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Ultrasonic soldering in electronics: new opportunities

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Abstract

Interest to processes flux-free ultrasonic soldering and tinning details and conclusions of electronic components is caused by transition on lead-free solders and environmental problems of the soldering in electronics. To formation of qualitative connections with metal and nonmetallic materials apply methods and devices of local ultrasonic activation solder melts.

1. Introduction

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 service of products [1]. Flux-free soldering in electronics is actual for some reasons:

– The increase in temperature of the soldering for lead-free solders complicates removal of the rests rosin fluxes [2];

– Traditional methods of clearing chlorinated hydrocarbons and in view of their ecological danger are forbidden or strictly limited to hydrocarbon solvents;

– Application of water-washed off fluxes demands water processes of clearing, in result the stream of sewage potentially pollutes resources of potable water.

Alternative soldering process the replacing chemical flux activity for removal oxides is application of energy ultrasonic (US) waves. 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 the fused solder, to increase spreading and capillary penetration [3].

The flux soldering of hybrid microcircuit substrates by fusible solders has the essential lacks caused by presence of the rests of a flux. At the soldering it is important to provide continuous contact of a surface of a payment and the metal basis as emptiness and or flux inclusions worsen a heat-conducting path, reduce durability of connections and are the reason of corrosion which can lead to refusal of micro assembly. Alternative is US soldering of microcircuit substrates in cases of modules.

In manufacture of electronic components, such as monolithic capacitors, piezoelectric converters, varistors and others widely apply metallization of contact surfaces by pastes of silver, palladium, platinum or other metals. US metallization by cheaper solders will allow to save precious metals, to increase productivity of processes and quality of contact connections in electronic components.

Desktop US baths are successfully applied for hot tinning details and conclusions of electronic components, and US soldering irons for the soldering and metallizations of ceramic and ferrite materials. Application of modern electronic sources of ultrasound makes the soldering by the reliable, non-polluting process excluding application of fluxes.

2. Physical bases of ultrasonic activation melts

Influence of mechanical fluctuations US frequencies 18–70 kHz on melts creates in them cavitation and a number of the secondary phenomena: US pressure, micro-and macro streams. At intensity of ultrasound (8–10)•10^3 W/m^2 in the liquid environment appear small bubbles – cavitations germs, which pulse with frequency US fluctuations. Cavitations germs can be formed on the firm particles not moistened with a liquid having cracks, filled by insoluble gas. As a surface of a crack not moistened the liquid coming into a crack forms concerning gas a convex meniscus with radius R_0. Condition of balance on border undressed melts – solid body it is determined by expression:

$$P_g = P_o + 2\sigma / R_o \ , \tag{1}$$

where P_g – gas pressure in bubble, P_0-external pressure, σ – superficial tension.

Values of a regional corner of wetting for germs on disperse solid particles in radius of 10^{-6}-10^{-7} m in melts make 100-175°. The solid particle with defect as a conic or spherical hollow is the center of formation of cavitation germs.

The amplitude US pressure, necessary for expansion of a germ of radius R_0 to resonant radius Rr is determined from expression [4]:

$$P_{US}^{1} = P_O - P_g + \frac{4\sigma}{3\sqrt{3R_o}}\left[1 + \ P_O - P_g \ \frac{R_o}{2\sigma}\right]^{-1/2} . \tag{2}$$

The cavitation threshold is defined at set Ro by size of a superficial tension σ, and resonant frequency fr depends both from σ, and on density расплава ρ:

$$f_r = \frac{1}{2\pi R_r}\sqrt{\frac{3\gamma}{\rho}\left(P_o + \frac{2\sigma}{R_r}\right)} . \tag{3}$$

For melts interval R_r makes $4\cdot10^{-6}$-$6\cdot10^{-5}$ m then explosive growth bubbles begins. 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.

