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Component level modelling of heat transfer during vapour phase soldering with finite difference ADI approach

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ABSTRACT

In this paper, the complex heat transfer process of the vapour phase soldering has been investigated on the level of electronic components. VPS is gaining increased attention lately, and the process needs alternative approaches in modelling, compared to conventional soldering processes in electronics mass manufacturing. Component level modelling was not studied deeply in the literature before, so our focus pointed to heat transfer on large size surface mounted electronic components. Applying the Fourier type heat conduction equation, a detailed 3D thermal model of a polyester capacitor on a printed circuit board was implemented, based on X-ray images of an actual assembly. Our model incorporates inner geometry, material inhomogeneity, composite materials and anisotropic thermal conductivity as important thermal features. Transient heating was calculated with Finite Difference Method combining an alternating direction implicit (ADI) approach, using averaged heat transfer coefficient. Validation measurements were performed in our experimental VPS system. The measured data show good agreement with the calculation results and points to possible application for use in advanced engineering and manufacturing environment.

1. Introduction

Vapour phase soldering (VPS) is a reflow soldering method used in electronics manufacturing. It is an alternative method compared to the widely used forced convection and nowadays less significant infrared heating processes [1–3]. During reflow soldering, solder paste is printed onto the pads of the printed circuit board (PCB), and then the electrical components are positioned and placed onto the deposits of the solder. The solder alloy is then melted by heat to form solder joints. In case of infrared or forced convection heating, electromagnetic radiation or hot air stream is responsible for energy transfer, respectively.

On the contrary, during VPS process a special heat transfer fluid is boiled to form a saturated vapour in a closed tank. The PCB assembly is immersed into the saturated vapour, indicating condensation on the assembly surface. While a continuous condensate film is formed, the latent heat of the condensation provides energy for heating. The heat transfer occurs through this thin layer on the surface. Nowadays the most widely used fluid in VPS applications is called Galden (perfluoropolyether – PFPE type fluid), which is considered as an inert material, and do not produce any harmful gases during the process. The main advantages of VPS technology are rapid heating, the reduced risk of overheating, due to the fixed boiling point of the fluid, and the oxygen-free environment. Oxidation-free solder joint forming is achieved with the presence of continuous condensate film layer.

VPS is studied mainly from the practical aspects originated from the needs of the industry, such as the aspect of soldering with lead-free materials [4]. The general comeback of the method was described in [5]. Recently VPS was compared directly with more conventional convection type reflow by Dziurdzia [6], while the others focused more on VPS itself. It was found by Pietrikova [7] and Liu [8] that the microstructure of the joints formed in VPS ovens are dependent of the given setting and mode of the applied ovens.

Real time temperature profiling [9] or optimizations with statistical methods [10] were also investigated by Livovsky and Tsai, respectively. Power electronics manufacturers apply VPS in their reflow processes due to the efficient soldering of large components [11–16]. Research of the energy efficiency is also under active investigations [17]. Special applications, such as Pin-in-Paste technology [18] or vacuum suctioning during reflow also fits in the focus of VPS studies. It was found by Synkiewicz [19] and Lungen [20] that VPS process with a vacuum step, after reflowing the

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solder alloy, is effective in eliminating voids and improving joint quality.

In the last few years, the method of VPS was also investigated on multiple levels. The basics of saturated vapour generation, condensation and film layer formation were investigated through detailed multi-physics modelling. Also, simpler models were applied to describe the heating of PCBs as 2D objects [1,2]. Continuing this line of research, we introduce 3D thermal modelling on component level during VPS. Similar modelling examples of electronic assemblies were presented recently for infra-red radiation based heat transfer on board level by Najib [21] and convection type heat transfer during reflow on component (package) level by Deng [22]. We considered a novel approach for VPS regarding inner geometry, material inhomogeneity, composite material content and anisotropic thermal conductivity. These component level aspects were not widely studied together in case of VPS before. We used the finite difference method with alternating direction implicit scheme (FDM ADI) due to its highly customable implementation possibilities and computation speed.

The proposed method may be able to reveal different quality aspects (such as failures during reflow processes), and an extension of overall knowledge on the method of VPS.

2. Experimental

2.1. VPS system and component specification

To prepare, verify and fine tune our proposed model, several measurements were carried out in an experimental model VPS system, which was described in our previous work [23]. A simplified overview is shown on Fig. 1. The system is based on a closed stainless steel tank with a removable lid. An immersion resistor heater boils the Galden fluid at the bottom. A cooling tube is positioned on the top of the tank with circulated ambient temperature water inside. In our experiment Galden HT170 [24] with 170 °C nominal boiling point was used to form saturated vapour blanket with the same temperature. The material is exchangeable with higher temperature fluids.

