Features of the formation of an electric field in a non-uniform conducting medium

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Abstract. The paper considers the influence of the electric field of the current on the behaviour of a gas bubble in an electrically conductive melt. We propose a model which makes it possible to predict a change in the size of gas bubbles in a metal, provided that its crystallization occurs in the presence of an electric current. The model takes into account the interaction of the charge induced on the surface of the gas bubble — metal-gas interface — with the electric field of the current. The force that deforms the gas bubble is introduced. The magnitude of the force is determined by the charges induced on the surface of the bubble due to the action of the electric field of the current. The surface density of the charges is proportional to the square of the current density and depends on the geometry of the object that is affected, as well as on the material parameters of the medium, such as electrical resistivity and magnetic permeability. Additional forces of electrical nature acting on the surface of the gas bubble contribute to its deformation in the electric field of the current. In the presence of such forces, the interfaces between the media — liquid metal and gaseous — can be deformed. Under the conditions of an orderly motion of free electrons and their collisions with ions of the crystal lattice, the size of the interfaces between the media can be changed. The gas bubble under the action of additional forces is deformed and can subsequently be fragmented.

1. Introduction

At present, the effect of electric current on the treatment processes of metals and alloys in the solid and liquid states is being actively studied. The impact of electric current leads to increased mechanical properties of the material due to the influence of the electric field on its microstructure, which could result from the physicochemical phenomena occurring at the interface under the influence of the electric field of the current.

Experimental studies of the effect of electric current on the physical properties of metals were conducted as early as the 19th century. In 1844, the German scientist G. Wertheim \cite{1} carried out the first experimental studies of the non-thermal effect of electric current on the physical properties of metals. Wertheim proved the fact of non-thermal effect of electric current on the deformation of samples by measuring the elongation of copper wire samples. In some experiments, the samples were heated, while in others a direct electric current was passed through them. According to the results of the sample elongation measurements, the modulus of elasticity of the tested material was indirectly determined. Also, the difference in the values of the modulus of elasticity of the same material during its deformation under the action of current and without passing current was revealed. The presence of the difference in values of the modulus of elasticity of the material served as the evidence of the non-thermal effect of electric current on the magnitude of the modulus of elasticity of the metal. These studies made it possible...
to indirectly reveal a relation between mechanical and electrical properties of metals and proved the non-thermal effect of current.

About 100 years later, scientists were able to practically apply electrical effects in the process of plastic deformation of electrically conductive materials. A method was developed and applied in practice, in which electric current was used in the process of plastic deformation of materials. Electroplastic deformation by electric current is important for processing hard-to-deform materials in order to improve their properties, such as strength, hardness, plasticity [2-7]. The effect of reducing the deforming force during transmission of electric current in the deformed zone was called the electroplastic effect. The effect was directly manifested in the form of characteristic drops (reliefs) of the deforming force. Deformation jumps were associated with the accumulation of a sufficient number of dislocations, the movement of which can be detected by a jump of a deforming force and indicates a non-thermal and an anisotropic effect of electric current. The presence of impurities and their concentration growth led to the increased jump of the additional mechanical stress under the action of current. This is due to the loss of stability of a larger number of dislocations under the action of current, that is, upon doping crystals, the uniformity of shear formation and the decrease in the effective size of the regions of incomplete shear are increased. Thus, the transformation of the structure during electroplastic deformation is caused by the electric current. In [6], the influence of current on the parameters of the recrystallization process, namely on the recrystallization temperature, as well as on the results of the recrystallization process — grain size and hardness — was established. In [7], the method of dynamic texturing of metals and alloys due to transmission of electric current was analyzed under conditions of intense cooling of the samples.

The studies illustrated the advantages of applying electromagnetic fields, as well as electric current in various technologies for treatment and production of metals, alloys, and composite materials — for example, when electrically conductive materials are subjected to electroplastic treatment [3], and alloys are modified and crystallized [8-14]. Electric current affects the intensity of mass transfer, gas content of metals, solubility of impurity components. Therefore, the castings crystallized when passing electric current through them, have better mechanical and performance characteristics compared to the castings crystallized without passing current.

For the aluminum alloyed castings crystallized by passing an electric current, a decrease in micro- and gas porosity was revealed [14, 15]. In [14], it was shown that during the crystallization of the aluminum alloy AK12M2MGN under the action of electric current of 82 A, the pore size on average reduced by 42%. The reduced alloy porosity during crystallization under the action of electric current can be associated with the activation of filtration processes in the two-phase zone, with the creation of directional diffusion flows of ions in the alloy, which leads to the movement of inclusions by activating the pore dissolution process [14]. The mechanism of the electric current effect on the structure and properties of alloys, however, is not entirely clear and open to study.

2. Experiments and results

A model to predict the change in the size of gas bubbles in the alloy, provided that its crystallization occurred in the presence of electric current, is proposed below.

