DIMENSIONAL STABILITY OF MULTILAYER PRINTED CIRCUIT BOARDS: INFLUENCE OF THE REINFORCEMENT

Jean-Christophe MINNI [a,b,*], Alain VAUTRIN [a], Patrick HENRAT [b]

[a] Mechanical and Materials Engineering Department, Ecole National Supérieure des Mines de Saint-Etienne, France
[b] Research and Technology Department, HEXCEL Reinforcements, Les Avenières, France

Internal stresses created during the manufacturing of multilayer printed circuit boards (PCBs) may cause dimensional movement resulting in a displacement of the electrical tracks, which in turn creates connection fault. Typical displacement can reach 1mm over a 600 mm board and should be compared to the 150 µm track width. The present study tends to model the dimensional changes of PCBs during processing and introduces a first attempt to monitor the deformations all along the process.
First, the properties of individual laminate plies are predicted by a multi-scale homogenisation of the fabric unit cell. The agreement between the experimental data and the model is within an error of 10%. Then, residual strains and stresses are modelled by using the classical laminate theory. A test to control the dimensional stability has been developed, first results show the high sensitivity to the laminate micro and meso scales.

1. INTRODUCTION

The present trend in electronics is to increase the number of functions to be fulfilled by a given equipment. This is possible with the development of integrated circuits and size reduction of the PCBs. The reduction of board size results from the development of PCBs with higher number of connecting layers and from the drastic reduction of the tracks size leading to higher density of tracks. Such an improvement is only possible if new advances occur in both processing and products so as to reach a higher reproducibility.

Multilayer printed circuit board manufacturing is basically a complex process. It includes several lamination steps and the temperature may exceed the glass transition temperature of the polymer matrix therefore leading to complex phenomena. These lamination steps result in residual stresses within the PCBs, which can generate in-plane strains and electrical track movement as well. Such strains obviously impede novel technical developments. The target is to reduce the dimensional variations of multilayer PCBs during the manufacture. Refined modelling should be used to approach the effect of the reinforcement upon the residual deformations.

This paper introduces the PCB structures first, their manufacturing process. The modelling is then presented, finally the experimental procedures are discussed.

2. PCB STATEMENT

2.1. PCB PRESENTATION

The multilayer printed circuit board is composed of innerlayers with insulating layers between them (Fig. 1). At present, the maximum number of innerlayers reaches 40 connecting copper layers to a total thickness of 3 mm approximately. Typical dimensions of a PCB board are 600 mm x 400 mm.

* Corresponding author. Tel.: +33474338847; fax: +33474339902.
Email address: Jean-Christophe.Minni@hexcel.com (J.-C. Minni).

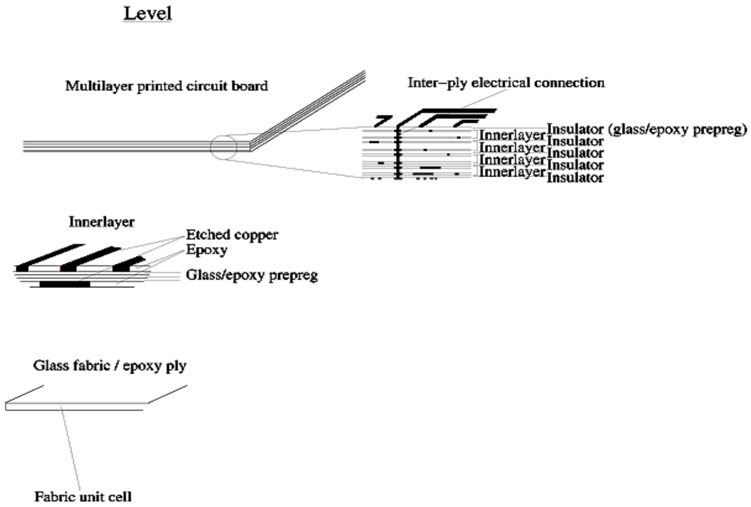

Fig. 1. Multilayer printed circuit board

An innerlayer is a sandwich structure with copper foils bonded on each side of a 1 to 4 ply stack of glass/epoxy prepreg. The fabric style is always the Plain Weave style, however, the weight of the fabric depends on the dielectric requirements. The prepreg resin content ranges from 40% to 60% in weight. The thickness if each prepreg ply is less than 230 µm and the copper foil thickness ranges from 12 to 103 µm.

