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Numerical modelling of the heat and mass transport processes in a vacuum vapour phase soldering system

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ABSTRACT

The heat and mass transport processes were investigated with numerical simulations in a vacuum vapour phase soldering system during the vapour suctioning process. Low vapour pressure/concentration is applied during vacuum soldering to decrease the number of gas voids in the solder joints. Three-dimensional numerical flow model was developed which based on the Reynolds averaged Navier-Stokes equations with the standard k-ε turbulence method. The decrease of the vapour concentration and its effects on the solder joints were studied in the case of different oven settings. It was found that vapour suctioning has considerable effects on the heat transfer processes in the soldering chamber which might lead to early solidification of the solder joints and reduces the efficiency of the void removal. Different oven settings were simulated in order to decrease the heat loss of the soldering chamber during the vapour suctioning. It was shown that with appropriate setting of the vacuum vapour phase soldering technology, the efficiency of the void removal can be increased.

1. Introduction

The physical phenomenon of condensation is widely used for heating and cooling technologies due to its high efficiency, such as facility heating with heat pumps [1], cooling refrigerators with hydro-chlorofluorocarbons (HFC) refrigerants [2], or microelectronics with heat pipes [3]. The Vapour Phase Soldering (VPS) or "condensation soldering" is a reflow soldering method. It is considered as a promising alternative of convection and infrared reflow methods [4,5]. Before the reflow soldering process, the solder paste is deposited onto the solder pads of a Printed Circuit Board (PCB) (Fig. 1a) with stencil printing (Fig. 1b). Then, discrete components of the circuits are placed onto solder deposits (Fig. 1c). Finally, the assembly is heated up over the melting point of the applied solder alloy which forms mechanical and electrical joint between the terminals of the components and pads of the PCB.

The principle of vapour phase soldering is using the heat transfer effect of condensation. During the process a special heat transfer fluid is heated at the bottom of a tank. When the fluid is heated up to its boiling point, a vapour space begins developing which fill up a closed tank (Fig. 1d). The excessive vapour is condensed on the top of the tank, due to a cooling pipe setup. When the vapour space is ready for soldering, the assembled PCB is immersed into the vapour (Fig. 1d), and a condensate layer forms on the colder surface of the PCB (Fig. 1e). 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.

After the melting and wetting of the solder alloy, the PCB is lifted out of the process zone in order to cool down, and to solidify the solder joints (Fig. 1f). Nowadays the most widely applied heat transfer fluid is Galden, which contains ether chains closed with carbon-fluorine bonds (Perfluoropolyether, PFPE). The boiling point of the Galden liquid can be set with the length of the ether chain between 150 and 260 °C [7].

The main advantages of condensation heating for soldering are lack of overheating [8] and lack of shadowing effect, which occurs due to larger components [4]. However, intensive heat transfer during VPS and the hermetically closed process zone can also cause soldering failures like voiding, paste sputtering, tombstone failures [9], since the heat transfer coefficient of Galden vapour can be 2–3 times higher than the heat transfer coefficient of gas streams in a convection oven [10]. Up to now, only limited researchers have dealt with thermal aspects of the process.

Leicht et al. showed that the heat transfer coefficient of vapour can be decreased with the application of non-saturated vapour

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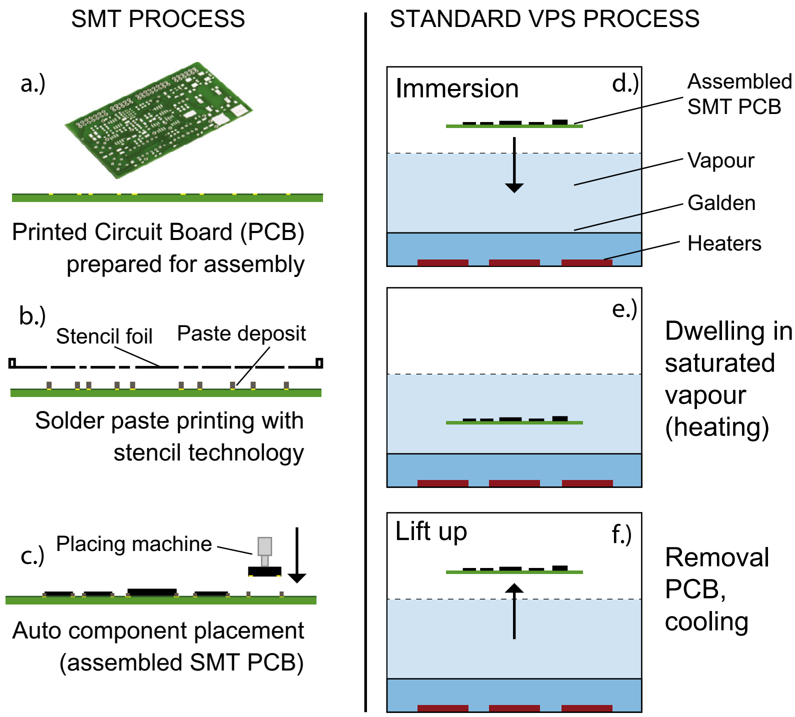

