PRODUCTION OF COMPOSITE ALLOY WITH AN IMMISCIBILITY GAP IN AN ALTERNATING ELECTROMAGNETIC FIELD

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The process of production of composite copper and cast iron alloy with an immiscibility gap in the alternating electromagnetic field has been investigated. The action of the electromagnetic field under experimental conditions on the liquid alloy station is characterised by the number of homochronous $\mathrm{Ho}_{\mathrm{AEMF}}$. It has been established that at $\mathrm{Ho}_{\mathrm{AEMF}} < 820$ the melt was a binary liquid, at $\mathrm{Ho}_{\mathrm{AEMF}} > 1100$ the melt was an emulsion with uniformly distributed drops based on cast iron. Electrodes of contact welding made of composite alloy processed by alternating electromagnetic field had essentially raised resource of their exploitation.

Introduction. Imposing the electromagnetic field on the melt allows controlling the melt motion, heat and mass transfer process, structures, properties and the form of casts. For liquid metals and alloys high heat conductivity, electrical conductivity and low magnetic permeability are typical. Alternating electromagnetic fields (AEMF) used in the induction crucible furnaces (ICF), in monotectic system alloys components melting provide generation of Joule heat in the metal of the order of 300–600 W/kg at frequencies 50–2400 Hz. This allows melting all types of monotectic system alloys up to high-melting ones in the ICF.

1. Analysis of electromagnetic action on alloy phases in smelting in the ICF. In alloy smelting process the electromagnetic field passes to the metal volume power P (W/m^3)

$$P = (E \cdot H)/2 = P_{\mathrm{h}} + P_{\mathrm{s}}\,,$$

where E is the intensity of an electrical field arising in the melt, V/m; H is the intensity of a magnetic field, A/m; P_{h} is the volume heat power, W/m^3; P_{s} is the volume power of stirring, W/m^3.

At frequencies 50–2400 Hz almost all power ($> 95\%$) is generated as heat heating of metal

$$P_{\mathrm{h}} = (I_m^2/2S_m^2)\rho_{\Sigma}^{\mathrm{e}}\,,$$

where I_{m} is the amplitude value othe electrical current generated in the metal, A; S_{m} is the area of the melt volume section, which is perpendicular to the current, m^2; $\rho_{\Sigma}^{\mathrm{e}}$ is the specific electrical resistance of a stock or melt, Ω·m. In the ICF crucible in the circulation in the liquid phases of a monotectic system alloy induces a different stirring power

$$P_{\mathrm{s}i} = F_i^{\mathrm{e}} \cdot \upsilon_i\,, \quad F_i^{\mathrm{e}} = \frac{I_{\mathrm{m}i}}{\sqrt{2}}\mu_i\mu_0 H = \frac{I_{\mathrm{m}i}B^{\mathrm{e}}}{\sqrt{2}},$$

$$\frac{\partial \upsilon_i}{\partial \tau} = \frac{F_i^{\mathrm{e}}}{\rho_i} = \frac{I_{\mathrm{m}i}B^{\mathrm{e}}}{\sqrt{2}\rho_i} = \frac{EB^{\mathrm{e}}}{\rho_i\rho_i^{\mathrm{e}}}, \quad \frac{\Delta\upsilon_1}{\Delta\upsilon_2} = \frac{EB^{\mathrm{e}}\Delta\tau}{EB^{\mathrm{e}}\Delta\tau}\cdot\frac{\rho_2}{\rho_1}\cdot\frac{\rho_2^{\mathrm{e}}}{\rho_1^{\mathrm{e}}} = \frac{K^{\mathrm{e}}}{K},$$

where $i = 1, 2$ are indices of melt phases; F^{e} is the volume electromagnetic force, N/m^3; Δ is an increase; υ is the melt phase velocity, m/s; B^{e} is the flux density, T; ρ is the density of liquid phase, kg/m^3; μ is a relative magnetic permeability of melt phase, $\mu_1 \approx \mu_2 \approx 1$; μ_0 is the magnetic permeability of vacuum, H/m; ρ^{e} is the specific electric resistance of the melt liquid phase, Ω·m; $K = \rho_1/\rho_2$ denotes

