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Numerical investigation on the effect of condensate layer formation around large-size components during vapour phase soldering

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ABSTRACT

The reflow soldering process of large size components was always problematic in microelectronics manufacturing due to the possibility of component displacement failures after soldering; like tombstone formation or skewing, which can be traced back to the different heating of the opposite component sides. During vapour phase soldering, the efficiency of heat transfer highly depends on the thickness of the condensate layer. In this paper, the inhomogeneity of condensate layer formation and its effects were investigated at large size components during vapour phase soldering by numerical simulations. For this purpose, a 3D computational fluid dynamic model was established. According to the condensate layer formation in different cases, the onset differences in the melting of the solder alloy at the opposite leads of the component were calculated. By the results, the risk of the component displacement during reflow soldering was analysed. It was found, that the congestion of the condensate layer around the large size components can cause considerable differences in the onset of the solder alloy melting, which can yield in component displacement failures after soldering. The extent of difference in the onset of melting depends on the location of the component on the board and on the applied soak temperature. Keep-out zones on the board were suggested to reduce the possibility of the component displacement failures during the vapour phase soldering process.

1. Introduction

The condensation based heat transfer is widely used in everyday life for heating purposes like facility heating with heat pumps [1], as well as for cooling purposes such as spiral wound heat exchangers in large-scale liquid natural gas plants. [2], cooling space vehicles by loop heat pipes with steam jet pump [3] or microelectronics with heat pipes [4]. The Vapour Phase Soldering (VPS) is a reflow soldering method. It is considered as an alternative of convection and infrared reflow soldering methods in the electronics industry [5]. The basic steps of the reflow soldering are the followings: first, the solder in paste is deposited onto the solder pads of a Printed Circuit Board (PCB) by stencil printing. Then Surface Mounted Devices (SMDs) are placed onto solder deposits. Finally, the whole assembly is heated up over the melting point of the applied solder alloy, which forms the joints between the leads of the components and the pads of the PCB [6].

In the VPS technology, condensation heating is used for reflow soldering. During the process, a heat transfer fluid is heated at the bottom of a tank to its boiling point; then due to the evaporation of the fluid, a vapour space begins to develop in the workspace. When the vapour space is ready for soldering, the assembly is immersed into it. The vapour starts to condense on the assembly and forms a continuously moving condensate layer (the condensate layer is flowing down from the PCB). This layer transfers the latent heat of condensing mass and the conducted heat from surrounding vapour to the assembly, which is heated up to the boiling point of the heat transfer fluid. The efficiency of the heat transfer depends mainly on the thickness of the condensate layer [6]. After the melting and wetting of the solder alloy, the assembly is lifted out from the process zone in order to cool down, and to solidify the solder joints. Nowadays, the most widely applied heat transfer fluid is Galden, which contains ether chains closed with carbon-fluorine bonds (Perfluoropolyether, PFPE) [7].

The main advantage of condensation heating for soldering is the lack of overheating [8] because of the limitation of the boiling point. The main disadvantage is the intensive heat transfer (it can be 2–3 times higher than in a convection oven [9]), which can also cause soldering failures like voiding, paste sputtering,

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and tombstone failures [10]. In the literature, most researchers investigated the practical use of the technology. Leicht et al. decreased the heat transfer coefficient of the VPS process by utilising non-saturated vapour [11]. Dumitru et al. investigated the effect of heating of VPS process on the mechanical characteristics of PCBs [12]. Branzei et al. studied the relationship between the heat transfer and the mechanical strength of the solder joints [13]. Synkiewicz et al. demonstrated the influence of the vacuum VPS thermal profile on the quality and reliability of solder joints for thermo-generators [14]. Livovsky and Pietrikova designed a real-time thermal profiling method for VPS process in order to approach defect-free reflow soldering [15]. Although the heat transfer of VPS process is considered to be generally uniform (compared to the infrared or convection type soldering systems), it was also shown that the thickness of condensate varies considerably on the surface of the PCB which results in spatial differences in heat transfer [6].

Using large size SMD components like power FETs, capacitors or inductors (having linear dimensions over 5 mm) is common in modern electronics devices. However, reflow soldering process of such a large-size components was always problematic for the industry, because of the higher risk of component displacement type soldering failures, like tombstone formation or skewing, which results in open solder joints [16]. The component displacement during the soldering can be traced back to the differences in wetting between the leads of the component [17]. The non-balanced wetting force (originating from the high surface tension of the lead-free solder alloys) [18,19] can move the component away from its proper location. The most prevalent problems, which can cause wetting defects, are uneven heating during soldering, oxidized or contaminated leads [20] and differences in printed solder paste volume at the leads [21]. Furthermore, not appropriate pad design (like imbalanced thermal mass distribution or asymmetrically connected heat sinks) or too large heating rate in the ramp up phase of the thermal profile can result in imbalance of the solder alloy melting at the different leads of the component [21,22]. This can definitely perturb the wetting balance, and can yield in component displacement during soldering.

