MECHANISM OF INFLUENCE OF NANOSECOND ELECTROMAGNETIC PULSES ON CRYSTALLIZATION BEHAVIOR OF ALUMINUM ALLOYS

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Abstract

It is shown from the point of view of the quasicrystalline model of metallic melts that during the liquid phase treatment by nanosecond electromagnetic pulses it may be possible the occurrence of energy fluctuations in the melt, change of short-range order structure in the atoms arrangement, reducing the cluster size and shortening their lifespan, decreasing the disordering temperature. These processes change the physical properties of the melt, crystallization parameters, physical-mechanical and operational properties of the obtained alloys. It is theoretically justified that irradiation of the melt with nanosecond electromagnetic pulses, by reducing the surface energy of an interphase boundary "crystal-melt" and contributing to increase in degree of the melt undercooling, increases the formation rate of nucleation centers in a unit volume of the melt and provides the refinement of microstructure of resulting castings. In addition, increasing the wettability of solid particles by the melt and reducing the surface tension at the interphase boundaries leads to substantial dispersion of nonmetallic inclusions and intermetallic phases, which causes the formation of additional crystallization centers. It is assumed that when the nanosecond electromagnetic pulses are applied to the liquid phase, the bond energy curve shifts toward a lower value of the interatomic distance, while the absolute value of the bond energy decreases. For this reason, the melt irradiation provides the possibility of an energetically and kinetically easier moving of atoms from one stable state to another, which accelerates diffusion processes and deactivates clusters.

Keywords: Electromagnetic pulses, aluminum alloys, crystallization, bond energy, quasicrystalline model

1. INTRODUCTION

Properties of alloys in the liquid and solid states can depend substantially on physical effects on melts during melting, casting, and crystallization [1]. The following effective methods of physical melt treatment are known: thermal-temporal and thermal-rate treatment, mechanical vibration, ultrasonic processing, electromagnetic effects, nanosecond electromagnetic pulses, etc. [2-8]. The energy interaction of short-pulse electromagnetic fields with an intensity of 10^5 ... 10^7 V/m with a metallic liquid helps to destroy its structure, increase the solubility of modifying and alloying elements and the uniformity of their distribution. The specificity of nanosecond electromagnetic pulses (NEPs) consists in the formation of local high-intensity fields that are characterized by the absence of oscillating motions and the directional action of magnetic forces that can purposefully influence on the nanostructure and properties of materials [9].

Metal alloys are very complex systems in the structural relation, in which elements of ordering of various scales can clearly appear in the absence of “long-range order”. Consequently, there is a microinhomogeneous structure, and in many cases also a microheterogeneous structure of metallic melts. Some types of the microinhomogeneity and microheterogeneity of liquid alloys are considered in the paper [10], and the source [11] reveals the essence of a new type of phase transitions - structural transitions in liquid metals.

For the theoretical explanation of the structural change of the liquid phase, the crystallization parameters, and the properties of metallic melts under the action of powerful nanosecond electromagnetic pulses, the present paper considers possible mechanisms of the NEPs effect on the above parameters from the standpoint of modern concepts of the liquid state model and interaction of substances with a pulsed electromagnetic field.

2. EFFECT OF NEPS ON THE MELT OF QUASICRYSTALLINE MODEL

The quasicrystalline model (theory of clusters, sibotaxises, etc.) considers a metal melt as a combination of two structural components: clusters (microvolumes with an ordered arrangement of particles similar to a crystalline structure of short-range order) and an unstructured "disordered" zone with a chaotic arrangement of particles, as a rule, more “loose”.

Clusters and an unstructured zone are thermodynamically unstable and, as a result of energy fluctuations, they continuously and locally transit into each other. The ratio of the volumes occupied by the clusters and the disordered zone is determined by the temperature of the melt and the duration of irradiation of the NEPs melt. The lifetime of clusters is large in comparison with the duration of the cycle of atomic vibrations in liquid metals (about 10^{-14} - 10^{-13} s), and their dimensions are several orders of magnitude greater than the dimensions of the atoms.

Under the influence of NEPs, the occurrence of energy fluctuations in the melt, the change in the structure of short-range order in the arrangement of atoms, the decrease in the size of clusters, the shortening of their lifetime, and the decrease in the temperature of disordering are possible. A decrease in the temperature of the melt disorder leads to a change in the degree of compaction and the coefficient of thermal compression of the melt during cooling, the physical properties of the melt, the crystallization parameters, and ultimately the physico-mechanical and operational properties of the resulting alloys.

