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Research Article

Local High-Frequency Heating in Electronics Technology

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Abstract: Modeling and investigation of HF electromagnetic heating in induction devices with unclosed magnetic circuit has allowed to optimize heating speed in local zones of formation of soldering connections and to improve their quality due to joint action of superficial effects and electromagnetic forces. For all magnetic materials is nonlinear decrease in heating power depending on frequency of HF. Installed the optimal parameters of HF heating for soldering electronics modules by inductor with open-ended magnetic conductor.

Keywords: Induction heating, High-frequency, Electronics technology

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1 Introduction

Importance of energy saving in electronics technology forces to 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[1]. HF electromagnetic heating allows to activate solder and to improve wetting solderable surfaces.

There is a big variety of induction heating devices designs. To through heating conducting bodies of round, square and rectangular section, solder balls in electronics modules apply circular type inductor, flat bodies - inductors with magnetic gap or as flat spirals[2]. For heating rings, small payments, wires use induction devices with closed and unclosed magnetic circuit. Using eddy current induced HF heating for the solder reflow of area array packages is feasible. The generated temperature in the solder balls would depend on the size of the solder balls. This characteristic may be used to perform selective soldering of Flip Chip and BGA packages[3]. Quality of soldering connections depends on HF frequency, speed of heating, adjustability of heating in time and on section solderable details[4].

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. Investigation of HF electromagnetic heating has allowed to optimize heating speed in local zones of soldering connections formation and to improve their quality due to joint action of superficial effects and electromagnetic forces.

2 Modeling the distribution of the electromagnetic fields

For heating of small sizes details use induction devices with the closed and open magnetic circuit (Figure 1). In the first case the heated detail takes place outside of a magnetic circuit, embracing its outdoor surface, and in second - in positive allowance of magnetic circuit. For induction heating systems effects of affinity, ring and concentration of a magnetic field are common. But it is possible to create power lines concentration of a field on the set heating surface of a conducting body using magnetic conductor of the certain design.

Solder balls on bonding pads form also induction heating in an electromagnetic field ring inductor (Figure 2). The flashing off of solder at the expense of selectivity of induction heating allows to avoid the negative effects inherent in traditional methods. Before an induction flashing off balls of solder Sn3, 5Ag in diameter of 0.76 mm are fixed on bonding pads of a pay from glass-cloth-base laminate FR4 in the thickness of 0.4 mm[5].

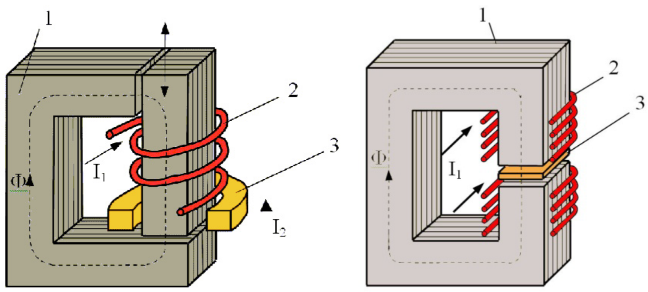

Figure 1. Induction devices with the closed and open magnetic circuit: 1 - magnetic circuit, 2 - winding, 3 - detail

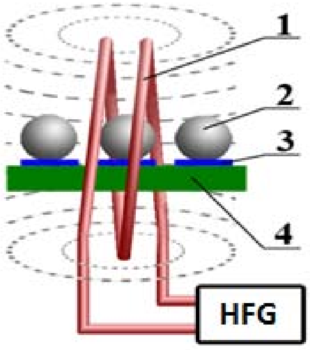

Figure 2. The circuit of induction heating solder balls: 1- ring inductor, 2 - ball, 3 - the bonding pad, 4 - PCB

For effective work of the induction system on the magnetic circuit it is necessary to optimize frequency and amplitude of drive current in a winding, and also to get distribution of eddy currents in the heated standard and variable magnetic-field in space. For this purpose modern applied packages of modeling are used, which based on methodology of eventual elements. A method is based on approximation of continuous function (in physical interpretation: temperature, pressure, etc.) a discrete model, that is built on the great number of piece-continuous functions, certain on the eventual number of the sub regions named eventual elements.

The investigated geometrical area is broken up on finite elements so that on each of them an unknown function is approximated by a polynomial. ANSOFT MAXWELL allows the calculation of the harmonic electromagnetic and electric fields, and also transients. The presence of the module of calculation of distribution of eddy currents allows modeling the induction heating.