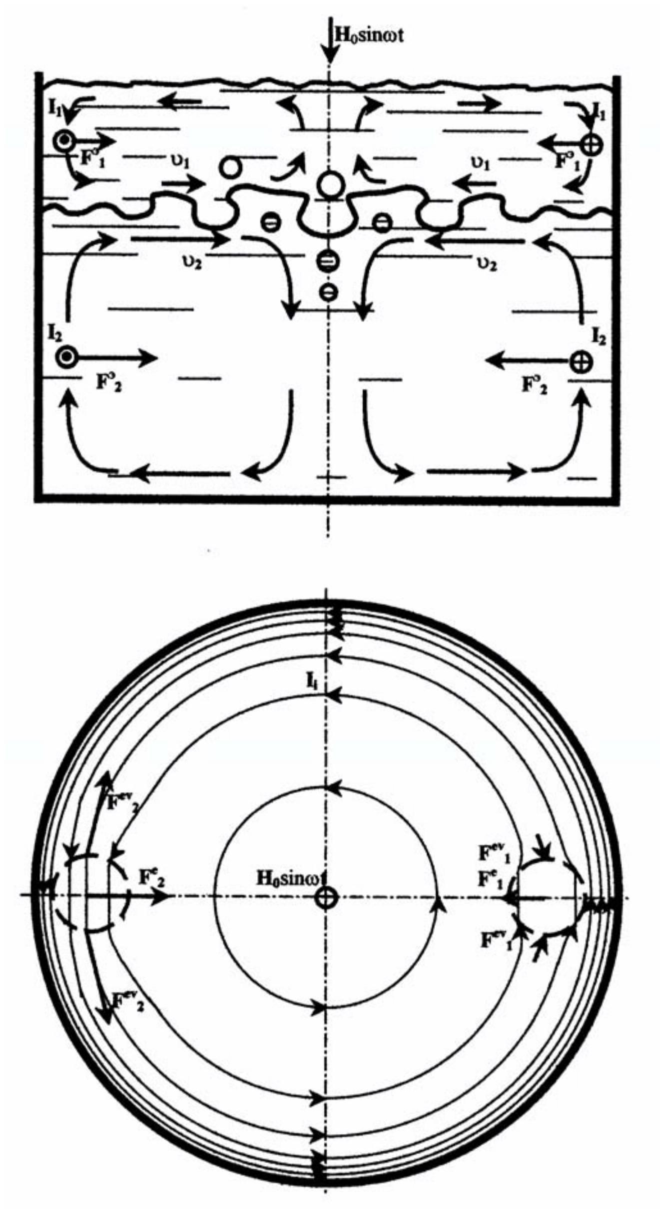

Fig. 1. Differential electromagnetic action on the melt: (*a*) instability development of the interface and emulsifying of liquid metallic phases, (*b*) deformation of separate liquid volumes.

correlation of densities of phases; $K^{\mathrm{e}} = \rho_2^{\mathrm{e}}/\rho_1^{\mathrm{e}}$ denotes correlation of the specific electric resistance of phases.

At the production of emulsified alloy in the ICF, after melting the components, the melt is a two-layer liquid with layers based on the alloy components. In each layer of the two-layer melt under the electromagnetic action the motion of the molten melt takes place. Different in value electromagnetic forces act on the layers owing to their different specific electric resistances. Differential electromagnetic action causes instability development of the interface of the liquid metallic phases in the two-layer melt (Fig. 1*a*: I – electric current). On the stage of solid metallic additions' melting this can intensify the process of their heating by the interface increasing in the "metal – melting addition" system and tearing drops of the melting addition from added metal basic mass and accelerate it passing to the emulsified state. As a consequence of distortion of electric current flow lines in the region of separate volumes and metallic emulsion drop in the melt layer owing to the difference of drop and matrix melt electric resistance, electrovortex flows arise with an interaction between the electric current and its magnetic field. These flows result in a force action on the separate volumes in the melt. As a result, such volumes can deform (see Fig. 1*b*: F_i^{ev} – force causing deformation of a separate liquid volume) and move in the melt. After full destruction of disperse phase layer the melt moves under the regime of one-contour circulation.

