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J. Zgraja

Simulation of Scanning Induction Heating of Flat Surfaces

INTRODUCTION

The induction heating of flat surfaces of massive elements, e.g. for induction hardening, is often realised in practice in the case of moving charge. The simulation of such complex process requires at least analysis of coupled electro-thermal field best with supply source simulation taken into account. In some examples this simulation can be simplified by using 2D models but in other 3D models must be used which makes the simulation more complicate. The reliable realisation of simulation process leads to a number of difficulties, as credible determination of thermo-electrical material properties or technical acceptable time of calculation. The first problem is especially important for grey-cast iron charges because this material commonly employed for large-size castings, is characterised by wide spread of material's properties.
In the paper the simulation of flat surface of massive element has been considered taking as examples the induction heating before hardening of cutter knife and of lathe bed, Fig.1.

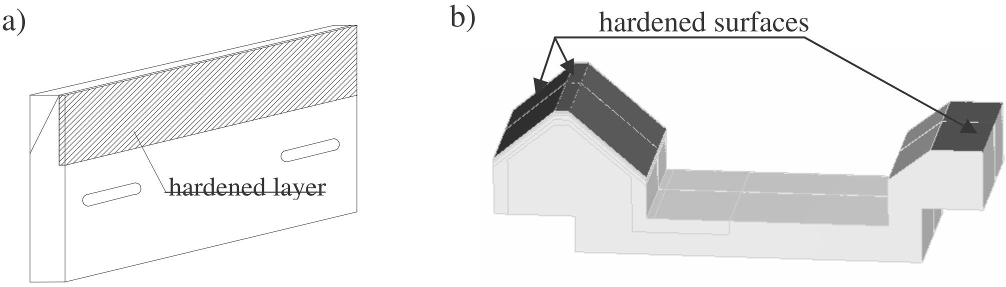

Figure 1. Considered examples of massive elements a) cutter knife, b) lathe bed.

The steel cutter knifes used in paper industry having even more than one meter length are volume or surface hardened . The induction heating method is usually used for surface hardening. It gives possibility to get a more elastic knife in which hardened part of the thickness 2÷5 mm is only at one side of the knife. To produce such a knife the steel slab is first one side hardened and then grinded. In the paper the simulation of induction heating before surface hardening of steel knife of 25mm thickness, of 200mm width and 1m length was considered. Its one side of 120 mm width should be hardened at the thickness of 3 mm. For the grey cost iron lathe bed the hardened surfaces are shown in Fig.1.

DETERMINATION OF MATERIAL CHARACTERISTICS

The problem of credible determination of thermo-electrical material properties has been considered in [1] for grey cast iron material specimen. This specimen has been subjected to experiments on the testing equipment presented in Fig. 2.

The cylindrical specimen has been subjected to induction end heating. The constant value of inductor current has been maintained and the following variables have been measured: inductor clamp voltage, temperatures in four measurement points (A-D) and the total linear extension of specimen. The thermo-elements were located in points A-D (Fig. 2), with the distance from the edge of the specimen: 4, 15, 35 and 55mm respectively.