Copper plies are etched according to a prescribed pattern to connect the different electrical layers together. There are two types of copper patterns: the *logical* and *ground* copper patterns. The logical style is a layer containing about 20% of copper in surface ratio. The ground style corresponds to 80% of copper in surface ratio. The insulating layer consists of one or two plies of glass/epoxy prepreg and it is made of the same type of prepreg as the innerlayers. The function in the PCB is to insulate two neighbouring innerlayers.

2.1. PCB MAIN PARAMETERS

"The Institute for Interconnecting and Packaging Circuits" (IPC) technical papers present most of the parameters which can lead to some dimensional movement during processing. IPC publications [1], [2], [3] and [4] overview the main parameters which are the following:

- the reinforcement construction,
- the resin content,
- the resin curing temperature,
- the etched copper ratio,
- the PCB design.

The parameters used to describe the PCB are related to:

the laminate

- the thermo-elastic properties and the thickness of the prepreg used to manufacture the innerlayers and the insulating separators,
- the lay-up of the PCB laminates.

the fabric unit cell (Fig. 2 and 3)

- the warp and fill yarn width a_w and a_f respectively,
- the thickness of the warp yarn h_w and the fill yarn h_f,
- the gap between warp yarns g_w and fill yarns g_f,

- the resin content of the impregnated warp and fill yarns V_{fw} and V_{ff} respectively,
- the unit cell thickness h,
- the thermo-elastic properties of yarns and resin,
- the geometrical shape of the yarns: ellipse or sine shape.

2.3. PCB MANUFACTURING

The PCB process is decomposed into three main steps. All curing process follows the same cure cycle (Fig. 4). The cure temperature 180°C exceeds the glass transition temperature of the resin matrix which is close to 110°C.

The three main steps characterizing the process (Fig. 4) are:

- innerlayer lamination (step 0),

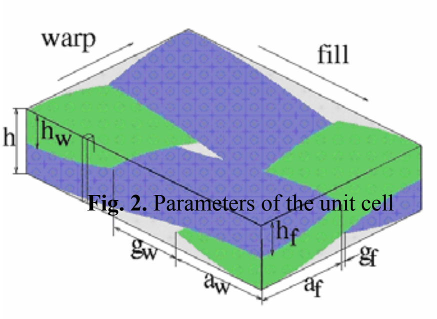

Fig. 2. Parameters of the unit cell

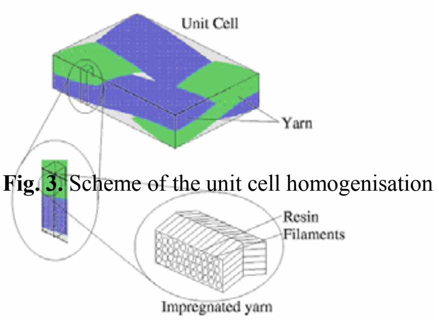

Fig. 3. Scheme of the unit cell homogenisation

- copper etching (step 1),
- multilayer relamination (step 2).

