ULTRSONIC SOLDERING IN ELECTRONICS

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Abstract Ultrasonic (US) soldering of electronic components, as an alternative to flux soldering, is environmentally friendly, improves the quality of soldered connections at the mounting elements after long-term storage, and allows to use lead-free solders. Methods of ultrasonic solder melt activation, lead-free solders in (US) and glassceramic capacitor metallization processes have been investigated.

Keywords: Soldering; Ultrasonic; Electronic components.

1.Introduction

Soldering problems in modern electronics have been widely developed for a number of reasons:

- the microminiaturization of components and functionally complicated microelectronic devices, in particular, very large scale integrated circuits allows packaging densities of 10 million per cm^3, while the soldering methods do not provide such high connection density through all the volume of the item;
- assimilating electronic assemblies of the fifth generation [1] – multichip modules (MCM), made on ceramic, silicon or metallic substrates to which unpackaged crystals are joined by soldering of upturned crystals with solder contact columns, requires density of assembly connections up to 200 per cm^2;
- soldered connections have found wide applications in mounting electronic equipment; however, they are not reliable enough. Inadequate automatization level and application of manual labour in some operations lead to the situation when 50-80 % of all equipment failures happen due to assembly connections defects, failure detection and correction cost in a assembly stage being 100 times less than during equipment tests [2];
- environmental aspects of soldering (the replacement of resin-containing fluxes requiring washing by water soluble or non-strippable fluxes, and also the replacement of toxic lead by other components in solder composition) has increased recently.

Recent processes developed for mass soldering in electronics are activated by concentrated energy flows such as ultrasonics, high-frequency, infrared, laser etc., ensuring local and mainly contactless effect of a heating source on parts to be soldered. In addition activation of physical-chemical processes create new possibilities of joining materials with diverse chemical structure and properties.

For US activation either dip soldering in a bath or manual soldering are used. Applying modern electronic US oscillation sources makes US soldering a reliable, environmentally friendly process eliminating flux application [3].

Toxicity of lead is the main problem in developing new solders. In the United States legislation, there are at least three laws stipulating or eliminating application of lead in electronics and other industries [4].

In research for electronics engineering application into lead-free solders have been investigated triple tin-based alloys(Sn-Bi-In, Sn-Bi-Zn, Sn-In-Ag, Sn-Sb-Zn, Sn-Sb-Ag etc.) which have a narrow crystallisation range 135-183^{0}C. However, Ag and In additives are expensive, Zn produce slag when soldering in air. The majority of solders investigated have had intermetallides reducing fatigue resistance [5].

Flux soldering of hybrid microcircuit substrates by tin-indium solders has essential faults due to residual flux. When soldering substrates in packages, it is important to supply a solid surface contact between the substrate and the metal basis, as the cavities and/or flux impurities sharply reduce heat transfer from the chip to the metal body, and reduce the soldering strength. Besides, flux impurities cause corrosion, which may result in failure. An alternative to the flux soldering is the US soldering [6].

In the present paper have been investigated US flux-free lead-free soldering processes have been investigated.

2.Experimental techniques

For US activation an alternative is to use baths wich provide excitation of the whole bulk of the solder (Fig.1, a) have been used local effect of ultrasound by means of an oscillator at the bottom of the bath (Fig.1, b). In the first case, it is possible to activate a large surface of the part. In the second case, there is a concentration of US energy at the end of the horn and a decrease of solder oxidation in the bath.

When selecting the horn it was taken into account that in a step design there is an appreciable concentration of stresses at the joint of stages leading to fast heating and failure. The least stresses are observed in an exponential horn, however, to obtain a high gain factor it is necessary to have considerable ratio of cross-sectional areas between the basis and the working end face. A Fourier type horn has smoother changes of stresses and a high gain factor. By numerical methods the Fourier concentrator form equation has been obtained [7]:

$$y = 22.845 + 0.209x - 5.548x^2 + 1.958x^3, \quad (1)$$

where y is the section diameter (mm); x the distance from the reference point.

To reduce US energy losses, the fluoroplastic outcome of the horn is used with a tinning pot. This allowed an increase the oscillation amplitude at the soldering zone and also reduced thermal energy transfer from the solder to the magnetostrictor.

For local input of oscillations piston oscillators with ratio L/D<1.5-1.8 where L is the length of the emitting surface, D is waveguide diameter have been used, which provides a plane wave radiation. The oscillator represents a plate in the form of a rectangle rigidly connected with the end face of the conical waveguide. The oscillator thickness is determined from the ratio h/l < 0.1-0.15, where l is the US wavelength, which allows to consider it as concentrated mass [8].

