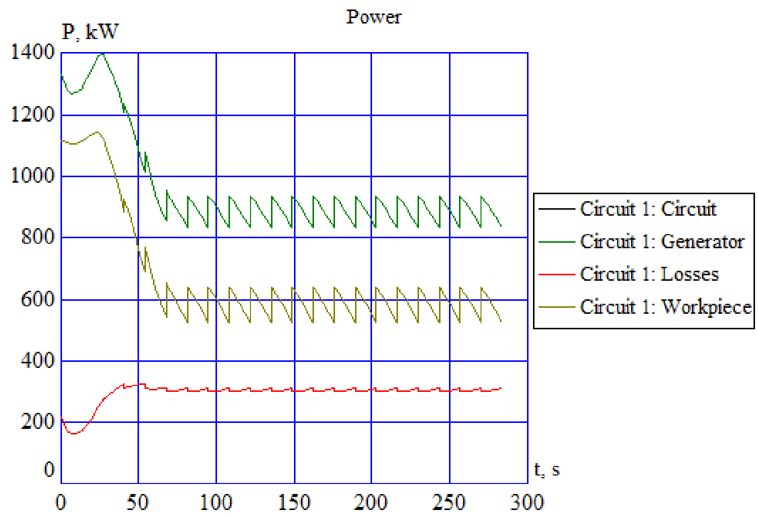


Figure 6A. Power circuit 1 of investigated induction system in 2DELTA program

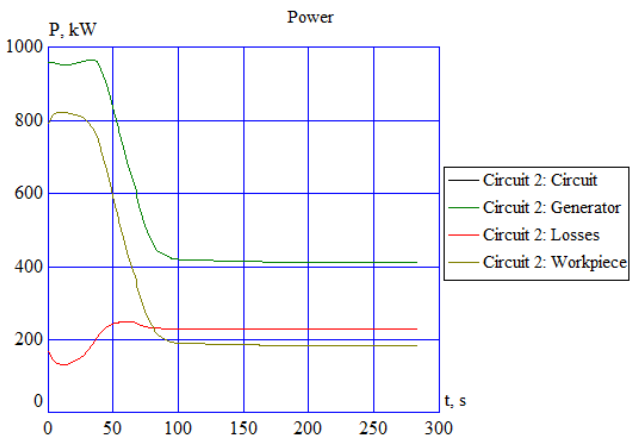


Figure 6B. Power circuit 2 of investigated induction system in 2DELTA program

Calculation shows that the average converter power in regime will be approximately 1180 kW, not taking into account the skid rails power losses and the time required to goes to set point will be approx. 170 sec using an energy approach to estimate the limitation starting time.

More detailed investigation of heating process that must be solved to achieve specification are:

a) distribution of temperature along the length and radius of work pieces, mainly the last one on the exit of the inductor and comparison to technological requirements (quality of heating);
b) investigation of end effects, e.g. how the displacement between inductor and last work piece end can influence on power density and temperature taking into account the heat losses.

2DELTA allows to follow each billet temperature evolution taking in consideration their position at the induction heating coil line. Results of simulation are shown in Figures 7A, 7B, 7C, 7D, 7E, 7F and in Table 2. Last workpiece has an offset of 100 mm as in Figure 4.

