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Application of Concentrated Electromagnetic Energy Streams in Electronics Manufacturing

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Aims: The concentrated streams ultrasonic (US) and high frequency (HF) energy are widely used in electronics manufacture in assembly and mounting process. US soldering is non-polluting and more economic process, as such operations as fluxing and clearing, demanding expenses of time and materials, are excluded. US soldering joining difficult soldering materials and nonmetallic materials: ceramics, glass, ferrite. HF electromagnetic energy possessing of local high speed heating of conducting materials in any environments provides formation of qualitative soldering connections in electronics products.

Methods: The US metallization of glass-ceramic materials was performed in the chamber with a residual rarefaction of 1–10 Pa and using IR heating. A low-melt Sn–10Zn solder and experimentally developed solder on the basis Sn with the addition of Zn and In were used. The cavitation pressure in the melted solders was evaluated according to the spectral density of the cavitation noise in the frequency band of 100–450 kHz using a cavitometer. The optimal frequency of US oscillating local soldering system is modelling with ANSYS. Two types of inductors are investigated: circular winding inductor and with open-ended magnetic circuit. The first contained HF generator, circular inductor with the cylindrical detail, and capacitor. In the second the generator was connected to winding coils on magnetic circuit of ferromagnetic material.

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Results and Conclusion: At local input US fluctuations in melts concentrate US energy in small volume and lower oxidation of solder in a bath. US fluctuations parallel to soldering surface are preferable to increase of soldering connections durability, maintenance of high stability of processes and reduction of mechanical influence by products. The efficient management of power and speed of induction heating is necessary to control the size of current power and speed of the induction heating in working winds.

Keywords: Electromagnetic energy; streams; ultrasonic; high frequency.

1. INTRODUCTION

Prospects of scientific researches and practical developments in electronics production are connected with use of the combined activation methods having high accuracy and adjustability of energy flows, allows to create the microprocessor program-controlled equipment and to provide high quality of assembly joints in the conditions of deficiency of materials and energy [1]. Modern processes of soldering in electronics production activate by concentrated streams of electromagnetic energy: ultrasonic, high-frequency, the infrared and laser, providing local and contactless source affecting of heating on soldered details, high efficiency and possibility of processes automation [2]. Transition on lead-free solders and application of clean soldering technology on ecological reasons causes a problem of a choice activation influences at formation of contact connections in a liquid phase. As the rests of a flux after the soldering keep some level corrosion activity, they are necessary for removing to guarantee adequate reliability of products. Alternative soldering process the replacing chemical flux activity for removal oxides is application of ultrasonic (US) wave's energy. US energy causes in liquid solder cavitation, which deletes oxide layer on a surface of the basic metal.

Though US activation successfully replaces function of removal oxides with a flux, but cannot protect the cleared surface up to the soldering, and also to lower a superficial tension of fused solder, to increase spreading and capillary penetration [3]. Fluxless ultrasonic soldering is non-polluting and more economic process, because 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 mounting and hermetic sealing of microelectronic devices. US metallization and soldering apply to joint difficult soldering materials: nickel, aluminum, magnesium and titanic alloys, and also nonmetallic materials: ceramics, glass, ferrite. It creates opportunity of economy of the precious metals rendered on dielectric surfaces of electronic components as metallization [4].

Induction heating by the high-frequency electromagnetic field has been successfully used for a long time in industry, as it allows to implement a high-performance non-contact and local heating due to eddy currents induced in conducting materials. The advantages of HF heating are: Selectivity by skin-effect; high density of energy; processing in any environment, including vacuum or inert gas; high ecological cleanliness, improvement solder flowing by electrodynamics forces increase the quality of soldering connections. HF electromagnetic heating allows to activate soldering and to improve wetting surfaces. The problems of increase of power indexes and efficiency of application are actual for all induction heating devices. The multiple-turn solenoid type inductors are characterized by considerable dispersion of magnetic stream, low efficiency, necessity of electric and thermal isolation from heated details and aquatic cooling in work. Application of induction devices on magnetic circuit allows to promote locality of heating, bring down watts-in, to refuse aquatic cooling and thermal isolation from heated details [5].

