Impact of the Chemical Elements Upon the Convective Flows in the Molten Metal of the Weld Pool

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Abstract. World production of surfacing materials requires a large amount of alloying elements extracted from the Earth crust. Efficient use of scarce alloying elements and development of resource efficient surfacing techniques which reduce consumption of alloying elements together with improvement of the functional properties of the surfaced layer is a relevant problem of material science and preservation of the environment. In the paper the authors consider the problem of modeling the convective flows emerging under the plasma jets in the process of surfacing. The authors formulate the basic requirements to the thermal cycle of the surfacing ensuring obtaining identical functional properties of the surface while the amount of scarce alloying elements reduces.

Introduction

At the present time the method of arc surfacing with flux cored electrodes is widely applied for producing wear resistant coatings [1]. It allows producing bimetallic products which combine high strength and low cost with increased service life although the main part of the component may be produced from the low-alloy steels. Application of the method for repairing the worn-out parts results in reduction of the amount of the spare parts of the operated equipment, reduction of delay technician time, reduction of servicing costs. On the other hand, the arc surfacing method implemented in spite of the simple design of the applied equipment and its high productivity leads to formation of coarsely dispersed heterogeneous structures with low impact strength and the quality of the surface requires after-treatment processing [2]. That is why it is necessary to find such surfacing conditions which allow forming the structure with high physical and mechanical properties. To solve this problem we need the data on the hydrodynamic processes taking place in the weld pool. The geometry of the surfaced layer, its structure, phase composition and mechanical properties depend on the characteristics of these processes [3]. Many researchers studied the hydrodynamic processes in the weld pool under the arc welding and among their papers works [4-9] are especially worth mentioning as the authors completed the numerical study of the heat exchange in the liquid and its flow under direct and pulse current welding. In [4] it has been established that the surface-tension gradient has the

most significant impact over the geometric pattern of the weld pool while other factors, such as magnetic inductive capacity, heat-expansion coefficient of the material make a smaller contribution. In paper [5] the authors obtain the results demonstrating that application of pulse current allows forming the surfaced layer of higher quality.

Thermocapillar convection in the weld pool was studied in [6-8]. In [6] the authors complete the numerical study of the impact produced by Marangoni effect upon the parameters of various metals under arc welding in the enclosed volume. As a result the ranges of current intensity were established under which the thermocapillar convection plays the most important role. Further increase of the intensity of current does not lead to the increase of the depth of penetration, thus, the linear dependence of the surface tension coefficient of pure liquid metals upon the temperature deteriorates the penetrating ability of the electric arc. In [7] the authors show that for the pure metals the thermocapillar convection plays the significant role only at the initial stages of materials fusion and then the deformation of the liquid impacted by the gravity force becomes the source of convective flows. On the other hand, study of the concentrated energy flows impact upon the metals shows that under large values of power density the heat-gravitational convection is insignificant [8].

It is also necessary to take into consideration the influence of the alloying elements [8]. In [9] the influence of these elements upon the surface tension of liquid iron was studied. It was shown that addition of sulfur results first in the growth of surface tension as the temperature grows and then decreases, thus, there is non-linear dependence upon the temperature. If sulfur is introduced directly into the weld pool it results first in the growth of surface tension and the pattern of vortex flotation undergoes a significant change. The matter involved into the vortex flotation will move to the centre and then downward to the bottom of the weld pool. The downward flow of hot metal in the weld pool operates as a heat drill. The penetration depth will increase accordingly and the geometric pattern of the pool will change.

This way, when developing the model of the convective flows in the weld pool it is necessary to take the influence of the alloying elements upon the hydrodynamic flotation into consideration. It is relevant for studying the convective processes in the weld pool when surfacing with flux-cored electrodes.

The alloying elements, components of the flux-cored wire, change the character of surface tension coefficient dependence upon the temperature. This results in alteration of the pattern of the convective flotation and effects the structure-phase composition of the surfaced metal. That is why the goal of our work is to develop the mathematical model of convective flows in the weld pool which takes the presence of alloying elements into consideration.