Consider the effect of an electric field of a current on the behavior of a gas bubble in a liquid conductive metal or alloy. The density of the current passed through the sample is \( j \).

In an electrically conductive environment, the electric field allows us to create an electric current determined by Ohm’s law \( j = \sigma E \), where \( \sigma \) is an electrical conductivity of the sample material. The electric field affects different inclusions (impurities), gas bubbles which can change their location and size in the electric field \( E \). In the case of a direct electric current, the interaction of electrons accelerated by the electric field with an ion core is the cause of movement, deformation and changes in the size of the gas bubble [16, 17]. The impurities determine the need to introduce a current that takes into account the movement of electrons, ions of the main lattice and impurities.
Furthermore, the charge induced on the surface of the gas bubble — metal-gas interface — interacts with the electric field of the current. In this case, the Coulomb force may be the force that stretches the gas bubble. This force acts on the charges induced on the surface of the bubble from the electric field of the current. Per unit of area:

\[ f_c = \frac{dF}{dS} = \sigma_{\text{ind}} E \]  

(1)

There is a presumption based on the Gauss theorem that the surface density of the bound charge induced by the field on the right surface of the gas bubble (Fig. 1) is determined by the expression:

\[ \sigma'_R = \varepsilon_0 (\varepsilon - 1) E \sin \varphi \sin \theta \]  

(2)

Here \( \varphi, \theta \) are the polar and azimuthal angles of the spherical coordinate system.

The surface density of the charge induced on the left surface of the gas bubble (Fig. 1) is determined by the following expression:

\[ \sigma'_L = - \varepsilon_0 (\varepsilon - 1) E \sin \varphi \sin \theta \]  

(3)

The maximum value of the surface density of the induced charge is

\[ \sigma_{\text{max}}' = \varepsilon_0 (\varepsilon - 1) E \]  

(4)

The maximum density of the force acting on an element of a spherical surface is determined by the expression:

\[ f_{\text{max}} = \sigma_{\text{max}}' \cdot E = \varepsilon_0 (\varepsilon - 1) E^2 \]  

(5)

The force acting on the right surface of the bubble is

\[ f_R = \sigma_R' \cdot E = \varepsilon_0 (\varepsilon - 1) E^2 \sin \varphi \sin \theta, \]  

(6)

where \( 0 < \varphi < \pi \) and \( 0 < \theta < \pi/2 \).

The force acting on the left surface of the bubble:

\[ f_L = \sigma_L' \cdot E = - \varepsilon_0 (\varepsilon - 1) E^2 \sin \varphi \sin \theta, \]  

(7)

where \( - \pi < \varphi < 0 \) and \( -\pi/2 < \theta < 0 \).

Under the flow of direct current through the sample, it is also possible to take into account the effect of the Lorentz force on the components of the liquid and gas phases, as well as alloying elements and impurities.

Lorentz field strength is

\[ \vec{E}_L = [\vec{v}, \vec{B}] \]  

(8)

Here \( \vec{v} \) is the electron drift velocity, \( \vec{B} \) is the magnetic field induction, \( \vec{B} = \mu \mu_0 \) H.

The density of the electric current in the sample is

\[ \vec{j} = en\vec{v} \]  

(9)

Given the relationship between the electron drift velocity \( \nu \) and the electric current density \( j \), the electric field strength due to the Lorentz force is written in the following expression:

\[ \vec{E}_L = [\vec{v}, \vec{B}] = [\vec{j}, \vec{B}] / en \]  

(10)
In contrast to the Coulomb field $E$, which is axial, the electric field due to the action of the magnetic force of the Lorentz $E_L$ is radial.

The magnetic field strength of a straight conductor with a current is determined by using the Stokes theorem for a magnetic field:

$$\oint (\mathbf{H}, d\mathbf{l}) = I$$  \hspace{1cm} (11)

Inside the conductor, $0 < r < R$, the tangential component of the magnetic field strength is $H = j r / 2$, and the magnetic induction is $B = (\mu \mu_0 j r) / 2$.

The modulus of the Lorentz electric field is determined by the expression:

$$E_L = \left( \left( \mu \mu_0 j r \right) / (2en) \right)$$  \hspace{1cm} (12)

The resulting electric field in the conductor consists of the Coulomb field $E$ and the field $E_L$ due to the action of the magnetic Lorentz force:

$$\vec{E}_r = \vec{E} + \vec{E}_L$$  \hspace{1cm} (13)

In isotropic conducting media, the resulting electric field in a conductor with current is defined as:

$$E_r = 2 \cdot E_E \cdot \cos 45^\circ = \sqrt{2} E_E \cdot$$  \hspace{1cm} (14)

where $E_E = \sqrt{E^2 + E_L^2} = \left[ (\rho j)^2 + \left( \frac{\mu \mu_0 j}{en} r \right)^2 \right]^{1/2}$.