Feature solders melts are considerably big density and viscosity in comparison with water, necessity of the account of hydrostatic pressure of a melt column, and also distinction in the initial sizes of cavitation cavities. Hydrostatic pressure Po in view of atmospheric pressure P_A and pressure of a melt column in height h is equal:

$$P_0 = P_A + h\rho g \ . \tag{4}$$

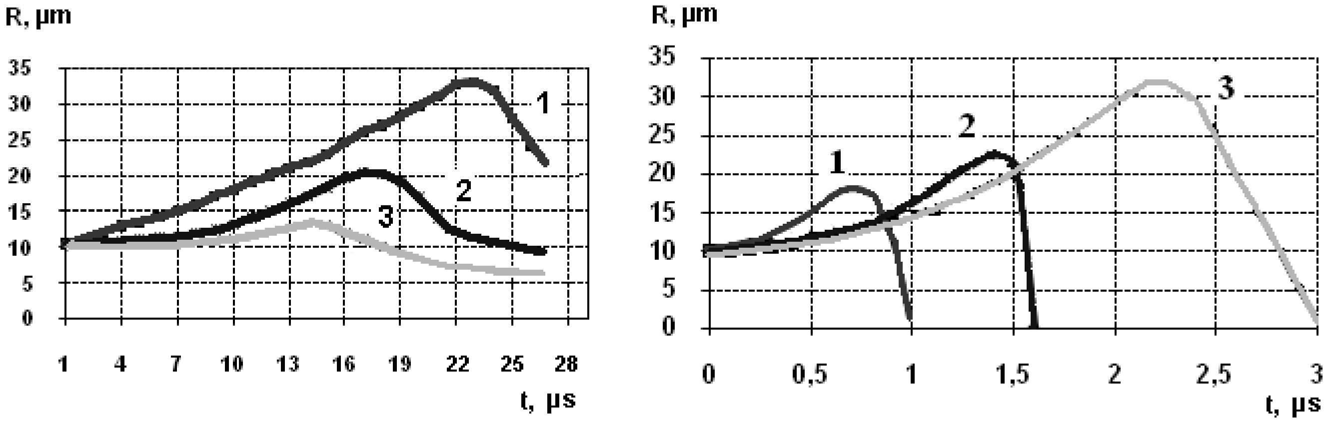
Dynamics of cavitation cavities in melts is described by the equation which physical sense will be, that the sum working on elementary melt volume pressure (hydrostatic, US and gas inside a cavity) is equal to zero, i.e. the cavitation cavity is in a condition of dynamic balance in any time interval. In view of viscosity расплава η the equation looks like [5]:

$$\left(R\frac{\partial^2 R}{\partial t^2}+\frac{3}{2}\left(\frac{\partial R}{\partial t}\right)^2+4\eta\frac{\partial R}{\partial t}\right)\rho+P_O-P_{US}\sin\omega t+\frac{2\sigma}{R}-P_g-\left(P_O-P_g+\frac{2\sigma}{R_O}\right)\left(\frac{R_O}{R}\right)^{3Y}=0\ . \tag{5}$$

The decision of the nonlinear differential equation (5) Runge-Kutta-Merson method for Sn-Zn solder melt viscosity 0,85 Pa·c with the initial sizes of cavitation cavities from 1 up to 50 μm, pressure of ultrasound **(**0,5–2)·10^5 Pa and US frequency 22, 44, 66 kHz has shown, that cavities in the size up to 5 microns pulse not slamming.

With increase in the initial size till 10-50 μm increases amplitude of pulsations of cavities and occurs them slam during 0,05 – 0,10 s with at pressure from above 0,15 MPa (Fig. 1, a). With growth of frequency with 22 up to 66 kHz the sizes of cavities decrease on the average in 2 times that results in reduction of cavitation intensity (Fig. 1, b).

To increase of cavitation efficiency apply gas saturation of melt when entered into melts gas bubbles in the sizes commensurable with resonant sizes of cavitation germs, i.e. (10-50)·10^{-6} m. The increase in the sizes bubbles conducts to their premature slam, and very small sizes complicate their cavitation growth in US field.



a б

Fig. 1. Cavities dynamics depending on pressure (a), kPa 1 – 200, 2 – 150, 3 – 100 and ultrasound frequency, kHz (b): 1-66, 2 – 44, 3 – 22

At bubbles slam concentrated in it is insignificant small volume kinetic energy it is transformed in part to a power pulse and in part in thermal energy, and from the center slammed bubble the shock spherical wave, the maximal pressure in which will be distributed, agrees Rayleigh on the distance equal of 1,587 radiuses from the center bubble, will make:

$$P=P_o\frac{R_o^3}{6{,}35R_r^{\ 3}}\ . \tag{6}$$

At $R_r = 1/10R_o$ the size of pressure near to a surface in 1575 times exceeds pressure inside a cavity.