In accordance with the quasicrystalline model, any physical property C of the metallic melt is the additive sum of the partial contributions of the melt constituents:

$$C = A_{un} C_{un} + A_{cl} C_{cl}, \qquad (1)$$

where A_{un} and A_{cl} are the ratio of the unstructured zone fraction and the cluster zone fraction, respectively; C_{un} and C_{cl} are the partial properties of an unstructured zone and clusters. A decrease in the fraction of clusters leads to a change in properties: a decrease in viscosity and surface tension, an increase in the solubility and uniformity of the distribution of alloying elements in the liquid phase.

Under the influence of NEPs, a decrease in the surface tension σ at the “melt-crystal” interface causes a decrease in the values of the critical size r_c of the crystallization centers of metals and alloys:

$$r_c = (2\,\sigma\, M\, T_S\,)/(\rho\, L\, \Delta T) \qquad (2)$$

where M is the molecular weight; T_S is the melting point; ρ is the density; L is the latent heat of fusion; ΔT is the degree of supercooling of the crystallizing melt.

The processing of melts by the NEPs changes their energy state, decreasing σ at the interfacial boundaries “crystal-melt” and “nonmetallic inclusions-crystal”. All this contributes to the formation of additional centers of crystallization and grain refinement. In the case of the crystallization of metal on the surface of nonmetallic inclusions, the melt processing by the NEPs facilitates to the removal of large particles during the melt irradiation and the dispersion of the remaining "floating" particles, which increases the surface energy. To reduce the surface energy, spontaneous "clinging" of clusters on these inclusions up to the critical size of the crystallization centers is possible. In this case, the crystallographic matching of the crystallizing phase with nonmetallic inclusions is not required.

According to the theory of fluctuations, the rate of nucleation is largely determined by the surface energy. Irradiation of the melt by NEPs, reducing the surface energy of the “crystal-melt” interface, increases the formation rate of nucleation centers in the melt unit volume and ensures the dispersion of the resulting castings microstructure. The formation rate of the crystallization centers V is determined by the formula:

$V = K\, e^{-B\, \sigma^3/T \cdot \Delta T^2}$, (3)

where K is the kinetic constant of crystallization; B is a constant, depending on the alloy nature; T is the temperature at which crystallization proceeds; ΔT is the degree of supercooling.

After taking the logarithm of equation (3), we obtain

$\ln V = \ln K - (B\, \sigma^3/T)/\Delta T^2$ (4)

Melt processing by NEPs can lead to an increase in the melt supercooling ΔT and, by decreasing the surface energy of the “crystal-melt” interface, increases the kinetic crystallization constant and, as equation (4) shows, causes acceleration of the formation of crystallization nuclei.

Increasing the wettability of the solid particles by the melt and reducing the surface tension at the phase interface leads to a substantial dispersion of the inclusions and causes the formation of additional crystallization centers that can significantly refine the microstructure of aluminum and its alloys.

3. MECHANISMS OF NEPS INFLUENCE ON SOLUBILITY OF ALLOYING ELEMENTS AND SECONDARY PHASES IN ALUMINUM ALLOYS

In the field of NEPs the currents are induced. The motion of electric charges seems to be quite powerful due to the small electrical resistivity of the metals and alloys, and the "transfer" of highly concentrated electropulse energy to them. There is a Lorentz force acting on the moving charge in the electric and magnetic fields:

$F = q\, E + q\, [V \cdot B]$, (5)

where V is the velocity of charge motion, *E* is the electric field intensity; q is the charge magnitude; *B* is the magnetic induction.

The action of the force *F* leads to the fact that the charges are "pressed down" to the outer surface. The Lorentz force creates a pressure difference, thereby, involving the fluid into the movement from the periphery to the center and vice versa.

Thus, the NEPs effect causes an intensification of mass transfer and blocks the growth of dendritic branches. In this case, after some supercooling, bulk crystallization is more likely, excluding the formation of a columnar crystal zone and determining a uniform fine-grained structure in the castings. Irradiation of molten metals by the NEPs provides an opportunity for an easier movement of atoms from one stable state to another, and accelerates the diffusion and dissolution of alloying elements. The increase in the solubility of alloying elements in the aluminum melt under the NEPs influence on them is explained by the effect of electrotransfer, which occurs in the entire volume of the melt in the electroimpulse field.

