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NUMERICAL AND ANALYTICAL EVALUATION OF RESIN FLOW DURING PCB PRESSING CYCLES

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Summary. This paper presents a comprehensive sequence of analytical methods for evaluating printed circuit board (PCB) pressing processes, augmented by numerical finite element (FE) simulations. The study considers the properties of the prepreg material, the structure of the PCB copper layer, and various pressing process parameters, all of which can be adjusted according to specific requirements. Our results are validated through experiments and compared with the established Squeeze Flow Model. The proposed methodology identifies potential weaknesses in the design of the copper layer, material selection, and pressing parameters prior to production. Additionally, the implementation of this methodology in an interactive user interface allows for rapid and efficient results, facilitating timely decision-making and process optimization.

1 Introduction

Since their introduction in 1943 by P. Eisler [1], printed circuit boards (PCBs) have become indispensable components in microelectronic systems, serving an ever-expanding market [2]. As the demand for electronic products continues to grow, so does the need for optimized PCB manufacturing processes. The primary materials used in PCB fabrication include copper-clad laminate sheets, known as cores, and glass fiber epoxy prepregs [3].

Among the various steps involved in PCB production, the pressing process of cores with prepregs is a major cost driver. This hot press lamination process can take several hours, and its parameters need to be precisely matched to the material behavior to ensure a high-quality final product. Before pressing, the thin copper layer of the core is etched away, leaving only the conductive patterns. During the pressing process, which occurs at elevated temperatures, the epoxy resin in the prepreg initially reduces in viscosity, allowing it to fill the voids in the copper structure. This high temperature also initiates the cross-linking (curing) reaction of the resin, ideally resulting in a copper structure filled with cured resin by the end of the process [4].

Locally unfilled areas can lead to mechanical weaknesses or limited functionality in the final product. Key factors influencing resin flow during lamination include the density and depth of the copper structure, the resin content in the prepreg, the resin viscosity, and the closing pressure. The methodology presented here considers all these factors, providing a comprehensive evaluation of the PCB pressing process using analytical models implemented in Python and numerical finite element (FE) simulations in the 3DTimon

CompositePRESS software. This approach allows for the optimization of existing press cycles and the validation of new ones.

Similar analytical approaches for determining PCB layer thickness after pressing have been documented in the literature. For example, B. Olney introduced a PCB stack-up planner that uses the total volume of voids in the copper structure to determine the dielectric layer thickness after pressing [5]. In contrast, the analytical approach presented here considers the local distribution of copper patterns, enabling an estimation of layer thickness distribution based on selected model parameters. The Squeeze Flow Model by A. N. Derose et al. calculates the flow behavior of the resin in the prepreg based on material and pressing process parameters [6]. This model assumes an impenetrable fiber layer in the prepreg, making only the pure resin film on the side facing the core relevant for the pressing process outcome. This simplification is also used in the analytical and numerical approaches presented in this work. While the Squeeze Flow Model is effective for calculating resin flow between two straight sheets, it is not suitable for the pressing process due to the presence of copper structures. Nonetheless, it is used here for validation purposes.

Although numerous publications exist on numerical process and structure simulations in the PCB field [7, 8], simulating the pressing of an entire copper layer geometry like presented in this work represents a significant scientific contribution.

2 Process parameters and material modeling

In the PCB pressing process, pressure and temperature are gradually increased to ensure their even distribution. Figure 1 shows a simplified setup of a typical multi-layer PCB process. Respectively, a core and a prepreg are pressed in pairs, with several pairs separated by steel and separator sheets possible in one pressing process step.

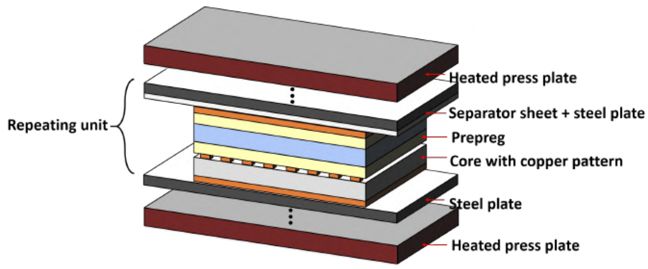


Figure 1: Simplified example of a PCB pressing setup

Figure 2 shows an exemplary parameter setting for the hot press lamination step as commonly proposed by the resin material supplier. Prepregs are classified into types based on the weaving style of the glass fiber fabric [4]. A prepreg of type 2116 with a total thickness of 125μm is used in the pressing process of a PCB copper layer. A prepreg of type 106 with a total thickness of 50μm is used for validation experiments. Both prepregs share the same resin and fiber materials.