Besides high local pressure at cavitation cavities slam there is a formation of local thermal micro fields. At adiabatic compression of volume of gas rise in temperature the is more, than value of a parameter of a polytrack γ is more than given gas. The temperature inside a cavitation cavity in any stage of its compression at adiabatic conditions is equal:

$$T\ /T_0=(R_0\,/\,R)^{\ 3(\gamma-1)}\ . \tag{7}$$

Believing, that γ=4/3 and temperature melt 250-300°C, and taking into account, that R can differ on the order from R_o aside reduction, we receive temperatures about 2600-3000°C

[6]. The high temperatures arising at cavitation increase chemical activity of solder, materials; accelerate processes of chemical interaction between them.

Influence of intensive ultrasound causes in melts micro-and macro streams which have a various direction depending on the form of a radiator, amplitudes of fluctuations, presence of obstacles in a way of distribution and other factors. The best conditions for acceleration of processes mass-and heat exchange, courses of chemical reactions of interaction of materials and solder create the generated macro streams having the focused direction from a radiator to a processable surface and stationary in time.

Theoretically hypothesis and experimental study prove that, in a US field, the tangential component σ_t of the vibration motion, which is proportional to the ultrasound power, is comparable with the surface tension value σ_0 in a no disturbed medium. In this case, the surface tension can be presented in the form $\sigma = \sigma_0 - \sigma_t$. Therefore, the physical properties of the phase interface change in such a way that the energy of the surface tension diminishes, the limiting wetting angle decreases, and the solder spreading improves. Therefore, metals with a lower value σ_0 should possess a better wettability under ultrasonic action at the same introduced power.

Experimental data presented in Fig. 2 shows that, for the aluminum alloy, the wetting force of the surface by the melt referred to the unit length of the wetted perimeter for Sn–Zn and Sn–Pb–Zn–In solders increases approximately by a factor of 5 at the cavitation pressure value in the solder of 1,5–2,0 kPa [7]. This more than 6 times exceeds the surface tension value for these solders at similar temperatures (0,5 N/m).

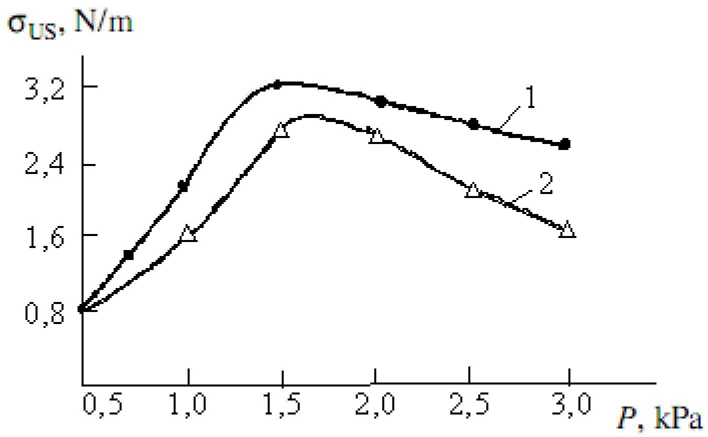


Fig. 2. Dependences of the surface tension at the melt–material interface vs. the cavitation pressure in the melt: 1– Sn–Pb–Zn–In, 2– Sn–Zn.

The solder spreading over the surface of a soldered material depends on the relation of the adhesion forces of the solder relative to the material surface and the cohesion forces that define the bond strength between the solder particles. The factor solder spreading can be determined from a condition of the relation of works of forces of adhesion and cohesion:

$$K_S = W_A / W_C = \sigma_{1,2}(\cos\ \theta + 1)/2\sigma_{1,2} = (1+\cos\theta)/2\,. \qquad (8)$$

The solder spreading stops when the equilibrium is reached between the surface tension values of the interacting media: $\sigma_{1,3}=\sigma_{1,2}\cos\theta+\sigma_{2,3}$, where $\sigma_{1,2}$, $\sigma_{1,3}$ and $\sigma_{2,3}$ are the surface tension values in the interfaces solder–gas, gas–solid, and solder–solid, respectively, and θ is the wetting angle. Thus, for the solder spreading, the following condition should be fulfilled: $\sigma_{1,3}>\sigma_{1,2}\cos\theta+\sigma_{2,3}$. This can be reached by decreasing the surface tension values $\sigma_{1,3}$ and $\sigma_{2,3}$.