The acoustic system (Fig.2) consists of a magnetostrictor 1, a waveguide 2 and an oscillator 3. The element was immersed into the solder 4 at a distance of 3-5 mm from the oscillator surface.

To investigate US metallization by solders an experimental installation has been developed [9]. Fig.3 shows block-scheme of the installation for US metallization. The installation includes an US oscillation generator (USG), an acoustic system, a heating device (H), an electronic frequency meter (EFM) and a voltmeter (EV) and a vibration meter (VM). The acoustic system serves as a source of longitudinal oscillations spreading along the waveguide. The system consists of a magnetostrictor 2 joined coaxially to a waveguide 1 parallel to its axis and an oscillator 4. To excite oscillations parallel to the work surface 5, two magnetostrictors 3 are used, joined to the waveguide perpendicularly at a distance $\lambda/2$, where λ is ultrasonic wavelength.

A continuous control of vibrations is implemented with a piezoelectric sensor of amplitude 6 [10]. The heating device contains a resistance heater on which power supply PS, temperature control device TC, and samples being investigated are mounted. The process parameters are as following: the frequency of US oscillations is 42.1 kHz, output voltage of the generator is 50±5 V, which corresponds to an amplitude of US vibration at 12±1 μm, interaction zone temperature is 230±5 °C [11].

To evaluate the cohesive strength of the solder with the sample surface, a 100 kgf tearing machine was used. In order to increase accuracy of measurements of pull-out force, and also to eliminate impact loads, samples were loaded in two stages: first at a speed of 1.5-2.0 kN/min and then at a speed of 8.8 kN/min; a special device with a calibrated spring was applied to achieve this.

When flux-free soldering microplates the body of the microassembly 1 was installed between two acoustic systems located coaxially against each other (Fig.4). For reliable acoustic energy transfer into the body of the microassembly the waveguides 2 of acoustic systems were pressed to the body by efforts F1 ensuring a rigid contact of all links.

The power of US oscillations came to the magnetostrictor windings 3 from two generators. The microplate is pressed to the body by an effort F2 through the solder gasket. The body was heated up by two infrared lamps 5. In the event of coincidence of frequency of both generators the superposition of US longitudinal waves excited in the body, provided a node of oscillations at the centre of the body. However, under real experimental conditions some incongruity of oscillation frequencies is inevitable, constant displacement of the node of oscillations is inevitable too, by virtue of it the process of microplate wetting is hindered.

In order to maintain of effective destruction of oxide films and uniform wetting of the whole substrate surface US oscillation frequency of the generators changed by a quantity appropriate to λ/8. The intensity of sound pressure at the mean operating frequency of magnetostrictor 20 kHz and at the an oscillations amplitude 10 μm is18.3 W/cm^2.

3.Experimental results and discussion

3.1.Ultrasonic soldering

Research of relationship between cohesive strength of solder with aluminium alloys and time of US processing at various directions of oscillations has shown that at shear oscillations the cohesive strength is higher by 10-20 MPa than at longitudinal oscillations with no dependence on the exposure time (Fig.5). The maximum cohesive strength between the solder and the material surface was observed during the time of oscillations 15-20 ss and it reached 20-24 MPa. At a smaller exposure time, the processes of destruction of oxide films and wetting of the whole material surface do not take place. At a longer exposure – the reduction of cohesive strength between the solder and the material happens at the expense of erosion of the material being metallized and oxidation the solder itself. The maximum cohesive strength between soldered connections and the surface was observed at the parallel oscillations amplitude 10-12 μm and was 24 MPa at exposure time 15±1 ss [12].

The amplitude of US oscillations at 3±0.5 μm is the cavitation threshold processes in a melt, when there is no solder adhesion to material surface and chemical interaction between them. If the amplitude is higher than 15 μm the cohesive strength decreases as the dynamic impulses cause degradation of near-surface layers and sufficient oxidation of the solder melt.

For longitudinal oscillations a significant part of energy is transmitted into the material, causing heating and destruction, where for parallel oscillations mainly spreads in the solder in parallel to the soldered surface and is spent for the cavitation phenomena near the interaction zone. Process of material wetting by solder is also improved at the expense of rubbing effect.

US tinning was used to prepare the electronic components for the soldering because some of them had lost solderability after long-term storage. This has avoided the need to apply active fluxes and mechanical stripping and to increased labour productivity (Table 1) and provide excellent solderability [13].