2. Conditions of the emulsified melt production in the ICF. The alternating electromagnetic action on the melt metallic phases has been investigated at the production of a monotectic system cast metallic composite alloy based on copper with 6.5%mas. cast iron alloyed by chromium. The given alloy has a hypermonotectic composition. Such alloy is perspective, in particular, for using as a material of electrodes for contact welding. Smeltings conducted in the induction crucible furnace with a graphite crucible, where AEMF, having frequency 2400 Hz, was created. The amplitude value of the field flux density (B_0^{e}) of the alternating electromagnetic field with frequency 2400 Hz when the current in the inductor $I_i = 54 \div 62$A was $(3.0 \div 3.5) \cdot 10^{-2}$T. The alternating electric current density (j_0), induced in the melt by the electromagnetic field was $(6.9 \div 7.9) \cdot 10^6\,\mathrm{A/m^2}$, the intensity of sine electric field induced in the melt was 2.1 V/m.

The alloy fusion temperature was taken 1460°C being close to the binodal temperature in the given alloy composition with the calculation melting temperature of higher melting alloy component (cast iron), which is 1350°C. Follows values of densities and specific electric resistances of the alloy liquid components were taken: cast iron alloyed with chromium – $\rho_2 = 6900$ kg/m^3, $\rho_1^{\mathrm{e}} = 1.3 \cdot 10^{-6}$ Ω·m, copper – $\rho_1 = 7700$ kg/m^3, $\rho_2^{\mathrm{e}} = 3.0 \cdot 10^{-7}$ Ω·m). Values of EMF damping degree were defined in the stock (Δ_{s}), in the melt (Δ_{m}) and in graphite (Δ_{g}). They were: $\Delta_{\mathrm{s}} = \Delta_{\mathrm{m}} = 0.005$m, $\Delta_{\mathrm{g}} = 0.03$m. Stock pieces with sizes (d_{s}) more than 0.01m and the crucible bottom ($d_{\mathrm{c}} = 0.13$m) corresponded to the condition $d_{\mathrm{s}} > 2\Delta_{\mathrm{s}}$, $d_{\mathrm{c}} > 2\Delta_{\mathrm{g}}$ and effectively heated in the alternating electromagnetic field. The crucible walls with the width $b_{\mathrm{c}} = 0.015\mathrm{m} < \Delta_{\mathrm{g}}$ and small pieces of the stock $d_{\mathrm{s}} < \Delta_{\mathrm{s}}$ were "transparent" for the alternating electromagnetic field with the frequency 2400 Hz and heated with the crucible bottom and pieces of metal of larger sizes.

When the stock started melting, the crucible bottom was covered with the melt, which was effectively heated by the electromagnetic field ($d_{\mathrm{m}} = 0.1\mathrm{m} > 2\Delta_{\mathrm{m}}$). The electromagnetic forces created in the melt had a maximum volume density $2.8 \cdot 10^5$ N/m^3 and pulsed with the frequency 4800 Hz. The value of necessary density of the current (j_0) passed through the melt during its heating and the time treatment was related to P_{h} by correlation $j_0 = \sqrt{P_{\mathrm{h}}/\rho_{\Sigma}^{\mathrm{e}}}$. Under these conditions the volume heat power (P_{h}) generated in the melt is equal to melt volume losses of heat (P_{los}) at the given temperature. Specific mass heat power generated in the melt at its heating to 1460°C was 500 W/kg. A uniform distribution of electromagnetic forces was provided about all height owing to the "long" inductor. When the stock was fully melted, liquid copper in the crucible moved under the regime of one-contour circulation under the action of electromagnetic forces. The maximum calculated velocity of circulation (υ_{c}) was $(1.4 \div 1.5) \cdot 10^{-2}$ m/c. This range of velocities entered the interval $\upsilon_{\mathrm{c}} \in \left[1 \cdot 10^{-2} \div 1 \cdot 10^{-1}\right]$ m/s. In this interval, as the disperse inclusion sedimentation (gravitational and centrifugal) as their coarsening by collisions slows down owing to the effect of levitation of drops with small sizes (< 50 μm). In the melt regime of laminar flow $\mathrm{Re} = 1167 \div 1250$ an active convection heat transfer characterized by the number $\mathrm{Pe} = 8.8 \div 9.2$ was provided. The value of relative frequency (ϖ) calculating influence of field change in time on its space distribution was 400. The interaction between volumes of copper and cast iron was according to the scheme shown in Fig. 1 in the number of magnetohydrodynamic interactions $N = 3.5$. At the action of electromagnetic forces on the emulsified melt copper volume an acceleration in the interface direction between copper and cast iron was greater in 4.5 times than for cast iron. When the melt passes to the emulsified state for copper drops in the cast iron melt, $K^{\mathrm{e}} = 0.2 < 1$, and for cast iron drops in the copper melt $K^{\mathrm{e}} = 4.3 > 1$.