Introduction of US vibrations in the melt intensifies the wetting process of the nonmetal material. The changes in the values of the coefficients of the surface tension, which occur in this case, to a lesser degree effect the $\sigma_{1,3}$ and $\sigma_{1,2}$ values, since the solid body and the gas phase are the least susceptible to the perturbations at the given introduced ultrasound power. Evidently, the greatest changes occur on the melted solder–soldered material interface, and this effects the value of the coefficient $\sigma_{2,3}$.

The action of the US field energy on the melt increases the diffusion coefficient and activates the nucleation process [8]

$$D' = D_0 e^{-\frac{E-\Delta E}{RT}} , \tag{9}$$

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

In the US field, the force F acts on the diffusing particles, and, under its action, the substance particles move with the average velocity

$$U = \upsilon F , \tag{10}$$

where υ is the particle mobility.

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

$$J = -D'\frac{\partial C}{\partial x} + UC_1 \cos\beta , \tag{11}$$

where C_1 is the concentration of mobile particles, and β is the angle between the vector of the force of the US field and the diffusion flux vector.

It follows from Eq. (11) that activation by the US field energy leads to an increase in the diffusion flux.

2.Experimental techniques

For processes flux–free soldering of details and electronic components fusible solders use US baths (Fig. 3) with excitation of all weight of solder and with local influence of ultrasound. In the first case it is possible to activate the big surface of a detail, and in the second – to concentrate US energy in small volume and to lower oxidation of solder in a bath.

To US baths with excitation of all melt weight cavitation intensity is maximal at the bottom and nun linear falls with increase in distance to the bottom, that it is necessary to take into account for components and details of the small sizes. At local US activation in a working zone is observed rather homogeneous cavitation intensity.

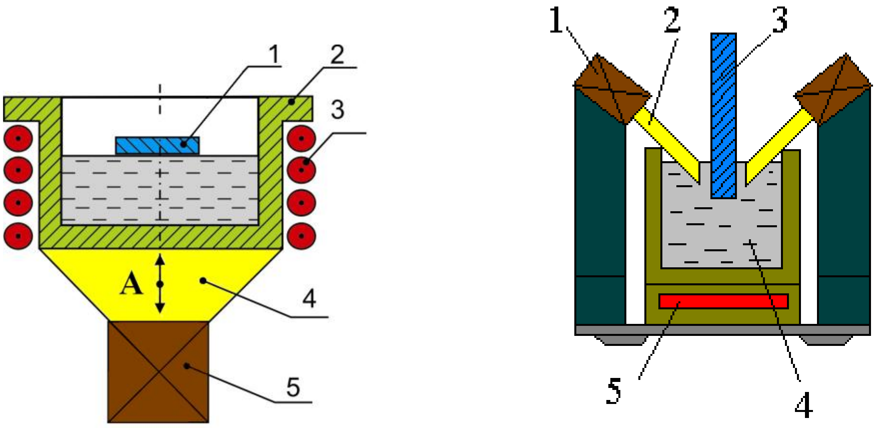


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Fig. 3. US bath with excitation of all solder weight (a) and local ultrasound input (b): 1-soldering detail, 2-bath, 3-heater, 4– radiator, 5 –converter

To local input of ultrasound in melts apply the radiators satisfying L_r/D<1,5-1,8, where L_r-length of a radiating surface, D–diameter of a wave-guide that provides a mode of radiation of a flat wave. The radiator represents a plate rigidly connected to an end face of a conic wave guide, the thickness satisfying a ratio h/λ < 0,1-0,15, where λ - length US waves that allows to consider it as the concentrated weight. The acoustic system will consist of the converter, a wave-guide and a radiator. The detail is immersed on distance of 3–5 mm from a surface of a radiator in melts [9].

At a choice such as a radiator it is necessary to take into account, that in the step concentrator there is a significant concentration of pressure in a place of a joint of the steps, resulting to heating and breakage. Therefore apply conic concentrators or such as Fourier which have smooth change of pressure and rather high factor of amplification.

At an arrangement of a radiator on depth h in a bath with the fused solder the local zone intensive cavitation in which occurs tinning details is created. Parameters of process: US frequency 42±1 kHz, a target voltage of the generator 50–60 V, that there corresponds to amplitude US vibrations 12–15 µm, temperature - 230±5^{O}C.