Methodology of modeling of distribution of the electromagnetic fields includes: creation of geometrical model, task of properties of material, source of excitation, border terms, tuning of options of calculation and net, decision of task of distribution and analysis of results. In the package ANSOFT MAXWELL the geometrical model of induction device (Figure 3, a) is built, and it included next component parts:

1. Material of magnetic circuit is ferrite F- 86, which properties were selected from ANSOFT MAXWELL library.

2. Excitation coil with the number of coils 25–50, winded on magnetic circuit and realized in models as two hollow cylinders with the thickness of walls, to the equal height of winding. Applied to them current excitations is given in the section of the cylinder indicating the amp / turns and directions.

3. Border terms: the field of H is continuously at crossing of borders of objects; Neumann condition on the boundary of modeling - field H does not cross the boundary of the simulation.

Then the parameters of construction of net of finite elements are set and breaking up of model is produced on finite elements (Figure 3, b).

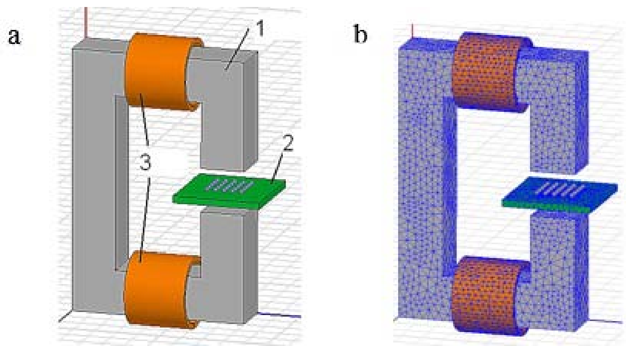

Figure 3. Induction device (a) and finite element model (b): 1 - magnetic circuit, 2 - PCB with ball grid array, 3 - excitation coils

ANSOF MAXWELL is based on fundamental Maxwell equations of electromagnetic field. Skin effect is significantly affects at the efficiency of the induction heating, because skin depth is determined by the distance, at which value of eddy currents reduce to 1/e from original value:

$$d_s = \sqrt{\frac{2\rho}{\mu\omega}} = 503\sqrt{\frac{\rho}{\mu_r f}}, \quad (1)$$

where ρ - specific electrical resistance, μ - magnetic permeability, μ_r - relative magnetic permeability, ω - angular frequency, *f* - frequency.

The surface density of the active power, released in the metal for the period *T* is given by[6]:

$$P_{cp} = \frac{1}{T}\int_0^T E(0)H(0)dt = \frac{H_0^2}{2\Delta\sigma} = 2\cdot 10^{-3}(I_\partial W_0)^2\sqrt{\rho\mu f}, \quad (2)$$

where *E*, *H* - intensity of electric and magnetic fields, respectively, *I* - eddy current, W_0 - winding density.

Convectional heat exchange in melted balls wasn't taken into account in model because it is not essential. At the same time the latent heat of solder phase transition and isotropy of materials was taken into account. Equation for calculating the temperature field is given by:

$$\rho c_P \frac{dT}{dt} = \lambda(\nabla^2 T) + q, \quad (3)$$

where ρ - density of the material, C_p - specific heat, λ - thermal conductivity, q - energy density of the heat source, which is generated by eddy currents.

Boundary condition for the heated surfaces:

$$q = \beta(T - T_0), \quad (4)$$

where β - density of thermal flow, *T* and T_0 - surface temperature and environment temperature.

Density distribution of the eddy currents for induction heating copper and steel plates was obtained with the following conditions: thickness 1mm, overlap factor is 4, excitation coils current from 4 to 10 A, frequency range 500 kHz -1 MHz (Figure 4). The analysis of dependences shows that the highest power of heating is characteristic for metals with the highest conductivity, i.e. copper. The density of eddy currents increases with the height of frequency, as a skin-effect affects stronger. The increase of frequency higher than 950 kHz does not result in the substantial increase of efficiency of heating. It is possible to manage speed of heating, changing the size of current in excitation winding[7].