In this work, a three-layer prepreg structure is assumed (see Figure 3 (a)). The fiber fabric in the middle of the prepreg is considered an impenetrable layer with two thin films of resin on each side. In the pressing process, a thin film of resin is thus pressed between the PCB copper layer on one side and the fiber fabric layer on the other. The layer thicknesses and fiber volume contents of the two prepreg types are listed in Figure 3 (b).

To determine the resin viscosity curve in a multi-layer pressing cycle, the temperature profile has to

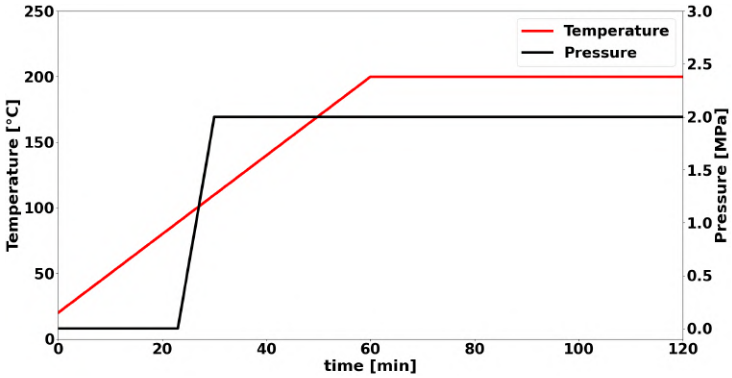
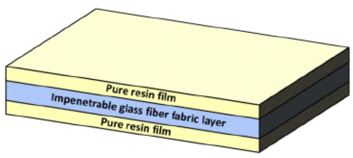


Figure 2: Temperature and pressure profile of PCB pressing process

a)



b)

Property \ Prepreg type	2116	106
Prepreg thickness	125μm	50μm
Fabric thickness	97μm	36μm
Resin film thickness	14μm	7μm
Resin content	53%	73%

Figure 3: Simplified 3-layer structure of prepregs (a), geometry data of used prepregs (b)

be measured as close to the resin as possible. Therefore, a pressing setup (press book) consisting of 8 PCB panels was chosen and an optimized temperature and pressure profile was applied using a vacuum heat press (UVL 5.0, Lauffer, Horb am Neckar, Germany). The temperature profile during the press test was then measured in the middle of the press book (between a separator sheet and a steel plate) using thermocouples to obtain the time-shifted temperature profile as it reached the prepreg. Rheometer tests were carried out on a rotational rheometer (MCR 302, Anton Paar GmbH, Graz, Austria) with this temperature profile, and the resin viscosity curve was determined (see Figure 4). The resin viscosity initially drops as the temperature increases, but then rises again due to the temperature-controlled curing reaction [9] of the epoxy resin.

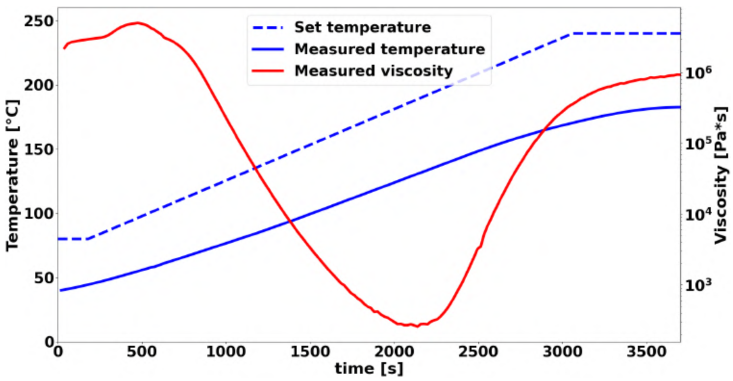


Figure 4: Temperature and viscosity curves of resin in the PCB pressing cycle

3 Analytical modeling of resin flow in PCB pressing process

This section introduces a novel analytical approach for evaluating the PCB pressing process, referred to as the Filter Approach model. The model setup requires TIF images of typical PCB copper layers provided by the industrial partner AT&S. Figure 5 (a) shows the copper layer analyzed in this work. The image is processed using Python and converted into a binary matrix to perform the required calculations.

