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Innovation ultrasonic assistant soldering in electronics

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The impact of powerful ultrasound on liquid media causes a number of widely known effects in them: acoustic cavitation, associated with pulsations and collapse of cavitation bubbles; ultrasonic capillary effect; sonoluminescence; vortex effects in the form of micro and macro flows; acceleration of diffusion processes and others [1]. Analysis powerful ultrasound effects in liquid media shows that the greatest number of secondary physical effects is created by cavitation (Fig. 1). Local thermal effects arising from the collapse of cavitation bubbles are used in ultrasound metallization of nonmetallic materials: ceramics, glass ceramics, ferrites, etc. [2], since conditions are created for the formation of chemical bonds between oxides at the interface. Dynamic effects ensure the removal of grease and oxide films from the surfaces of materials, which is the physical basis for ultrasonic cleaning in liquid media [3] and ultrasonic brazing of hard-to-solder materials [4]. Some primary effects, such as the electrokinetic, wetting, have not yet been widely used in technology due to the limited possibilities of implementation. At ultrasonic (US) processing in liquids and melts: pollution removal, metallization of nonmetallic materials, disperse micro- and nano- dimensional powder materials it is important to form cavitation area with adjustable erosive activity. However US fields in baths with various quantities of radiators are characterized by non-uniformity of distribution US pressure and distinctions in intensity cavitation areas [5]. In liquids the quantity of cavitation germs does not give in to the exact account as depends on many factors: gas maintenances in a liquid, quantities of firm particles, ambient temperatures, external pressure etc. Not all cavitation germs participate in cavitation process, but only those from them which under action US pressure have reached of the critical sizes. The cavitation threshold decreases, if the liquid environment to influence an ionizing radiation or an electric current. Both these influences are connected with formation of new cavitation germs in the liquids. However at these methods of activation cavitation process remains non-stationary and difficultly operated [6].

Innovative approaches in ultrasonic assistant soldering consist in increasing the activity of cavitation and accelerating diffusion processes at the interface between the solder and the soldering material. Perspective direction in increase of cavitation processes efficiency is gas saturation of a liquid by cavities, with the sizes not exceeding the resonant sizes of germs, i.e. (10-50)$\cdot 10^{-6}$ m. Increase in the sizes of cavities will lead their premature collapse, and very small sizes complicate cavitation growth of cavities in US field. Another direction is the introduction into the solder melt of insoluble particles of diffusion-active metals, on which nuclei of cavitation bubbles can form. The replacement of traditional solders with lead-free alloys has caused a number of problems in the field of solder metal science. Eutectic alloys of the Sn Ag–Cu (SAC) type are widely used despite the higher cost (3 times higher than cost of solders) due to ease of use and low creep [7]. However, the reliability and mechanical properties of soldered joints very much depend on microstructure of solder, the morphology, and thickness of intermetallic compounds at the interface. The formation of Ag_3Sn and Cu_6Sn_5 intermetallides has main negative effect on fatigue processes and causes cracking at solder – metal interface [8]. In some cases to obtain high-strength aluminium butt joints with corrosion resistance, ultrasonic soldering was conducted using quasi-melting Sn-Zn hypereutectic alloy. Ultrasonic vibrations were applied at soldering temperatures ranging 220–300°C through Al rods without a solder bath [9]. To improve the wettability of ceramic material with Zn–Al–Mg solder, soldering with the assistance of active ultrasound was employed. The tensile strength of Zn–Al–Mg soldering alloys ranges from 82 to 169 MPa; the highest strength was observed in the solder with the lowest Mg content [10].

Ultrasonic energy activates the molten solder alloy and cause different structure of soldering joints. Analysis of samples micro sections with copper soldering pads confirm the influence of ultrasound on structure of solder joints. The highest share strength, have been achieved for solder joints which ware prepared by ultrasonic soldering on pads with copper surface finish. It is possible to use this technology for creating the electrode system for solar cells [11].
To modify lead-free solders used to form contacts in electronics, alloying adhesive active additives in the form of antioxidants, such as Ce, Ti, as well as metals that reduce the growth of intermetallic compounds: Ni, Ge, are most promising. So, in BALVER ZINN solder, due to introduction of number of metal additives: Cu–0.6–0.7, Ag–0.05, Ge – 0.005–0.007, Ni–0.04–0.06 [12], the mechanical strength is significantly improved, number of inclusions and solder bridges is reduced.