Diffusing ions are a directed “electron wind” from the macroelement dissolved. The concentration of ions around the still undissolved macroparticle of the alloying element decreases, intensification of the withdrawal of the interaction products and the acceleration of the diffusion stage occurs, which is the limiting stage in the process of dissolution of the alloying elements and secondary phases. As a result, the solubility of the alloying elements is increased and their uniform distribution in the base alloy is ensured.

The effect of NEPs on the melts causes the formation of local impulsive electromagnetic fields with high intensity, partially destroying the clusters in the melt and thereby substantially increasing its fluidity. Due to the energy interaction of these short-pulse electromagnetic fields of 10^5 ... 10^7 V/m with melt particles, a deep restructuring of the considered microheterogeneous systems takes place. Dispersion of the particles is observed, their size becomes so small that it abnormally reduces the forces of internal friction of the substance. As a result, the viscosity of the melt under the NEPs effect is substantially reduced, and the fluidity increases. At the same time, the decrease in the fluidity of an alloy under the influence of NEPs is possible, if the solubility in the α-solid solution of the second component in the binary system increases, shifting the alloy composition to the more hypereutectic.

4. CHANGE OF BOND ENERGY UNDER THE NEPS EFFECT

The type of binding that occurs between elementary particles in the liquid state is determined by the electronic structure of the interacting atoms. Elementary particles in a liquid, like their behavior in a crystal, approach to a certain distance, which provides the greatest thermodynamic stability of the "quasi-lattice". The distance to which the particles approach is determined by the interaction of forces acting in the short-range order structure.

The attraction force arises from the interaction of electrons with the positively charged nucleus of an atom of its own, as well as the positively charged nuclei of neighboring atoms. The repulsion force arises as a result of the interaction of positively charged nuclei of neighboring atoms as they approach each other. The repulsive force manifests itself at a strong convergence and increases more intensively than the attraction forces (**Figure 1**).

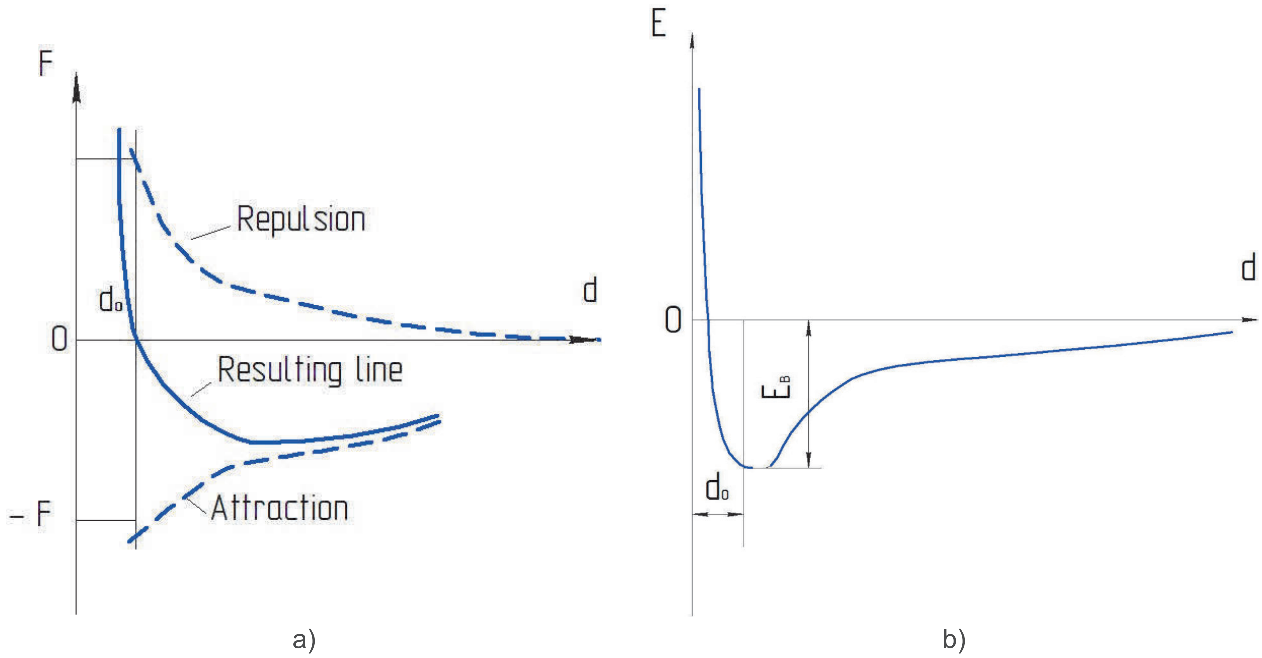

Figure 1 The change in the interaction force (a) and the bond energy (b) during the interaction of atoms in a liquid alloy