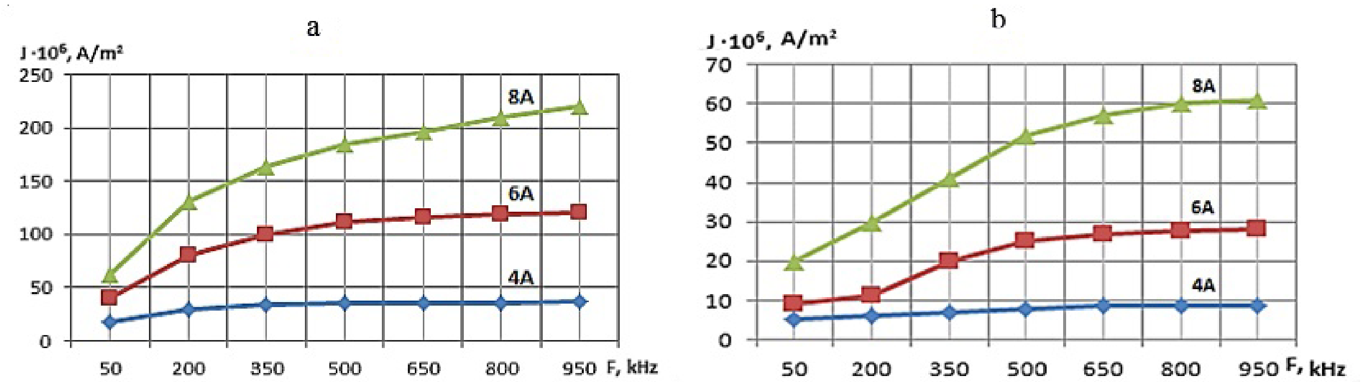

Figure 4. Eddy currents density vs. frequency and current for a copper (a) and steel (b)

For the induction heating of marbles of solder of Sn-Pb by a diameter a 0.8 mm on PCB from the fiberglass of FR4 in the range of frequencies 500 kHz - 1 MHz and 2 A drive current was achieved the distribution of magnetic-field in space and eddy currents is in the marble of solder. Results evidently show the role of magnetic circuit as a concentrator of electromagnetic energy, as the basic part of energy of the electromagnetic field is concentrated in area of gap (Figure 5). The small losses of electromagnetic energy are observed in the places of bend of magnetic circuit, therefore in the construction of magnetic circuit it is necessary to envisage rounding of direct corners for minimization of losses.

The results of distribution of eddy currents in the marble of solder confirm the presence of

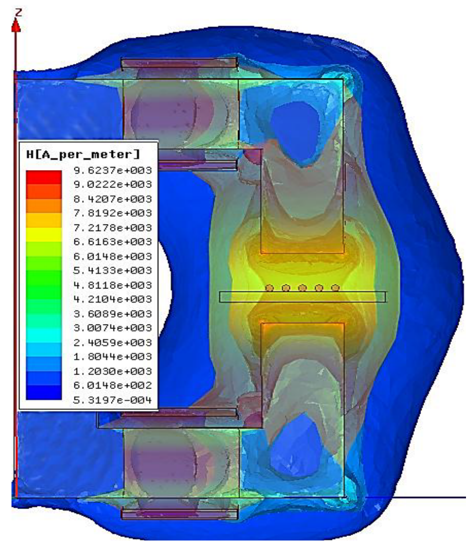

Figure 5. Distribution of magnetic-field intensity on frequency 800 kHz

skin-effect. With the increase of frequency there is expulsing of eddy currents to the surface of marble of solder and increase of numeral value of current density. Thus, frequencies in a range from 500 to 1000 kHz are suitable for realization the induction soldering in the gap of magnetic circuit. According to the Figure 6 the depth of eddy currents penetration is 0.1mm, which allows to use frequencies more than 800 kHz to control the geometry of the soldered connection.

3 Experimental HF heating techniques

For local HF heating the HF generator was connected to a winding inductor with conductor of ferromagnetic material. In a gap of magnetic conductor the connections on PCB were heated. Frequency was controlled on an output of generator with accuracy 0.1 kHz; amplitudes of a voltage and a current - by universal digital voltmeter; time - by timer with accuracy 0.1 sec; temperature - by device 6 with accuracy 1 °C.