The effect of rise of solder on a surface of a wave guide is used in the device automatic US soldering glass–ceramic capacitors (Fig. 4) which contains two US oscillatory systems consisting from magnetostrictor converters 1, acoustic transformers of elastic fluctuations 2, wave guides 3 which working ends of the special form are shipped in a bath 4 with solder 5. For fusion of solder and maintenance of necessary temperature of the soldering the heater 6 is used. Wave-guides of the special form change in a half-wave resonance that results in occurrence of two maxims and unit of fluctuations. The zone of the top maximum located above of a level of solder in a bath, is the worker, as provides an opportunity of automation of the soldering of the capacitor 7.

At occurrence of force of wetting to US field of melts of solder rises on height H on a varying surface of a wave guide, to determine which it is possible proceeding from a condition of balance of capillary pressure of a meniscus of solder under action US fluctuations and pressure of a column of solder:

$$H = \frac{2\Delta\sigma_{1,2}\cos\theta}{\rho \cdot g \cdot a} \quad , \qquad (12)$$

where σ_{12} – a superficial tension of solder, *a* – backlash width, ρ - density of solder, *g* - acceleration of free falling forces.

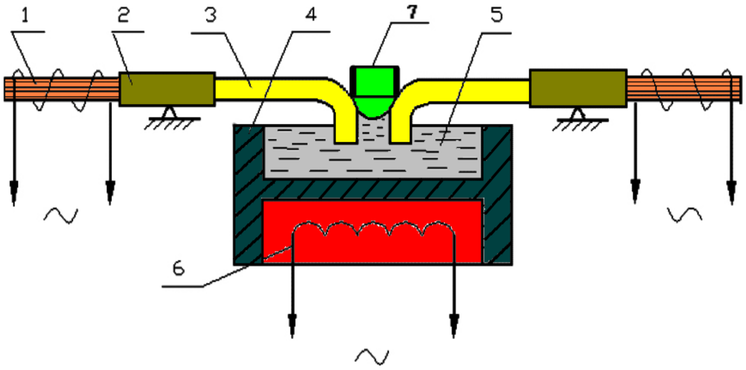

Fig. 4. Scheme of US soldering glass–ceramic capacitors

Automatic installation US soldering of electrodes glass–ceramic capacitors from aluminum foil submit preparations to a zone of oldering with the help of a rotor with clips with a speed 50–100 mm/s. In acoustic systems are applied magnetostrictor converters with resonant frequency 44±1 kHz, in bath–solder (Sn-15 %, Zn-65 %, Cd-20 %) at temperature 430-470°C.

3. Experimental results and discussion

Amplitude US fluctuations 3±0,5 μm are threshold for cavitation processes in melt, is lower which there is no wetting and adhesion of solder to a surface of a material and chemical interaction between them. 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 a material, causing its heating and destruction, and at parallel in the greater degree is distributed in solder lengthways soldering surfaces and spent for the cavitation phenomena.

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 (Fig. 5). High durability of connections is reached at duration of ultrasound 15-20 s. At greater time there is a reduction of durability of soldering connection due to erosion of the 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±1s.

At US soldering of aluminum by solder 70Sn-30Pb in the environment of argon during 4 s the greatest durability of connections (0,25 MPa) depending on temperature of the soldering it is achieved for the samples chemically cleared before the soldering in an alkaline solution [10]. A little bit smaller durability had samples with coverings solder or tin.

For processes US soldering in electronics are investigated lead–free alloys on the basis of tin: double Sn-Zn, Sn-Bi, threefold: Sn-Bi-In, Sn-Bi-Zn, Sn-In-Ag, Sn-Sb-Zn, Sn-Sb-Ag and a quarter alloy: Sn-Zn-In-Sb [3] which have temperatures of fusion in an interval 135-220^0 C. Additions Ag, In and Bi are expensive, and Zn forms at the soldering on air a plenty of slag. At formation of connections can be formed intermetallides, lowering resistance of weariness. Mechanical durability of soldering connections depends on structure of solder (Table).