The Filter Approach model first divides the image into square cells of a defined size and calculates the copper and void volume content in each cell. By comparing the resin volume available from the resin film of the prepreg to the void volume, it can be determined whether there is enough resin to fill all voids in the respective cell. An average filter is then applied to each cell to represent the in-plane resin flow between the cells. The average values of surrounding cells replace each cell's copper and void contents. The filter size is set to 3x3, 5x5, or 7x7 cells. The more surrounding cells are used for the average value of each cell, the more the in-plane resin flow is considered. Depending on the pressing process setup, resin bleed-out can also be taken into account by including empty cells outside the image area in the filter calculation. Furthermore, the Filter Approach model can be used to estimate the local layer thickness distribution and the fiber volume content after the pressing process.

For a fast and user-friendly application, a graphical user interface (GUI) was created using Python to process TIF images of copper layers and graphically display the results of the analytical evaluations (see Figure 5 (b)).

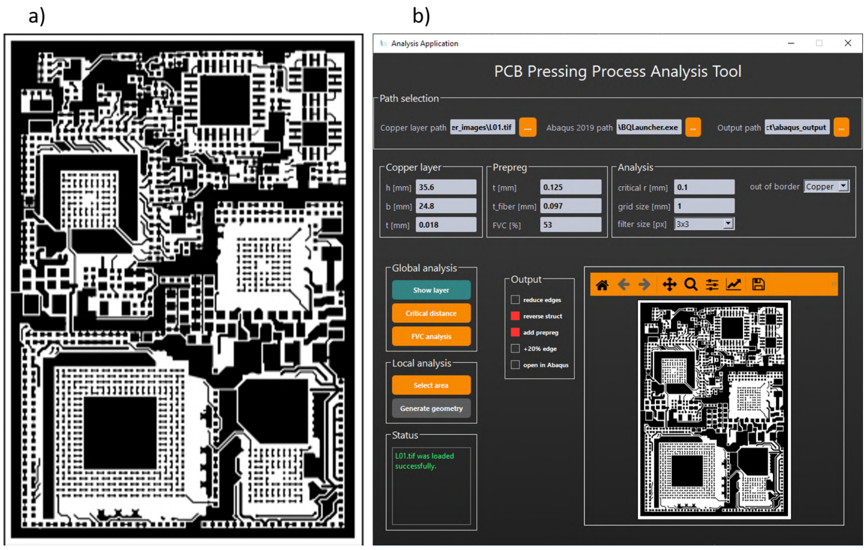


Figure 5: PCB copper layer (a), Python GUI for analysis (b)

4 Numerical simulation model of resin flow in PCB pressing process

To investigate the resin flow behavior in the PCB pressing process, simulation models were set up and calculated in the commercial FE simulation software 3DTimon CompositePRESS (version 10 R8.20) from TORAY Engineering. The software specializes in process simulations of composite materials and was chosen because it provides results within a reasonable amount of CPU calculation time compared to other in-house software.

The first step for the simulation setup is the generation of the PCB copper layer geometry. As with the analytical models, the TIF image of the PCB copper layer is converted into a binary matrix using a Python script. The matrix is used to generate a 3D geometry of the copper layer in the FE program Abaqus (R2019, Dassault Systemes Simulia Corp., Providence, RI, USA) which is then saved as a STEP file. The STEP file can then be imported into 3DTimon. The copper layer has the dimensions 24.6x35.6 mm², and the depth of the copper structure is 18µm. Figure 6 shows the TIF image of the copper structure and the resulting simulation model in 3DTimon. The prepreg is simplified in the simulation model so that only the pure resin film facing the copper layer is considered. This resin film contains all the resin available for filling the voids in the copper patterns. The resin film has a thickness of 14µm.