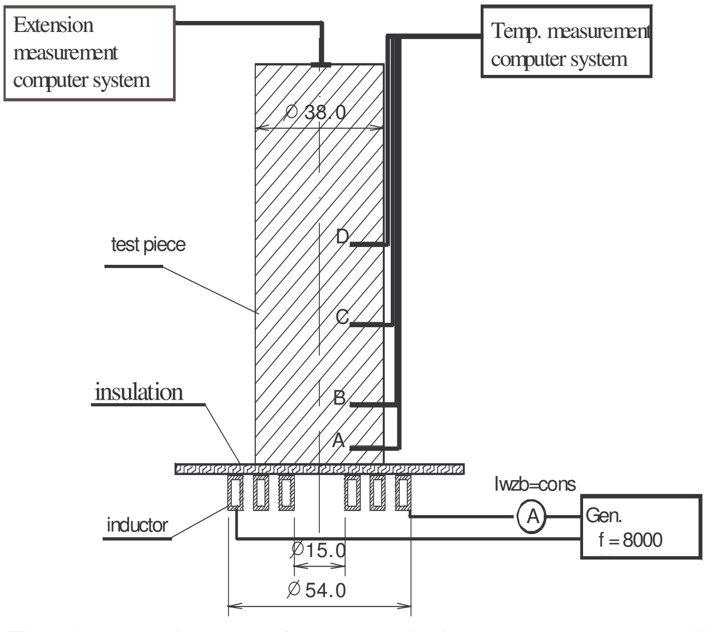

Figure 2. Testing equipment for material’s parameters verification.

Preliminary analysis of system presented in Fig. 2 has been carried out for the reference selected values [2] of the material properties, i.e. resistivity, magnetic permeability, thermal conductivity and the specific heat. The variation of temperature in the function of time in point A received by the PC simulations and measured for three different specimens of charge are presented in Fig.3. Temperature acquired in point A as well as in points B-D significantly vary from that obtained from the experiments.

The complex analysis of sensitivity of particular material parameters on the measured thermal distribution has been carried out. The substantial impact of control points (A-D) location on efficiency of realised analysis was observed. There was observed the much greater effect of electrical material properties (resistivity, magnetic permeability) on the temperature distribution in points A and B placed close to the internal sources of heat (eddy currents) than for other two points C and D, where impact of thermal material properties (thermal conductivity and the specific heat) was dominating. The realised investigation of sensitivity allowed to estimate the material parameters variations, for which the temperature functions derived by simulations were coherent with the functions obtained experimentally.

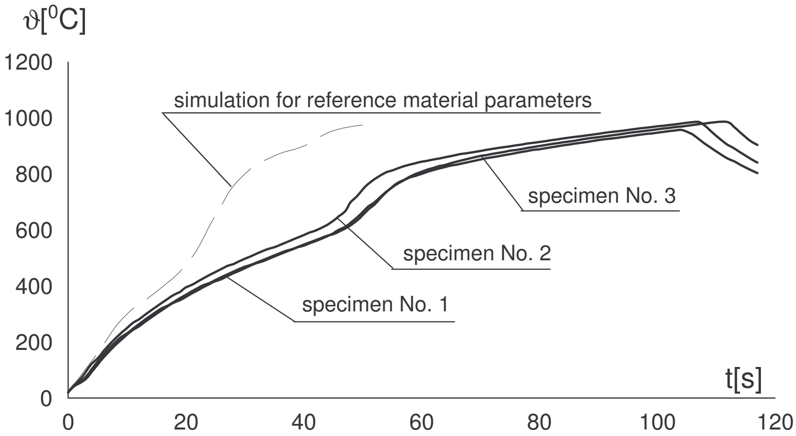

Figure 3. Comparison of temperature variation obtained in experiments and simulation based on reference charge material parameters.

The results of temperature in testing points A-D, obtained for experiment and simulation realised for chosen [3] charge material parameters, are presented in Fig. 4. As it can be

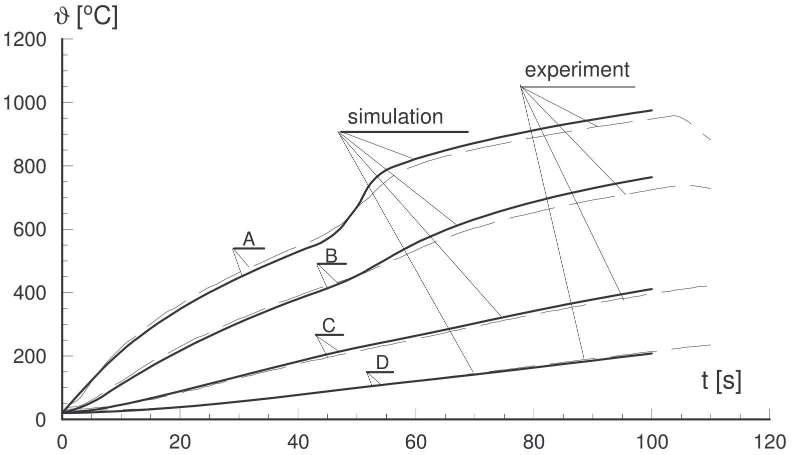

Figure 4. Comparison of temperature variations obtained, in points A-D, for experiment and simulation basing on chosen charge material parameters.

noticed variation of $\vartheta(t)$ from experiment and simulation are similar, which certifies the proper selection of the material properties.