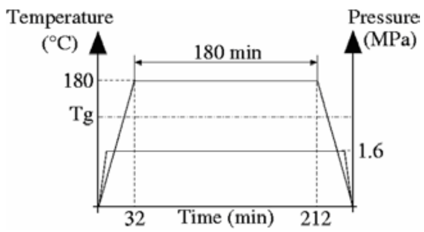

Fig. 4. Cure cycle

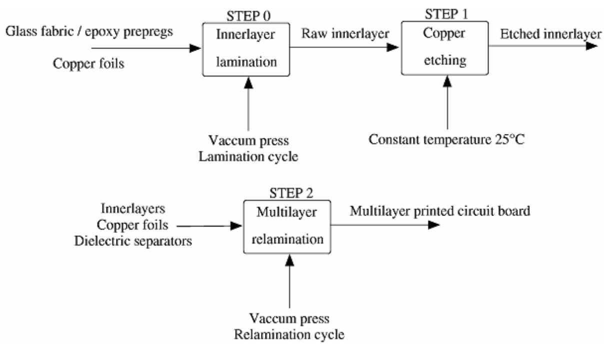

Fig. 5. Multilayer printed circuit process manufacturing

Step 0: the innerlayer lamination results from the lamination of glass fabric and epoxy prepregs with two non-etched copper plies. The resulting product is a raw innerlayer. (Fig. (5)). This lay-up is then press cured.
Step 1: the raw innerlayer copper sides are etched according to a defined pattern. This step is done at a constant temperature of about 25°C. The resulting product is an etched innerlayer. This product is then electrically controlled.
Step 2: the innerlayers with insulating separators are laid up and cured once more. The number of innerlayers in a PCB depends on its design. After that, the multilayer is ready for electrical connections between layers. This latter point is not cover here because the thermo-mechanical history (from step 0 to step 2) only is responsible for the dimensional changes.

2.4. DIMENSIONAL STABILITY

As different constituents are cured at temperatures above the service temperature, internal stresses used to be created during the cooling down from the curing plateau to the room temperature. So, it is the innerlayer curing which induces the dimensional changes during the process and the electrical copper tracks movements. Those changes will consequently create a connection fault within the PCB thickness.

For a better understanding, if we consider an innerlayer with two marks and an initial distance between them of L_0 (Fig. 6). After the etching step, this distance changes from L_0 to L_1 (Fig. 6). So, there is a displacement $\Delta L = L_1 - L_0$ induced by the reduction of the internal stresses allowed by the etching step. After the relamination step, the distance changes from L_1 to L_2 (Fig. 6). The laminate structure changes from an innerlayer structure to a multilayer structures inducing also a change of the residual stresses in copper plies.

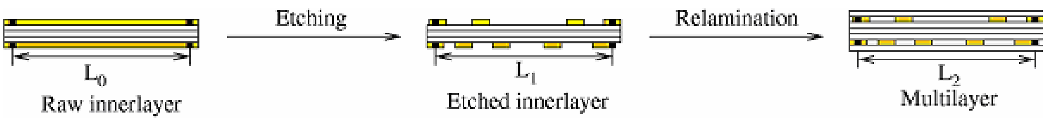

Fig. 6. Dimensional changes during PCB manufacturing

3. MODELLING PRODECURE

The prediction of the dimensional variations of PCBs requires a well founded understanding of every subsequent level (Fig. 1). The thermo-elastic ply properties are obviously needed and should be drawn from the unit cell through a multi-scale homogenisation.

3.1. PLY LEVEL – FABRIC UNIT CELL MODELLING

The unit cell is defined by the following parameters:

- the width, thickness, gap between yarns, fibre content in impregnated yarns,
- the sinusoidal equation, describing the crimped yarn with constant cross-sectional area and sinusoidal or elliptical yarn section shape.

From the description of the unit cell, an analytical multi-scaled modelling can be derived (Fig. 2). The different steps of the approach are the following:

- the effective yarn properties by using the Halpin-Tsai equations, [5], crimp method,
- the infinitesimal plate elements through the classical laminated plate theory then integration over the laminate thickness of the stiffness matrices of impregnated yarns and neat resin areas (Fig 2),
- the homogenisation over the unit cell of infinitesimal plate elements assuming that the strains (resp. stresses) are uniform,
- the final deliveries are the effective properties of the unit cell: the elastic moduli in warp and fill directions; Poisson's ration, in-plane shear modulus and coefficients of thermal expansion.

3.2. PCB LEVEL – PROCESS MODELLING

The model to predict the dimensional changes within the laminate during the manufacturing process is based on the laminated plate theory and an homogenisation step to take into account the etching step. The first step is to model the raw innerlayer, i.e. before copper etching when the laminate is submitted to internal stresses due to the lamination step only.

The model integrates the different processing steps, which are the copper etching at 25°C and the multilayer relamination cycle with the temperature exceeding the Tg of the prepreg. The assumption made here is that the material properties above the Tg are elastic, however some reduction of the resin properties has been applied. The stresses and strains are obtained via the classical laminated plate theory and take into account the temperature and thermal expansion differentials. The calculation of the strains and the stresses within the laminate is performed at each step of the manufacturing process.