US tinning in baths involving general excitation of melt mass the cavitation intensity is maximum at the bottom which reduced at the distance to the bottom increases. This must be taken into account for elements with pins by the size of 15-20 mm.

For local US activation at the tinning zone, quite a homogeneous cavitation intensity (Fig.6) is observed.

US tinning process control is realized by a computer-aided system based on the personal computer PC/AT and controlling means [14].

The process of US flux-free soldering microplates into microassembly packages by a Sn-In solder has been investigated. The microplates were made of polychloride, size 48x60 mm^2 with coating of gold 3 μm or tin-bismuth alloy (6 μm), and the packages were made of duralumin, size 110x54x20 mm^2 with multilayer electroplated coating: nickel (15 μm), cooper (6 μm), tin-bismuth (9 μm).

Studies of the relationship between substructure wettability degree and time of US oscillations have shown that good wettability is reached within 15 seconds. Thus the best wetting characteristics have been obtained for tin-bismuth electroplated coating. This is explained by best solder castability, in comparison with tin-lead one, and also while soldering tin-bismuth coatings the formation intermetallide wich worses the process of wetting (as in case of gold coatings) not occur.

The relationship between a substructure wettability degree and pressing force to the body is shown on Fig.7. The analysis of relationship shows that an optimum load for substructures is 2-5 N. This is dependent upon solder viscosity in the US field and external friction processes between a liquid solder and both surfaces of the substrate and the body.

3.2.Ultrasonic metallization

The physical-chemical properties and structures of metallization by solders with glass-ceramic materials have been investigated. The glass-ceramic material structure contains glass as group of oxides SiO_2, BaO, PbO, (including oxide components Na_2O, K_2O, TiO_2 in quantity 20-30 %) and ceramic materials in terms of oxides $SrTiO_3$, $CaTiO_3$ and TiO_2. They are used in electronics for manufacturing monolithic constant capacitors, both ordinary and integrated. The solders in terms of Sn not containing Pb and including metal components Zn, In, Sb, Ag, and standard solders containing Pb have been investigated.

The bonding strength between various solders and glass-ceramic materials at US soldering depends on the solder composition (Table 2).

The structure of ordinary tin-lead solder (Sn-Pb type) represents a mechanical mixture of lead and tin grains of various size. The grains are soft and plastic and have tetragonal body-centered and face-centered cubic lattices. The metals belong to inactive group, i.e. they have low chemical affinity and adhesive activity with materials to be soldered [13]. At US soldering these sorts of solders have high oxidation and low bonding strength.

Adding Ag and Sb into solder structure increases their hardness and reduces granularity.

The Sb crystals have abrasive grain structure which increases abrasing effect on oxide film surface and to some extent increases bonding strength (Fig.8).

Solders of eutectic system Sn-Zn have very hard acicular zinc crystals insoluble in tin, which considerably increases solder abrasing effect on oxide films and a number of cavitation events under US oscillation. In addition, Zn belongs to a group of active diffusive mobile metals, and it causes chemically react with most soldered metals.

The eutectic system Sn-In is a mechanical mixture of indium and tin grains. Indium increases solder wettability (as it is oxidation resistant); it is a noble metal and has high plasticity. However, it is fusible and expensive, which hinders its application in soldering.

Good results have been obtained in the preparation special solders, good outcomes have been obtained at ultrasonic intermixing alloy additions at the expense of microflows.

The solder has fine-grained structure, some components are spread throughout the volume of solder.

At optimum US metallization modes, the cohesive strength between glassceramic and solders of systems Sn-Zn and Sn-Zn-In equally depends on the degree of glass-ceramic surface roughness (Fig.9, a). When the roughness decreases, the cohesive strength between the glassceramic and the solders is reduced, this can be explained by decrease the contact area of the solder with the glass-ceramic. Where rougher microrelief is, there are fatigue processes and local microcracks in microasperity cavities that are good stress concentrators.

The study of the influence of cavitation pressure arising in liquid solder on the cohesive strength between both solders and glass-ceramic has shown that the maximum value of the cohesive strength corresponds to cavitation pressure of surface roughness from 1,5 up to 2,5 kPa (Fig.9, b). If the cavitation pressure is less than 1,0 kPa, it is insufficient to fill all microcracks by a liquid solder uniformly and fast.

