Computer Simulation of Induction Hardening of Moving Flat Charge

Jerzy Zgraja

Abstract—**The computer simulation of the process of induction surface hardening based on the example of cutter knife hardening is presented. For the two-dimensional (2-D) arrangement, the total system containing inductor, moving charge, cooling system, and energy source as a series bridge transistor inverter has been simulated. The source parameters (voltage and frequency) depend on the load parameters obtained by numerical calculations of the coupled fields. For the 3-D model, the influence of the inductor–charge arrangement on the temperature distribution near the charge edge has been estimated.**

Index Terms—**Coupling circuit, electromagnetic heating, inverters, simulation.**

I. Introduction

THE CUTTER knifes used in the paper industry that have even more than 1-m length are volume or surface hardened. The induction heating method is usually used for surface hardening. It gives the possibility to get a more elastic knife in which the hardened part with a thickness of 2–5 mm is only at one side of the knife.

To produce such a knife, the steel slab is first hardened on one side and then it is grinded. The induction hardening process can be made in the arrangement presented in Fig. 1.

To receive the correct thickness and hardness of the hardened part of the knife, the parameters of the hardening process must be precisely chosen. An induction heating system comprising the energy source, inductor, and charge for computer simulation is usually simplified to inductor and charge only. In such a case, the energy source is considered only as a device supplying the constant voltage or the constant current at a given frequency. Such a simplification can lead to serious simulation errors, especially when electronic source supply is used [1] in which output parameters depend on an inductor–charge system. Resulting in big differences between heating time and the period of inductor voltage supply, the time harmonic simulation of the electromagnetic field is the most efficient one for simulation of induction heating systems, although it brings some problems with charge and power supply nonlinearities.

In this paper, an induction heating system with transistor inverter has been simulated by the connection of numerical finite-element-method (FEM) simulation of coupled harmonic electromagnetic and transient thermal field with analytical description of series transistor inverter. The inverter simulation takes into account the dead-time t_d necessary for proper ON and OFF switching of transistors of the bridge inverter and assumes the existence of only first harmonics of inductor voltage and current.

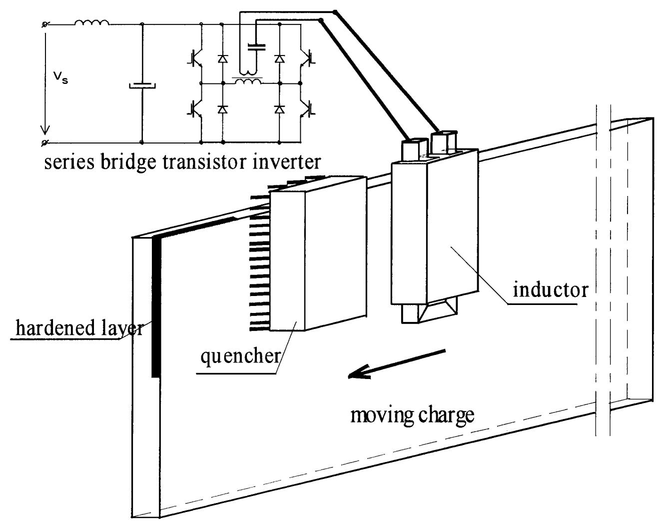

Fig. 1. Considered system for induction hardening of moving charge.

In simulation of induction hardening of moving charge, the simulation of the cooling part is very important as well. It allows us to calculate not only the rates of temperature drop in a workpiece, but also the maximum allowed value of inductor-quencher distance, length of quencher, and correct value of temperature after heating.

The described problem in the two-dimensional (2-D) domain has been solved by using a commercial Flux2-D program combined with the author's own GEN program simulating the series transistor inverter and own procedure COOL allowing to simulate the cooling process of moving induction heating charge.

The sequence of simulation of moving charge hardening is presented in Fig. 2.

However, a 2-D analysis of a considered system with moving charge allows a simplified consideration of the beginning and end part of the charge, but to consider temperature distribution near the charge edge (cutter knife), a 3-D analysis is required [2], [3]. The 3-D analysis has been used for appropriate choice of the inductor length and its position relative to charge edge. Such analysis could be made only for the middle part of the moving charge and, thus, it was made without simulation of a real energy source (transistor inverter) and simulation of cooling system.