The use of ultrasonic vibrations during modification of solder allows to solve these problems. The main effects of action of cavitation and microstreams on liquid metals are acceleration of nuclei primary formation, the initiation of secondary nucleation of crystallization centers due to physical mixing and acceleration of diffusion. Ultrasonic modification of alloys is characterized by such effects as grain refinement, improved structure uniformity, wetting, and mechanical properties of soldered joints [13]. However, to obtain the best properties of soldered joints with lead-free solders in electronics, optimization of parameters of ultrasonic effect on solder melts is necessary.

Interest in flux-free ultrasonic soldering processes is caused by transition to lead-free solders and environmental problems of soldering in electronics. To form high-quality compounds, methods and devices for local ultrasonic activation of solder melts are used. US soldering is preferable for electronic applications because flux is a corrosive agent and it is necessary to remove flux resides as to ensure adequate service reliability of electronic assemblies [14].

A new approach in the technology of melt processing is inducing ultrasonic pressure waves leading to cavitation in alloy melts by high frequency electromagnetic induction coil. This presents an alternative 'contactless' approach to conventional US immersed probe techniques. The method can potentially offer the same benefits of traditional ultrasonic treatment (UST) such as degassing, microstructure refinement and dispersion of particles, but avoids melt contamination due to probe erosion prevalent in immersed sonotrodes. An added benefit is that the induction heating and stirring produced by Lorentz force, enables a larger melt treatment volume [15].

The main objective of this work is to develop methods to improve the efficiency of ultrasonic soldering processes for the mounting of modern electronic devices.

Fundamentals

For estimation intensity cavitation processes in liquids use the index of a cavitation defined by the relation of total volume of cavities ΣV_κ to volume of a liquid V [16]:

$$\chi = \Sigma V_K / V. \qquad (1)$$

The total volume cavities ΣV_κ is equal:

$$\sum V_\kappa = 4/3\pi \cdot N \cdot R^3_{\max}, \qquad (2)$$

where N – number cavities, R_{max}– radius of cavities in a stage of the greatest expansion.

Experimental data testify, that cavitation area is, as a rule, in a near zone US radiator, therefore US activated liquids volume it is possible to present as product of the area of radiator S_r on height of cavitation area h. Taking into account these assumptions expression (1) will assume the following kind:

$$\chi = \frac{4\pi \cdot N \cdot R_{\max}{}^3}{3 S_r h}. \qquad (3)$$

Using the equation of ideal gas condition receive:

$$pV = m_M NRT \qquad (4)$$

where p– gas pressure, V– gas volume, m_M– weight of gas molecules , R–gas constant, T– gas temperature.

Regulating pressure and speed of gas distribution it is possible to operate number of the gas molecules N entered into a near zone of US radiator as potential cavitation germs.

At gas activation to a liquid from the compressor with the help of nozzle submitted air or inert gas argon with pressure to 0,1–0,2 MPa. For uniformity of the size of gas cavities in a liquid on exit of nozzle is established the filter-membrane with cells which were formed by laser radiation with high accuracy and repeatability of the sizes. The nozzle include two porous filters with the sizes of apertures 2–5 microns. For creation of cavities of the micron sizes it is necessary to satisfy following conditions: pressure of air should not exceed 0,2–0,3 MPa, and the distance between apertures in the filter in comparison with diameter of cavities should be considerable. These conditions in certain degree prevent association of cavities of the micron sizes in the big gas cavities.

The resonant frequency of cavitation cavities collapse depends both on its radius Rp, the surface tension of the melt σ and on density ρ according to Minert's expression:

$$f_p = \frac{1}{2\pi R_p}\sqrt{\frac{3\gamma}{\rho}\left(P_o + \frac{2\sigma}{R_p}\right)}, \qquad (5)$$

where γ – isothermal coefficient, Po– external pressure.

The action of the US field energy on the melt increases the diffusion coefficient and activates the nucleation process [17]

$$D' = D_0 e^{-\frac{E-\Delta E}{RT}} \qquad (6)$$

where D_0 is the pre exponential factor, E is the energy of the diffusion activation, Δ E is the change in the energy of the diffusion activation in the US field, and R is the gas constant.

