Effects of substrate thermal properties on the heat transfer coefficient of vapour phase soldering

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A B S T R A C T

In this paper, dependence of heat transfer coefficient during vapour phase soldering on the substrate properties was investigated by numerical simulations. A three-dimensional model was developed to describe the phase change on the substrate and the transfer mechanisms in the condensate layer. Five different substrate materials were studied: FR4, polyimide, 94% alumina, LTCC glass–ceramic and insulated metal substrate. The effect of the substrate aspect ratio was also studied. The results present dynamic heat transfer coefficient values of the process for different substrate materials. It is shown that during vapour phase soldering – which is a transient-state condensation process – the heat transfer coefficient can be characterized with the thermal diffusivity of the substrate material together with the filmwise condensate layer thickness on the substrate. The formation of the condensate layer is determined by the thermal diffusivity of the substrate material. It was also found that the aspect ratio of the substrates influences the movement of the condensate on the surface of the substrate, ultimately leading to a substantial effect on the heat transfer coefficient.

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1. Introduction

Condensation heating or cooling is widely used in everyday life e.g. for facility heating with heat pumps [1], cooling refrigerators with HFC refrigerants [2] and microelectronics with heat pipes [3] or simply for increasing the efficiency of boilers [4]. In the Vapour Phase Soldering (VPS) technology, condensation heating is used for reflow soldering. During reflow soldering process, solder paste is deposited onto the solder pads of a substrate with stencil printing. This is followed by the placement of discrete components of the circuit onto the solder deposits. Then, the assembly is heated up over the melting point of the applied solder paste which forms mechanical and electrical joints between terminals of the components and pads [5].

A schematic of a batch type VPS oven is presented in Fig. 1 [6]. The working principle of the VPS technology is the following: a special heat transfer fluid (usually Galden) is heated at the bottom of a closed tank. When the fluid reaches the boiling point, vapour development begins and it starts to fill up the tank. The excessive vapour condenses on the cooling pipes at the top of the tank. After the vapour space is ready for soldering, the assembled circuit is immersed into the vapour, and continuous condensate layer forms on the surface of the substrate. Condensate layer transfers its latent heat of condensing mass and the conducted heat from the vapour into the assembly. After a given time (which depends on the thermo-physical properties of the assembly and the temperature requirements of the applied solder paste), the assembly is elevated out of the tank in order to cool down and to solidify the molten solder.

Galden liquid is composed from ether chains with carbon–fluorine bonds (Perfluoropolyether, PFPE) [7]. Different Galden types are used within a boiling temperature range from 150 to 270 °C, according to their application. In the case of VPS the applied type is selected according to the melting temperature of the applied solder paste.

The main advantage of VPS is the uniform heating compared to infrared or convection heating technologies [8,9]. This technology also helps to avoid overheating (since the soldering temperature cannot exceed the boiling temperature of the heat transfer fluid [8,9]). On the other hand VPS can perform with a more intensive heating than the regular soldering technologies. This can be a root cause of soldering failures (e.g. voiding, paste sputtering, tombstone failures, etc.) [10]. Heat Transfer Coefficient (HTC) values of the condensation heating can be one order of magnitude larger than the HTC of the forced convection heating [11].

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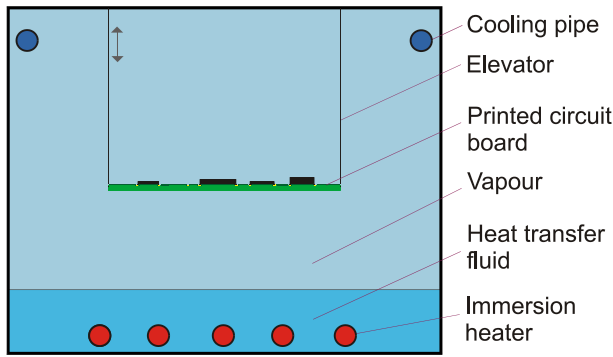   E-mail address: billes@ett.bme.hu (B. Illés).

Fig. 1. Schematic of a batch type VPS oven [6].

The most important finding about VPS from the past few years can be found in the works with low temperature soldering on biopolymers [12], quality improvements [13] and microstructural analyses of the solder joints [14] prepared with VPS. Some important experimental results about this technology were discussing the characterization of the temperature distribution of the vapour space [15] and vapour concentration [16]. Many relevant results about VPS were achieved by numerical simulations, such as the modelling of the vapour space formation [17], the condensation process [18] and the condensate layer formation [19]. It was found that the condensate layer has substantial spatial and time dependence which may have considerable effects on the heating ability of the system. Considerable layer thickness differences can form on the top side of the soldered assembly between the middle and the edges of the substrate [19]. The condensate thickness differences should result in HTC differences on the surface of the substrate, since the thinner condensate layer ensures more effective local condensation [19]. This effect can be a root cause of aforementioned soldering failures since lead-free soldering processes are very sensitive for planar temperature differences [20].