Step 1: the etching step (Fig 5).
The laminated plate theory is required to understand how the etching step will reduce the stresses due to the curing of the innerlayers. However, by using the laminate theory only, the etching step cannot be modelled. A virtual step is therefore introduced to consider the etching of the copper plies *prior to* the innerlayer lamination. The stresses resulting from the temperature decrease during this step characterize the mechanical state after etching.
Nevertheless, the effective properties of etched copper plies need to be evaluated for this virtual cooling. Electrical patterns of PCB can be divided into tracks in the warp and the fill reinforcement directions (Fig 7).
In order to understand the role of the copper ply within the laminate, consideration needs to be paid to the following phases: serial and parallel track configuration, for modelling purpose the track is divided into horizontal and vertical elements, and homogenisation of copper and voids created by copper etching.
For temperatures above Tg, both composite and resin properties have been modified to take account for the change in the resin properties. Strains introduced by the etching step are determined by calculating the difference between the raw innerlayer lamination strains and the virtual etched innerlayer lamination strains.

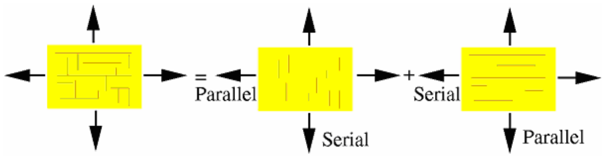

Fig. 7. Etching decomposition

Step 2: the relamination step (Fig 5) is divided into two sub-steps according to the increase or decrease of the temperature.
Step 2a: increase of the temperature during the relamination step.
For temperatures below Tg, properties of the copper ply take into account the presence of voids associated to areas where the copper has been removed during the etching step. For temperature above Tg, the resin o the insulating prepreg fills the voids within the copper plies. The properties of the copper ply should reflect the fact that the effective 'copper' layer is an heterogeneous ply made of copper *and* resin. The residual strains have been computed for a temperature variation from the room temperature to the relamination temperature.

Step 2b: decrease of the temperature during the relamination step.
For temperature above Tg, the properties of the copper ply are the same as those at step 2a. It is possible to consider the laminate to be composed of innerlayers and dielectric insulators. For temperature below Tg, the effective properties of copper plies are derived from the homogenisation of copper and resin with properties below Tg (Table 1). Relamination strains are finally obtained by adding the strains of the two sub-steps. The total strains are the sum of the etching strains and the relamination strains.

Table 1. Thermo-mechanical properties of constituents, Tg=110°C, from [6]

Constituent	Copper	FR4 resin		7628	2116
		T>Tg	T<Tg	T<Tg	T>Tg
E_w (GPa)	117	3.4	23	18	0.07
E_f (GPa)	117	3.4	21	15	0.07
ν_{wf}	0.35	0.33	0.17	0.21	0.33
α_w (10^{-6}/°C)	17	58	14	19	197
α_f (10^{-6}/°C)	17	58	17	18	197

4. EXPERIMENTAL APPROACH

4.1. FABRIC THERMOELASTIC PROPERTIES

Thermo-elastic properties of glass and carbon fabrics are determined. Two styles of fabrics are selected. Glass fabrics references are 7628 (203 g/m²) and 1080 (47 g/m²). These two references are typically used in PCB manufacturing. Carbon fabrics references are 43193 (193 g/m²) and 48192 (193 g/m²). The first one is composed of 3K carbon tows and the second with 12K carbon tows. These two fabrics are typically utilized in aerospace or industrial applications.

Elastic properties are the two moduli in warp and fill directions, Poisson's ratio in agreement with ISO CD/527 standard and in-plane shear modulus in agreement with prEN 6031 standard. Strains are measured with 0/90° HBM XY91-10/120 strain gages.
The coefficient of thermal expansion (CTE) is measured when the specimen is submitted to a thermal cycle, the specimen strains are monitored with HBM LY11-10/120 strain gages. The specific thermal strain of the strain gage is taken into account. A strain gage is bonded on a titanium silicate specimen whose CTE is close to zero, the thermal strain measured by this strain gage is the specific thermal expansion.

