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Model of Temperature Control by Electrically Stimulating Action Parameters

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Abstract—Technologies for pressure shaping of metal workpieces using powerful current pulses are becoming increasingly widespread both in Russia and abroad. Unique electromechanical processes are studied and improved in laboratory and production environments. The application of current to the workpiece is accompanied by a change in its physical properties as a result of the so-called electroplastic effect (EPE). At the same time, the temperature of the workpiece in the deformation zone increases. An automatic force and temperature regulation system is necessary for maintaining high-quality and reliable operation of the drawing mill at electrostimulated drawing (ESW). In order to implement the temperature control circuit, it is necessary to synthesize the transfer function of the control object—steel wire wrought under pressure by rolling or drawing. The synthesis and analysis of the parameters of the temperature control object model are considered. Several known relations are used, such as the dependence of the pulse generator power on the calculated parameters (initial temperature, diameter, specific weight and electrical resistance of the workpiece, pulse duration), dependence of the generator's RMS current on the amplitude and frequency of pulse reproduction, dependence of the magnetic permeability of the workpiece on its temperature, and dependence of the specific electrical resistance of the conductor material on temperature. The Matlab–Simulink software suite is used to synthesize a model of the temperature control object as a function for parameters of a generator of powerful current pulses (amplitude and frequency), as well as the parameters of the workpiece in processing (diameter, sample length, linear velocity, initial temperature, and resistivity at the initial temperature). The model is analyzed, and transients in different operating modes are presented. The developed model is used for deriving the dependences of the temperature, power, and equivalent resistance on the parameters of the generator and the workpiece at various generator pulse frequencies and workpiece diameters. The developed model can be used for laboratory studies of the electroplastic effect, as well as in producing electrostimulation drawing autocontrol systems in order to implement the controlled object as a model.

Keywords: generator of powerful current pulses, system of automatic control of generator parameters, metal workpiece heating model, controlled object, transfer function of controlled object transfer function of controlled object

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INTRODUCTION

This past decade has attracted the attention of researchers and technologists in the domains of material physics and metal working to study the influence patterns of fields and currents, as well as to use the plasticization of metals and alloys in modern deformation practices. A special term has even been coined, that is, electrically assisted manufacturing (EAM) [1]. This mode of metal working involves drawing, rolling, forging, punching, and new technologies in development [2–12]. The most popular practice of such kind in Russia is electrostimulated drawing (ESD) [13] based on using pulse currents of various frequencies, lengths, and densities. There is an intensive for interpreting observed effects and identifying their physical essence [1, 13].

ESD [13] is based on using generators of powerful current pulses (PGs). The cost efficiency, fast action, safety, and high level of parameters of modern generators is ensured by the fact that they contain a charging device with thyristor converters and a system of autocontrolling the frequency and amplitude of pulses [14, 15].

Special emphasis must be made on electrical contacts allowing the reliable transfer of electricity from the pulse generator to the zone of deformation [16, 17]. Stable ESD must be maintained by a high-quality and fast-acting system of automation regulation (ARS) of drawing parameters [18]. In order to lay a temperature control loop, it is necessary to calculate the transfer function of the control object's parameters, first of all, drawing temperature and effort. In ESD, this object is steel wire.

One of the issues with the DPARS is the temperature variations in the zone of deformation. Thermocouples are forbidden for use due to their inertia, whereas photosensors and other electronic devices are very unreliable due to powerful noises generated during pulse propagation as well as possible sparking and scaling, which makes it necessary to constantly clean the sensor window.

One of the possible solutions for this problem is to use not a regulated object but its model.

This work is intended for analyzing and synthesizing the model of a temperature control object.

MATHEMATICAL DESCRIPTION OF THE CONTROLLED OBJECT AND THE SYNTHESIS OF TRANSFER FUNCTION

A metal workpiece affected by electricity allows converting electric energy to thermal. After the workpiece temperature equals the ambient temperature, its heat is emitted into the ambient by convection, beam emission, and heat conductance.

The main calculations of the dynamic mode of heating the controlled object (processed wire) [19, 20] are presented below.