INDUCTION HEATING OF THE EDGE PART OF MOVING CHARGE

The considered examples are in fact the coupled electro-thermal 3D problems connected with motion and supply source. In real existing arrangements for induction heating of moving charges, the relative movement inductor-charge is usually realised as a uni-directional movement, giving fixed position of inductor and the edge part of charge during movement. In such situation it is possible to analyse separately the problem of induction heating of the beginning (ending) and edge parts of charge by using 2D and 3D simulation, [4]. The heating of beginning part of charge with taking into account the supply transistor inverter and inductor-charge system collaboration has been considered in [5]. To consider the induction heating of the edge part of the charges, the 3D analysis should be done. As it was said before, this analysis can be done only for middle part of moving charge and thus it would be made without simulation of real energy source (transistor inverter).

The 3D analysis, even if only induction heating of moving ferromagnetic charge is considered, leads to very high computer cost, as a result of complex numerical analysis of coupled magneto-thermal fields realised for such big part of charge to take into account the whole necessary temperature history of the workpiece. Hence, it is necessary to look for a replacing calculation model, which will allow realisation by means of standard PC in time of the order of one twenty-four hours, with relatively low decreasing of calculations accuracy.

The big influence on the computing cost of induction heating process simulation takes into consideration the magnetic charge non-linearity, describes by non-linear $B(H,\vartheta)$ characteristic. The possibility of applying, in considered example, the replacing of the real charge by magnetic linear one (keeping all other electro-thermal non-linearities, e.g. the $B(\vartheta)$) has been analysed. The analyses lead to determine the equivalent magnetic linear charge based on 2D computer model of inductor-charge system. At the beginning, for fixed middle part of the charge, the electromagnetic field of considered system for "cold" state of charge has been analysed by comparison the power dissipated in non-linear P_n and linear P_l (with different relative magnetic permeability μ_r value) charge at constant inductor current, [3].

In Fig. 5 the ratio P_l / P_n as a function of inductor current, for different inductor-charge gap Δ, has been presented. As can be noticed, in some examples, it is possible to find such linear charge equivalent relative magnetic permeability $\mu_{r,e}$ for which calculated dissipated power P_l is equal P_n. This is especially for small inductor-charge gap and strong inductor current.

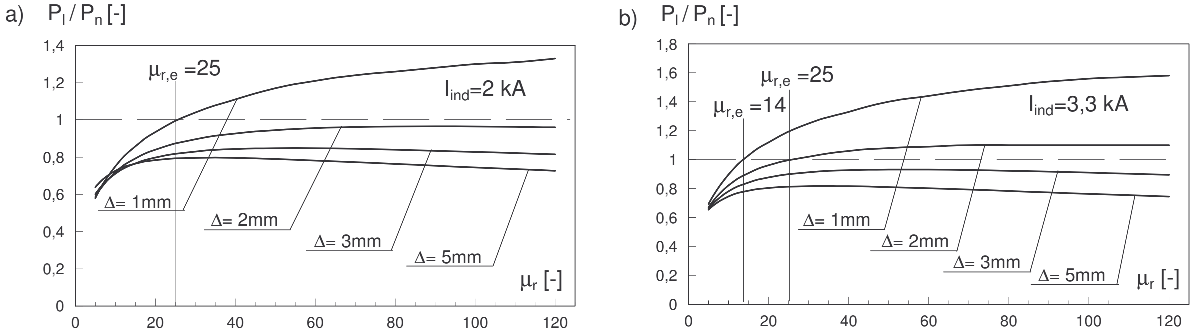

Figure 5. Influence of relative magnetic permeability of equivalent linear charge (of grey cast iron) on calculated dissipated in charge power:
a) inductor current I_{ind}=2kA, b) I_{ind}=3,3kA.