The heating of melts in the metallization area by IR radiation possesses several technological advantages, though their realization depends on the correct construction of IR heating installation. Nowadays, two kinds of IR heating have become wide-spreading technological processes of soldering: local focused and precision dissipated. As dependent on the specified conditions, reflectors with various geometry are used to form the defined heating area. From all spectrum of IR radiation a narrow range of the wavelength (from 1 to 5 μm) is usually used, which can be divided into the shortwave range (from 1 to 2.5 μm) and the medium wave range (from 2.5 to 5 μm) [4].The shortwave range of IR radiation allows to heat the object with a greater rate. According to the Wien displacement law the maximal value of the spectral intensity of the radiation shifts in the direction of shorter waves with increasing of temperature. Laser technique with precisely focused laser beam provides controlled heating of the solder alloy leading to fast and non-destructive of electrical joint. The process uses a controlled laser beam to non-contact transfer energy to soldering area where the absorbed energy heats the solder until its melting temperature [6].

2. METHODS

2.1 Ultrasonic Power Streams

Influence of US streams frequencies 18–70 kHz on melts creates in them cavitation and a number of secondary phenomena: US pressure, micro- and macro streams, chemical activity and acceleration of diffusion [7]. At intensity of ultrasound $(8–10)\cdot10^3$ W/m^2 in liquid environment appear small bubbles –cavitation germs, which pulse with frequency US fluctuations. According to D. Ensmiger and L.G. Bond [8] cavitation's germs can be formed on the firm particles not moistened with a liquid having cracks, filled by insoluble gas. Cavitation germs getting in area of negative pressure lose stability, start to grow on a half-cycle of a stretching and quickly slam on a half-cycle of compression.

US field in liquid medium is characterized to variables sound pressure in each point:

$$P=\rho cA\omega=\rho cV_m, \qquad (1)$$

where ρ – density of medium, V_m– amplitude of oscillatory speed, *c*– wave speed.

The US soldering metals and metallization of glass-ceramic materials was performed in chamber of experimental setup (Fig. 1) with residual rarefaction of 1–10 Pa and using IR heating. 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 for the metallization [9].

US vibrations with amplitude of 10–15 μm and frequency 22 kHz were introduced into the melt using a radiator in the form of Fourier type concentrator. The melt was heated by IR radiation from two halogen lamps with a power of 1 kW located in parabolic reflectors. The voltage for IR lamps was supplied from stabilized power source (SPS) operated by control block (CB). The IR heating rate amounted to 10–15℃/sec. The temperature of the melt was measured in working zone using thermocouple and controller TRM-210. The cavitation pressure in the melted solders was evaluated according to the spectral density of the cavitation noise in the frequency band of 100–450 kHz using a cavitometer [10]. The pressure in the cavitation region was registered by a measuring probe with a working area of 1.0 cm^2 connected to piezoelectric transducer by elastic waveguide. Amplitude US fluctuations were measuring by vibration detector and piezoelectric transducer [11].

Modelling US oscillating local soldering system by ANSYS were made including following parts: magnetostrictive transducer, acoustic transformer from material with low thermal expansion coefficient, conical waveguide for energy transmission to radiator and radiator itself for putting US oscillations into the melt (Fig. 2). The second model has two-sided radiator, which allows concentrating US energy in the space between radiators surfaces 4 and 5. For modal analysis by ANSYS each material has Young's modulus, Poisson's ratio and density level.

During the calculation of natural frequencies, the boundary conditions were lapped on detail fixation positions in US system: over two parallel planes of transducer and over all the bath surfaces. Five resonance frequencies were achieved at frequency range of 19-24 kHz. For the one-sided radiator the optimal frequency is 22 kHz with the maximal amplitude of 6.1 units (Fig. 3) because the amplitudes maximum of melted solder is located close to radiator. For optimal frequency for two-side radiator system with 20.7 kHz the oscillation amplitude of melted solder is 9 units (Fig. 4).

The distribution of oscillations amplitude on melt surface perpendicular to the radiator plane is shown at Fig. 5. The oscillation amplitude over the melt surface for both types of radiators is increasing with approaching to radiator. The maximal amplitude for one-sided radiator is 5.9 units when the distance between radiator and surface is 25-35 mm. With the distance increase the amplitude value is lowering, but still stays at relatively high level all over the surface area, what causes solder oxidation. The maximal amplitude for two-sided radiator in the gap between the radiators is almost 2 time more (9 units) than for one-sided radiator. The amplitude decrease out of gap lowers the solder oxidation. The analysis of received data shows the superiority of two-sided radiators.