Full capacity P used to heat the workpiece is defined as

$$P = P_{\rm use} + P_{\rm loss},$$

where $P_{\rm full} = mc_p((t_2^\circ - t_1^\circ)/\tau)$ is the useful capacity used to heat the workpiece, W; m is the weight, kg; $c_{\rm p}$ is the heat capacity, J/(kg K); $(t_2^\circ - t_1^\circ)$ is the difference between the initial and the final temperature, °C; t is the heating time, s; $P_{\rm loss} = P_{\rm cnv} + P_{\rm rad} + P_{\rm t}$ is the lost capacity, W; $P_{\rm cnv} = 3.5 \times 10^{-4}\ F((\Delta T^{5/4}/{\rm d}^{1/2})$ are the convection losses, W; $P_{\rm rad} = 5.7\varepsilon_{\rm o}\left[((T_2^\circ/1000)^4 - (T_1^\circ/1000)^4\right]F$ are the radiation losses, W; $P_{\rm t}$ are the losses on thermal conductance, W; F is the surface area, cm^2; T is the temperature, K; $\varepsilon_{\rm o}$ is the emissivity coefficient [19]; d is the workpiece diameter, cm; $m = \rho_{\rm dns}V$; $\rho_{\rm dns}$ is the density, g/cm^3; V is the workpiece volume, cm^3; $V = \pi {\rm d}^2/4$, cm^3; $P = I_{\rm msq}R_{\rm eq}$, W; $I_{\rm msq}$ is the mean square current flowing through the workpiece, A; $R_{\rm eq}$ is the equivalent resistance of the workpiece, Ohm.

The calculations are simplified by considering that the generator pulses are sine-wave in shape, the pulse length is 75 μs, and the maximal amplitude is 8 to 10 kA (these values are constant). The formulae for the mean square current are

$$I_{\rm msq} = \sqrt{\frac{\int_0^{T/2} A^2(\sin\omega t)^2 dt}{T}} = \frac{A}{2}\sqrt{T_0 f},\quad {\rm A}, \tag{1}$$

$$I_{\rm msq}^2 = \frac{A^2}{4}f. \tag{2}$$

MODELING

The derived dependences are used to synthesize the model of a unit implementing the dependence of the generator's mean square current $I_{\rm msq}$ on the generator's pulse reproduction frequency f.

The formulae are used to derived the following dependence of the generator capacity on the calculated parameters:

$$P = I_{\rm msq}^2 R_{\rm eq} = mc_p\frac{t_2^\circ - t_1^\circ}{\tau} + 5.7\varepsilon_{\rm o} \times\left[\left(\frac{T_2^\circ}{1000}\right)^4 - \left(\frac{T_1^\circ}{1000}\right)^4\right]F + 3.5\times10^{-4}F\frac{\Delta T^{5/4}}{d^{1/2}}.$$

The parameters used as constant values in the program are initial workpiece temperature T_2, K; workpiece diameter d, cm; metal workpiece density ρ, g/cm^3; electric resistance R of the workpiece, Ohm; length $T_0/2$ of a powerful electric pulse shaped by the pulse current generator, μs.

The temperature in the deformation zone is calculated by transferring value A of pulse amplitude $A_{\rm tr}$ to the model's input. The generator current is calculated in unit B1 according to the above-specified dependences.

It is known that the passing of pulse current through the conductor is attended by two significant effects that change the constant resistance value. The moment, when the pulse current passes through the metal, the current is displaced to the surface due to the weakening of the magnetic field at the conductor surface and faces a higher induction resistance closer to the center of the conductor. The above effect is called the surface or skin effect and results in an uneven heating of the parts: the surface layers are heated more intensely, whereas the center of the workpiece is heated only slightly due to the thermal conductance of steel.

The depth, to which the metal is penetrated by the current (the surface layer thickness), is defined according to a formula from [21, 22]. The formula is

$$\delta = \sqrt{\frac{\rho}{\mu_{\rm cm} f}} = \sqrt{\frac{\rho 2T_i}{\mu_{\rm cm}}}, \tag{3}$$

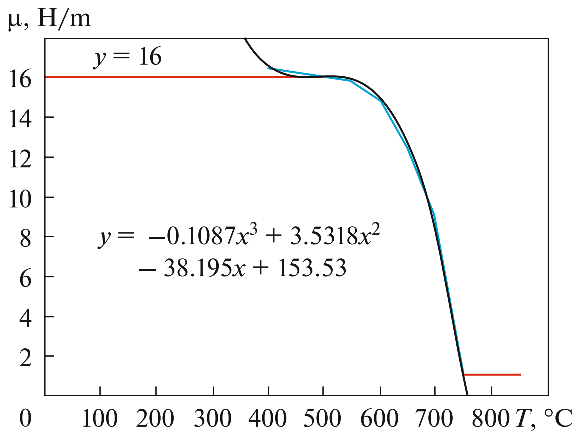

Fig. 1. Magnetic permeability changes as a function of heating temperature.

where f is the pulse current oscillation frequency, Hz; μ_{cm} is the permeability of the conductor's material, H/m; T_i is the current pulse length (half-period), s; δ is the current penetration depth in the conductor, m.

