Simulation of Heat Transfer in Reversed Polarity Current Plasma Surface Heat Treatment

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***Abstract*—A mathematical model of reversed polarity current plasma surface thermal treatment of heat-resistant steels was developed. The model introduces two heat transfer mechanisms for plasmatron using reversed polarity current: by plasma flow and by cathodes on the surface. It is proposed to use the combined heat source for temperature fields estimation by the reversed polarity processing. The heat amount, developed by the plasma flow is represented as a surface heat source with normal heat flow allocating at the heating spot. Due to the high speed random motion and fugacity of cathode spots, their combined impact was changed to evenly allocated surface heat source. The boundary problem of thermal conduction was solved by the finite-element method, using the Comsol software , on the basis the energy transfer equation.**

Keywords—plasma, reversed current polarity, surface thermal treatment, mathematical simulation

Introduction

To solve thermal conduction problems analytical and numerical methods are used. Analytical methods involve selection of the process equation in accordance with the differential thermal conduction equation and boundary conditions. The most widely used analytical methods are methods of integral transformations (Hankel, Laplace, Fourier transformations).

Currently the most spread method is a numerical finite element method (FEM). Modern software, like ANSYS, COMSOL offers large scale of thermal conduction analyses by welding. In contrast to the analytical method, the numerical method does not provide a general solution of a problem, but can be useful for engineering analysis when an analytical method becomes laborious or completely unreachable.

Plasma surface thermal treatment is a high-speed local heating of a surface segment to high temperatures with the higher critical speed aftercooling due to heat dissipation to inner layers of the unit material. By this the high performance structure is being formed [1]. The plasma surface thermal treatment technological parameters include current magnitude and polarity, speed of plasmatron movement relatively to a unit, shielding and plasma-supporting gas flow, plasma-forming nozzle diameter [2]. The certain surface segment hard-facing is achieved by sequential formation of hardening localized zones as long-length end-to-end bands.

Analysis of a unit real form can significantly harden the plasma surface thermal treatment temperature problems solution. That is why by heating calculations the real form is being viewed as an ideal, as one of the following heat balances where thermal conduction equation solution can be found analytically. For our research we took a semi-infinite body.

Research materials and methods.

The heat transfer in a unit by reversed polarity current plasmatron is determined by near-electrode processes and plasma flow heat transfer and may be equated as:

$$P_{ио} = I_{\partial} \cdot (u_{к} - \varphi_{в}) + P_{п} \qquad (1.1)$$

$u_{к}$ *–cathode drop*

$\varphi_{в}$ *–work function*

$P_{п}$ *–plasma flow power*

I_{∂} *–plasma arc current intensity*

By the reversed polarity plasmatron operation, the arc contact area consists of many relatively small, but separated unsteady spots of different types; high temperature only appears on the segment where the arc spots are based, other area remains relatively cool. One of the unsteady spots distinctive features is their fugacity and high current density ($j \sim 10^5$-10^6 Acm^{-2}). High current density means that specific heat flow rates reach the value of ($q \sim 10^6$-10^7 Wt/cm^2), resulting in heating and cooling speed needed for surface hardening. Cathode spots are not fixed at one point, they are moving within the whole area under treatment, limited by one and a half diameter of protection nozzle, that provides more uniform surface heating.

Considering all the above stated information we propose to use the combined heat source by research of temperature fields for current polarity treatment.

Let’s take the plasma flow heat as a surface heat source with a normal heat flow distribution at the heat spot with r-radius [3]:

$$q_2(r) = q_{2m}\exp(-kr^2), \tag{1.2}$$

$q_2(r)$ *– specific heat flow rate at any heat spot*

q_{2m} *– the highest specific flow rate at the heat spot centre*

k – heat flow density coefficient

Considering the high speed random motion and fugacity of cathode spots, assuming uniformly spread probability of occurrence of cathode spot in the arc and metal contact area, the cooperation of cathode spots may be replaced by uniformly spread surface heat source at simulation.