II. Mathematical Model and Simplifying Assumptions

The mathematical analysis of coupled electromagnetic and temperature fields was carried out by solving Maxwell and Fourier–Kirchhoff equations. For the considered problem, the

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The author is with the Department of Electroheat, Technical University of Lodz, 90-924 Lodz, Poland (e-mail: jzgraja@p.lodz.pl).

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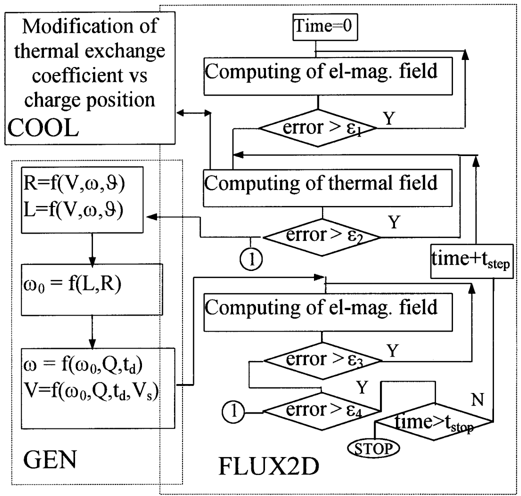


Fig. 2. Simplified flowchart of the simulation program.

electromagnetic field was assumed to be harmonic, which allowed employing a complex vector potential $\boldsymbol{A}$. Hence, the analysis was reduced to solving mutually coupled equations

$$j\omega\gamma\boldsymbol{A} + \text{curl}\left[\left(\frac{1}{\mu}\right)\text{curl}\boldsymbol{A}\right] = \boldsymbol{J}_{\text{s}} \tag{1}$$

where ω is angular frequency, γ is electrical conductivity, μ is magnetic permeability, $\boldsymbol{J}_s$ is excitation current density, and

$$\text{div}\left[(-\lambda)\text{grad}\,\vartheta\right] + \rho c\frac{\partial\vartheta}{\partial t} = P_v \tag{2}$$

where λ is thermal conductivity, ρ is density, c is specific heat, and P_v is volumetric heat source power density, with the existing boundary conditions taken into consideration.

The magnetic permeability $\mu(H,\vartheta)$ (1) is a function of magnetic field strength H and of charge temperature ϑ. To consider magnetic nonlinearity in harmonic analysis of electromagnetic field, the $B(H)$ characteristic of the charge has been modified to have the same magnetic energy for linear and nonlinear $B(H)$ characteristic assuming that magnetic field strength H is harmonic.

The inductor–charge system supplied by a series inverter can be considered, from an electrical network point of view, as an equivalent resistance R, equivalent inductance L, and constant series compensating capacitance C connected with nonlinear voltage source [4]. The source parameters depend on R, L, C values, on inverter dead-time t_d, dc inverter supply voltage V_s, and drive angle α. To calculate transistor inverter output parameters, the transient analysis of an electrical circuit should be done. To match it with harmonic analysis of the electromagnetic field of the system, an analytical analysis of transistor inverter has been made.

Assuming that

- transistors are ideal (transistors losses are neglected);
- transistors are full drive and dead-time t_d is small compared with current period;
- the inverter load is inductive;

the series inverter output current can be described by [1]

$$i = \frac{V_S - V_C}{\sqrt{\frac{L}{C}}\cos(\omega_0 t_d + \eta)}e^{-\frac{k\omega t}{2Q}}\sin(k\omega t - \omega_0 t_d) \tag{3}$$

where V_s is dc voltage supplying the inverter, ω is angular frequency, ω_0 is angular frequency of *RLC* circuit

$$\omega_0 = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

and Q is quality factor

$$Q = \frac{\omega_0 L}{R}$$

and

$$\eta = \text{arc tg}\left(\frac{1}{2Q}\right); \quad k = \frac{\omega_0}{\omega}$$

$$V_C = -V_S\frac{\cos(\omega_0 t_d + \eta) - e^{-\frac{k\pi}{2Q}}\cdot\cos(k\pi - \omega_0 t_d - \eta)}{\cos(\omega_0 t_d + \eta) + e^{-\frac{k\pi}{2Q}}\cdot\cos(k\pi - \omega_0 t_d - \eta)}$$