Fine disperse melt emulsification is achieved by superheating under the binodal temperature (its exact value is unknown). Melt emulsification is produced by concentration supersaturating of the melt under isothermal conditions and complex action of the AEMF (electro-thermal, electrovortex and electromagnetic). The more melt is closer to the monotectic temperature, the closer are the compositions of liquid phases the equilibrium state, in which the high-melting phase crystallizes. Taken from thermodynamic and technological considerations, minimum superheating of the melt under a monotectic temperature was 115°C. In this case the aim of minimum saturating of the liquid matrix by cast iron components and preservation of its high electric and heat conductivity was haunted. In the ICF crucible, the scheme of gradual saturating of a less high-melting matrix superheated higher than its melting temperature by 376°C by a more high-melting component superheated higher than its melting temperature by 110°C was realized. It has been found that under the temperature and concentration conditions of the experiments (1460°C, copper 93.5%mas. + cast iron 6.5%mas.) $\mathrm{Ho}_{\mathrm{AEMF}}$ is the determining number. The character of the liquid alloy obtained structures depended on this number.

$$\mathrm{Ho}_{\mathrm{AEMF}} = \frac{0,65 \cdot H_{\mathrm{m}} \cdot r \cdot \mu}{\tau \cdot \sqrt{2\rho}},$$

where H_{m} is the maximum intensity of the AEMF within the inductor, A/m; τ is the time of alloy phases interaction process, s; r is the circulating binary flux radius, m.

3. Emulsified melt formation. Analysis of successively obtained samples of the melt from the furnace crucible show that a higher melting volume of cast iron destroyed successively. In the first sample obtained from the upper melt volume later melting stock,the volumes' interface had not essential distortions, the cast iron structure less differed from its initial structure, but in it local zones of copper saturation were already observed. Inclusions based on cast iron having a different composition were identified in colour by etching. Inclusions having an essential quantity of copper were dark and inclusions having an unessential quantity of copper were light. The copper matrix had at the interface ficiently small inclusions of cast iron ($\sim 25\,\mu$m in the initial cast iron structure; $< 15\,\mu$m in a structure of cast iron containing copper). The distribution density of the cast iron inclusions in the copper matrix (q) was not high (Table 1).

The second sample (see Table 1 and Fig. 2*a*) shows that process of cast iron destruction intensified. At the interface sufficiently big formations (about 320μm) feared from the cast iron volume were found. In the copper matrix directly at the interface spherical inclusions are placed: (*a*) cast iron inclusions with an unessential quantity of copper (light inclusions) of sizes 9–150μm; (*b*) cast iron inclusions with

Table 1. Characteristics of the melt state.

Sample No	Time of sampling τ, s	$\mathrm{Ho}_{\mathrm{AEMF}}$	q, mm^{-2}
1	360	201	357
2	720	403	476
3	1380	828	1800
4	1440	864	3200
5	1615	969	3700
6	1860	1116	3800

an essentially larger content of copper of sizes 3–9μm (dark inclusions). In the cast iron volume in the direct proximity from the interface extensive zones appeared with the phase on copper base. Big copper inclusions (length $> 100\,\mu$m) in the cast iron had a flat shape stretched mainly along the horizontal plate. This indicated an essential influence of electrovortex flows on the copper volume having a higher electric conductivity in the liquid cast iron. When the sizes of copper disperse