Thermal cycles applied to the different fabrics depend on the resin. For 7628 and 1080 glass fabrics, a FR4 epoxy resin is used. It is a typical resin for PCB with Tg = 110°C. The thermal cycle applied is the same as for the PCB manufacturing (Fig. 4) except that the plateau duration is one hour. For 43193 carbon fabric, a M18 epoxy resin with Tg = 198°C is used. The thermal cycle is the same as for the 7628 or 1080 fabrics. A M10 resin with a Tg of about 120°C is used for the 48192 carbon fabric. The thermal cycle is the same as for the other fabric but the plateau temperature is 130°C and not 180°C as for the other. Input data used for the different fabrics are summarized in table (2).

Table 2. Input data for glass and carbon style

Style	a_w (µm)	g_w (µm)	h_w (µm)	V_{fw} (%)	a_f (µm)	g_f (µm)	h_f (µm)	V_{ff} (%)	h (µm)
7628	575	0	90	77.3	598	235	93	72.5	180
1080	191	233	43	73.9	353	202	28	66.6	71.5
43193	1924	154	171	47.6	1501	527	172	60.3	252
48192	7199	995	157	75.1	7249	1256	114	73.6	267

Comparisons between predicted and experimental results are presented in Fig. 8. The deviation between the average experimental data and the ply model prediction is less than 10%, this is considered as a reasonable agreement.

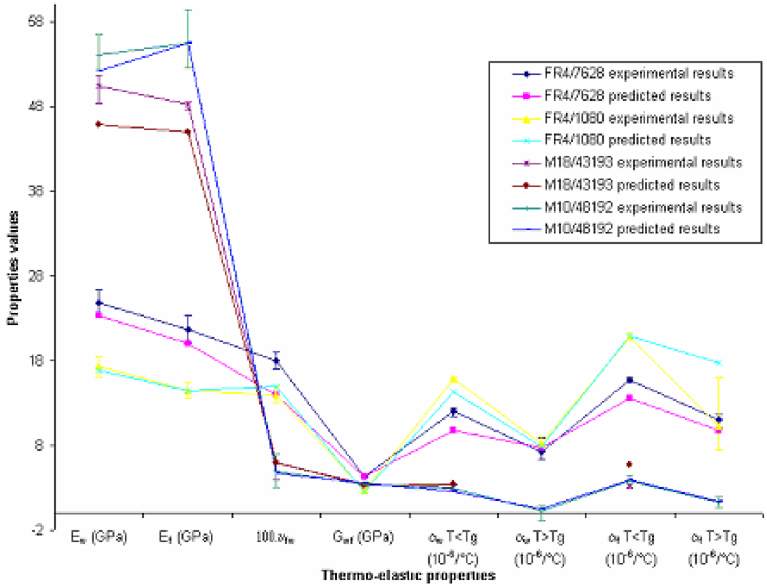

Fig. 8. Comparison between experimental and predicted results on glass and carbon fabrics

Experiments are performed on 7628 and 1080 styles to characterize the effect of the temperature on the mechanical properties over the resin Tg. Elastic moduli at 150°C and 180°C in warp and fill directions are determined.

The first experiment aims to detect whether the behaviour is elastic at temperatures above Tg. A tensile test is carried out at two different speeds 2 mm/min and 20 mm/min. Results on the both fabrics are presented in table (3). Comparisons between data at 150°C and 180°C show that there is no significant difference in terms of measured moduli. This experiment leads to the conclusion that the elastic assumption for temperature above Tg can be reasonable.

A second experiment leads to the moduli at 150°C and 180°C. Results are presented in table 3. We can notice an important scatter of the moduli. The specimens are difficult to handle at testing temperatures above resin Tg and three specimens have been used for each direction and temperature. Nevertheless, we can conclude that there are only a few changes in moduli values between 150°C and 180°C. Finally, we have considered constant values for the moduli above Tg in numerical simulations.

A third experiment is performed at both temperatures. It consists in maintaining the specimen at constant temperature for two hours and monitoring the moduli values. Results are presented in table 3. We can notice some tendency of the moduli to decrease after the two hours curing. However, we have to be careful since this experiment has been performed on one specimen only for each direction and each temperature and in a oven without inert atmosphere (vacuum or nitrogen). A possible resin degradation would be associated with a decrease of the moduli value.