Available literature contains only a few studies about horizontal condenser surfaces, since most of the applications work with vertical condensers. Most of the horizontal studies are based on the Bejan model, which give a stationary, two-dimensional analytical solution for condensation on upward facing rectangular surfaces with free edges [21]. Chiou and Chang showed similar solution in the case of disks [22]. Marto et al showed improvements compared to the previous results, although their model even had an over prediction of 20–25% compared to measurements [23]. Ten years later Wang and Cheng reached important results about steady-state filmwise condensation on horizontal flat plates and disks embedded in a porous medium [24,25]. According to the findings of previous results, there is an important gap in the literature regarding transient-state studies. The application results of simplified steady-state modelling approaches of VPS can be significantly enhanced with transient investigations, which describes the heating process of the assembly in a more detailed way.

Consequently, there is a need to study the HTC in transient-state during the VPS technology and for different substrate materials since the thermal diffusivity of the substrate materials influences on the heat transfer during the process (a direct proof is the solder wicking defect [20]). The obtained results are important from the aspect of thermal profile calculations and optimizations during
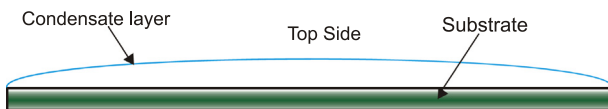
industrial application of VPS technology improving the quality of production.

2. Modelling condensation layer formation

The change of the HTC was studied on the top side of different substrates. It was found in previous works [18,19] that thermal cross effects are negligible between opposite sides of the substrate, so top and bottom sides can be examined separately. For the investigations a three-dimensional numerical model was developed (Fig. 2) which includes the phase change on the substrate and transfer mechanisms in the condensate layer. The modelling concept is the following: condensation causes mass transfer from the vapour towards the surface of the substrate where the condensed mass forms a condensate layer on the surface. For condensation layer formation a basic concept can be adopted from the Bejan model [21] where horizontal boards can be considered as upward facing surfaces with free edges, where condensate is able to spill down. At the edges of the substrate the height of the condensate layer is supposed to be zero which means zero hydrostatic pressure as a boundary condition. This results in a pressure gradient in the condensate layer. Pressure gradient initializes the movement of the condensate layer towards the edges of the substrate.

Condensing mass can be calculated according to the energy change which is caused by the condensation. During the condensation the latent heat and the internal energy of the condensing mass are given to the condensate layer:

$$\frac{\partial Q_c}{\partial t} = h \cdot \frac{\partial m_c}{\partial t} + C_S \cdot T_b \cdot \frac{\partial m_c}{\partial t} \tag{1}$$

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] and T_b is the given boiling temperature of the Galden liquid [K]. The energy increase due to the condensation enables heat flow:

$$\frac{\partial Q_c}{\partial t} = q_c = \lambda \cdot A \cdot \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \tag{2}$$

where λ is the specific heat conductivity [W/m K], A is the condenser surface [m^2] and T is the temperature [°C]. So the condensing mass can be calculated by right sides of Eqs. (1) and (2):

$$\frac{\partial m_c}{\partial t} = \left(\frac{\lambda \cdot A}{h + C_S \cdot T_b} \right) \cdot \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) \tag{3}$$

Temperature change of the condensate layer due to the condensation can be calculated from Eq. (1):

$$\frac{\partial T_c}{\partial t} = \left(\frac{h + C_S \cdot T_b}{C_S \cdot m_c} \right) \cdot \frac{\partial m_c}{\partial t} \tag{4}$$

Hydrostatic pressure of the formed condensate layer can be described with:

$$p_h = (\rho_l - \rho_v) \cdot l \cdot g \tag{5}$$

where ρ_l and ρ_v are the densities of the Galden liquid and the vapour [kg/m^3], g is the gravity acceleration [m/s^2] and l is the height of the condensate layer [m].

The hydrostatic pressure change of the condensate layer has no effect on the density of the condensate, therefore the continuity equation for incompressible fluids can be applied:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \tag{6}$$

However hydrostatic pressure differences in the condensate layer result in the movement of the condensate layer. Components of temporal velocity change in the used Navier–Stokes equation are the following:

Fig. 2. Top side condensate layer model.