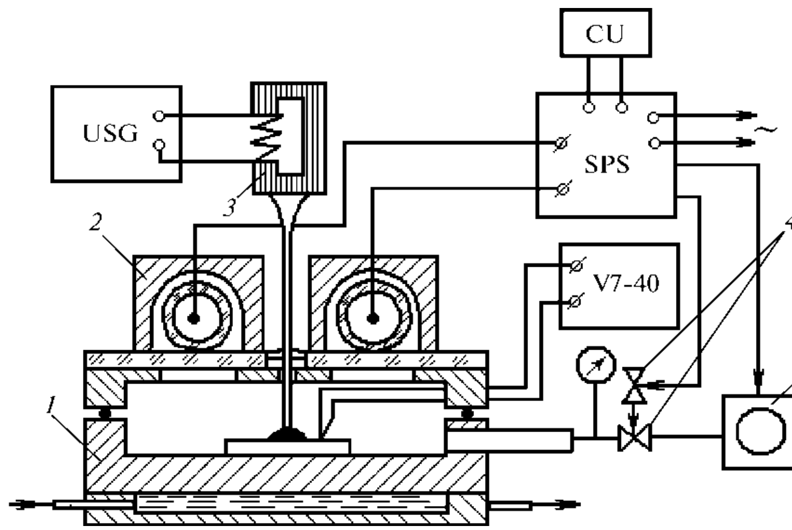
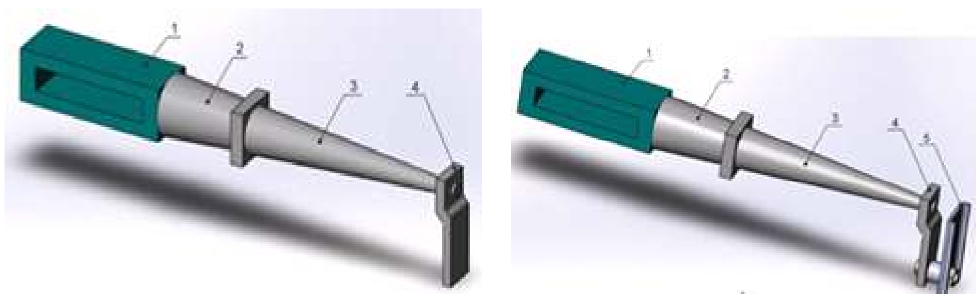


Fig. 1. Schematic view of the melt activation by US and IR energy fields: (1) chamber, (2) IR heater, (3) US transducer, (4) cranes, (5) compressor



(a) **(b)**

Fig. 2. US local soldering oscillating system with one-sided radiator (a) and two-sided radiator (b): 1 – transducer, 2 – concentrator, 3 – waveguide, 4 – radiator, 5 – additional radiator