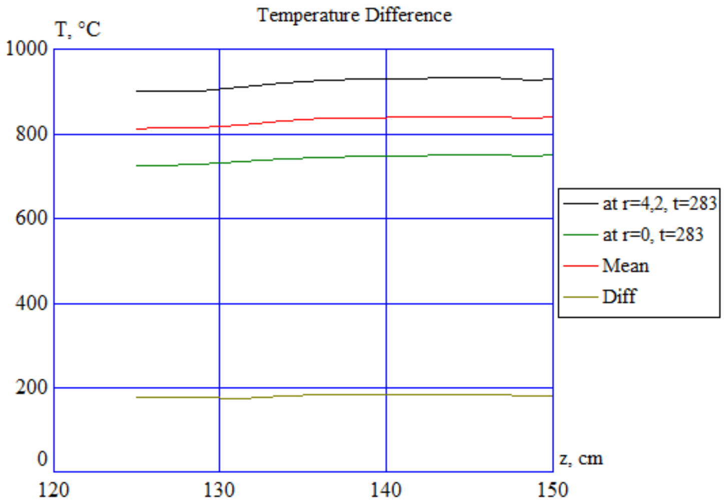


Figure 7A. Temperature difference for workpiece #6 in 2DELTA calculation

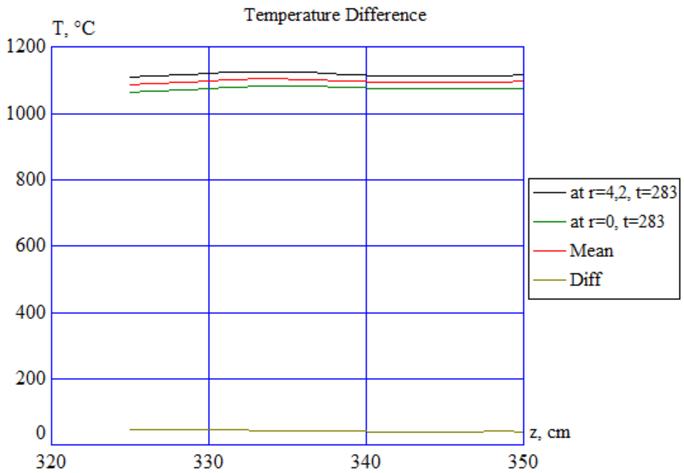


Figure 7B. Temperature difference for workpiece #14 in 2DELTA calculation

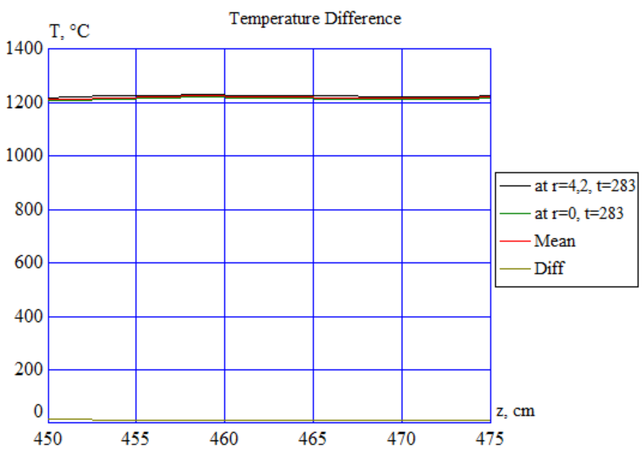


Figure 7C. Temperature difference for workpiece #19 in 2DELTA calculation

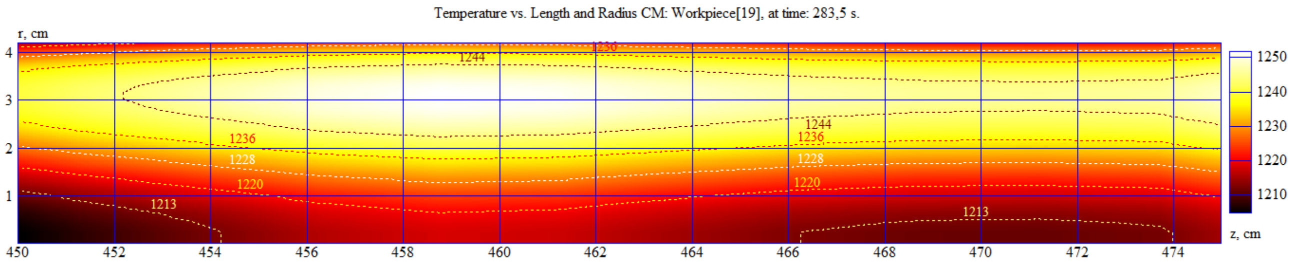


Figure 7D. Temperature map for workpiece #19 in 2DELTA calculation

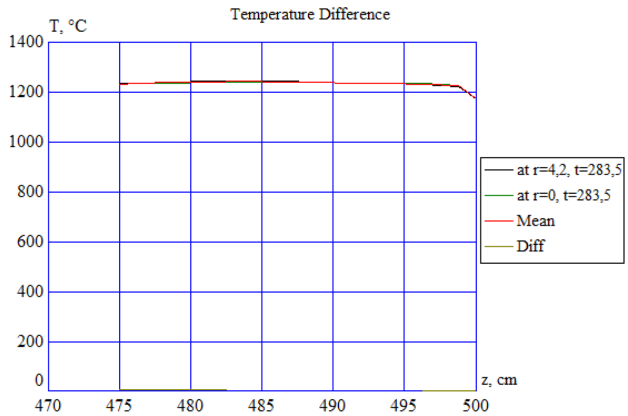


Figure 7E. Temperature difference for workpiece #20 in 2DELTA calculation

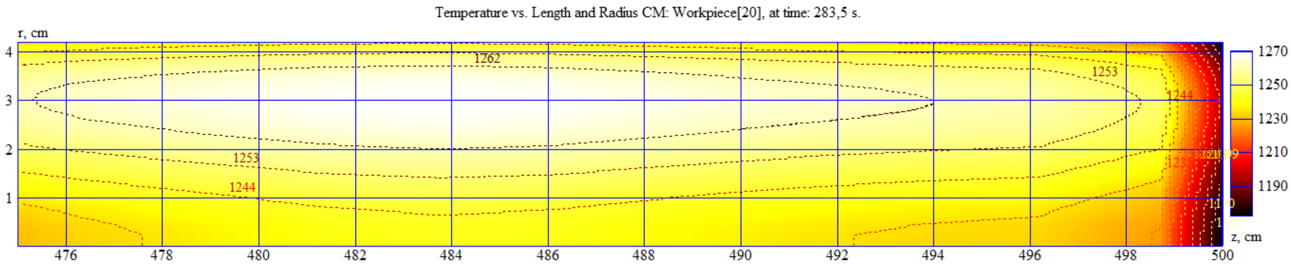


Figure 7F. Temperature map for workpiece #20 in 2DELTA calculation

As the last billet is in direct contact with air at the exit of induction heating coil line there are additional energy losses and consequently lower temperatures as well as generation of scale due to the chemical reaction of Fe and O_2 for one pusher cycle time. Temperature map feature from 2DELTA calculation helps design temperature gradient along the billet length when required by a specific heating process design like typical aluminum workpiece specification prior to extrusion. The values of temperature on the length of last workpiece at 40 mm radius are: 1244 – 1252 – 1243 – 1180 °C.

Color map shows that due to heat losses from last work piece end to the environment this one is sufficiently under-heated which can decrease the quality of the forgings. The power density at the last work piece end is not enough to compensate the heat losses.

There are three variants to improve the negative situation: increase the displacement of inductor and last work piece end, increase frequency and use the end insulation cover. All variants may have disadvantage - decreasing the electrical efficiency, increasing the temperature difference along the radius and mechanical inconvenience respectively.