For the process of charge heating important are not only the value of generated power but also its distribution during whole heating procedure. At the beginning the comparison of temperature distribution calculated for real and chosen equivalent (magnetically linear) charge has been made for heating of stationary charge. For equivalent charge all material parameters except *B(H)* characteristic, were the same as for real charge. In the Fig. 6, for grey cast iron charge heated to temperature above 1000^0C, the variation of ratio of temperature obtained at different points of equivalent linear charge ϑ and of real non-linear charge ϑ_n as well as ratio of generated power P_l / P_n were presented.

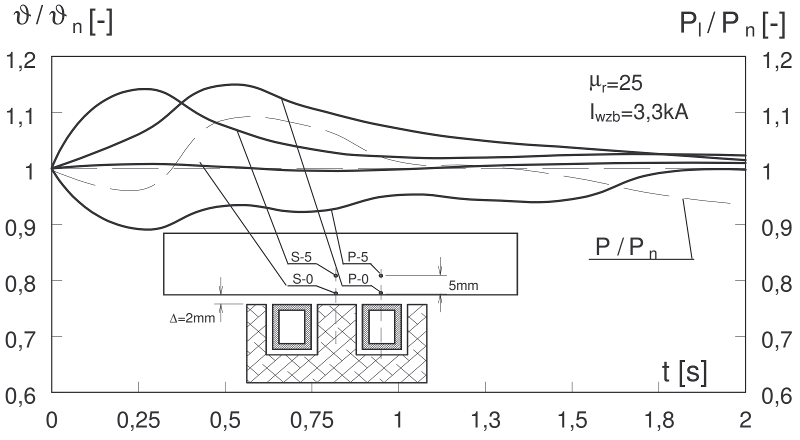

Figure 6. Variation of ratio of temperature ϑ / ϑ_n and ratio of power P/P_n obtained for equivalent linear and non-linear charge stationary heated.

As can be seen, although for cold equivalent linear charge the dissipated power was the same as in real non-linear one, during heating process the differences in dissipated power as well as in reached temperatures were observed. The errors of calculating the temperatures reached about ±(10÷15%). Such kinds of errors suggest the improvement in precision of calculation realised for induction heating of moving charge.

For induction heating of moving charge, the motion of charge reduces the influence of errors of calculated power distribution (in direction of moving) on temperature of charge leaving inductor. In Fig. 7 (for grey cast iron and steel charge) the comparisons of temperature variations obtained from simulation of inductor-charge system for real and equivalent (magnetically linear) charge of induction heating in moving are presented.