If the US energy introduced into the melt without taking into account losses activates the diffusion process, then

$$\Delta E = 0.5\,\rho c (A \cdot \omega)^2, \qquad (7)$$

where ρc is acoustic impedance, *A* – amplitude of fluctuations, ω – circular frequency.
In the US field, the force *F* acts on the diffusing particles, and, under its action, the substance particles move with the average velocity overcoming the force of medium friction F_f

$$V = \upsilon F - \frac{F_f d}{\eta S_p}, \qquad (8)$$

where υ is the particle mobility, *d* – medium layer thickness, η – dynamic viscosity, S_p – particle area.
The strength of the ultrasonic field, affecting the particle flow section S:

$$F = \rho c \cdot \omega A \cdot S. \qquad (9)$$

At the activation in the US field, a flux of particles, which move under the action of the force of US vibrations *F*, is added to the diffusion flux; then, the entire flux amounts to [18]

$$J = -D'\frac{\partial C}{\partial x} + VC_1 \cos\alpha = -D'\frac{\partial C}{\partial x} + (\upsilon\rho c\omega AS - \frac{F_f d}{\eta S_p})C_p \cos\alpha, \qquad (10)$$

where C_p is the concentration of mobile particles, and αβ is the angle between the vector of the force of the US field and the diffusion flux vector. It follows from Eq. (10) that activation by the US field energy leads to an increase in the diffusion flux.

Experimental

At gas activation of a melt submitted on the converter 1 electric fluctuation by frequency 20-44 kHz and amplitude 50-75 mkm from US generator. In a solder melt immersed US radiator 2 so that a backlash between it and soldered element 5 made 0,25–1,5 mm. Through a tube 3 and a capillary-porous body 4 in a direction to a soldered surface in a melt of solder 6 entered inert gas – argon (Fig. 2). The sizes of capillaries in a porous body are chosen such that the sizes of formed gas cavities did not exceed the resonant sizes of cavitation germs in a melt of Sn-Pb solder, i.e. 10-50 microns [19]. Quantification the spectral density of cavitation noise it is possible to determined the cavitation intensity in liquid surrounding [20]. The greatest spectral density of cavitation noise is in the frequency band from 10-th up to 40-th harmonics of the base frequency of the ultrasonic converter at acoustic pressure $2 \cdot 10^5$ Pa (Fig. 3) [21]. It is offered to quantification cavitation pressure in liquid media by measure the square of a noise level over the range of the greatest spectral density of a cavitation noise The scheme of a cavitometer (Fig. 4) consists of a piezoelectric sensor, an active filter creating a shear sternness of frequency characteristic curve less than 24 dB an octave, a square-law detector, and a recording device. The indications of this device have linear dependence on active power in range of 0–2 kW. The cavitometer measures cavitation pressure from 5 up to $5 \cdot 10^4$ Pa in the frequency band 18–60 kHz with accuracy ±10 %.
The pressure in cavitation area is perceived by a measuring probe 1, attached to a piezoelectric transducer 3 with the elastic waveguide 2. The electrical signal from the transducer 3 comes to the amplifier 4, arranged in a body of the sensor and serving for coordinating a high-ohms circuit of the transducer with the input of the measuring device. The attenuator 5 serves for attenuation of input signal. The band-pass filter 6, made on the Chebushev scheme of the third order with band of 200–800 kHz, selects a portion of the spectrum of a signal, characteristic for cavitation impulses. After the amplification, the signal passes through circuits of the mean-square detector 8 and the amplifier 9 and then moves to indicator. Unit 10 is a power supply of the measuring device and sensor.

To the analysis of thermal fields it is applied mobile thermal camera MobIRM4 with a sensitive element - microbolometer UFPA (160x120 pixels, 35 mm), 8-14 microns working in a spectral range. The size of a field of the analysis has made 25° x 19°, focus of 12,6 mm. Sensitivity of the thermal camera 0,1 °C.
Measurements were spent on distance of 50 sm from a liquid upper edge. Device adjustment has been made on a reference source of boiling water. For stability of results the measurements were spent in the form of several series after

bath warming up in a current of 20 minutes, and then by means of program IR Analyzer V1.7 the thermal fields of distribution of temperatures in the set sites of a bath is received. The US metallization of glass-ceramic materials was performed in the chamber of the experimental setup (Fig. 5) with a residual rarefaction of 1–10 Pa. For the metallization, a low-melt Sn–10Zn solder and experimentally developed Pb-Sn-Zn-In solder on the basis Sn with the addition of Zn and In were used [22].