Problem formulation

It is appropriate to start modeling of the convective flows from determining the bulk forces acting upon the liquid and from calculating the electromagnetic fields. The volume force acting on the liquid includes the gravity and the electromagnetic forces.

$$\vec{F} = \vec{F}_g + \vec{j} \times \vec{B} = \rho_0 \vec{g} - \rho_0 \vec{g} \beta (T - T_{ref}) + \vec{j} \times \vec{B} \tag{1}$$

We shall calculate the electromagnetic fields on the basis of Maxwell-Lorentz equations

$$\nabla \cdot \left(\sigma \nabla V + \sigma \frac{\partial \vec{A}}{\partial t} \right) = 0, \ \sigma \frac{\partial \vec{A}}{\partial t} + \frac{1}{\mu_0} \nabla \times \left(\nabla \times \vec{A} \right) + \sigma \nabla V$$

$$\vec{E} = -\nabla V - \frac{\partial \vec{A}}{\partial t}, \quad \vec{j} = \sigma \vec{E}, \ \vec{B} = \nabla \times \vec{A} \tag{2}$$

With consideration to (1), (2) let us put down Navier-Stokes and thermal conductivity equations

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\nabla\vec{u}\right) = -\nabla p + \mu\Delta\vec{u} + \vec{F}_V, \nabla \cdot \vec{u} = 0,$$

$$\rho C_p\left(\frac{\partial T}{\partial t} + \vec{u}\nabla T\right) = \nabla \cdot (k\nabla T) + Q_V$$

(3)

where $\vec{u}$ - velocity vector, p - pressure, ρ - density, μ – dynamic viscosity, $\vec{F}_V$ - bulk forces, which are prescribed by the total of Lorentz force and gravity force, T - temperature, C_p - specific thermal capacity, k – heat conductivity coefficient, Q_V – volume heat sources. Only Joule effect is the volume heat source for the cathode and anode $Q_V = \vec{j} \cdot \vec{E}$.

Let us consider the impact of electric arc plasma upon the plate of hardening steel 45 (Figure 1).
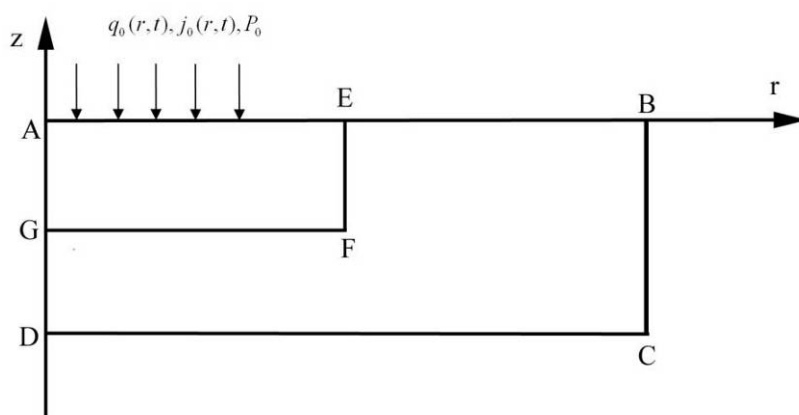

Figure 1. The computational region

At the top surface AB we shall set the density of current, pressure and heat flow which are the result of plasma action upon the surface of the metal, like in [3-5].

$$-\vec{n} \cdot \vec{q} = q_0\left(r\right) = \frac{dUI\eta}{\pi r_0^2} G(r,t)$$

$$-\vec{n} \cdot \vec{j} = j_0\left(r\right) = \frac{dI}{\pi r_0^2} G(r,t)$$

(3)

$$p = p_0\left(r\right) = \frac{\mu I}{4\pi} j_0\left(r\right)$$

where q_0, j_0, p_0 - heat flow, flow density, pressure accordingly; U, I - voltage and strength of current; η - performance factor; G(r,t) – the function of impact surface and time distribution:

$$G(r,t) = \exp\left(-\frac{d(r^2 + (r_0 - V_e t)^2)}{r_0^2}\right)$$

(4)

where V_e - electrode feed, d, r_0 - distribution parameters.