Then the maximum surface density of the electric charge is $\sigma_{\text{max}} = \sqrt{2} \varepsilon \varepsilon_0 E_E$.

The maximum density of the force acting on the element of a spherical surface:

$$f_{\text{max}} = \sigma_{\text{max}} \cdot E = \varepsilon \varepsilon_0 \cdot \sqrt{2} \cdot E_E \cdot E$$  \hspace{1cm} (16)

Taking into account Ohm’s law and the expression (14), the dependence of the maximum force density on the current density in the sample is obtained:

$$f_{\text{max}} = \sqrt{2} \varepsilon \varepsilon_0 \cdot \rho j^2 \cdot \sqrt{\rho^2 + \left( \frac{\mu \mu_0}{en} r \right)^2}.$$

3. Discussion

The emergence of additional forces acting on the surface of the gas bubble contributes to its deformation in the electric field of the current.

Figure 1 schematically shows a gas bubble with a distributed electric charge and a change in its configuration due to the action of forces from the electric field of the current.
In the presence of such forces determined by expressions (6), (7), (17) the interfaces between the media — liquid metal and gaseous — can be deformed. Under the conditions of an orderly motion of free electrons and their collisions with ions of the crystal lattice, the size of the interfaces between the media can be changed. The bubble is deformed and fragmented. In the future, it can go beyond the melt boundary, or it can participate in chemical reactions (oxygen and other gases chemically react with the components of the liquid medium).

The maximum of the force density (17) acting on a gas bubble is proportional to the square of the current density and depends on the geometry of the object of action and on the material parameters of the medium, such as electrical resistivity and magnetic permeability. In the case of additional thermal effects, especially in the phase transition conditions, the impact of the material parameters of the medium will not be unambiguous.

The distribution of the induced charge on the surface of the gas bubble is shown in Figure 2. Thus, the gas bubble is an electric dipole, which is influenced by a force from the Coulomb electric field $E$ and the electric field due to the Lorentz force $E_L$. Therefore, the bubble can deform and move under the influence of these effects.
The maximum value of the electric field due to the Lorentz force $E_L$ (12) is reached on the surface of the conductor, $E_L \sim r$. At the same time, as the analysis of the microstructure of the material shows, the gas porosity of samples subjected to electric current in the peripheral region decreases significantly. To control the process of gas porosity formation and increase the density of the sample material structure, it is possible to recommend the use of an external magnetic field. For example, the usage of an external axially symmetric magnetic field under the conditions of passing an electric current through a liquid metal makes it possible to create the Ampere compressive force [18, 19]. The usage of alternating and high-frequency electric current in the indicated conditions will increase the effectiveness of the force action on the peripheral region. By choosing the material of the sample and adjusting the frequency of the current, it is possible to control the effective depth of the force action. The influence of the magnetic field on the creation of the deforming force in the volume of the conductor made of magnetic material will be more effective.

The above ratios are estimates. This is due to the complication of regularities for direct current in liquid metals, especially under the conditions of the phase transition of the material. It is also necessary to take into consideration [20] that during polarization in electrolytes the surfaces of solids with electronic conductivity including metals, surface tension and hardness at the interface change depending on the potential jump. Moreover, in accordance with the classical electrocapillary curve, a characteristic maximum for an uncharged surface and a decrease in the values of hardness and surface tension are observed, regardless of the sign of the charge.

4. Conclusion

Electric current is a source of electrical, magnetic, mechanical and thermal energy. Therefore, the usage of this type of influence during the crystallization of metals and alloys will directly affect the formation process of the crystal structure and control the formation of the alloy properties. The presented physical model makes it possible to qualitatively explain the change in the size of gas bubbles in the alloy when crystallized under the action of electric current. This was supported by experimental results. Experimental studies show that passing the current through the melt during its crystallization leads, in particular, to a decrease in the content of gas pores in the sample material [8, 14]. The above ratios for the force stretching the gas inclusion are merely estimates. This is due to the complication of regularities for direct current in liquid metals, especially under conditions of a phase transition. For example, during polarization of electrolytes of the surfaces of solids with electronic conductivity, including metals, surface tension and hardness at the interface are changed depending on the potential jump. In this case, in accordance with the classical electrocapillary curve, there is a characteristic maximum for an uncharged surface and a decrease in the values of hardness and surface tension, regardless of the sign of the charge. Findings of research, especially consideration of electrostatic pressure in the gas bubbles of the melt, can be useful for correcting the criterion of microporosity formation [15]. This criterion takes into account a number of significant technological factors, including atmospheric and metalostatic pressure, gas saturation of alloy, and is recommended to be used to more accurately predict the formation of microporosity.

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