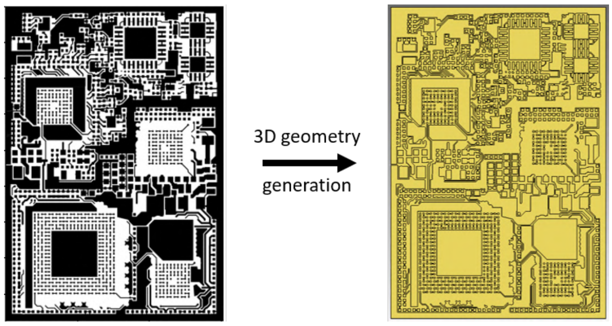


Figure 6: TIF image of PCB copper layer (a) and generated 3D geometry (b)

The geometries of the pure resin film and the copper structure were meshed with a regular Euler mesh (rectangular 8-node elements). The element size was set to 100x100 µm² in the XY plane with 7 elements over the entire model thickness (Z direction), resulting in a total of 4.6E5 elements. The element size was chosen to be as small as possible so that the CPU time of the simulation is still within an acceptable range. The pressing simulation setup with this element size was further examined in Chapter 8.

Based on the temperature, pressure, and resin viscosity curves during the pressing process, a simulation time window of 100s around the minimum resin viscosity was defined, in which most of the resin flow movements are expected (see Figure 7). Starting at 125°C and a constant pressure of 2MPa, the resin is further heated at 3°C/min. The temperature-dependent viscosity curve of the epoxy resin during this period was fitted with a polynomial function and implemented in the simulation model via a user subroutine. The simulations end automatically when either all voids are filled or no more resin flow is possible.

5 Results of the analytical Filter Approach model

The PCB pressing process was analyzed using the Filter Approach model. It shows how cell and filter size affect the results for resin availability, thickness distribution, and fiber volume content after pressing.

The critical volume calculation of the PCB copper layer estimates whether there is locally enough resin available to fill all voids within the pressing process. It was carried out with different cell and filter sizes to determine their influence on the in-plane resin flowability and the required resin volume in the pure resin film. In Figure 8, the cell size is given as the side length of a square cell. The total volume of cells is listed in which, according to the analysis, there is not enough resin to fill all gaps in the local copper structure. Increasing the in-plane resin flow via adjusting the filter size leads to a better distribution of the resin and thus to fewer incompletely filled cells. Taking resin bleed-out into account,

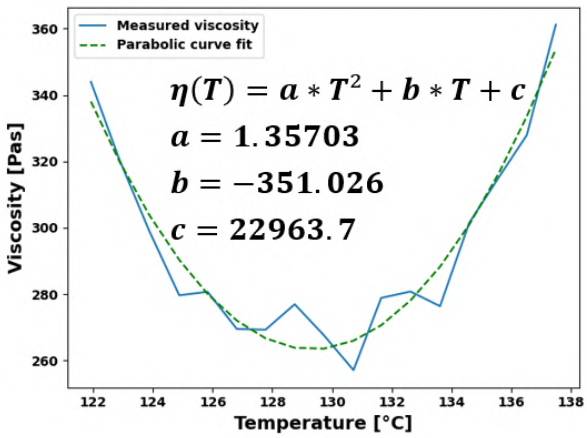


Figure 7: Resin viscosity fit for simulation

however, a higher in-plane flowability results in more resin being lost via the outer edges of the layer, which can lead to more cells without sufficient resin in those areas (see Figure 9).