On the bottom surface CD we set the condition of convection heat transfer and electromagnetic continuity;

$$-\vec{q} \cdot \vec{n} = h_0(T - T_0)$$

$$\vec{j} \cdot \vec{n} = 0$$

(5)

On the side boundary BC there is similar condition of convection heat transfer and equal-zero electrostatic scalar potential:

$$-\vec{q}\cdot\vec{n} = h_0(T-T_0)$$
$$V = 0$$

(6)

The condition of contibuity was set for the magnetic field at all boundaries: $\vec{n}\times\vec{A} = 0$. The slipping condition was fulfilled at EF and FG boundaries for the speed.

The model of phase transition from the solid state into the liquid one was based on the concept of dynamic viscosity coefficient growth in the solid region. It looks as follows:

$$\mu = \mu_L(T)*(1-f_s) + \mu_S f_s$$

(7)

where f_s - the coefficient determining the solid phase, μ_L - viscosity of the liquid phase, μ_S - viscosity of the solid phase, which is large enough to stop the movement in the solid phase.

The calculations were completed according to the final element analysis in the kit Comsol Multiphysics. In Table 1 we provide characteristics of the material and the treatment conditions.

Table 1. Input parameters of the problem

Designation	Description	Value
U	Voltage	30V
I	Strength of current	250 A
r_0	The radius of efficient action of the plasma jet	10mm
T_l	Temperature of the liquid phase	1723K
ρ_s	Density of the solid phase	7500kg m^{-3}
ρ_l	Density of the liquid phase	6350kg m^{-3}
C_{pl}	Coefficient of heat capacity of the liquid phase	720 J kg^{-1} K^{-1}
C_{ps}	Coefficient of heat capacity of the solid phase	602 J kg^{-1} K^{-1}
k_l	Heat conduction coefficient	20 W m^{-1} K^{-1}
k_s	Heat conduction coefficient	26 W m^{-1} K^{-1}
σ	Electrical conductivity of metal	7.7×10^5 Ω^{-1} m^{-1}
μ	Dynamic viscosity coefficient	0.05 kg m^{-1} s^{-1}
L_f	Melting heat	247×10^3 J kg^{-1}

In Figure 2 we provide the dependence of the surface tension upon the temperature

Results and discussion

It is known that the flotation in the weld pool is determined by Marangoni convection which is characterized by the temperature gradient of the surface tension $\partial\sigma/\partial T$. In Diagram 2 we can see that $\partial\sigma/\partial T > 0$ under the subcritical temperatures $T < T_c = 2300K$ and $\partial\sigma/\partial T < 0$ for $T > T_c$.