The coefficient k can be calculated from [1]

$$\text{tg}(\omega_0 \text{t}_d) = \frac{\sin \text{k}\pi}{e^{\frac{\text{k}\pi}{2\text{Q}}} + \cos \text{k}\pi}. \tag{4}$$

The current i (3) has a shape of exponentially damped sinusoid. This function has a property of skewed symmetry and, therefore, the Fourier series has only odd harmonics. The amplitudes of the harmonics depend on k parameter and indirectly on dead time t_d and Q factor. Taking into account that time t_d is small in comparison with current (3) period and assuming that Q changes during heating of ferromagnetic material are in the range of 4–20, the third harmonic of current can be neglected (the error in calculation of I_{rms} for $t_d = 3\ \mu$s, $f = 20$ kHz, $Q = 4.4$ is smaller than 2%, and for $Q = 11$ is smaller than 0.7%). Therefore, the real current i has been substituted for first harmonic only. Based on the Fourier analysis, the first harmonic i_{1h} of the current i can be expressed as follows:

$$i_{1h} = \frac{B_1}{\cos\varphi_1}\sin(\omega t + \varphi_1)$$

where

$$\varphi_1 = \text{arc tg}\frac{C_1}{B_1} \tag{5}$$

and coefficients B_1 and C_1 can be calculated by solving integrals

$$B_1 = \frac{2}{\pi}\int_0^\pi i(\omega_0 t)\sin\omega t\, d(\omega t) \tag{6}$$

$$C_1 = \frac{2}{\pi}\int_0^\pi i(\omega_0 t)\cos\omega t\, d(\omega t). \tag{7}$$

The considered system, Fig. 1, has been simulated in two ways by using 2-D and 3-D simulations.

Calculating the required speed of heating and cooling allowing to reach an appropriate thickness of hardened layer, it is necessary to determine the appropriate supply parameters, speed of moving, quencher length, and inductor–quencher distance. The simulated calculation of the aforementioned parameters, also for the beginning and end part of charge, requires at least 2-D analysis of coupled electromagnetic and thermal fields taking into account the inductor-source supply interaction and simulation of quenching process. This has been made by coupling the commercial FLUX2D program, used for computation of a time harmonic magnetic field coupled with transient thermal field with the elaborated GEN program, which simulates the inverter operation and COOL procedure allowing the simulation of the quenching process of moving charge, as shown in Fig. 2. Data exchange between both programs increases calculation time, so it is important to minimize the number of data exchange connections during the calculation process. Computations of magnetic and thermal fields are nonlinear calculations of coupled fields. Such calculations require an iteration process for magnetic and for thermal calculations, as well as an updating of heat source power for thermal calculations. The changing of frequency and voltage supply was realized by the GEN program only once at the beginning of every update of heat sources power. They were constant for iterated calculation of magnetic field. Such a solution requires more iterations for updating of sources power, but demands lower computer cost than for changing frequency and voltage value during iterated calculation of magnetic field for every heat source updating. The quenching process of moving charge has been simulated by using the COOL procedure, which collaborated with a program for thermal field computations. It was realized by dynamically changing the thermal exchange coefficients on the charge surface, depending on its position in relation to quencher position. For charge surface under the quencher, the convection exchange coefficient rapidly increases to value 5000–12 000 $\mathrm{W/m^2 \cdot K}$, depending on cooling medium and charge surface temperature.

To calculate the appropriate inductor position near the charge edge, the 3-D analysis is necessary. From a technical point of view, it was assumed that inductor position in relation to charge edge line would be the same for the whole heating process of a moving charge. In such a situation, the 3-D analysis could be made for the middle part of the moving charge and it could be made for constant supply parameters (voltage and frequency) and without consideration of cooling system.

III. Numerical Analysis

The 2-D analysis has been made by the considered model of the system presented in Fig. 3.

By coupling of the computer simulation of the series inverter with numerical calculation of coupled electromagnetic and thermal fields of the inductor-moving charge system, the inverter output voltage V_{out} and power P as a function of time t (for initial period of induction heating of moving flat charge) is presented in Fig. 4. Time dependencies of charge temperature at the surface point A positioned 20 mm from charge beginning and at point B positioned 5 mm under point A are also presented in Fig. 4.