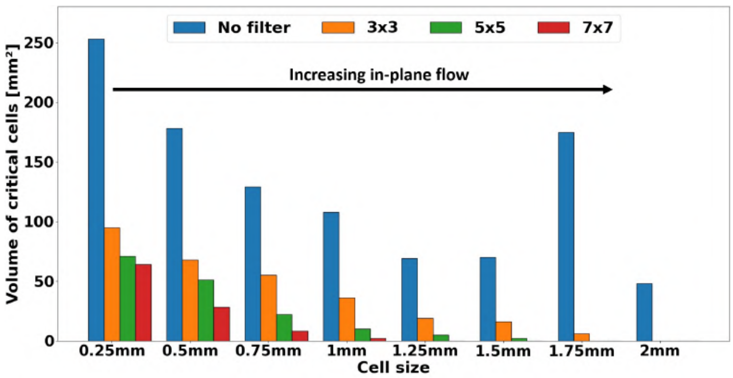


Figure 8: Volume of critical cells of PCB copper layer without bleed-out consideration

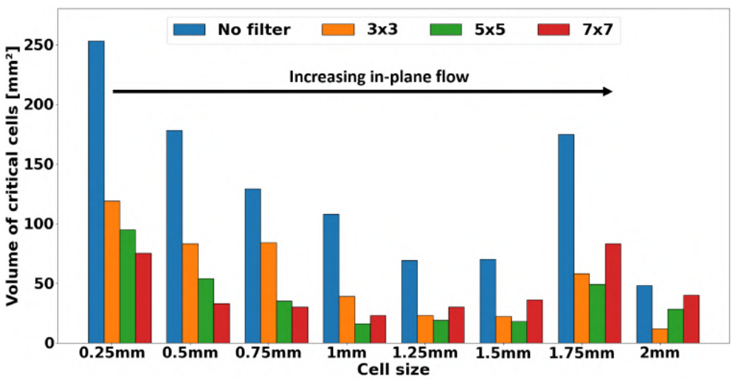


Figure 9: Volume of critical cells of PCB copper layer with bleed-out consideration

A cell size of 1.75mm is a local maximum for the number of critical cells, as some edge areas fall just within the critical range. One example of the distribution of critical cells in terms of resin availability with a cell size of 1mm is shown in Figure 10.

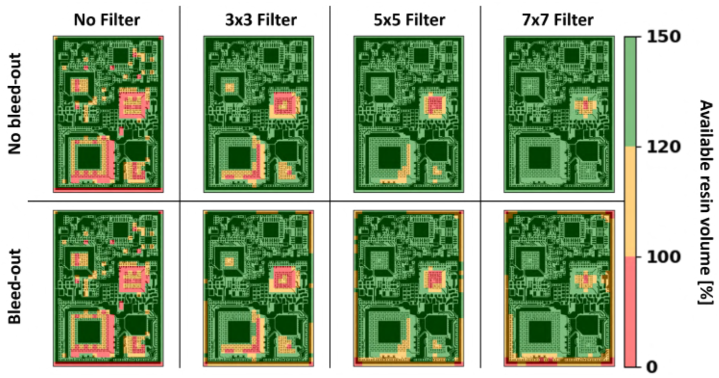


Figure 10: Critical volume evaluation of PCB copper layer with 1mm² cell size

Furthermore, the Filter Approach model was used to calculate the new thickness distribution of the prepreg after pressing. In Figure 11 a cell size of 1mm was used to illustrate the effect of different filters on the in-plane resin flow and thus the thickness distribution. While the calculated thickness after pressing is higher in copper-dense areas, it is more and more evened out when increasing the in-plane resin flow via the filter size. The average copper layer thickness after pressing is mostly not affected by the cell and filter size. If bleed-out is considered, it decreases by up to 3% with a 7x7 filter. The Filter Approach model also estimates the new fiber volume content distribution after the pressing process from the prepreg thickness distribution. The fiber volume content is higher in areas with lower thickness. Figure 12 shows the distribution of the fiber volume content with a cell size of 1mm and different filter sizes.