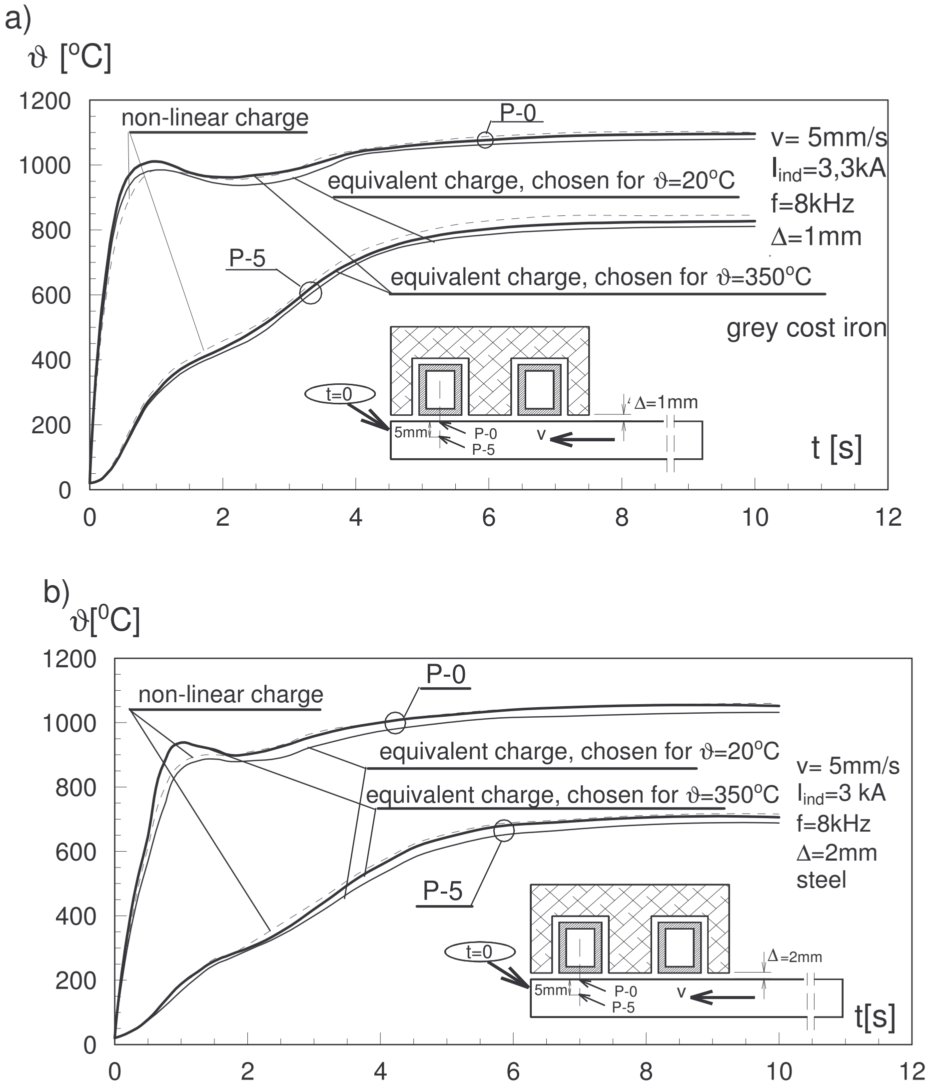

Figure 7. Comparison of temperature variations obtained for real and equivalent magnetically linear charge heated in motion: a) grey cost iron charge, b) steel charge.

The magnetic parameter of equivalent linear charge has been chosen for start temperature of cold state (temperature equal 20 ^{0}C) and average temperature of cold state 350 ^{0}C.

The presented, as example, moving charge temperature variations show that for moving ferromagnetic charge heated above temperature of Curie point it is possible to use in numerical calculation the equivalent magnetically linear charge (if such a charge for considered example exist; see Fig.5). The temperature calculation errors, especially for middle part of charge, are usually below some percents. The precision of output temperature calculation in quasi- steady state can be increased if magnetic permeability of equivalent charge is chosen not for beginning but for average temperature of the cold state of charge. In such a situation the precision for transient state of heating decreases. The remarks mentioned above are really useful for 3D simulation of induction heating with charge motion. This kind of simulations, especially for induction heating of massive charge at temperatures above Curie point by middle frequency source, are very computer costly. For such examples the good solution can be expected in using equivalent magnetic linear charge. In such case by using 2D electromagnetic field simulation the equivalent magnetic permeability of charge should be found. Than for such chosen equivalent charge and real non-linear charge, the 2D simplified comparison analysis of coupled magneto-thermal field of the system should be considered. To reach the similar results in both analyses (for equivalent and real charge) gives possibility to use chosen equivalent magnetically linear charge in simplified 3D analysis of coupled magneto-thermal field for inductor-moving charge system.

The presented method has been used for analysis of induction heating of edge zone of steel cutter knife, as presented in Fig.8. The heating was realised for inductor current I=3000A and frequency f=8 kHz.

