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COUPLING OF WIRED PCB WITH MICROWAVE RADIATION – 3D SIMULATION AND EXPERIMENTAL VALUATION

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Abstract: Modern electronic assemblies and printed circuit boards (PCB) with their sensitive structures and elements have to be protected against environmental influences by conformal coating or casting compounds. It has already been proved that a curing process supported by microwave irradiation can improve and accelerate the polymerisation process of coatings [1], [5]. In this case the main challenge is the simultaneous curing of the polymers and the safekeeping of the electronic elements and structures on the PCB. This implies the investigation of heating process based on antenna effects due to the interaction of microwave radiation and conductive wires on PCB. COMSOL has been applied here to solve this problem because of its benefits in using multiphysics simulations [4]. To estimate the calculated results, series of wired PCBs with similar structures to the models were tested in laboratory microwave oven. The final valuation demonstrated a substantial similarity between the simulations and the experimental results.

Keywords: Microwave, curing, PCB, permittivity, simulation.

1. Introduction

The drying and curing of conformal casting compounds is typically accomplished after the application to the electrical device or the PCB [6]. Thus sensitive electrical elements and structures attend the heating process.
The main concept of this investigation here is the behavior of the metallic structures of the PCB interacting with microwave radiation.
For the investigation, the metallic cavity with antenna injection as well as different PCB structures were modelled. Parameters such as: metallic structures of PCBs, material properties and frequency were changed to specify the most impactful adjustment.
It has been shown by COMSOL that the dimensions of the heating distribution depend on microwave frequency and permittivity of the attending materials (e.g. PCB base). In this context, a functional relationship could be deduced, that explains the observed structures. Furthermore opportunities were illustrated to subdue the response of the wires to microwave irradiation. The final step was the analysis of the interplay of microwave radiation, wired PCB and polymer coatings.

2. Models and basic equations

To solve the problem and reconstruct the laboratory microwave oven, the microwave heating module of COMSOL was chosen [4]. The COMSOL model was built according to the parameters of the laboratory microwave oven such as: the microwave cavity, the rod antenna, magnetron, ...

2.1 Model definition

A rectangular wave-guide in connection with an antenna leads the electromagnetic wave to the conductive cavity. The antenna is a metallic cylinder which results an electric current by its conductive character. Symmetry was utilized for saving memory and computing time due to the symmetric geometry. The symmetric plane was taken vertically through the wave-guide, antenna, oven and underlay. The investigated PCB load was located on the underlay (figure 1).

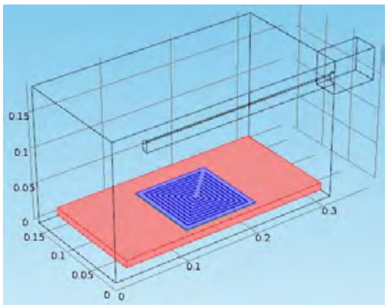

Figure 1: COMSOL Model of the microwave cavity.

2.2 Basic equation

The basic data of the microwave cavity are:

Dimensions	315 x 310 x 190 mm^3
Power	200 W
Time of testing	30 seconds
Frequency	2.45 GHz

The transverse electric (TE) wave has no electric field component in the direction of propagation and the TE_{10} mode is the only propagation mode through the rectangular waveguide.
With the stipulated excitation at the rectangular port, the following equation is solved for the electric field vector E inside the waveguide and oven [3], [4]:

$$\vec{\nabla}\times(\mu^{-1}\vec{\nabla}\times\vec{E})-k_0^2\left(\varepsilon'-\frac{j\sigma}{\varepsilon_0}\right)\vec{E}=0 \qquad (1)$$

Where μ is relative permeability, j is the imaginary unit, σ is the conductivity, ω is angular frequency, ε_0 is the permittivity of free space, ε´ is the real part of the complex relative permittivity ($\varepsilon^*=\varepsilon'- j\varepsilon''$ [4], ε´´is the imaginary part), k_0 is the microwave wavenumber [3].