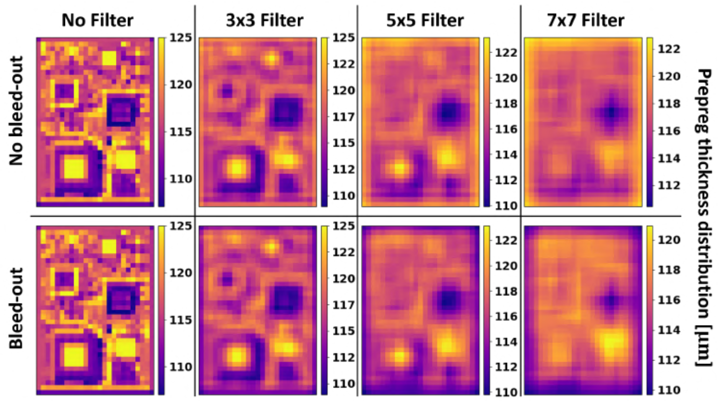


Figure 11: Thickness evaluation of PCB copper layer with 1mm² cell size

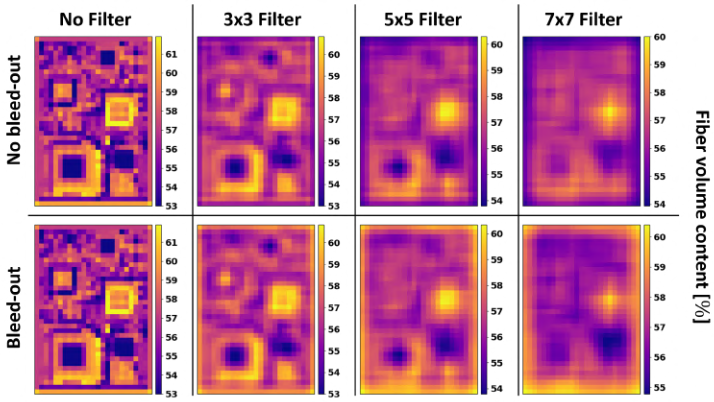


Figure 12: Fiber volume content evaluation of PCB copper layer with 1mm² cell size

6 Results of the numerical pressing simulations

Press simulations were carried out according to the setups described in Chapter 4. Figure 13 (a) shows the PCB copper layer's filling time and pressure distributions for simulations without considering bleed-out. All voids in the copper structure were filled after a pressing time of 14.64s and a CPU calculation time of 60.3h. The filling time graph reflects the resin flow during the pressing process and shows which areas of the copper layer were filled first and last. Large void clusters near the middle of the layer are filled last. The pressure distribution at the end of the simulation shows pressure peaks above copper clusters and at the edges of the layer, as no outflow is possible there. While the average pressure on the entire layer does not exceed 2 MPa, local maxima of up to 40 MPa were observed.

Figure 13 (b) shows the PCB copper layer's filling time and pressure distributions for simulations with bleed-out. Not all voids could be filled with resin. The simulation ended after a simulation time of 7.175s and a CPU calculation time of 20.5h because the maximum press distance (equal to the resin film thickness) was reached. The filling time graph shows which areas of the layer are filled last and which areas are not filled after the simulation time (transparent). While the edge areas are filled, it is mainly the large empty areas in the middle of the copper layer that are not filled. Local pressure maxima are to be expected in the areas of large copper structures, but the distribution is more spread than in Figure 13 (a) due to the consideration of bleed-out. In addition, there are no pressure maxima at the edges of the copper layer.

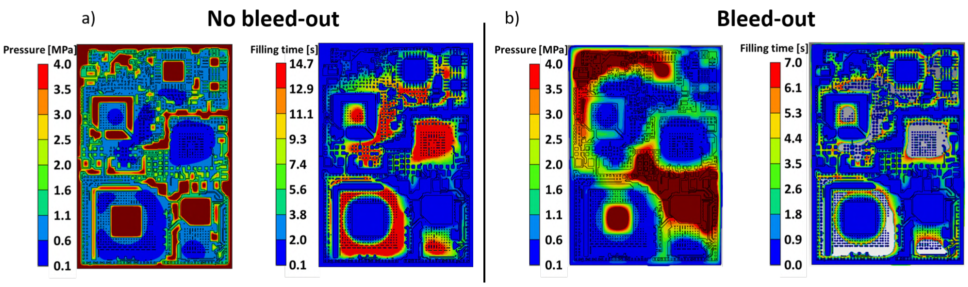


Figure 13: Filling time and pressure distribution at the end of the pressing simulation with bleed-out (a), and without bleed-out (b)

7 Validation of the Filter Approach model

To validate the Filter Approach model, a press card was produced to compare the thickness distribution of the prepreg layer after a pressing cycle to the predictions of the Filter Approach model. Figure 14 shows the TIF image on the left side, and the manufactured press card on the right side. The press card consists of a single 100x100 mm² core layer and locally different copper patterns with a depth of 14µm. It is divided into four sections with different copper volume contents, ranging from 33% to 67% (see Figure 14 (a)).

