PERIODIC STRUCTURES ON THE SURFACE OF LIQUID METAL ELECTRODES IN CONTACT WITH PLASMA

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The experimental and theoretical investigations, performed at the Institute of Physics of the Academy of Sciences of Ukraine, of short-wavelength periodic structures on the surface of liquid-mental electrodes are briefly reviewed. The impurity mechanism of excitation of structures on the surface of a thin metal melt, the phenomenon of cyclicity of explosive emission, and Rayleigh instability in the melting channel are examined.

The problem under consideration has a direct bearing on the erosion of electrodes in high-current arc discharges, the erosion of the surface of limiters and the first wall of thermonuclear reactors, the phenomenon of cyclicity of explosive emission, and the appearance of defects of seams in deep welding. These questions are examined below.

I. When the surface of a solid (metal, semiconductor, or dielectric) melts under the conditions of ion, plasma, and laser bombardment, short-wavelength periodic structures are observed on the cooled surface [1-4]. Up to now, in order to explain this phenomenon it was assumed that the structures arise at the time the surface layer of the liquid is bombarded and the mechanism of excitation of these structures is determined by different forms of thermocapillary or parametric instability. It was assumed that when the bombardment ceases these structures can become fixed on the cooled surface under corresponding conditions of "freezing," and the process of solidification of the melt in itself has no relation to the excitation of the structures.

New experimental data [5, 6], obtained with ion, electron, and plasma melting of copper and titanium surfaces, have shown that when impurities are present these structures appear as a result of instability of the front of solidification of the melt. We now present these data:

1. During bombardment the melt has a close-to-mirror sheen. The sheen gradually changes from mirrorlike to dull only after bombardment ceases. This fact indicates that structures appear on the surface of the film during the solidification process.

2. Structures were observed only with an appreciable concentration of impurities in the target. In the case of a copper target the structures arose when the impurity concentration exceeded 0.1% (commercial M1 and M2, copper containing impurities of tin, nickel, and other elements). No structure appeared in the case of copper targets of higher purity (impurity content less than 0.01%). The sheen of the melt remained mirror-like even after solidification. No structure appeared on the surface of pure titanium melted by gas ions (He_4^+). Structures appeared under quite prolonged bombardment of the target with a beam of yttrium ions. Structures (with wavelength $\lambda \approx 5\ \mu m$) were fixed well with electron melting of VT6 titanium alloy, containing aluminum and vanadium impurities (up to 5%).

On the basis of these data, experiments were performed with controllable amounts of impurity introduced into the initially "pure" samples [5, 6]. These experiments made it possible to determine the critical concentration of the impurity at which wave structures are fixed on the solidified surface. It was found that the critical impurity concentration increases with increasing heat removal and it is significantly different for copper–tin, titanium–yttrium, and titanium–aluminum, vanadium alloys. Near the excitation threshold the structures have the form of smoothed protuberances, and as the impurity concentration increases they become sharp peaks. The wavelength in the case of copper–tin ($\lambda = 40\ \mu m$) is significantly longer than in the case of the indicated titanium alloys.

It was found that this phenomenon is caused by the instability of the solidification front under conditions of concentration supercooling of the liquid phase. The concentration supercooling is caused by displacement of the impurity into the liquid phase during the motion of the solidification front. The instability of the interphase boundary has been studied intensively under conditions of zone melting [7], and the mechanism of this phenomenon was pointed out by G. P. Ivantsov [8]. It was shown that

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of a thin melt solidifies at a constant rate and in this sense this process is the natural analog of zone melting. The computed values of the period of the structures and the excitation criterion correspond to the observed values [5, 6]. In the case of a thin melt the period of the structures is determined by the concentration and by the coefficient of displacement of the impurity as well as by the temperature gradient in the solid phase. This mechanism of excitation of period structures on the surface of melted silicon, containing tin as an impurity, was discussed independently in [9].

After bombardment ceases, analogous structures can be excited on melted sections of electrodes and the surface of the first wall, if the material of the electrodes and the wall contains an impurity. During subsequent pulses a multipeak structure on the surface of the melt can result in strong erosion and generation of microdrops.