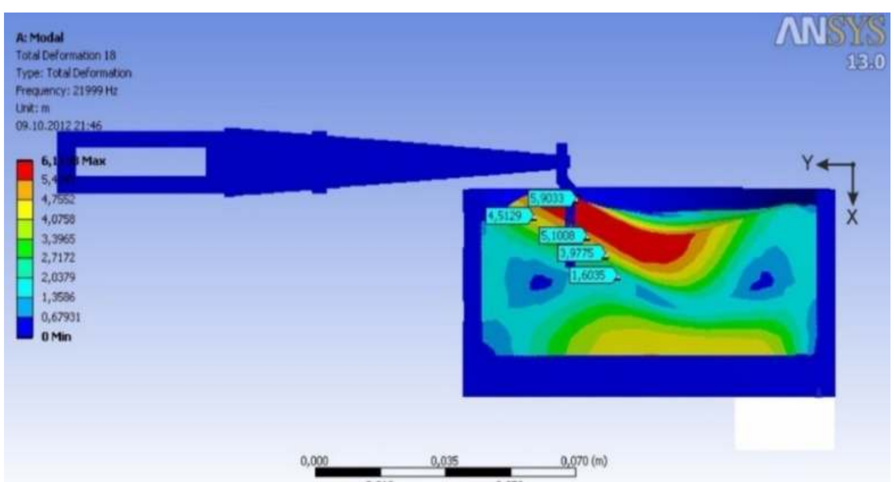


Fig. 3. The distribution of oscillation amplitude at the frequency of 22 kHz

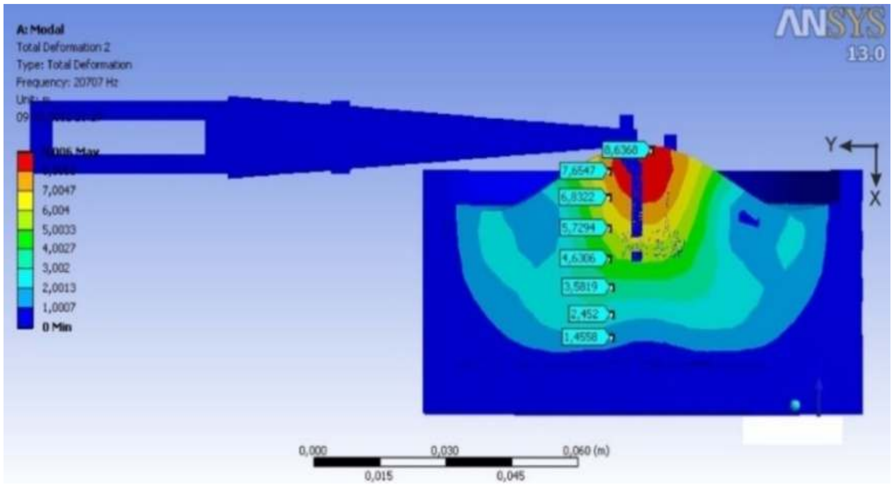


Fig. 4. The distribution of oscillation amplitude at the frequency of 20.7 kHz

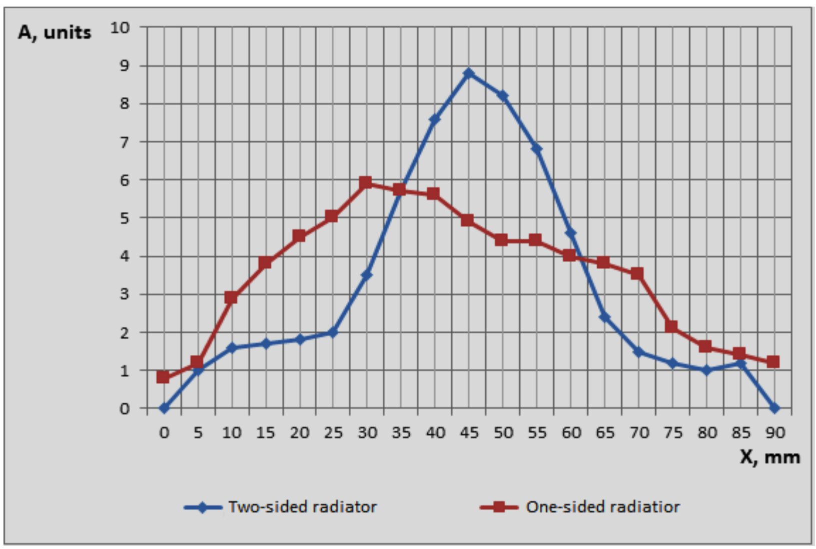
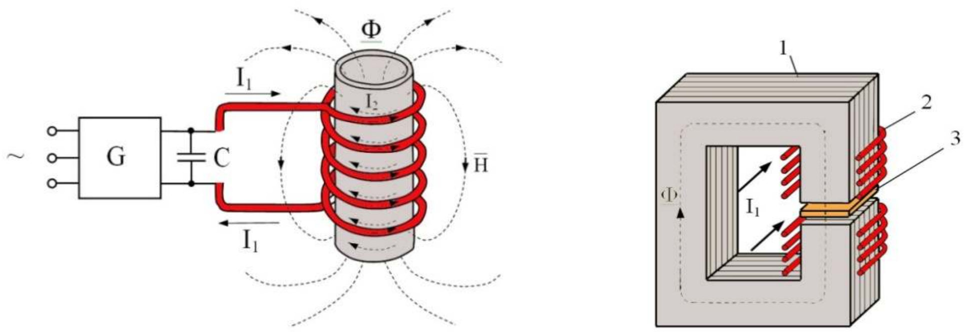