The material properties used in the simulations are presented in the following table [7]:

Material	Properties	Value
Air	σ	0[S/m]
	μ	1
	ε´	1
Underlay	σ	0[S/m]
	μ	1
	ε´	2.55
Copper	σ	5.998e7[S/m]
	μ	1
	ε´	1
PCB	σ	0.004[S/m]
	μ	1
	ε´	4.5

[S/m]: Siemens per metre
To represent the forced cooling (by fan systems) in the experiment, convective cooling condition is applied with the heat coefficient of air h= 30.

3. Observation of regular heating

First of all, the investigation was carried out with a single copper wired PCB to get the basic knowledge of the interaction between PCB and microwave radiation. Afterwards the investigation concentrated on PCBs applied by quadratic shaped copper wires due to the intensive interaction with microwave. The typical substrate material is glass- reinforced epoxy resin (FR-4) and the thicknesses of PCBs were 1.5 mm. The thickness of the copper wires was 0.02 mm for all investigations.

3.1 PCB with a single wire

A simple structure that can be analyzed is an even wire. Therefore a PCB with a straight copper wire was modeled. The length of PCB as well as copper wire increases from 50 to 100, 150 and 200 mm to observe the interaction (figure 2).

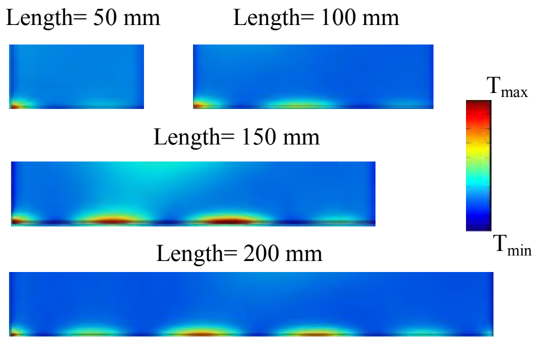

Figure 2: Temperature distribution of single wired PCB after irradiated by microwave

The blue color represented the temperature of 25°C and the red color showed the highest temperature. The areas of significant heating which appeared only around the metallic structure are called hot spots. This was also demonstrated by experimental investigation (figure 3).

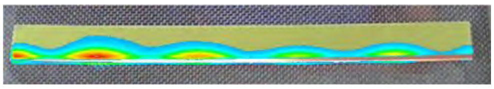

Figure 3: Overlay picture that combines the real picture and the thermal imaged picture. Presented is a PCB (200 mm length) with a copper wire at the lower area and the heating areas through microwave irradiation

3.2 PCB with quadratically shaped wires

The dimensions of quadratic PCB are (1.5 x 100 x 100 mm^3). The investigation was carried out firstly with unwired PCB. The quadratically structural wires were added subsequently (figure 4).

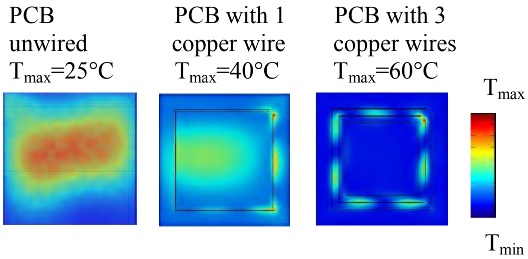

Figure 4: Hot spot distribution on PCB when coupling with microwave radiation

On the unwired PCB the interaction was weak and the difference of temperature was small (circa 0.5 K). Due to the influence of metallic components, the interaction became stronger as well as the increase of maximum temperature. It is shown more clearly in the case PCB with 3 wires. The experiment was realized with full copper structures on the surface of PCB. The temperature distribution was similar to the PCB with 3 wires (figure 5).

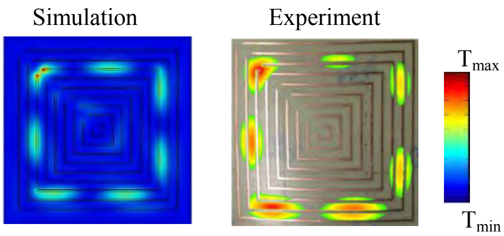

Figure 5: Overlay picture of the quadratically wired PCB (right) and simulated irradiated PCB (left). The temperature distributions have a substantial similarity.