When the beginning or end part of a moving charge is heated (empty inductor) and inverter load quality factor increases, the

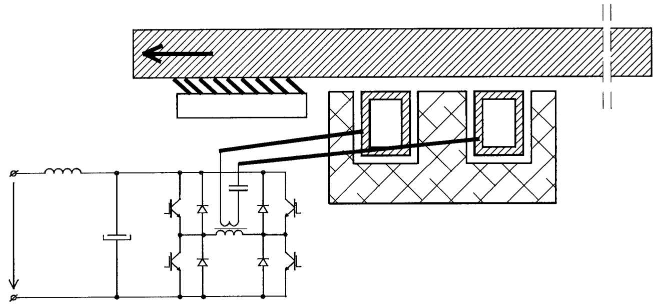


Fig. 3. Model of the system in 2-D analysis.

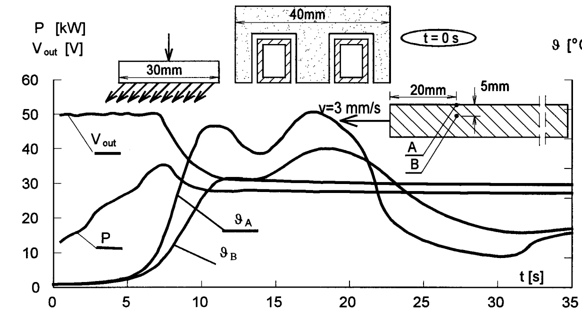


Fig. 4. Power, voltage, and temperature as a function of time.

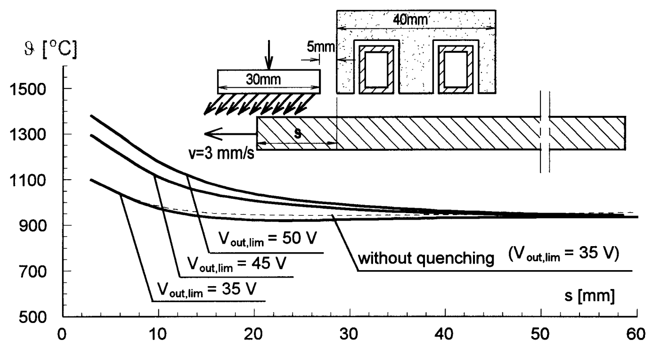


Fig. 5. Temperature of the charge leaving inductor.

inverter output voltage can reach high value. In a real transistor inverter, it is usually limited by limitation of transistor current or compensating capacitor voltage. Such limitation has been made in the simulated inverter model too. As can be noticed, the inverter voltage protection does not allow an increase in the output voltage V_{out} over 50 V, thus, it should protect the beginning part of charge against melting. On the other hand, the considered voltage protection $V_{\mathrm{out,lim}}$ can be used, for simulation purposes, as set value of inverter output voltage controller. Controlling the inverter output value, the limitation of overheating of the beginning and end part of charge can be realized. In Fig. 5, the surface temperature of the charge leaving the inductor has been presented. It has been done for three values of voltage limitation $V_{\mathrm{out,lim}}$, and for inductor–quencher distance equal to 5 mm. One can notice that by limitation of inverter output voltage, the overheating of the beginning part of charge can be reduced, but on the other hand, it can lead to insufficient heating of the next following part of charge. Additionally, in Fig. 5, the charge temperature values computed without simulation of quenching processes have been shown.

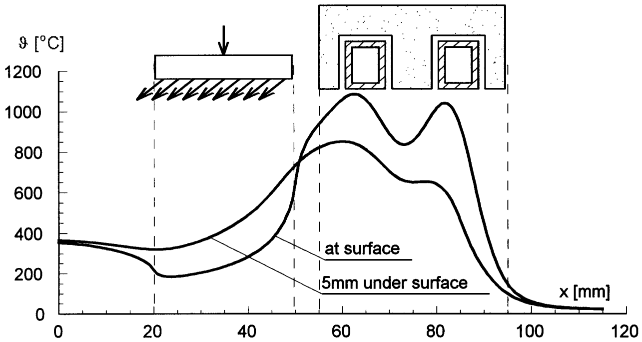
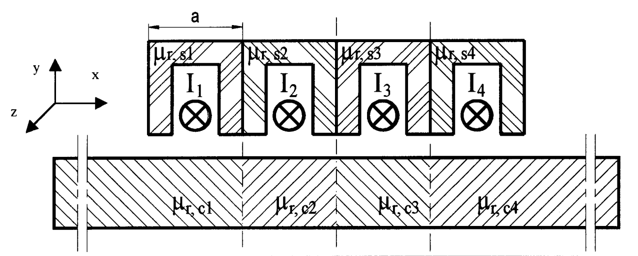