Fig. 5. The oscillation amplitude distribution over the melt surface

2.2 High Frequency Electromagnetic Heating

Importance of energy saving in electronics production address to high-frequency (HF) electromagnetic heating providing of local high speed heating of conducting materials in any environment. The advantages of HF heating are the following: selectivity by skin-effect; high density of energy; processing in any environment, including vacuum or inert gas; high ecological cleanliness, improvement solder flowing by electrodynamics forces increase the quality of soldering connections. The choice of heating frequency, induction design and optimization of heating modes is necessary for formation of qualitative soldering connections in electronics products [12]. HF electromagnetic heating allows to activate solder and to improve wetting solderable surfaces.

The soldering in electronics is characterized by small specific capacity of heating, small dimensions of modules and their sensitivity to electromagnetic fields. Therefore, it is necessary to optimize effective HF heating power and heating efficiency. HF electromagnetic heating has allowed optimizing heating speed in local zones of soldering connections formation and improving their quality due to joint action of superficial effects and electromagnetic forces.



(a) **(b)**

Fig. 6. Induction heating systems with winding inductor (a) and open magnetic circuit (b): 1–magnetic circuit, 2–winding coils, 3–detail

The effect of magnetic field concentration in induction heating systems is common. It is possible to create power lines concentration of a field on the set heating surface of conducting body using magnetic conductor of the certain design. Two types of inductors are more often used in production: circular winding inductor (Fig. 6a above) and with open-ended magnetic circuit (Fig. 6b above). The first scheme contained HF generator G, circular inductor with the cylindrical detail, and capacitor C. In the second scheme the generator was connected to winding coils on magnetic circuit of ferromagnetic material. In a gap of magnetic conductor detail was heated. The winding coils are connected by a direct current to input of regulating rectifier.

Power distribution on a thickness of a detail in case of superficial heating looks like,

$$P = P_o \cdot \exp\left(-2\,x/\delta\right) \quad (2)$$

where P_0– power on detail surface, x – co-ordinate, δ – depth of penetration.

Skin effect is significantly affects at the efficiency of induction heating, because depth of penetration is determined by distance, at which value of eddy currents reduce to 1/e from original value:

$$\delta = \sqrt{\rho/\pi \cdot f \cdot \mu_o \cdot \mu} \quad (3)$$

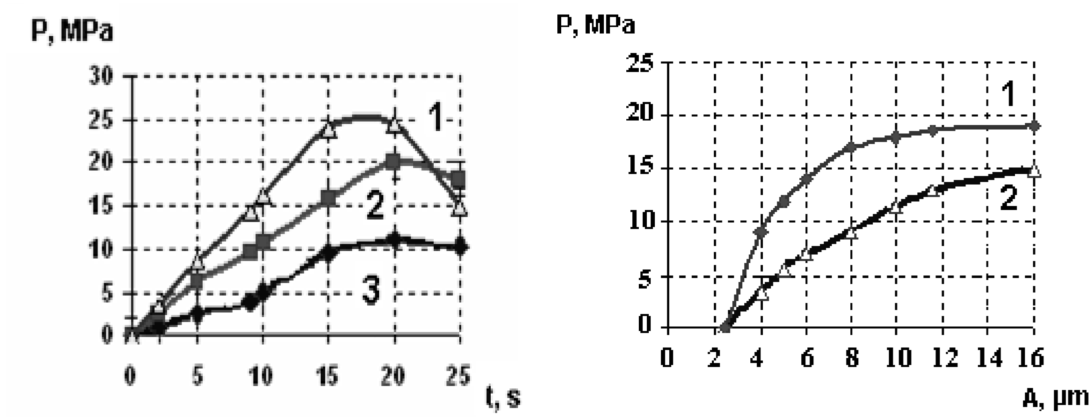
where ρ–specific electrical resistance, μ – magnetic permeability, μ_o– relative magnetic permeability, f – frequency.