To verify the used simplified 3D model with equivalent magnetically linear charge, the obtained temperature distribution for middle part of charge was compared with that obtained for 2D analysis realised for really non-linear charge in moving, Fig.9. It was made for temperature of charge surface and 5 mm under surface obtained in zone under the inductor in thermal quasi steady state in motion. For 3D model the temperature of the middle part of charge along inductor was presented.

As can be noticed the rather good convergence of 2D in simplified 3D model results were reached. The differences were less than 10% what from technical point of view is usually satisfying.

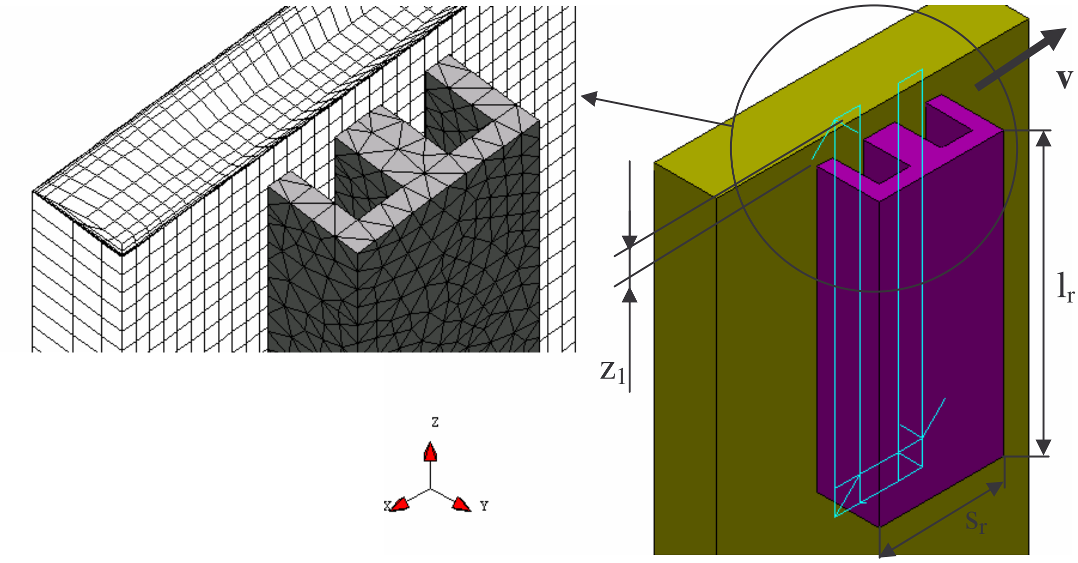

Figure 8. Inductor-charge 3D model for analysis of induction heating of edge zone of cutter knife.

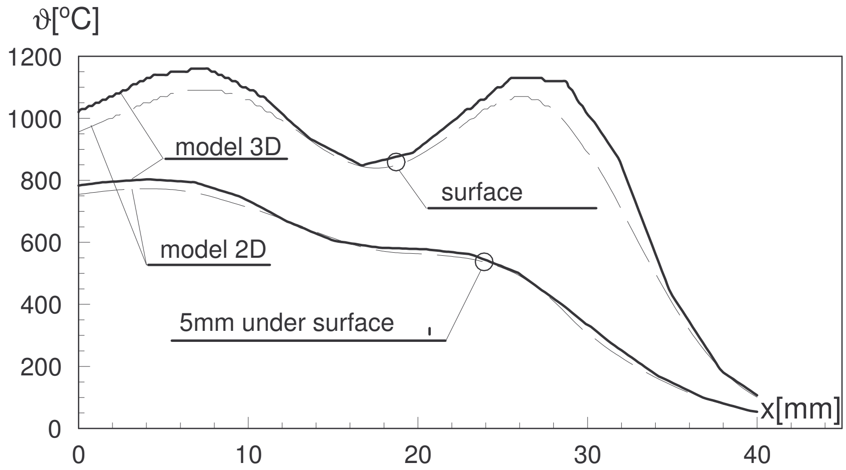

Figure 9. Comparison of charge temperature under the inductor obtained in quasi steady state for 2D and simplified 3D calculations.