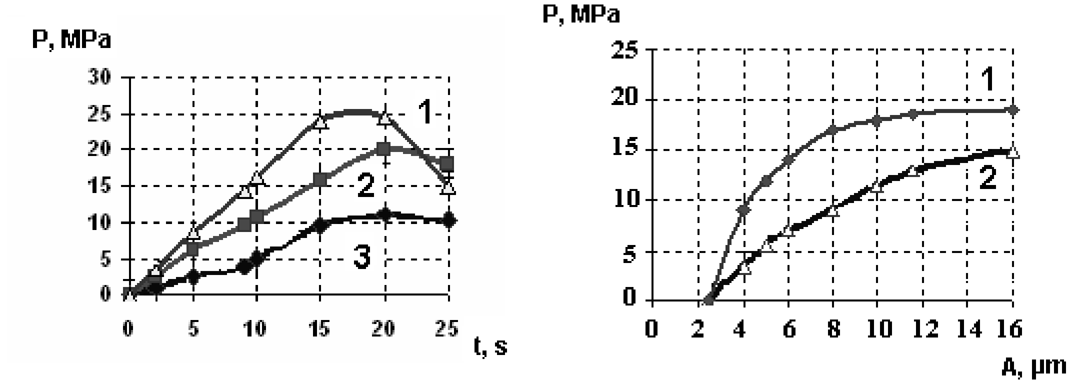

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Fig. 5. Relationship between durability of soldering connections and time (a), amplitudes and a kind of fluctuations (b): 1–parallel, 2–longitudinal, 3-turn

Table
Mechanical durability of soldering connections

Solder composition, %	Solder temperature, ^0C	Strength, MPa
Sn-61, Pb-39	230-250	0,25–0,5
Sn-59, Ag-2	220-240	3,0–5,0
Sn-10, Sb-2, Pb-88	268-285	5,0–7,0
Sn-38, Zn-4, Cd-58	180-190	4,0–6,0
Sn-90, Zn-10	220–225	8,0–10,0
Sn-80, Zn-20	240-250	10,0–15,0
Sn–78, Zn-10, In-10, Sb-2	220-230	18,0–20,0

Dependence of durability of connections with a surface of a ferrite material on time and temperatures (Fig. 6) is established. At small time US processing (5-10 s) durability of connections low as processes of physical and chemical interaction of components of solder with oxides on the ferrite surface have not time to proceed.

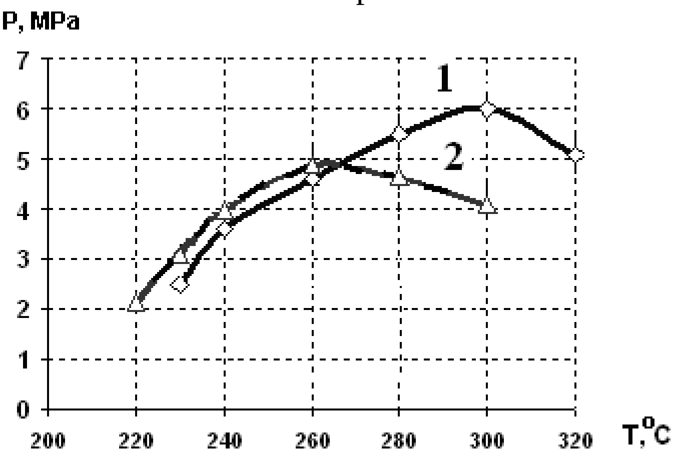

Fig. 6. Relationship between durability of connections and temperature:
1 – Sn-10Zn, 2 – Sn-39Pb

The maximal durability for solder Sn-Zn is achieved at duration of processing 15-20 s. With increase in time of processing durability is reduced owing to development of fatigue processes in the ferrite. The interval of temperatures 280-300 ^{O}C when durability of connections makes 5–6 MPa is optimum. The increase in temperature from above 300 ^{O}C results in decrease in durability owing to oxidation of solder.

4. Conclusion

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 metallizations and 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.

At local input US fluctuations in melts appears an opportunity to concentrate US energy in small volume and to lower oxidation of solder in a bath. US fluctuations parallel to a processable surface, are preferable to increase of soldering connections durability, maintenance of high stability of processes and reduction of mechanical influence by processable products.

At a choice of solders for US flux–free soldering and tinning various materials it is necessary to take into account their solderability, chemical affinity of connected materials and an opportunity of formation of qualitative connection according to the diagram of conditions. Application lead–free solders with additives Zn, In, Ag increases adhesive activity melts and reduces their oxidation at US soldering.

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