Dielectric loss tangent measurement method is one of the structural sensing methods for studying junctions with ceramics. The method allows indirectly to confirmation of the availability of a transient zone in a junction. For this purpose glass-ceramic samples have been grounded by diamond grinding wheel up to thickness 2,0; 1,5; 1,0; 0,8; 0,6; 0,4 mm, then metallized by a solder of the system Sn-Zn-In at the temperature 270±5 ^{0}C within 10 ss. Capacity and Q-factor of samples were measured on frequency 10 MHz by standard devices, and the dielectric loss tangent was calculated through the known techniques. When the sample thickness decreased, the sample capacity changed insignificantly, while tgδ increased almost twice, which may indicate availability of a transient zone, or significant solder infiltration into the glassceramic. The microstructural research of US junctions (by metallographic MIM-8 and electron microscope EMMA-2) has shown, that in the junction along the glassceramic surface a thin intermetallide zone is observed. The intermetallide is up to 3 microns and it forms in a solder boundary layer that is immediately contiguous to the glassceramic surface.

Besides availability of the intermetallide zone, glass-ceramic surface wetting by indium is clearly marked in the photograph of microsection of the junction. Spreading along the solder boundary with the glass-ceramic, large indium grains moisten the glass-ceramic surface and thus increase the junction strength. At the same time brightly expressed diffusion zone between the solder and the glassceramic, and solder infiltration into a depth of the glassceramic are not marked.

X-ray analysis of metal-glass-ceramic junctions, made by the installation DRON-2 using radiation CuKα, has revealed a number of features of junction formation mechanism. The X-ray picture analysis of pure source materials (glass-ceramic and solder) has shown: (1) lines appropriate to the oxides $2PbO\cdot SiO_2$, $BaO\cdot SiO_2$, formed during glassceramic mass sintering; (2) availability of zinc oxides ZnO and ZnO_2 in the solder formed during solder preparation. When decoding X-ray picture of the junctions, lines appropriate to complex intermetallides $Pb_2Zn\cdot\cdot Si_2O_7$, $BaZnSiO_4$ and oxide In_2O_3 have been revealed, which demonstrates oxidative character of the chemical reactions.

The glass-ceramic chemical analysis structure shows that lead and barium oxides have the least glass-ceramic stability in amorphous phase. However, interaction between these oxides and solder components will only occur if it has thermodynamic possible. The thermodynamic calculations of the most portable ways for obtaining intermetallide $Pb_2Zn\cdot\cdot Si_2O_7$ and $BaZnSiO_4$ (made according to Gibss-Gelmgolz equation) have shown that the chemical reaction of complex intermetallide formation is possible at the temperature 600 K and higher and reactions:

$$BaO + 2SiO_2 + ZnO = BaZn \cdot SiO_4 \quad (2)$$

Thus, the isobaric potential of the chemical reaction $\Delta Z = -3.7$ kcal.

When US oscillations affect molten solder, local thermal microfields arise through cavitation phenomena developing strongly at the boundary between solder and glass-ceramic. Temperature in the microfields can reach up to 10^3 °C. Complex oxide compound formation arises at the expense of oxide film destruction on older surface and intensive solder turbulization. The formation is the result of oxidation reaction between double oxides of glassceramic amorphous phase (having smaller thermodynamic stability) and oxides of a diffusive mobile component of solder – Zinc of the following type:

$$Me_nO + Me_{D1}Me_{D2}O_2 \rightarrow Me_{D1}Me_nMe_{D2}O_3 \ (3)$$

4. Conclusion

Activating soldering processes by US energy permits flux-free soldering and tinning of most metals and alloys used in electronics. Flux-free soldering is more economical because operations requiring time and material costs, such as fluxing and clearing, are excluded. In a number of cases, flux-free soldering is a necessary condition of internal mounting and sealing of microelectronic devices. When using US soldering and metallization it is possible to join such materials with small solderability as nickel, aluminium and magnesium alloys as well as materials without solderability: ceramics, glass, ferrite. It creates a significant saving of precious metals metallized on dielectric surfaces of electronic components.

It has been determined, that for US soldering processes the application of oscillations spreading in parallel to the work surface (especially at a local input of energy into the interaction zone) is preferable from the point of view of increasing soldered connection strength, maintenance of high process stability and decreasing mechanical effect on the work items.

The results obtained make it possible to conclude that when the active mechanical factor – ultrasound is present, a character of the junction formation process is thermochemical. The effect ultrasound on a solder greatly intensifies the wetting processes of non-metallic materials and also to promotes processes of chemical interactions between solder components and the amorphous phase of glass-ceramic due to thermal effects.

Application of lead-free solders with the components Zn, In, Ag increases solder adhesive activity and reduces their oxidation in the ultrasonic soldering.

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