This depth increases with an increase in the heating temperature and reaches its maximum at the so-called Curie point when the workpiece loses magnetic properties.

At temperatures above 700 to 750°C, the magnetic permeability is almost independent from the workpiece temperature and reaches the minimal value of vacuum permeability $\mu_o = 1$ (Fig. 1).

Function $m = f(t)$ is approximated by modeling unit B3 (Fig. 2) with cell Fcn5 of mathematical calculations, that implements dependence $y = f(x)$, and also modeling restriction unit SD implementing functions $y = 16$, $y = 1$.

Thus, the following technology of heating the workpiece using pulse current is defined: first of all, the steel is intensely heated in a small surface layer of the same depth as the depth of current penetration into the cold metal; then, after this layer is demagnetized, the current penetrates deeper and a deeper layer is heated, which is attended by a slowdown in the temperature increase in the first heated layer.

The temperature changes are also attended by the changes in specific electric resistance ρ of the conductor's material, which is recorded as

$$\rho_t = \rho_{t1}[1 + \alpha(t - t_1)], \tag{4}$$

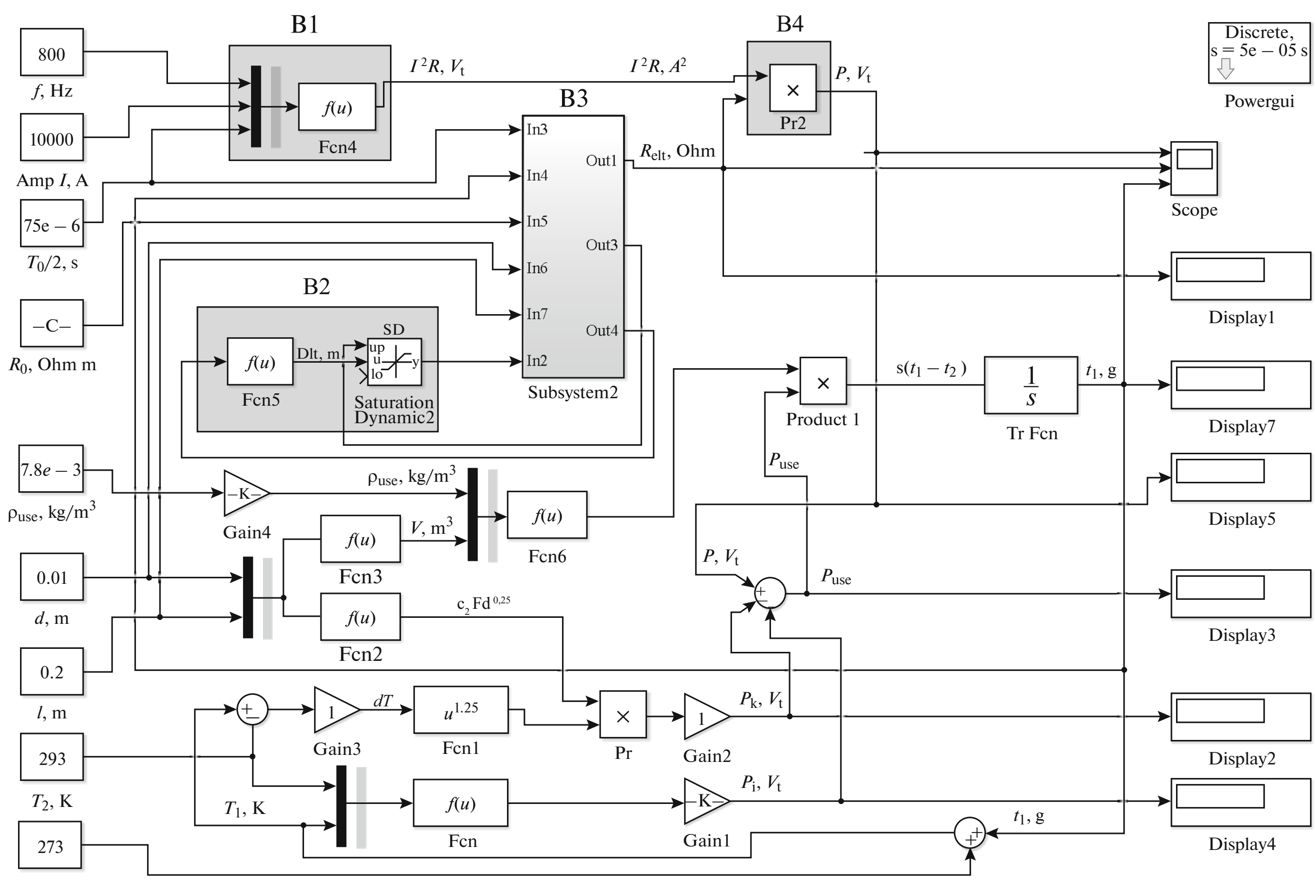

Fig. 2. Model of unit B, which implements the dependence of the workpiece temperature on the parameters of the workpiece and pulse generator in MATLAB–Simulink.