In figures 3-5 the development of the melt is shown at various time intervals. The following pattern is observed. Before the heat flow reaches its maximum q the downward flow formed by two symmetric vortexes moves from the centre of the pool stirring the melt full-width the pool (Fig. 6). When the thermal influence of the plasma jet decreases the stage of cooling starts which is characterized by the motion of the downward flow towards the centre of the pool and further formation of single vortex near the symmetry point. This downward flow reaches the depth of 6 mm.
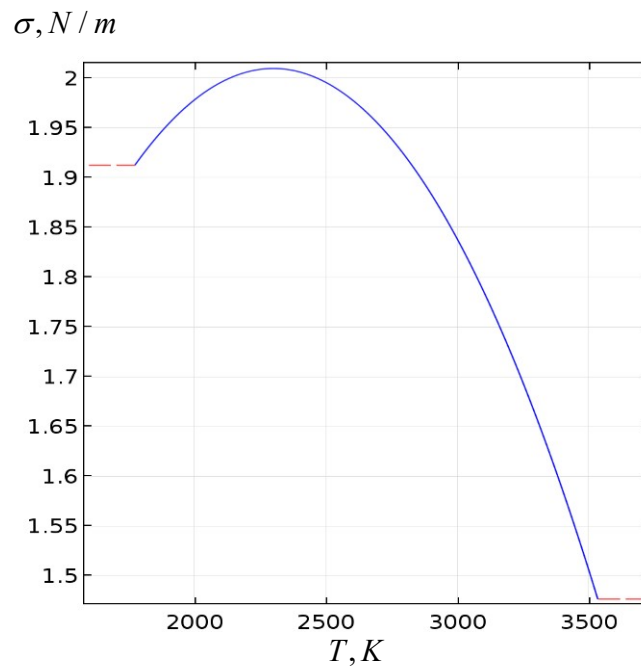
$\sigma, N/m$

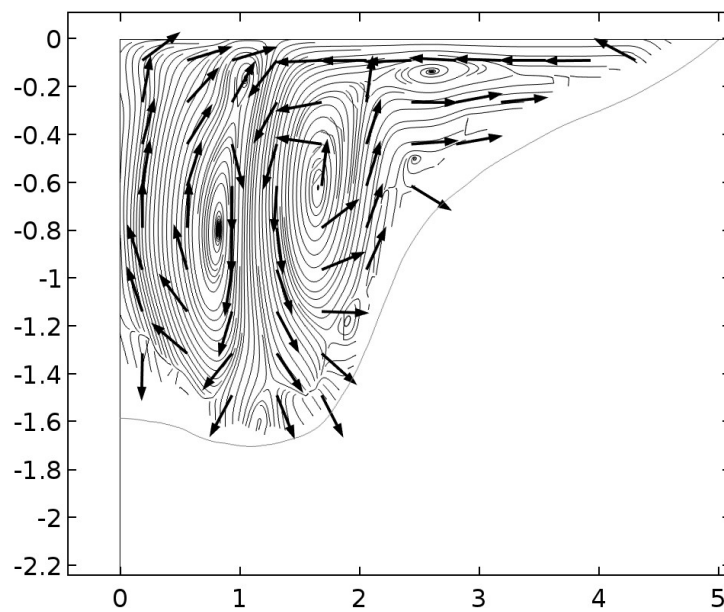**Figure 2.** Dependence of the surface tension upon the temperature

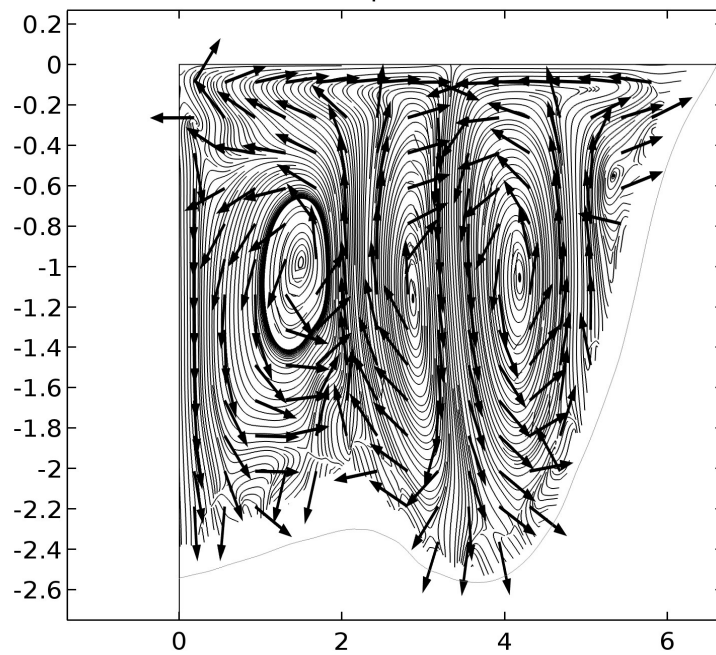Figure 3. The lines of fluid flow in the melt and the field of velocities at time interval t=2.7s