For modelling purposes, we chose a multilayer polymer (MLP) surface mount (SMD) capacitor (4036, $5.5 \times 10 \times 9$ mm). In MLP capacitors the core comprises metal film electrodes with a dielectric material (polyethylene terephthalate (PET) in our case) sandwiched in between. The metal film layers and contact metallization are made of aluminium (Al); the film layers are 100–300 Angstrom thin, while the dielectric layers have the thickness between 0.9 and 1.2 μm. These extremely thin film layers make possible to stack several thousand layers to form the capacitor core, which is encapsulated in epoxy case (epoxy encapsulant and thin plastic box) with Al contact termination on both sides. The MLP capacitors are used widely in high frequency applications [25,26].

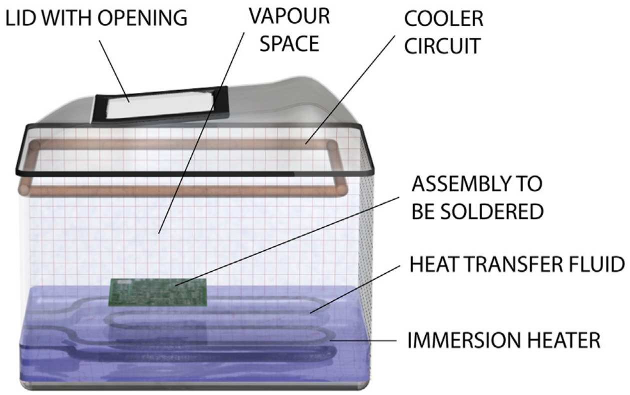

Fig. 1. Experimental VPS system with electronic assembly immersed in vapour space.

We used XiDAT XD6600 X-ray microscope imaging to chart the build-up and inner geometry of the capacitor, where the results can be seen on Fig. 2.

Two capacitors were fixed on a bare laminate (1.6 mm thick FR4 - standard PCB material) with ~60 μm thick layer of epoxy adhesive (Loctite 3621 [27]) between the component and the PCB. The PCB was 10 cm × 10 cm in size, and the capacitors were 5 cm apart from each other. From the PCB side a small bore of 0.5 mm diameter was prepared through to the center of the capacitors. A 0.2 mm thin K-type thermocouple (±1 °C precision) was positioned into each bore with the aforementioned epoxy adhesive. The adhesive gives good thermal coupling, enabling accurate temperature monitoring of the surrounding body. Later, the measurements will be used for verification of the FDM model with averaged transient temperature data of the two capacitors.

We also measured the time delay between the beginning of the condensation and the temperature rise in the center of the capacitors. An additional thermocouple was attached 1 cm below the board to indicate the start of the process.

The average heat transfer coefficient of the condensation was derived from the transient heating curve of a bare PCB as an approximation. Multiple thermocouples with different positions were placed into the board with the same technique as described above. The heat transfer coefficient was obtained from the averaged data using lumped system calculation. As a starting point for our model, we assumed that the capacitor is heated with the same average heat transfer coefficient as the PCB.

All material properties used in our calculations can be found in Table 1.

2.2. Average heat transfer coefficient during condensation

The heat transfer coefficient of the condensation can be calculated from transient temperature data if the interior temperature of the body remains nearly uniform during the heating process with lumped (concentrated) system modelling [28,29]. It was shown previously, that PCB plates can be treated such way in most cases [2]. The lumped model is written as [28,29]:

$$c \cdot m \cdot \frac{dT}{dt} = h \cdot A \cdot (T_{sat} - T) \quad (1)$$

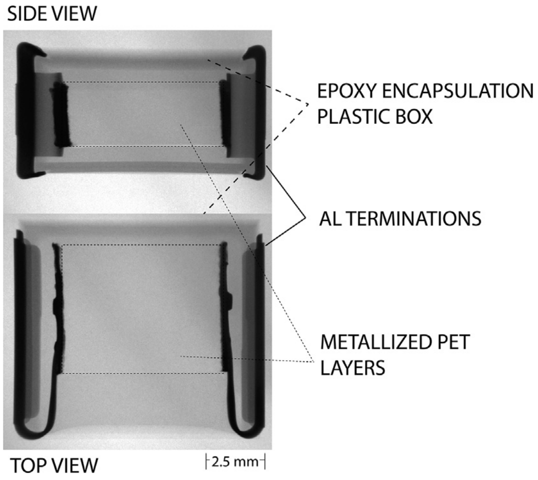

Fig. 2. X-ray images of the capacitor's inner structure with highlighted core (top: side view, bottom: top view).