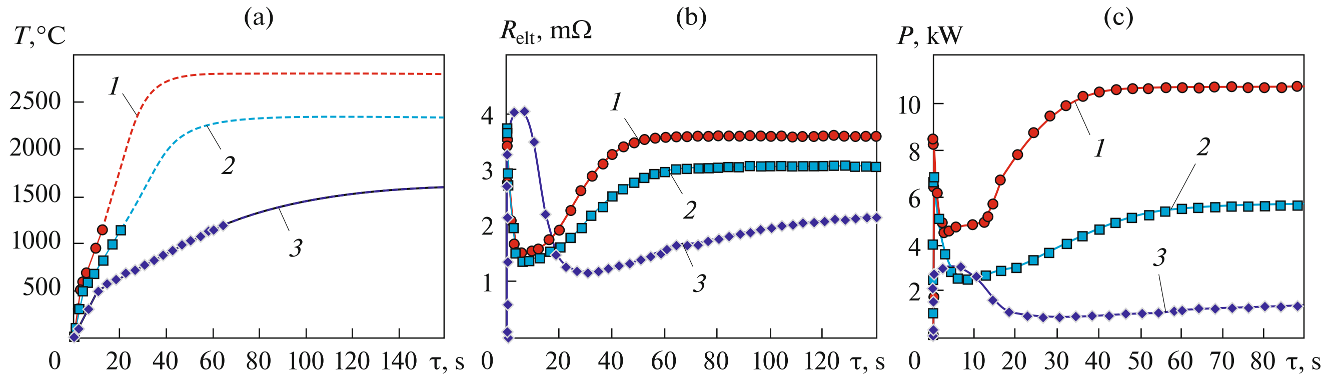

Fig. 3. Dependence of temperature (a), equivalent resistance (b) and generator power (c) on time at a pulse reproduction frequency of 800 Hz (*1*), 500 Hz (*2*) and 200 Hz (*3*) (the workpiece diameter is 10 mm).

where ρ_{t1} is the specific resistance of the metal workpiece at initial temperature t_1 (usually, 20°C), Ohm·m; α is the capacity of the pulse generator.

Unit B3 is used to calculate the workpiece's equivalent resistance R_{eq} as function μ, t according to formulae (3) and (4), whereas unit B4 is used to calculate the capacity of the pulse generator.

Magnetic permeability μ and specific electric resistance ρ of the heated steel workpiece change simultaneously and significantly change the equivalent resistance of the workpiece depending on time and temperature.

The dependences from Fig. 1 have been used to synthesize the unit's model for changing the temperature of the workpiece of length l and cross section S at initial ambient temperature t_1° of 20°C from RMS current.

For the general ARS model with units 1–4, see Fig. 2. The input parameters are initial workpiece temperature T_2, K; workpiece diameter d, cm; metal workpiece density ρ, g/cm^3; workpiece electric resistance R, Ohm; length $T_0/2$ of the powerful current formed by the pulse current generator, μs.

The design model has been used to derive the dependences of the object's temperature, capacity, and equivalent resistance on the parameters of the generator and the workpiece at various frequency of the generator pulses and workpiece diameters presented in Fig. 3. The idle state zone of the workpiece (above its melting point) is shown in dashed lines.

CONCLUSIONS

The simulation model of regulating the temperature of a metal workpiece object exposed to current pulses as a function of the parameters of the pulse generator and workpiece has been developed in Matlab–Simulink. The model has been synthesized using the known equations of the dynamic heating of the controlled object on exposure to current, the dependence of the RMS current of the generator on the amplitude and frequency of pulse reproduction, and the temperature-induced change in the current penetration depth of the metal and in its specific resistance. The analysis of the model has helped derive the transient processes of the temperature and specific resistance of the workpiece and the generator's capacity.

The developed model can be used for laboratory studies of the EPE, in design works, for determining the current source strength depending on the workpiece parameters and temperature, and also in production of electrostimulation drawing autocontrol systems in order to use the control object's model instead of the object proper.

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