Fig. 1. The SMT and the basic VPS process [6].

[11]. Dumitru et al. investigated the effect of heating of VPS process on the mechanical characteristics of PCBs [12]. Cucu et al. studied the mechanical stability of the solder joint prepared by VPS process from low melting point alloys [13]. Krammer showed that a proper VPS thermal profile can increase the reliability of solder joints [14] since both the thickness and the shape of the intermetallic layer will differ from the conventional soldering technology. Synkiewicz et al. presented similar results about the general quality of the solder joints for thermo-generators [15]. Géczy et al. optimized temperature profiling methods for VPS process [16]; they also proved with pressure measurements that temperature saturation of the process zone occurs before vapour concentration saturation in time [17]. It was shown that condensate thickness changes considerably on the surface of the PCB which results in spatial heat transfer differences. In addition it was proven that the dense vapour space takes place considerably (~20%) in the heating of the assembly [18,19].

The gas voids in the joints causing serious reliability problems since it decrease the joints life time and electrical conductivity. Krammer et al. proved that one of the key points to prevent of void formation is the appropriate amount of solder paste [20]. However, voids can even form during the stencil printing, which highly depends on the viscosity of the solder paste [21]. The issue of voiding was thoroughly investigated in the case of VPS and the problem was found even more serious than in the case of conventional soldering technologies [9]. Therefore, studies have started about the possible application of the low pressure for VPS system, where the voids are removed from the molten solder [22]. The suction process takes place while the alloy is above its melting point [22]. The pressure in the "vacuum chamber" is usually approximately 40–50 mbar during the suction part of the process [23]. However it was never studied that how does the decrease in vapour concentration affect the heat transport mechanism of the soldering process, and with this aspect, how does it affect the efficiency of the void removal and the forming of the solder joints microstructure. The question is relevant from the aspect of mass manufacturing, while vacuum type ovens recently started to spread out in electronics assembly plants.

2. Numerical modelling of vacuum VPS process

Investigating the VPS process by numerical simulations is necessary because of the closed environment (high temperature, dense vapour, etc.) in the soldering chamber. There were experimental studies about application of the temperature, pressure or optical probes in VPS ovens [16,24,25] but it was found that the introduction of the probes is complicated even in the case of simple VPS ovens. In the case of vacuum VPS process when the soldering chamber is hermetically closed, the measurement inside the soldering chamber is not possible with such probes which need to be connected to an outer device (like thermocouples, pressure sensors, borescopes, etc.).

2.1. Physical description of the model

According to the preliminary calculations, the vapour concentration decreasing in the vacuum chamber causes a turbulent gas flowing [26], so the numerical calculations are based on the 3 dimensional Reynolds Averaged Navier-Stokes (RANS) equations. The RANS equations compute the average movement in a turbulent flow, while the effect of fluctuation is modelled by Reynold's stress tensor which was related to the mean flow with a standard k-ε turbulence model [27]. The decrease of the vapour concentration is initialized by a pressure drop generated by a vacuum pump.

The governing equations of the vapour space are the following: the transient continuity equation for compressible Newtonian fluids is used since the local pressure change has effect on the density of the vapour:

$$\frac{\partial \overline{\rho}}{\partial t} + \overline{\rho}\frac{\partial \overline{u_i}}{\partial x_i} = 0 \quad (1)$$