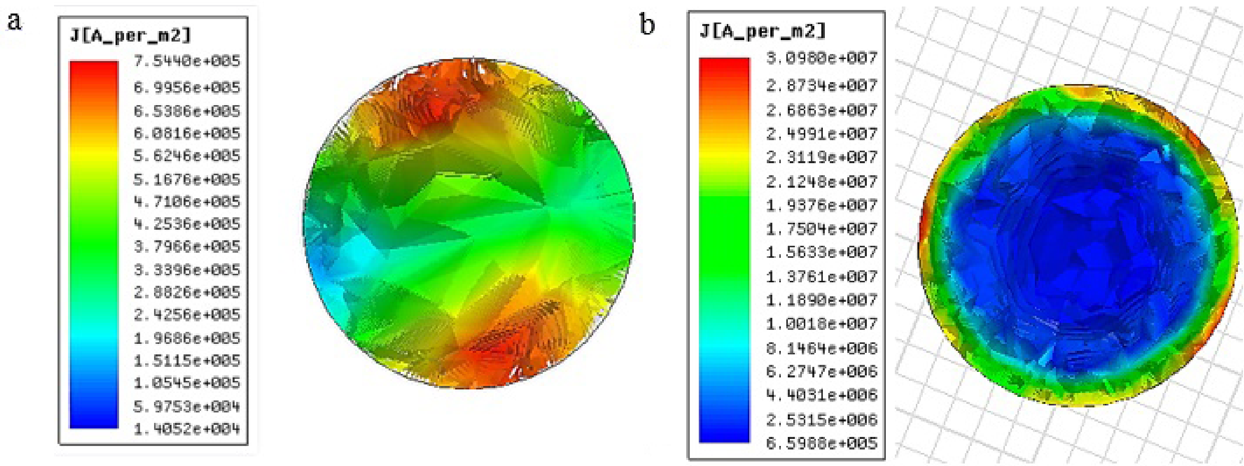

Figure 6. Distribution of eddy currents in the marble of solder on frequencies: a - 100 kHz, b - 800 kHz

Materials with low electrical conductivity at overlapping gap optimum are heated up with a speed up to 50˚c/s. Heating speed of details in a magnetic gap falls with growth of frequency, because the intensity of an electromagnetic field decreases. For improvement quality of soldering connections due to increase of the solder spreading area and filling of capillary gaps with it in connection from the moment of the beginning solders spreading before the termination of the soldering details informed low-frequency vibrations by submission of an alternating current by frequency of 50–400 Hz and amplitude 7–10 A in inducing winding. The amplitude of vibrations of details made 0.5–1.0 mm.

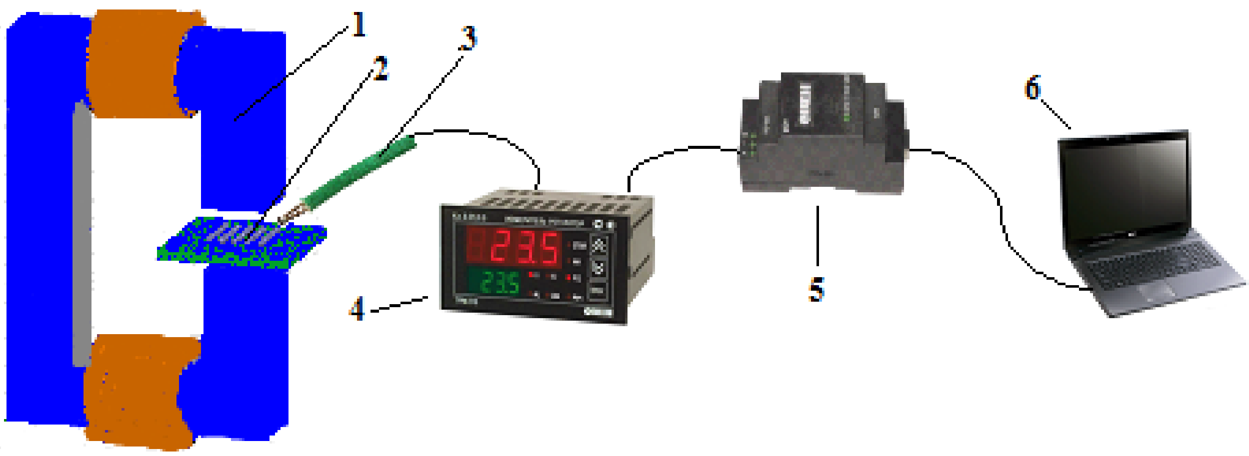

Figure 7. Local HF heating schemes: 1 - inductor, 2 - electronic module board, 3 - temperature sensor, 4 - temperature measuring instrument, 5 - automatic interface converter, 6 - computer

4 Investigation and optimization local HF heating

The analysis of HF temperature profiles of solder balls (Figure 8) has shown that growth rate of temperature substantially depends on heating power and can reach 40°C/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.

But at such speed of heating it is difficult to provide a flat site at solder fusion temperature when there is a 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. As a result of flux boiling occurs solder dispersion in the form of small balls on a PCB surface.