US vibrations with an amplitude of 10–15 mkm and a frequency 22 kHz were introduced into the melt using a radiator in the form of a concentrator of the Fourier type. The melt was heated by IR radiation from two halogen lamps with a power of 1 kW located in parabolic reflectors. The voltage at the IR lamps was supplied from a stabilized power source (SPS) controlled by a control block (CB). The rate of the IR heating amounted to 10–15°C/sec. The temperature of the melt was measured in the working zone using thermocouple and digital measuring device-regulator TRM 201(OVEN).

Results and discussions

The analysis of thermal fields has shown, that the liquid temperature in US bath as a result of cavitation process raises. The greatest increase (to 10°C) occurs in a zone of the developed cavitation that is connected with warmth allocation at a collapse of cavitation cavities. At gas activation temperature of the liquids near to a nozzle approximately on 0,7°C above in comparison with temperature on some distance from it. Gas saturation of liquids and melts causes increase in cavitation pressure depending on speed of gas and sizes of filter cells. Under the influence of elastic US fluctuations the formed cavitations germs pulse in a melt near to a surface of a soldered surface and slam at US pressure $2 \cdot 10^5$ Pa, created on a compression half-cycle. Pressure at which inert gas moved in a melt, depended on viscosity of solder and amplitude US fluctuations.By help of cavitation indicator it is established that gas cavities with the sizes 10–50 microns slammed, increasing level of cavitation pressure that activates US processing, including metallization by fusible solders of nonmetallic materials. Local cavitation pressure in a melt at the expense of initiation of a considerable quantity of cavitation germs increased on 20–25 %, and reached a maximum at speed of inert gas of 4-6 m/min and the sizes of cells 10 microns (Fig. 6.) The big sizes of cavities (over 100 microns) result to formation of a gas cavity which does not slam at levels of US intensity of $(2–5) \cdot 10^5$ Pa.The results of modeling diffusion process showed that the US activation increased the concentration of the diffusing elements of Zn and Al in the interface depth by 15–20% on average, and the combined activation by the US and electric fields increased it by 30–45%. With increase amplitude and frequency of US vibrations, the concentration growth was observed, since the energy quantity adsorbed by melt increased (Fig. 7). The combined activation of melt–soldered material system by US vibrations energy and powerful current pulses additionally increased the heat energy. This allows reaching the soldering temperature at a greater rate, increasing wettability of the surface by solder.

The width of the diffusion zone measured using the scanning electron microscope, in this case, amounted to 4–5 μm for Sn-10Zn and Sn-39Pb (Fig. 8). For the Sn-10Zn solder, the diffusion zone was slightly wider because of the electro mobile Zn presence in the melt, which migrated to the interface and then deeper in the aluminum alloy thus increasing the width of the diffusion zone. The width of the interface increased to 6–8 μm owing to the enhancement of the diffusion interaction and aluminum electro migration into the solder if compared with it’s size of 1.5 μm at the US activation

Conclusions

Gas saturation of liquids and melts raises level of cavitation pressure upon 20–25 % that allows to intensify US processing, for example, clearings in liquid environments, to increase durability of coupling of metallization with ceramic and glass-ceramic materials, to reduce time of soldering processes, a tinning, metallization, to raise reliability of electronic devices at the expense of reduction of thermal influence. Practical verification of the combined effect of concentrated energy flows of ultrasonic and electrical current on the processes of contact joints formation of Al alloys using Sn-Pb and Sn-Zn solders showed that strength of joints of materials with different chemical composition increases by 1.5–1.8 times due to the intensification of diffusion processes. Flux–free ultrasonic soldering is non-polluting process and is more economic, as such operations as fluxing and clearing, demanding expenses of time and materials, are excluded. US soldering in some cases is a necessary condition of internal installation and hermetic sealing of the microelectronic equipment. US soldering connect to the help difficult soldering materials: nickel, aluminum, magnesium and titanic alloys, and also nonmetallic materials: ceramics, glass, ferrite. It creates an opportunity of economy of the precious metals rendered on dielectric surfaces of electronic components as metallization.

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