The mathematical model is based on the energy transfer differential equation solution:

$$\frac{\partial T}{\partial t} = a\cdot\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + V\frac{\partial T}{\partial x} + \frac{Q}{c\rho} \tag{1.3}$$

Q – effective arc heating capacity Wt

V – speed of treatment m/h

a –coefficient of temperature conductivity m2/s

*c –specific heat capacity J/kg*K*

r – density of material kg/m3

The energy transfer differential equation is a mathematical model of the whole class of thermal conductivity effects and has an infinite set of solutions . In order to get one particular solution, featuring the certain process it is necessary to have additional data, more than the initial differential equation contains. These extra specifications , which determine the certain aim together with the differential equation are called *uniqueness specifications.*

1) The 3rd side boundary data:

2) Thermal and physical characteristics: *c, λ, ρ, a*;

3) Starting temperature is 20°C.

We have:

$$Q = q_1 + q_2\cdot f\,, \tag{1.4}$$

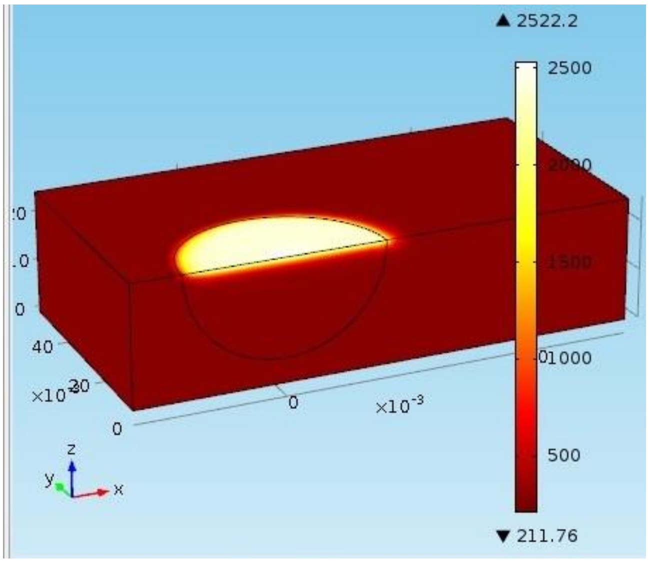
q_1 –power transferred by plasma flow, Wt

q_2 –specific power transferred by cathode spots Wt/m2

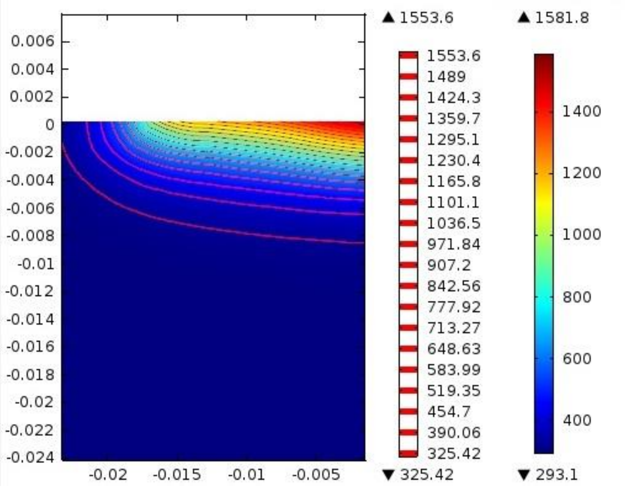
f –area of cathode spots random walk, m2