Figure 4. The lines of fluid flow in the melt and the field of velocities at time interval t=4s (the peak of heating)
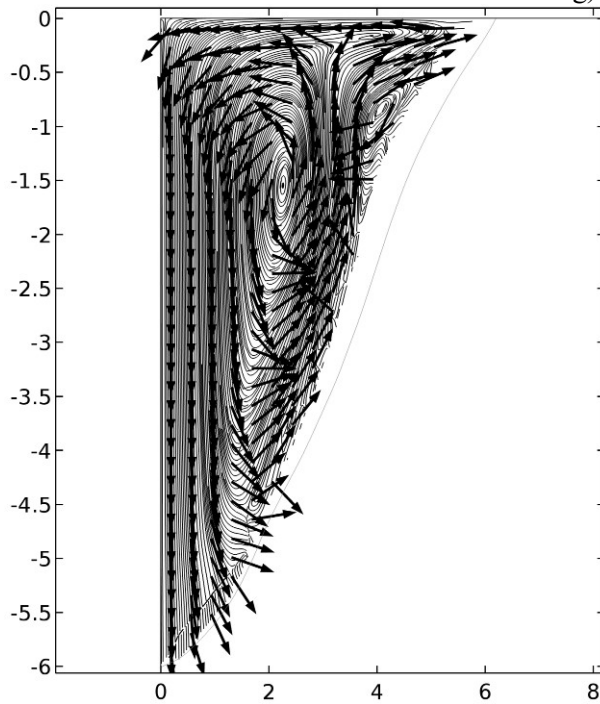

Figure 5. The lines of fluid flow in the melt and the field of velocities at time interval t=5.3s (the phase of cooling)