Unfortunately, during the VPS process, the large components can cause congestion of the flowing condensate layer, resulting in both the accumulation of the heat transfer fluid and the variation of the heat transfer locally. This phenomenon might cause difference in the onset of solder alloy melting at the different leads of the component, which can also yield in a component displacement / skewing failures after soldering. The aim of our investigations was to examine the condensate layer formation around large size components, calculate the imbalance in the melting of the solder alloy and predict the possible component movement failures.

2. The applied numerical model

A 3D Computational Fluid Dynamics (CFD) model was established to describe the condensate layer formation and the temperature change of assemblies during VPS process. The model is based on the general Navier-Stokes (NS) equations and the condensate flow is supposed to be laminar.

2.1. Physical description of the model

After immersing the room temperature assembly into the vapour space, the vapour starts to condensate onto its surface and forms a condensate layer. The condensing Galden gives the latent heat and the internal energy of the condensing mass to the condensate layer:

$$Q_c = (h + C_S \cdot (T_b - T_l)) \cdot m_c \quad [\mathrm{J}] \tag{1}$$

where h is the latent heat of the Galden [J/kg], m_c is the condensing mass [kg], C_S is the specific heat capacity [J/(kg·K)], T_b is the boiling temperature of the Galden liquid [K] and T_l is the temperature of the condensate layer [K]. The energy increase due to the condensation introduces the heat flux into the condensate layer:

$$q_c = \lambda \cdot \frac{\partial \overline{T_i}}{\partial x_i} \quad [\mathrm{W/m^2}] \tag{2}$$

where λ is the specific heat conductivity [W/(m·K)] and T is the temperature [K]. Since the amount of the condensing mass depends on the amount of heat that the condensate layer can conduct away, the condensing mass can be calculated by Eqs. (1) and (2):

$$\frac{\partial m_c}{\partial t} = \left(\frac{\lambda}{h + C_S \cdot (T_b - T_l)} \right) \cdot A_c \cdot \frac{\partial \overline{T_i}}{\partial x_i} \quad [\mathrm{kg/s}] \tag{3}$$

where A_c is the condenser surface [m^2]. The condensate layer formation (the flow) was described at two levels. A full dynamic approach at board level and a half-dynamic approach were introduced at component level.

In the full dynamic approach, the condensate layer flow is initiated by the hydrostatic pressure differences in condensate layer:

$$p_h = (\rho_l - \rho_v) \cdot l \cdot g \quad [\mathrm{Pa}] \tag{4}$$

where ρ_l and ρ_v are the densities of the Galden liquid and the vapour [kg/m^3], g is the gravitational acceleration [m/s^2] and l is the height of the condensate layer [m]. The condensate is supposed to be homogenous from the density point of view; therefore, the continuity equation for incompressible fluids can be applied:

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0 \tag{5}$$

where u is the velocity [m/s]. The NS equation for incompressible, Newtonian fluids in a laminar flow space is used:

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j} \frac{\partial \overline{u_i}}{\partial x_j} = g_i - \frac{1}{\rho_l} \frac{\partial \overline{p_h}}{\partial x_i} + \upsilon \frac{\partial}{\partial x_j} \frac{\partial \overline{u_j}}{\partial x_j} \tag{6}$$

where υ is the kinematic viscosity [m^2/s]. In the condensate layer, conductive and convective energy transport is calculated by the heat equation:

$$\frac{\partial \overline{T}}{\partial t} + \overline{u_j} \frac{\partial \overline{T}}{\partial x_j} = \frac{\lambda}{\rho C_s} \frac{\partial}{\partial x_j} \frac{\partial \overline{T}}{\partial x_j} \tag{7}$$

The lateral dimensions of the component are one order of magnitude smaller than the lateral dimensions of the board. Therefore, the application of full dynamic approach in the calculation of the condensate layer flow at the component level is not recommended, since considerable increase in the time of calculation is expected. So, a half-dynamic approach was introduced at component level. The dynamic flow field of the condensate layer is not calculated, only the mass transfer is estimated for approximating the steady-state condensate thicknesses both on the walls and on the top of the component. The steady-state condensate thicknesses (τ) are calculated in each calculation step according to Bejan's approximation [23]:

$$\tau_{\max\_top} = 1.28 \Big/ \left[\frac{(h + 3/8C_s(T_b - T_l))(\rho_l - \rho_v)g}{\lambda_l (T_b - T_l) \upsilon_l (L/2)^2} \right]^{1/5} \quad [\mathrm{m}] \tag{8}$$

$$\tau_{\max\_wall} = \left[\frac{\lambda_l (T_b - T_l) \upsilon_l}{(h + 3/8C_s(T_b - T_l))(\rho_l - \rho_v)g} 4z \right]^{1/4} \quad [\mathrm{m}] \tag{9}$$

where T_l is the temperature of condensate layer [K], L is the characteristic length of the top surface (practically the half width of a surface) [m] and z is the length of the wall [m].