Table 3. Young moduli in GPa for 7628 and 1080 at 150°C and 180°C

Style	150°C			180°C		
	2 mm/min	20 mm/min	2 hours curing	2 mm/min	20 mm/min	2 hours curing
7628 – Warp	14.1	14.5	13.2	12.7	12.8	10.6
7628 – Fill	10.0	9.3	10.1	7.9	7.4	7.7
1080 – Warp	9.9	10.3	9.6	11.2	11.2	10.3
1080 - Fill	5.7	5.7	5.9	5.8	5.7	5.3

4.2. DIMENSIONAL STABILITY OF THE PCBs

4.2.1. DESCRIPTION OF THE TEST

The aim is to follow the displacement of marks drawn on the laminate surface at each step of the process. An IPC standard test [7] has been set up to characterize the dimensional stability of PCBs. Nevertheless, this test aims to determine the displacement of marks on an innerlayer after the total copper etching and a second cure cycle only. Obviously, this test does not allow to measure the effects of the copper etching pattern and the insulating prepregs used between innerlayer on the displacement of the marks. Therefore, a new experimental approach has been developed and is described in the following. It proposes to follow the different steps of the manufacturing process and to monitor the displacements of the marks after each step. The steps are the copper etching and the multilayer relamination. A multilayer is manufactured by bonding insulating prepregs on both sides of the innerlayer laminate.

The first step is to cure the innerlayer, to this purpose several glass/epoxy prepregs are laid up between the two copper foils. This lay-up is cured according to the same cure cycle as for PCBs manufacturing (Fig. 4). Once the laminate is cut at the right dimensions 240 mm (warp direction) x 150 mm (fill direction) marks are drilled into the corners of the laminate. The distances between the marks are measured by an optical equipment with an accuracy of 4 μm.

Copper sides are then scrubbed to improve the bonding capability and photosensitive films are bonded on the copper foils. They are used to transfer the etching patterns onto the copper after exposition to UV light and development in chemical solutions. The patterns are then transferred on the innerlayer, the copper is etched with a chemical solution at the temperature of 25°C. After that, the distances between the marks are measured again. The effect of the etching step on the innerlayer can be characterized by the displacements of the marks.

Then, the innerlayer is laid up with insulting prepregs and cured according to the same cure cycle than previously. The resulting laminate is cut at the right dimensions (240 mm x 150 mm) and the distances between the marks measured. The relamination effect is characterized by those displacements.

4.2.2. FIRST RESULTS

First experiments are conducted with 7628 prepreg for the innerlayer and 1080 prepreg for the insulating separators. Different etching patterns have been used: no etching, 20% copper removed and 80% copper removed. The results are presented in Fig. 9. We can notice important deviations both for copper etching and relamination results. We can also note that the movements are not completely homogeneous after etching and not homogeneous after relamination. At the moment, the nature of the deviations is not fully understood but the test is quite complex to perform and composed of steps where defaults can be critical.

At the innerlayer lamination preparation, the prepreg lay-up positioning is quite difficult because of the light weight of the product. Yarns are very difficult to detect. A small deviation in the positioning of the prepregs can lead to non-homogeneous movements over the laminate. At the etching step, the way to put in place the pattern transfer films may control the marks displacements. At the relamination step, it is the same case as for the innerlayer preparation.
So, at every step, the way to manufacture the product controls the deviation and the non-homogeneous displacements over the laminate. This test needs to be fairly improved to reduce the deviation and increase the accuracy of each preparing steps.