Magnetic materials require smaller specific power of HF heating. The general law for all magnetic materials is nonlinear decrease in heating power depending on frequency of HF currents that is connected with superficial effect [13]. The optimal parameters of HF heating by inductor with open-ended magnetic conductor: frequency 300–500 kHz, intensity of magnetic field (2.5–5.5)$\cdot 10^4$ A/m, current amplitude 10 – 20 A in inductive coils. The interactions of electromagnetic fields in melted metals accelerate spreading over solid surfaces owing to the action of the ponderomotive forces.

3. RESULTS AND DISCUSSION

Amplitude US fluctuations 3±0,5 µm are threshold for cavitation processes in melt. There is no wetting and adhesion of solder to material surface and chemical interaction between them at lower amplitude. At amplitude more than 15 µm durability is reduced, as arising dynamic pulses cause degradation of superficial layers solder and its intensive oxidation. At longitudinal fluctuations the significant part of energy is transferred in material, causing its heating and destruction. At parallel fluctuations the greater degree energy is distributed in solder lengthways soldering surfaces and spent for cavitation phenomena [14].

Durability of soldering connections with aluminum alloys at parallel fluctuations is higher on 10–12 MPa, than at longitudinal, without dependence from time of influence. High durability of connections is reached at duration of ultrasound 15–20 s. At long time there is a reduction durability of soldering connection due erosion of basic material and oxidation of solder. The maximal durability of soldering connections corresponds to amplitude of parallel US fluctuations 10–12 µm at time 15±1 sec (Fig. 7).



(a) (b)

Fig. 7. Relationship between durability of soldering connections and time (a), amplitudes and a kind of fluctuations (b): 1–parallel, 2–longitudinal, 3–turn

Introduction US oscillations in solder melt parallel the soldered surface of class-ceramic at distances between an end face of US tool and surface of 0.1 mm increases cavitation pressure in solder on average by 25%. It allows to raise productivity process of metallization and to improve quality of joints [15].

The action of electric field energy increases thermal energy of soldering system. This allows reaching soldering temperature at greater rate, facilitates solder spreading, and improves the quality of connections [16]. The mass transfer in liquid at US activation occurs owing to both convective motions in the form of macro- and micro flows and diffusion. US energy activation increase diffusion coefficient and electric field energy activation increase the ions streams of reactive components in interaction zone and, hence, increase velocity and depth of diffusion. The width of diffusion zone measured using scanning electron microscope amounted to 4–5 µm for Sn-39Pb. For the Sn-10Zn solder the diffusion zone was slightly wider because of electro mobile Zn migrated to interface and then deeper in aluminum alloy thus increasing the width of diffusion zone. The width of interface increased to 6–8 µm owing to enhancement of diffusion interaction and Al electromigration into solder if compared with its size of 1.5 µm at US activation.

The action of low US frequency on cavitation zone generated by the high frequency field is effective with the aim to increase the cavitation efficiency. The range of bubbles dimensions involved in cavitation process increases owing to the interference and also to generation of combination frequencies and the expansion of spectrum of the resulting field. At the ultrasonic desperation of nanoparticles in liquid media, it is effective to generate microstreams in the boundary layers of the Schlichting type at high uniformity of the distribution of the US pressure over the volume of the medium.

The combined action US and electric fields on melts create the electro diffusion process which depends on correlation of forces, which act on thermally excited metal ion, both in direction opposite to electric scream (action of external field) or in direction of «electron wind» [17]. The influence of electric field is small owing to shielding influence of electrons, therefore, the force of electron wind prevails. It increases with the current density increasing. Consequently, there is greater probability for excited ion to transform into a vacancy when it moves in the direction of electrons than when it moves in opposite direction. Therefore, the vacancies move to negative e-pole, and the metal ions move to the positive pole. When current densities exceed 1–1.5 A/mm^2 the directional diffusion of solder components or material into solder owing to electromigration of particles of easily diffusive metals increases width of diffusion zone and connections durability. The durability of aluminum soldering by Sn-Pb solder versus the direct current in direction from radiator to workpiece (frequency of 22 kHz, amplitude 10 µm, temperature 240℃, and time 10 s) increases for the currents exceeding 10 A and decreases when the current exceeds 15 A.