Research results, discussions of results

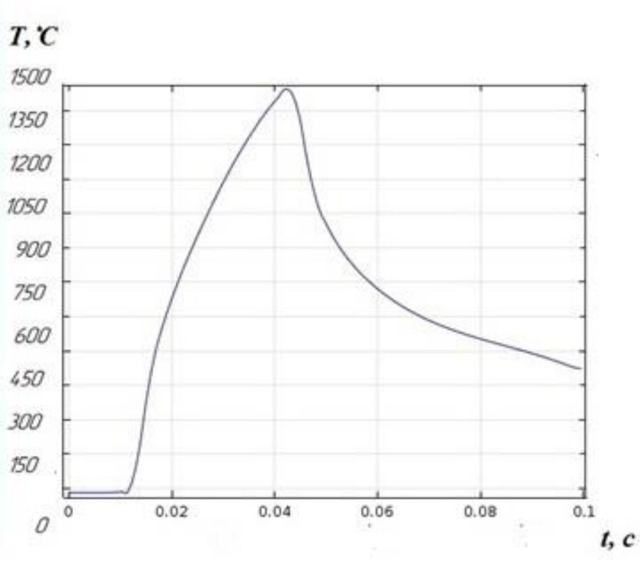
So, after we have solved the combined equation in COMSOL [4] Multiphysics, we have the following result:



Pic.1 *Temperature field of the sample surface*

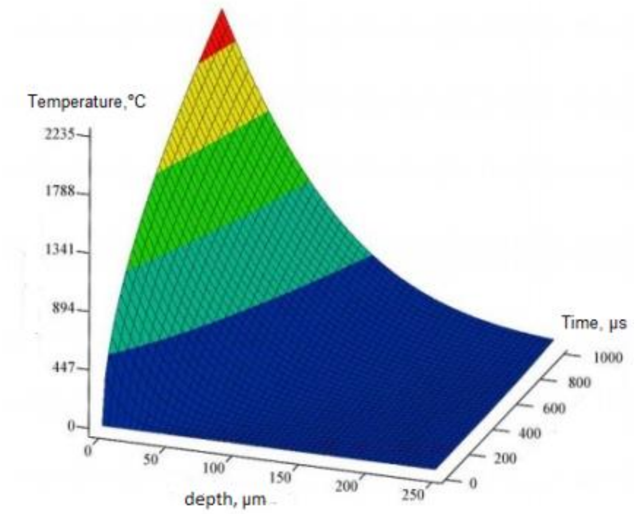


Pic.2 *Temperature distribution at the sample cross-section*

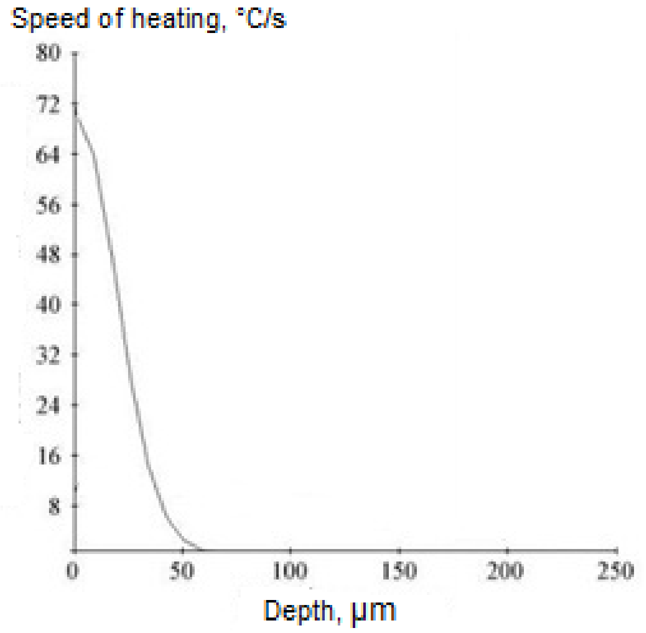


Pic.3 *Thermal cycle of heating-cooling when using combined heat source*

Thus, the thermal fields achieved after the updating and thermal heating-cooling cycle proves the efficiency of such a treatment.



Pic.4 *Surface temperature distribution by heating depth*



Pic.5 *Speed of heating in depth by one spot impact*

Conclusions

So, reversed polarity current plasma surface hardening may be used for getting hardened layers with no surface melting with dept of 2 mm, or for getting thin hardened layers with depth of about 0,25 mm using low amperage arc. Besides, due to temperatures high gradients, made up by walk cathode spots, current of reversed polarity is useful for getting wider melting rollers and lower content of the main metal in the weld pad by plasma hardening.

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