II. It has been established [10] that explosive electron emission is of a cyclic character ($f \approx 10^9$ Hz). After the thermal explosion of an emission center (EC) the current density increases sharply and then decreases (the EC disappears). A liquid-metal phase forms at the location of the vanished EC. The interaction of this phase with the plasma of the cathode flame results in regeneration of microprotuberances and maintains the explosive emission process [10, 11]. A possible mechanism of such regeneration is examined in [12]. After the explosion of an EC a comparatively wide zone of melt forms on the cathode surface as a result of splashing of the liquid melt out of the microcrater. The plasma concentration in the cathode flame at the moment the center disappears is $n_p \approx 10^{20}$-10^{21} cm^{-3} [13]. After electron emission stops, an ionic Langmuir layer forms near the surface of the melt and an ion current (ions of the cathode material) flows out of the plasma onto this surface. The current density is sufficiently high to cause instability of the capillary relief by the Tonks–Frenkel mechanism [14]. Strictly speaking, the possibility of such instability in the case of an ionic Langmuir layer is not obvious, since it is known that in the case of a flat cathode surface the ion and electrostatic pressure are compensated at the cathode. On the humps of the periodically curved surface of the cathode, however, the electrostatic pressure is higher than the ionic pressure [15, 16], since because of the inertia of the ions there is not enough time for the ions to be focused totally on the humps. It is precisely this decompensation of the pressure that makes possible generation of capillary waves in the electrostatic field of the ionic layer. The necessary condition for excitation of capillary waves in the case of an ionic layer has been determined. This condition is satisfied with sufficiently large ($\approx$50 V) voltage drops across the layer near the cathode. The computed values of the wavelength ($\sim 10^3$ Å) and the instability growth rate ($\sim 10^9$ sec^{-1}) correspond to the sizes of the newly appearing ECs and the frequency of explosive emissions. Further evolution of the capillary relief proceeds through the formation of Taylor cones [17] and liquid jets at the tips of the cones. Due to the Rayleigh instability [18] (constriction) these jets decompose into microdrops (with radius $R \approx 20$-100 Å). The cyclic process of explosion and regeneration of sharp protuberances can result in parametric excitation of larger-scale capillary waves on the surface of the liquid bath (Faraday effect [19]) and generation of larger drops ($R = 200$-500 Å). Thus, in the cyclic explosive emission regime, intense generation of microdrops of metal occurs. This fact is pointed out in [13].

III. In [20] it is shown that the Rayleigh instability can also arise in the melting channel (welding channel). The development of constrictions in the channel results in the formation of alternating gas bubbles (cavities) after a deep welding channel is filled, and this degrades the quality of the seam. We determined the dispersion relation for a hollow cylindrical layer of liquid of finite thickness and we investigated the nonlinear stage of the development of constrictions and the parametric excitation of capillary waves (Faraday effect) on the surface of the channel with high-frequency modulation of the channel radius (for example, due to hf modulation of the beam current and, correspondingly, the vapor pressure in the channel). The Faraday effect, which produces a more complicated structure on the surface of the channel, can suppress the formation of gas bubbles when the channel closes up. Corresponding estimates were given. Independent experimental data obtained with an hf modulated beam indicate that such a mechanism for eliminating gas bubbles is possible.

As one can see from the results enumerated above, the explanation of the observed effects is based on the classical results of Faraday, Rayleigh, Tonks, Frenkel, Ivantsov, and Taylor. The population expression "manuscripts do not burn" no doubt also applies to the works of these physicists.

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THERMAL TURBULENCE IN AN ELECTRIC ARC

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By analyzing the correlations of current–voltage characteristics we show the predominance of turbulent heat exchange by convection and conduction in a longitudinally blown helium arc. The presence of "thermal" turbulence in the near-axial zone of this arc has been verified experimentally by investigating the radiation intensity.

In the process of developing and utilizing electric arc plasma devices, the nature of flow of the plasma flux, on which the arc interaction with the heated medium in the discharge chamber of the plasmotron has a decisive effect, is very important. The presence of an intense source of heat release, such as an electric arc, complicates substantially the nature of flow of the operating medium in a discharge channel in comparison with a cold flux without an arc discharge. To determine the flow regime in this case it is insufficient to simply compare the Reynolds number with its critical value.

Firstly, the plasma flux density in an arc column $\rho_{pl}v_{pl}$ is lower than in a heated cold flux $\rho_{cld}v_{cld}$. This leads to some reduction in the decisive size. Secondly, the heating of the operating medium increases strongly the flux viscosity. Therefore, the actual meaning of the Re number is much more restricted than when it is determined from "cold" parameters. Consequently, the calculation of the Reynolds criterion from the mean-mass temperature has become widely used. This method, however, is far from perfect, since the mean-mass temperature is not the primary given parameter, while the temperature itself depends on the operating regime of the device – the current intensity, the gas discharge, the pressure, and the geometry of the discharge channel. Consequently, the determination of the Re number value from the mean-mass parameters is the essential parameter, i.e., it is not an independent generalized argument.

There also exists an additional complication, besides the difficulties mentioned. In an electric arc there exist intrinsic instability sources of thermal and electric nature. More precisely, these play a more substantial role than the interaction forces on which the Reynolds number depends. An attempt of generalizing its current–voltage characteristics (CVC) [1, 2] is an indication of the decisive effect of energy exchange processes on the properties of arc discharge. Obviously, the effect of energy

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