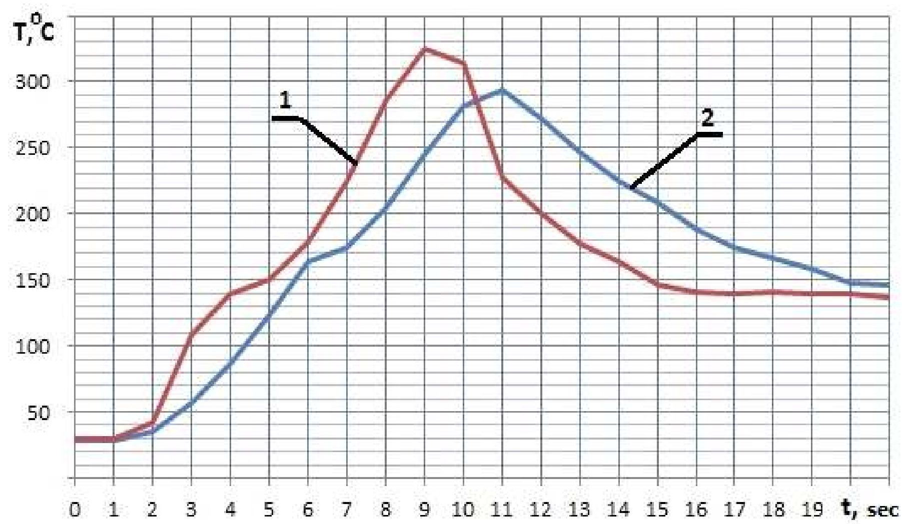


Fig. 8. Solder balls temperature profiles at HF heating power: 1 – 1,2 kW, 2 – 0,9 kW

Application of the US effects arising in liquid media is promising for fabrication of nanostructured materials both at sonochemical synthesis and for desperation of nanoparticles in liquids with the aim to disintegrate their agglomerates [18].

This increases the spreading area of melt and its penetration ability into the capillary slits in connections. This ultimately facilitates increasing of mechanical durability of soldered connections and lowering of their transient electric resistance. The soldering of telescope connections of brass tubes with diameters of 6.0 and 6.5 was performed using Sn-Pb solder ring with a diameter of 1.0 mm for 5–7 sec by induction heating. In addition application of electric current with a density up to 10 A/mm^2 across details and they rotation at a rate of 60° ensured 100% filling with a depth of 10 mm. The durability of soldered connection increased by 20–25%.

In a modern radio electronic apparatus, such, as mobile telephones, smartphones, computers and other, integral microcircuits are widely used in BGA package, that allows considerably save place on PCB and promote the fast-acting of electronic circuits. For soldering of BGA package on the PCB it is necessary form matrix of solder ball pins. Application of induction heaters on magnetic circuit allows to promote locality of heating, bring down a watts-in, get rid from the aquatic cooling and thermal isolation from the heated details [19].

The analysis of HF temperature profiles of solder balls (Fig. 8 above) has shown that growth rate of temperature substantially depends on heating power and can reach 40℃/sec and more. With increase in number of amperes-coils in inductor and magnetic permeability of magnetic circuit energy of a magnetic field increases, and density of eddy currents directed by an electromagnetic field in solder balls grows [20]. But at such speed of heating it is difficult to provide a flat site at solder fusion temperature when there is wetting of soldered surfaces and solder spreading. It conducts to premature flux evaporation, an overheat of solder and, as consequence, to deterioration of solder balls.

Induction heating by inductor with internal magnetic core is efficient for formation of solder ball leads with the aim of assembling of integrated electronic components in BGA packages. The solder ball leads with the specified dimensions are formed by virtue of reflow of solder paste deposited on PCB contact pads. The rate of heating is as high as 40–50℃/s for 10 coil inductor with diameter of 40 mm and internal magnetic core, which induced eddy currents in solder balls at frequency of 2 MHz.

4. CONCLUSION

Ultrasonic soldering is non-polluting and more economic process, 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 devices. US metallization and soldering joining 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. At local input US fluctuations in melts concentrate US energy in small volume and lower oxidation of solder in a bath. US fluctuations parallel to processable surface are preferable to increase of soldering connections durability, maintenance of high stability of processes and reduction of mechanical influence by electronics products.

For the efficient management of power and speed of induction heating is necessary to control the size of current power and speed of induction heating in working winds, and it is possible to carry out the general or local superficial heating by the frequency change of the supply current.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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