The metallic structures then were modified as all corners of copper lines opened and closed (figure 6).

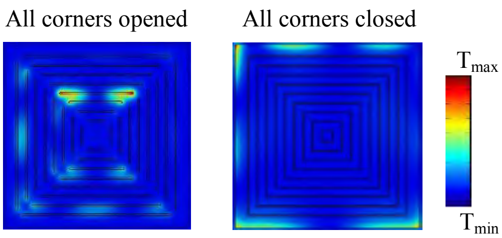

Figure 6: PCBs with all corners opened (left) and closed (right)

As seen in figure 6, an interruption of the conductive wires disturbs the antenna effect and leads to separated couplings, like in case of all metallic corners opened. On the other hand, the PCB with all metallic corners closed shows no interaction inside the metallic area.

4. Discussion

4.1 PCB with typical substrate material (FR-4)

From the illustrations of the whole PCB tests which substrate material is FR-4, it would appear that the distances between hot spots do not change. The distances between the maximums amount to circa 40 mm. This observation can be interpreted as a formation of standing waves along the wires. This causes locally constant currents and a heating process based on the Joule effect, like in antenna technology. The distances between the hot spots result from the reduced wavelength λ_c of the propagating waves on the PCB.
The corners of metallic structures have a relevant roll in the influence to the interaction. The heating of the enclosed copper wires due to microwave irradiation failed to appear. This indicates a total reflection of the incident microwaves [2].

4.2 The impact of permittivity and frequency

a) Temperature distribution in dependences on the relative permittivity of substrate material

The conformance of experiment and simulation (e.g. figure 5) concerning the microwave interaction inspired an analysis of the temperature distribution in dependence on the relative permittivity ε_{PCB}' of the substrate material (normally consisting of FR-4). At this the supposition could confirm, that the conductor wavelength λ_c of the propagating microwaves is directly a function of the relative permittivity ε_{PCB}' of the substrate material. The microwave-PCB interaction was simulated for different relative permittivity ε_{PCB}', while the other boundary conditions were kept constant. The hot spot interspaces decrease while the relative permittivity ε_{PCB}' increases (figure 7).

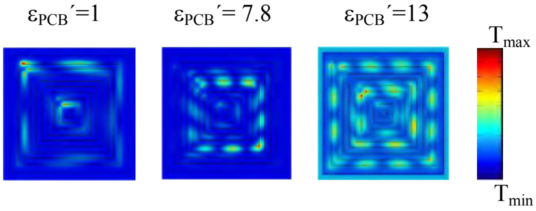

Figure 7: Thermal imaged pictures of the simulated microwave - PCB interaction in dependence on the relative permittivity of the base material.

The link between the maximum distances d and the correlated wavelength is given by λ_c=2d [3]. The whole test series is presented in figure 8. The interpolation equation is based on the correlation between the conductor wavelengths λ_c, the wavelength in vacuum λ_0, the relative permittivity ε_r as well as the relative permeability μ_r of the dielectric medium

$$\lambda_c = \lambda_0 / (\varepsilon_r \mu_r)^{1/2} \sim \lambda_0 / (w_{PCB}\varepsilon_{PCB}' + w_{AIR}\varepsilon_{AIR}')^{1/2} \quad (2)$$

with the approximation $\mu_r \sim 1$ [4]. Furthermore ε_r is given by the participating materials ε_{PCB}' and ε_{AIR}' as well as weighting factors w_{PCB} and w_{AIR}. The simulation shows a decrease of λ_c with an increase of ε_{PCB}'. For $\varepsilon_{PCB}' \sim 1$ (air) the conductor wavelength λ_c becomes 122 mm, which means the microwave wavelength in air. The interpolated equation does well conform to the experimental results.

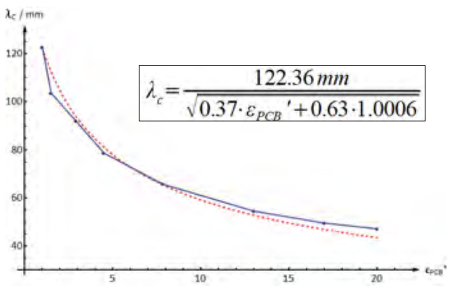

Figure 8: Dependence of the conductor wavelength λ_c and the relative permittivity on the base material ε_{PCB}' (blue plot with markers). The dashed curve represents an interpolation based on the shown equation.