The forces equilibration occurs when the elementary particles approach each other by a distance d_0. This approach is facilitated by a minimum of the bond energy E_b, which makes the structure of short-range order thermodynamically stable. It determines the melting point, the temperature coefficient of linear expansion, and other properties. A decrease in the parameter of the crystal lattice and an increase in the amplitude of the vibration of atoms from the equilibrium position in aluminum melt upon irradiation by the NEPs during 10-15 min allows us to make the following assumption (**Figure 2**).

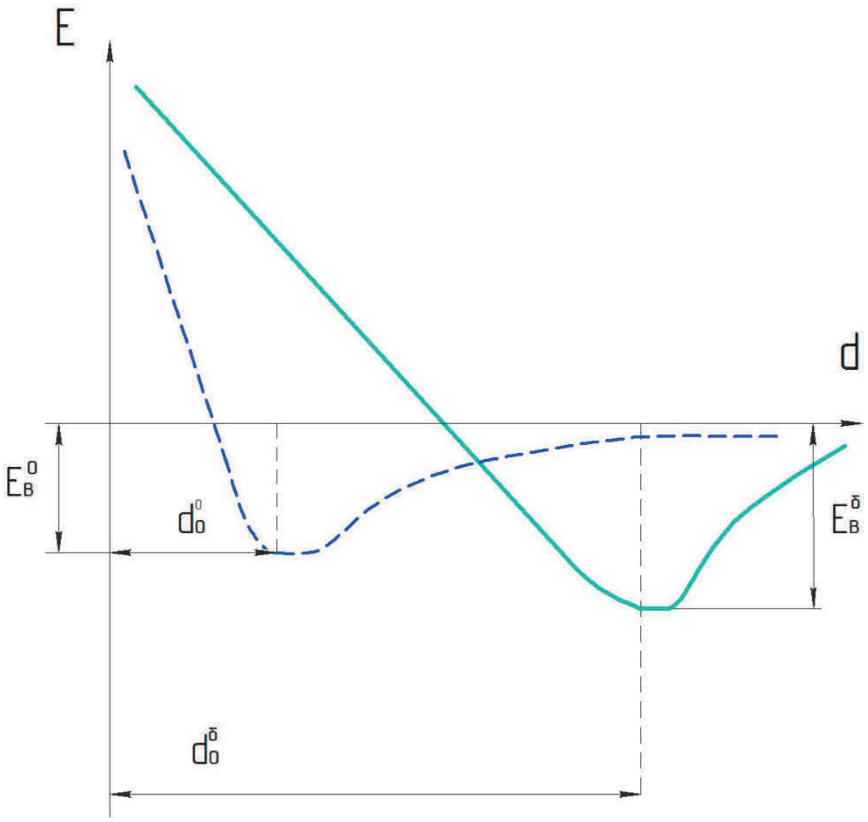

Figure 2 The change in the bond energy at the approach of atoms in liquid metals under the influence of NEPs: d^δ_0 and d^0_0 are interatomic distances in unirradiated and irradiated liquid metals, respectively; E^δ_b and E^0_b - bond energies in unirradiated and irradiated liquid metals, respectively

Under the influence of the NEPs on liquid phase, the bond energy curve shifts toward a smaller value of d_0. In this case, the absolute value of the bond energy E^o_b decreases. For this reason, the melt irradiation by the NEPs provides the possibility of an energetically and kinetically easier moving of atoms from one stable state to another, accelerates diffusion processes, and deactivates clusters.

5. CONCLUSION

The theoretical explanation of structural change of a liquid phase, crystallization parameters and properties of metal melts at influence of powerful nanosecond electromagnetic impulses is presented. The possible mechanisms of NEPs influence on various melt parameters from the position of modern representations about the model of liquid state of the substance and its interaction with the pulse electromagnetic field are considered.

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