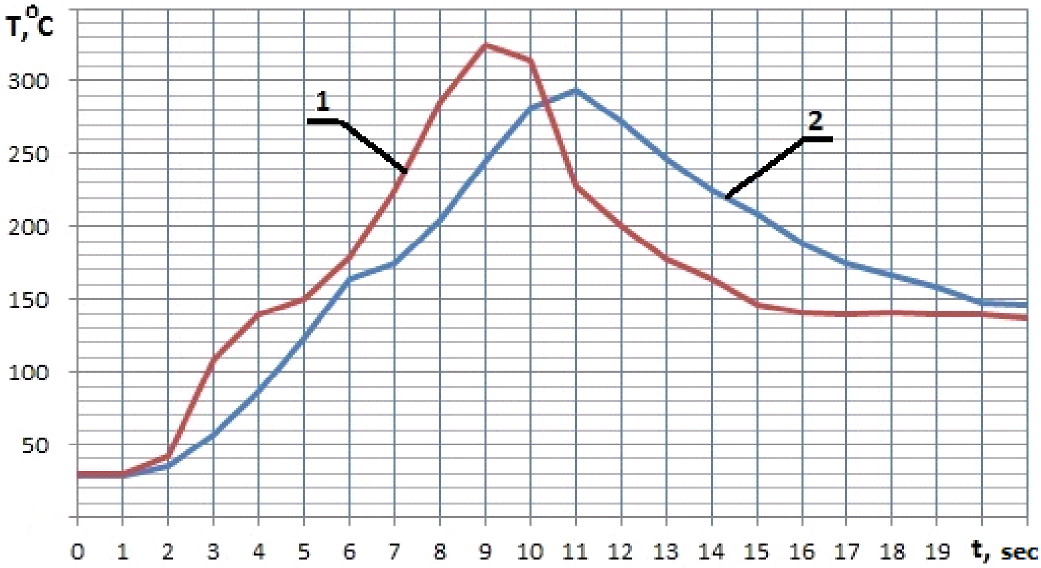

Figure 8. Temperature profiles of solder balls at heating power: 1 - 1.2 kW, 2 - 0.9 kW

The optimal parameters of HF heating with inductor with open-ended magnetic conductor: f=300 kHz, H=2, $5 \cdot 10^4$ A/m, current amplitude 7–10 A in inducing winding. At local HF heating the blanket of solder ball is melted down and forms a soldered joint, and the firm kernel in the center supports BGA component on necessary distance from PCB. Appearance of solder balls on bonding pads in diameter 400 microns is shown on Figure 9.

a

b

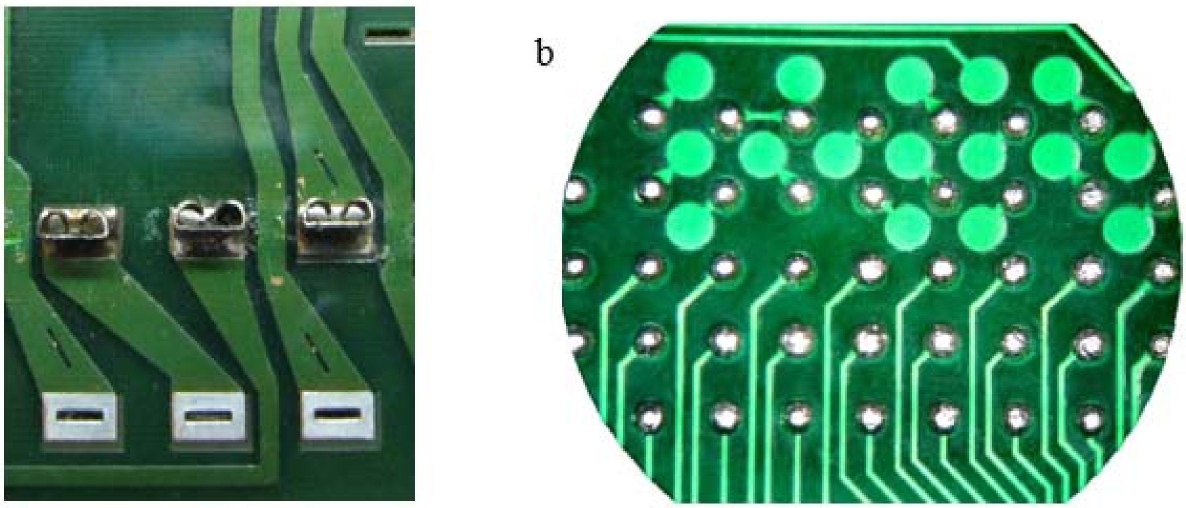

Figure 9. Soldered power contacts (a) and matrix structure of solder balls (b) on PCB

5 Conclusion

Modeling and investigation of HF electromagnetic heating has allowed to optimize heating speed in local zones of formation of soldering connections and to improve their quality due to joint action of superficial effects and electromagnetic forces. To small-sized details from nonmagnetic materials it is preferable to use inductor with a magnetic backlash as its' working frequency much below, so it increases inductor's efficiency. 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 to display of superficial effect. The optimal parameters of HF heating by inductor with open-ended magnetic conductor: frequency 300–400 kHz, intensity of magnetic field (2.5–4.5)·104 A/m, current amplitude 7–10 A in inducing winding.

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