The equation λ_c (ε_{PCB}') identifies the influence of the base material ε_{PCB}' and the surrounding air (ε_{AIR}'=1.0006) on the velocity of microwave propagation along the copper wires. It is presented by the weighting factors with w_{PCB} = 37% for the base and w_{AIR} = 63% for the air. Therewith the structure of the temperature distribution can be attributed to the real part of the relative permittivity of the participant dielectric materials.

b) Temperature distribution in dependence on microwave frequency

The typical frequency for most microwave ovens is 2.45 GHz and that is also fixed for the laboratory oven used in the experiment. Nevertheless, the problem can be calculated by COMSOL with variable frequencies (figure 9).

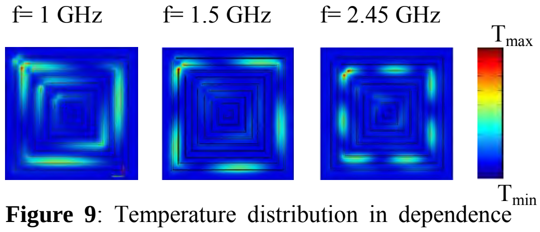

Figure 9: Temperature distribution in dependence on microwave frequency

It is illustrated that λ_c decreases while microwave frequency increases. This dependence can also be attributed to the functional relationship (2).

4.3 PCB in combination with polymer coating

The investigation was developed with a combination of PCB and a polymer coating applied on the PCB top (thickness= 1 mm and $\varepsilon_{COATING}'$= 4).

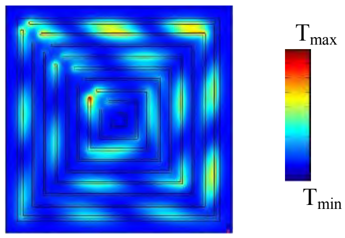

Figure 10: Temperature distribution of PCB in combination with polymer coating

Figure 10 shows that the temperature distribution was changed due to the effect of the coating. In comparison with PCB in figure 5 (without coating), there are more hot spots and the distances between hot spots decrease. As discussed above, the propagation depends on the substrate material and the ambient environment (air). In this case, the coating on top has different property. Therefore the hot spot interspaces changed. The higher value permittivity ($\varepsilon_{COATING}'$= 4 instead of ε_{AIR}'=1.0006) make the decrease of the λ_c.

5. Conclusion

The results show that conductive structures have a significant influence on microwave supported curing process of PCB-coatings. The coupling of copper wires and electromagnetic field can lead to a weighty heating of the wires. Numerical simulation via COMSOL and experimentally results demonstrate that this effect is more influential then dielectric heating of the coating (figure 4).

Furthermore the temperature rise of conductive wires due to microwave irradiation is based on the formation of standing waves and leads to a periodical heating distribution. This applies to straight wires (figure 2, 3) as well as quadratically shaped ones (figure 5).

Closed wires that are close to each other can suppress this heating effect (figure 6). In this case the wire structure affects like a homogeneous conductive area, where microwave radiation will be reflected. However in this case a dielectric heating of the applied coating will fail to appear.

It has also been demonstrated that the heating distribution of the wires depends on the permittivity of the attending materials and the microwave frequency (figure 7, 9). This is another indication of the formation of standing waves due to microwave irradiation.

Additionally the numerical analysis via COMSOL confirmed a functional relationship concerning wave propagation on wired PCB (figure 8). This knowledge demonstrates opportunities to influence the heating process.
In conclusion the applying of a coating to a PCB influences the hot spots distribution and has to be considered in order to predict and optimize the heating process.

The knowledge of the interaction effects is an important contribution to the development of microwave supported curing process of PCB coatings.
The finding of defined conductive PCB structures assisting a microwave curing process by additional heating is the main challenge in near future.

Acknowledge

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6. References

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