Best practice approach is to make sure to have more than 6 workpieces inside the induction heating coil line.

Real x Calculated Processing parameters:

Final average temperature for last workpiece 1220±50 °C (1270 -1170), frequency of power converter in stationary stage of heating 275 Hz, constant coil voltage 1060 V (coils are connected in parallel), production rate is 2910 kg/h (rate of push 13.5 sec). 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 $t = T\times(n+1)$, with T – rate of push and n – number of workpieces in the coil, i.e. heating time for coil line is 20+1 x 13, 5 = 283.5 sec).

Results of calculation are shown in Table 1.

Table 1. Integral parameters of induction coils

N	*Icoil*, A	*Pcoil*, kW	*Ucoil*, V	cos φcoil	*Zcoil*, Ohm	$\eta_{el.}$	η_{tot}	T_{mean}, °C
1	3342 - 3402	936 - 834	1060	0.264 – 0.231	0.317 – 0.313	0.680 – 0.628	0.645-0.581	835
2	2773	410	1060	0.140	0.382	0.444	0.260	1213

From Figure 6A and Figure 6B average generator power is 1343 - 1244 kW @ 275 Hz which means that at 2910 kg/h the energy consumption is 462 - 427 kWh/t for this process. Investigated workpiece diameter is equal to 84% of maximum coil workpiece (100 mm diameter) for this line.

From reactive power Figure 8A and 8B in stationary regime it is possible to calculate the capacitor bank for this application. Total reactive power is 3508 + 2912 = 6420 kVAr.

Cpar from 2DELTA calculation are 1808 and 1500 microfarads. At the circuit configuration (parallel) running at 275 Hz and 1060 V the capacitor bank will be: 3308 microfarads.