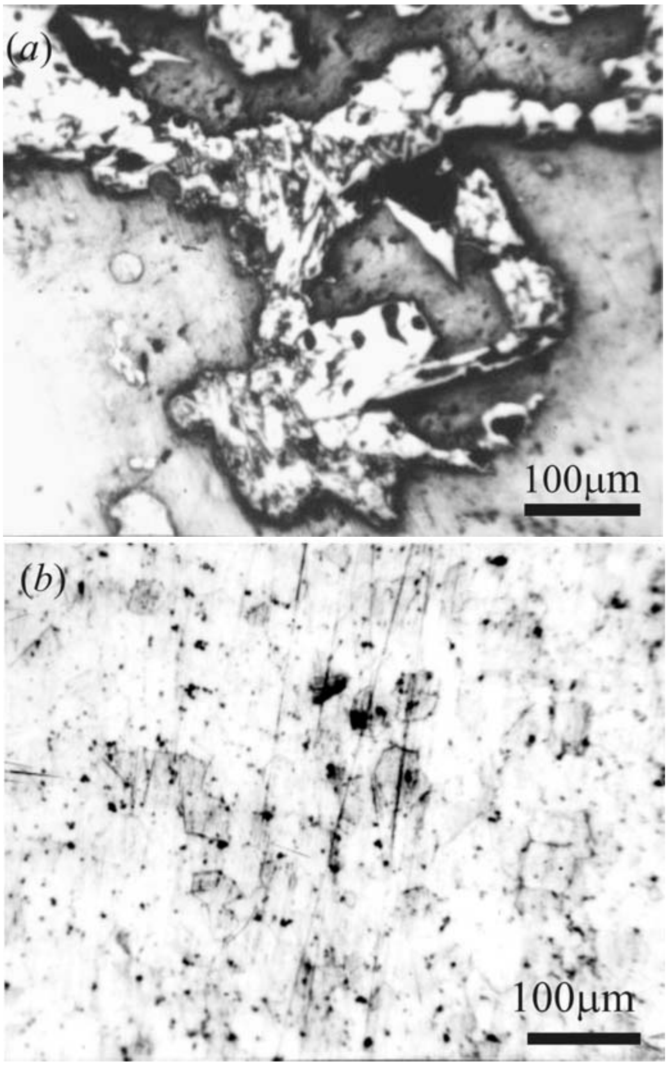

Fig. 2. Micrographs of structures of melt samples: (*a*) $\mathrm{Ho}_{\mathrm{AEMF}} = 403$, (*b*) $\mathrm{Ho}_{\mathrm{AEMF}} = 1116$ (etched).

volumes decreased, the action of forces with electromagnetic nature on the shape deformation reduced. The electrovortex action on separated cast iron volumes in the copper was less expressed than their action on analogous in size copper volumes in the cast iron.

Sample 3 (see Table 1) demonstrates that the liquid alloy already has no cast iron inclusions with initial structure. It was from the copper melt with drops of metallic emulsion and volumes with irregular content of cast iron components in the copper. Many disperse inclusions with sizes < 3–36μm were in the alloy structure. Inclusions were as branching as of spherical shapes. It was defined by etching that the main mass of inclusions based on cast iron had an essential quantity of copper and the rest inclusions had an unessential quantity of copper. In comparison with the preceding samples, the quantity of small spherical dark inclusions (< 3–9μm) increased.

The next samples (4, 5 – see Table 1) exhibit a tendency to the decrease of quantity of branching inclusions and to the increasing share of small spherical dark inclusions (< 3–9μm). In sample 5 only individual branching inclusions based on cast iron were found. The rest inclusions were mostly small (< 3–6μm) and individually bigger (from 15μm) dark spherical formations. Increasing the time for melt processing in the induction crucible furnace resulted in full disappearance of the branching inclusions in the alloy matrix. Only small (< 3–6μm) dark spherical inclusions were observed in the alloy structure of sample 6 (see Table 1 and Fig. 2*b*). It can be confirmed that all the melt achieved the emulsified state at $\mathrm{Ho}_{\mathrm{AEMF}} > 1116$.

4. Conclusion. It has been found out that the melt emulsification goes in two stages. When $\mathrm{Ho}_{\mathrm{AEMF}} \in \left]0 \div 820\right]$, liquid copper-contained cast iron volumes with initial composition, cast iron volumes are saturated with copper and individual drops based on cast iron of hypermonotectic composition (I stage). In this state melt pouring into the casting forms leads to a bimetallic structure of ingots. At the next stage (II stage), when $\mathrm{Ho}_{\mathrm{AEMF}} \in \left]820 \div 1100\right]$ the quantity of inclusions based on cast iron saturated with copper is increased essentially. Liquid copper consists of volumes with a different quantity of soluted components of cast iron. At $\mathrm{Ho}_{\mathrm{AEMF}} > 1100$ a copper matrix achieved the homogeneous state and all volume of the liquid alloy corresponded to a hypermonotectic composition. The melt was an emulsion with uniformly distributed drops based on cast iron. The advantageous size of drops was 3μm in inclusion density distribution $3.8 \cdot 10^9$ m^{-2}. The obtained composite alloy has been used for the production of electrodes for contact welding and allowed to raise essentially their resource of exploitation.