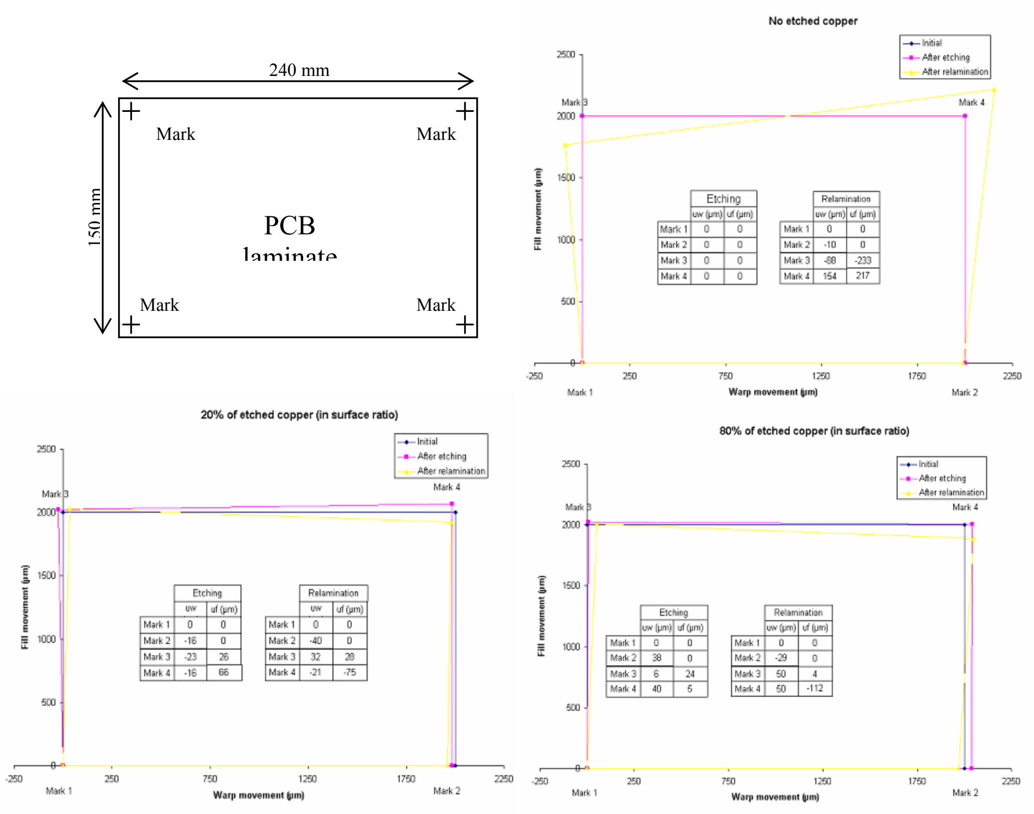

Fig. 9. Dimensional stability test first results

4.2.3. FIRST IMPROVEMENTS

Specific setups suited to each step needs to be designed to improve the reliability of the test. The first step is the cutting of the prepregs and their positioning in the lay-up. Every angle deviation needs to be reduced. The proposal is to design a device permitting to align the prepreg plies and to position them with three pin-holes. These pin-holes will be positioned asymmetrically on the prepreg plies to define a unique position of plies and laminates. The lay-up will be positioned with pin-holes in the curing oven. These pin-holes will be used also to cut the laminate at the right sizes and position the pattern transfer films with accuracy. Finally, they would be useful to relaminate the innerlayer with insulating prepregs. Deviations to right positioning should be characterized as well to correlate with experimental scatter.

5. CONCLUSION

The multilayer PCB manufacturing process generates internal stresses during the cool down stages. These stresses used to be reduced during the etching or relamination step. The variations of the state of stress during the processing induce strains that cause electrical track displacement, that in turn induces electrical connection faults through the PCB thickness. Controlling this dimensional variation that is clearly a key issue in the manufacturing of multilayer PCB.

The modelling to approach the dimensional change in multilayer PCB is based on a multi-scale definition of the product and on a refined analysis of the different manufacturing steps. It leads to the prediction of:

- the properties of glass fabric/epoxy prepreg by homogenisation of the fabric unit cell,
- the strains resulting from the manufacturing process by using the classical laminated plate theory and the process description.

Finally, some experiments have validated the ply modelling and checked the elastic behaviour of composite materials at temperatures above the resin Tg. A special test has been developed to monitor the displacements in typical PCBs all along the manufacturing process, to characterize the effects of every steps. However, the test needs to be further improved to reduce the deviation due to the lack of accuracy in the manufacturing. Furthermore, in the future this test will allow to validate the modelling of the process.

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