Fig. 6. Temperature distribution in the middle part of moving “long” charge.



t [s]	I_1	I_2	I_3	I_4	$\mu_{r,s1}$	$\mu_{r,s2}$	$\mu_{r,s3}$	$\mu_{r,s4}$	$\mu_{r,c1}$	$\mu_{r,c2}$	$\mu_{r,c3}$	$\mu_{r,c4}$
0-a/v	I	-I	0	0	1000	1000	1	1	1	B(H)	B(H)	B(H)
a/v-2a/v	0	I	-I	0	1	1000	1000	1	1	1	B(H)	B(H)
2a/v-3a/v	0	0	I	-I	1	1	1000	1000	1	1	1	B(H)

Fig. 7. Concept of 3-D temperature calculation in moving charge.

The results presented in Fig. 5 show that the existence of the quencher must be taken into account even if only heating process of moving charge before hardening is simulated.

In Fig. 6, the temperature distribution obtained for the middle part of the moving charge is presented. Depending on charge material and quenching medium, the appropriate quencher width can be chosen.

To calculate the appropriate inductor position near the charge edge, 3-D analysis has to be made. In general, such 3-D analysis, as aforementioned, can be made for the middle part of moving charge, constant supply parameters and without consideration of cooling system, but the coupled electromagnetic and thermal field and moving of charge should be considered. Taking into account that in the considered example no temperature distribution in the charge should be calculated, but only relative temperature distribution in z direction (Fig. 1) near charge edge, the simplified calculation has been proposed. It is based on one direction coupling of electromagnetic and thermal field. The movement of charge has been simulated by simple modification of material parameters and inductor position (in x direction), as shown (in 2-D cross section) in Fig. 7.

The calculations have been made in three steps valid for time $(0 - a/v)$, $(a/v - 2^*a/v)$, and $(2^*a/v - 3^*a/v)$, where a is half of the width of inductor magnetic shunt and v is speed of the charge. In every step, 3-D electromagnetic field calculations have been made and volumetric power density p_v distribution in the charge has been determined, which then has been used as a heat source in transient thermal field 3-D computations. In thermal computations, the temperature field distribution from the previous step of calculation has been used.

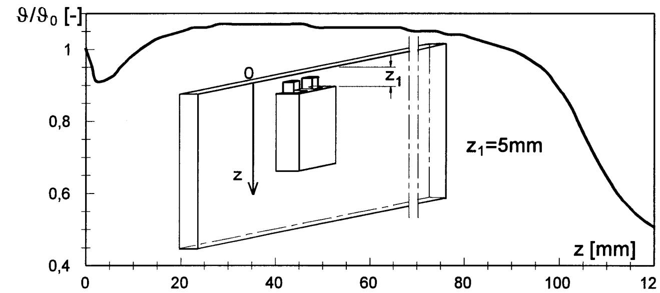


Fig. 8. Temperature distribution uniformity near charge edge.

In Fig. 8, the charge surface temperature distribution along charge width has been presented. The temperature distribution has been related to edge of charge temperature value.

IV. Conclusion

In simulation of induction heating systems, the supply sources are usually replaced by constant current or voltage and constant frequency. Especially for electronic sources, as transistor inverters, it can lead to serious simulation errors. In a rather simple way, the simulation of whole induction heating system can be realized by connection of numerical simulation of coupled harmonic electromagnetic and transient thermal field with analytical analysis of the source giving the possibility to use harmonic description of inverter output current. Computer simulation of induction hardening process, even when only heating part of this process is considered, required simulation of the quencher to get the correct charge temperature distribution.

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