The presented above replacing of non-linear magnetic charge by equivalent magnetic linear one was used for simulation of induction heating the considered lathe bed too. In Fig.10 the 3D model [3] for coupled magneto-thermal simulation of heating lathe bed in motion has been presented. Using this 3D model it is possible on PC to reach the thermal quasi steady state during only some hours of computer calculations. The obtained temperature distribution in charge gives possibility to design the appropriate inductor construction, to choose its position to charge as well as power supply parameter and charge speed of moving.

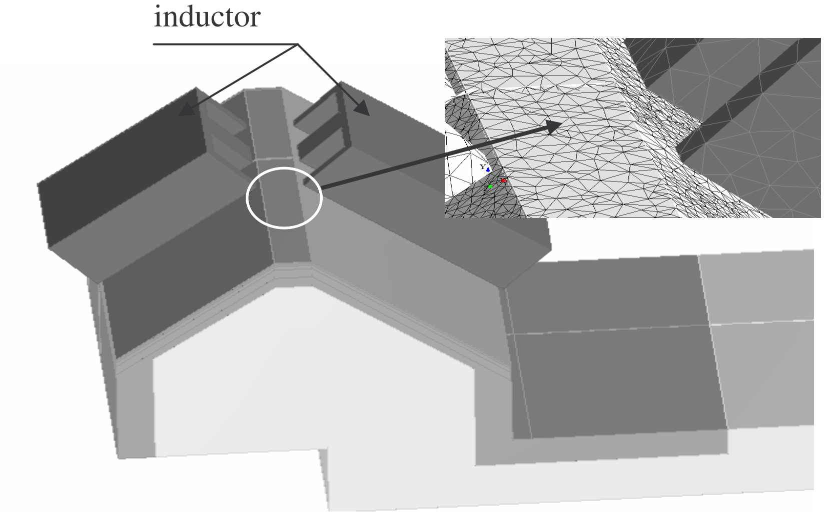

Figure 10. 3D model of induction heating of lathe bed.

As an example in Fig. 11, for considered 3D model, the temperature distribution along whole inductor length calculated on leaving the inductor charge surface is presented.

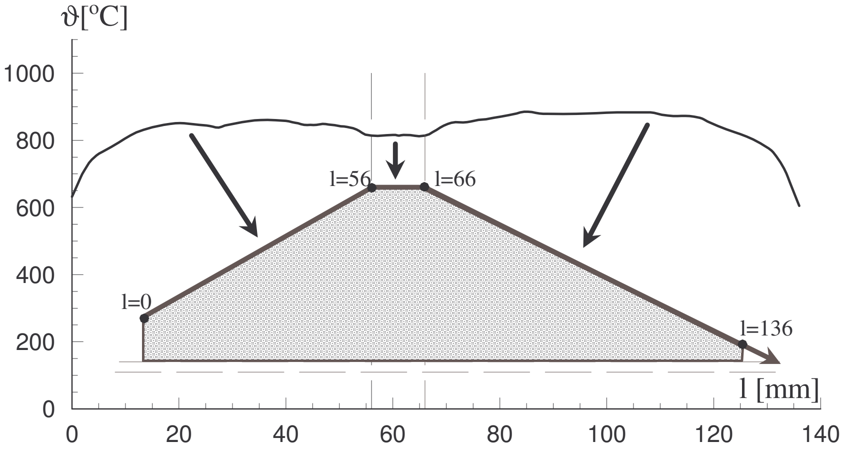

Figure 11. Charge surface temperature distribution under the output inductor turn.

The examples presented in the paper show that in 3D simulations of induction heating of moving ferromagnetic charges the using of equivalent magnetically linear charge can be useful. The choosing of such equivalent charge can base on simplified 2D inductor-charge analysis.

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