Formation of the given downward flow formed by two vortexes can be explained by the change of the sign of the temperature gradient of surface tension $\partial\sigma/\partial T$. When we compare Fig. 7 with the pattern of flow in Fig. 3-4 we can notice that the downward flow is where $T = T_c$. It is also proved in Fig. 8.
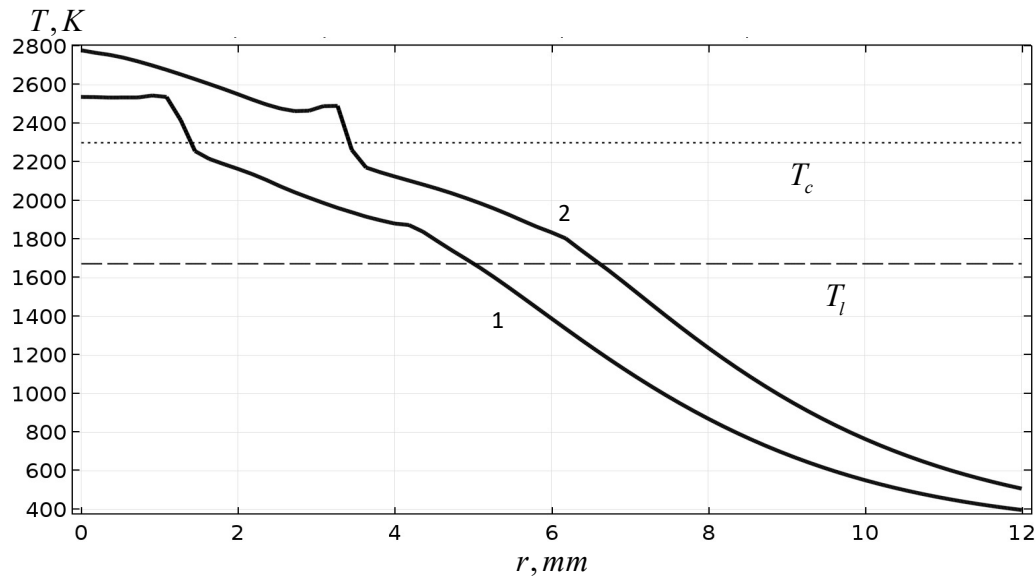
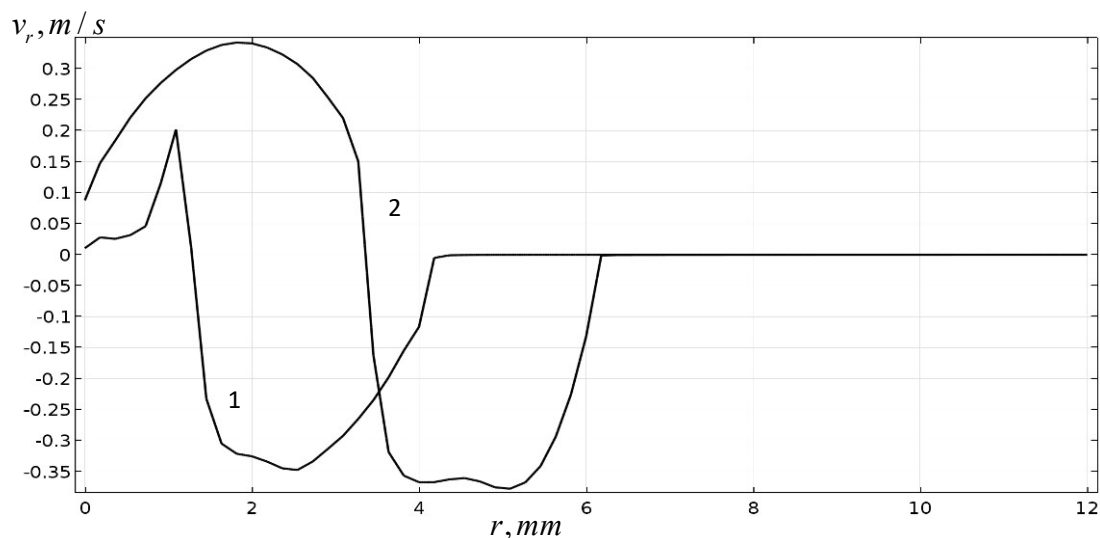Figure 6. Dependence of surface temperature on the distance from the center. 1 – time interval t=2.7s, 2 - t=4s

Figure 7. Dependence of radial speed on the surface of the pool upon the distance from the center: 1 – t=2.7s, 2 – t=4s

Modeling of the processes of convective flows of plasma jets [10] allowed formulating the basic requirements to the thermal cycle of surfacing for obtaining a layer surfaced with flux-cored electrodes with the smaller content of alloying elements and basic performance characteristics (hardness, thermal endurance, wear resistance) with high enough strength and viscosity.

Thus, to obtain high performance characteristics of the surfaced layer and reduce the costs on the base of modeling we can formulate the basic requirements to the thermal cycle of surfacing for efficient use of alloying elements. To do this it is necessary to develop the methods allowing

combining the surfacing and the hardening. To improve the cold cracking resistance of the surfaced parts at the first stage of the thermal cycle it is necessary to prevent the overheating in the heat-affected zone [11] and formation of coarse columnar structure in the surfaced metal. This is used when welding heat-treated steels by regulating the parameters of the welding thermal cycle through reduction of the heating time and increase of the cooling rate within the temperature range of the least stability of austenite.