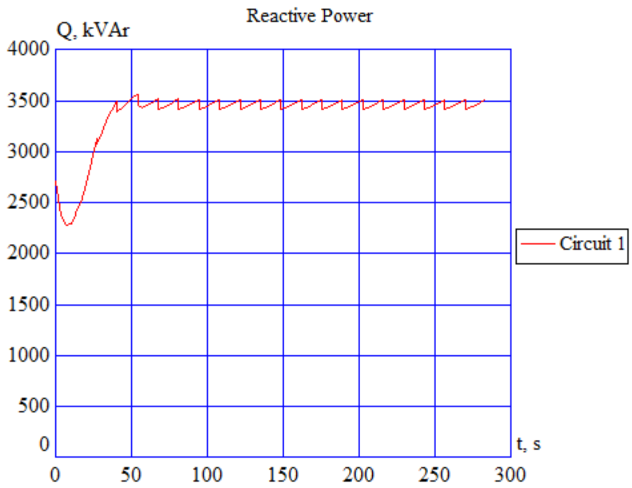


Figure 8A. Reactive power for first coil

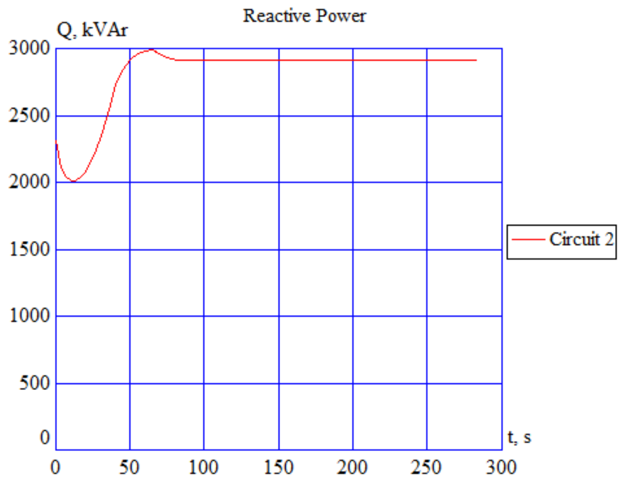
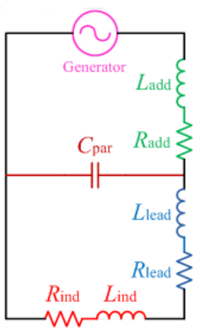


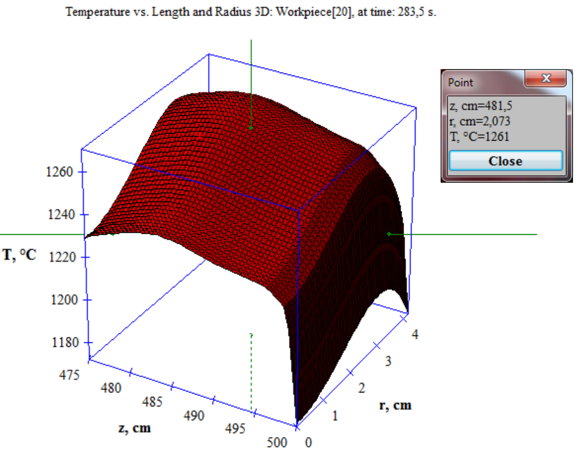
Figure 8A. Reactive power for second coil



As Ladd, Radd, Llead, Rlead were not available they were let = zero for this case study.

Power meter = 1300 kW , Freq meter = 275 Hz, Voltage meter= 1060 V. Heat station capacitance Cpar = 3190 microfarads (Figure 9).

Figure 9. Circuit in 2DELTA



Maximum temperature expected from 3D map temperature at the external layer:

1268°C (Figure 10)

A pyrometer with a peak detect measurement approach is being used at exit of the induction coil line to accept workpiece quality temperature :

Average peak temperature got from a 10 measurement:

1186°C

Pyrometer emissivity: 0,95

Figure 10. 3D temperature map for one workpiece being extracted from the coil line

Conclusion:

This investigation shows that observed results at the real operation condition of an existing induction heating line before forging are very close to the that 2DELTA calculation.

2DELTA calculation shows that thermal temperature quality is within the specification.

Further simulation shows that a better energy efficiency operation (approx. 15%) with the same thermal process can be achieved by improving the coupling of workpieces to the coil.

The time required to the power converter getting to set point was measured as 152 sec and compared with the calculated estimated time of approx. 170 sec. This verification and additional simulation allows end users to simulate stationary regime (starts with cold workpieces) and get the best starting point to the pusher mechanism in order to minimize starting time before first good work piece delivered to the press.

2DELTA is an important tools for teaching, design and troubleshooting induction heating process..

Further investigation must be done to set the influence of the scale generation on the temperature measurement and thermal conductivity restriction at the external surface of work piece.

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