A prepreg of type 106 with a thickness of 50µm was selected for the pressing test. The pressing tests were carried out on a vacuum heat press (UVL 5.0, Lauffer, Horb am Neckar, Germany) with the same pressing parameters as for the PCB copper layer. The prepreg layer thickness after the pressing process was determined through cross-sectioning and subsequent observation under an optical microscope (VHX-5000, Keyence, Osaka, Japan).

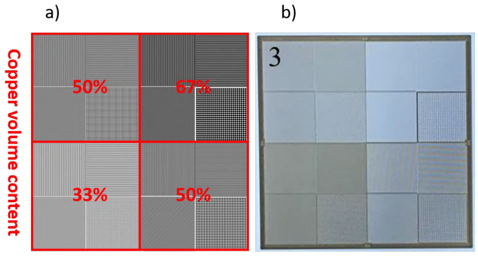


Figure 14: Press card TIF image (a), image of manufactured press card (b)

Figure 15 (a) shows the application of the Filter Approach model on the press card TIF image. A cell size of 1mm and a 3x3 filter were used. However, the cell and filter size do not affect the average thickness values in the respective areas. The thickness distribution of the press card was plotted in eight regions along specified cut directions, as illustrated in Figure 15.

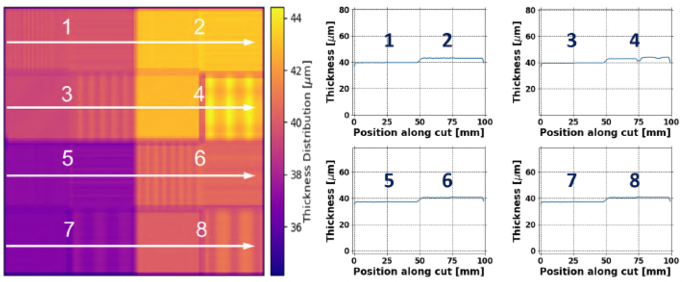


Figure 15: Thickness distribution of press card (a), Thickness distribution plotted along four arrows

Table 1 compares the average thickness values calculated by the Filter Approach model in those eight regions of the press card to the average thickness values from cross-sectioning in these areas. The thickness values are proportional to the copper volume content in both the model and the experiment. Higher copper volume content areas show a higher thickness after pressing compared to the lower copper volume areas. However, the experiments revealed a higher variance in the initial prepreg thickness distribution than expected. For the Filter Approach model, the initial thickness of the prepreg was assumed to be constant, although, in reality, it deviated by more than the 10% specified by the supplier.

Table 1: Comparison of thickness calculation from Filter Approach model with cross-section measurements

Position	1	2	3	4	5	6	7	8
Cross section [um]	40	50	42	48.5	36	50	28	31.5
Filter Approach [um]	40	43	40.5	43.5	37	40.5	37	41

8 Validation of the simulation setup

The simulation model was validated using the Squeeze Flow Model. It is an established analytical model based on the continuity equation for fluids and the Navier-Stokes equations to describe the in-plane flow of fluids squeezed between two plates (see Figure 16 (a)). It was specifically designed to calculate the squeezing of prepregs when assuming a three-layered prepreg structure as described in Chapter 2. The model is used to validate the numerical simulation setup as described in Chapter 4. The exact derivation of the model is described in [6], and the resulting equations are given here:

The reduction of the initial resin film thickness h during pressing is described as follows (Equation 1):

$$h(t) = h - \dot{h}t \tag{1}$$

where $\dot{h}$ is the speed of the pressing plate and t is the time. Based on the given geometries of resin film and plates, an incompressible resin and an exclusively pressure-controlled resin flow, the continuity equation and the Navier-Stokes equations for the X and Y directions can be simplified to obtain the following equation for the plate speed $\dot{h}$ (Equation 2):

$$\dot{h} = \frac{h^3}{6\psi\eta a^4}\frac{F}{\hat{F}} \tag{2}$$

In the above equation, h is the initial resin film thickness, F is the closing force and ψ is a geometric factor equal to the ratio of the width of the laminate, b, to the length of the laminate, a. $\hat{F}$ is the dimensionless closing force and was determined in [6] as a function of ψ. For a square laminate, a value for $\hat{F}$ of 0.035 is given.

To validate the simulation setup in Chapter 4, a simulation model was created for pressing a pure resin film between two plates. The thickness reduction of the resin film during pressing was then compared to the Squeeze Flow Model. The pure resin film has a thickness of 14µm while the in-plane dimensions were varied: Simulation models with 10x10, 20x20, 25x25, and 30x30 mm² resin film dimensions were prepared. The element size was set to 100x100 µm with 7 elements over the thickness, similar to the simulation setup described in Chapter 4. The resin viscosity and the load conditions were also set equally as in Chapter 4. Figure 16 (b) shows the comparison of press strokes (which equals the thickness reduction of the resin film over time) from the FE simulations and the Squeeze Flow Model calculations for different resin film dimensions.

The result shows a good agreement between the simulation and model of the press strokes in the range of 20x20 to 30x30 mm² with the selected simulation parameters. As the copper layer investigated

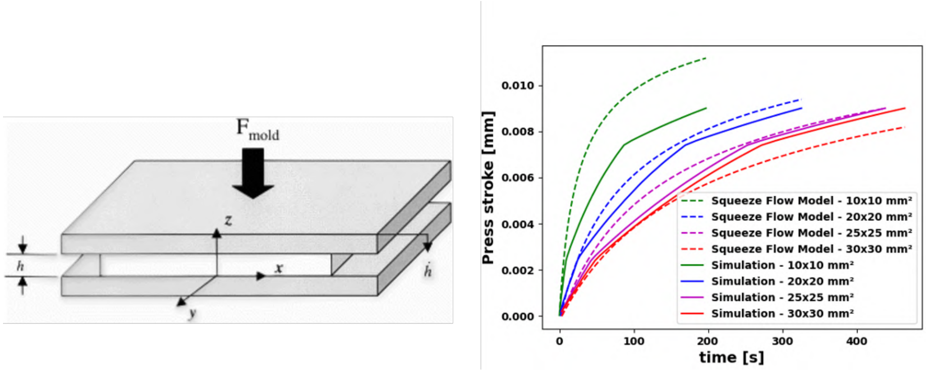


Figure 16: Squeeze Flow Model setup (a), Squeeze Flow Model vs simulation result

in this work has the dimension 24.6x35.6 mm², it can be assumed that the simulation results are valid. To simulate a smaller layer of 10x10 mm², the element size would have to be adjusted accordingly.

9 Conclusions

This study provides a detailed examination of PCB pressing cycles focusing on resin flow. Using 3DTimon CompositePRESS, a stable simulation environment capable of handling significant variations in the thickness, length, and width of PCB copper layers, while maintaining an acceptable range for CPU computation time was developed. The filling simulations incorporated all relevant material and process data to yield meaningful results.

The analytical Filter Approach model presented in this work, while only considering the position and depth of the copper structures and the available resin from the prepreg, proved being effective in predicting resin distribution post-pressing. The model's cell and filter sizes must be calibrated through experiments to accurately reflect the resin behavior during pressing. Once the optimal settings are identified, the Filter Approach model can quickly evaluate PCB pressing cycles in seconds.

Determining whether to consider resin bleed-out in analytical and numerical models depends on the material parameters and process setup. In practical applications, large panels are often used and cut to size after pressing to mitigate edge effects such as bleed-out. This study highlights the importance of considering these factors to ensure the reliability and efficiency of the PCB pressing process.

10 ACKNOWLEDGEMENTS

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