The specific feature of the suggested thermal cycle is in three stages of thermal heating. The first ensures the limited time of heating and the increased cooling rate in the high-temperature region, thus, preventing growth of grain and austenite transformation with formation of equilibrium low-strength structures. The first stage of the thermal cycle is achieved by application of highly concentrated heating sources and accompanying cooling of the surfaced part. The second stage of the thermal cycle ensures that the surfaced metal remains in the austenite state when adding all layers in the process of surfacing. It is achieved by application of preheating by 50-100 C over the temperature of abnormal plasticity. Cooling of the surfaced part at the third stage of the thermal cycle after the surfacing is over induces phase transformations in the chrome-tungsten surfaced metal accompanied by development of abnormal plasticity.
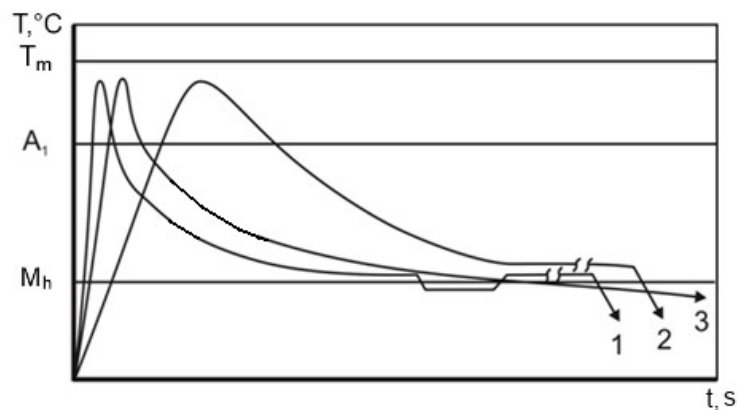

Figure 8. The welding thermal cycles: 1 – under the multiple-bead deposit of hardening steels; 2 – under surfacing thermostrengthened steels; 3 – under electron-beam surfacing
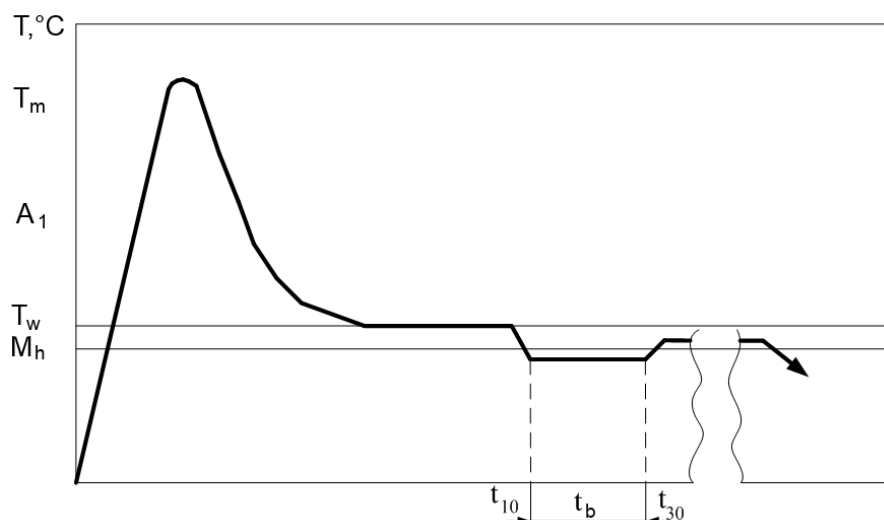

Figure 9. The diagram of the thermal cycle under plasma surfacing

Under these conditions the internal temporary stresses in the surfaced item are partly relaxed which allows obtaining the surfaced metal with the required mechanical properties under lower concentration of alloying elements in the surfacing materials with low levels of residual stresses and, thus, with low ability to cold cracking.

Conclusion

1. Modeling of convective flows and determining the bulk forces acting on the liquid as well as calculation of electromagnetic fields allowed formulating the optimal conditions for transferring the alloying elements of the flux-cored wire onto the faced surface depending on its structure-phase state.

2. The thermal cycles of surfacing for imparting the required properties to the formed surface were determined. The specific features of the given cycles are the increased metal cooling rates in the region of minimal stability of austenite and keeping the austenite condition of metal until the crystallization process is over.

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