# Board Warpage during Reflow Soldering– Need for Board Support?

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**Abstract**
In the high temperatures during board assembly reflow soldering, the base material becomes soft and there is a severe risk for permanent warpage.

There are many parameters that could affect board warpage during reflow soldering. The board width, board thickness, layer count, amount of copper, distribution of copper, glass fiber weave style, milling, type of base material, symmetry in all directions, component population and component weight are, among others, important factors.

It is very difficult for the board designers to decide when an area on the secondary side should be left free of components to give place for board support during the reflow soldering process in order to mitigate board warpage. An evaluation was therefore performed that aimed at formulating an easy-to-use rule for this purpose.

A board with a 10 mm wide area free of components on its secondary side (marked with red lines) is given in Figure 1.

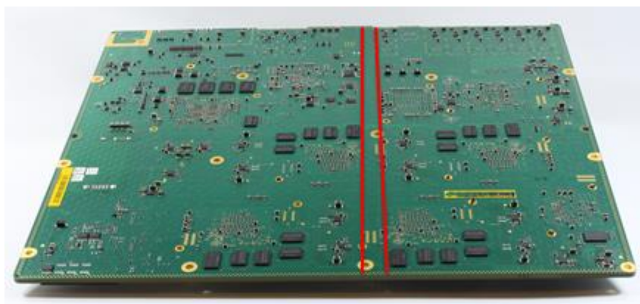

**Figure 1 – Board with an area free of components to give place for board support during second reflow soldering.**

## I. Introduction

This paper has its roots in discussions between production and board design departments about when there is a need to leave an area on the secondary side free of components to give place for board support during the reflow soldering process in order to minimize board warpage.

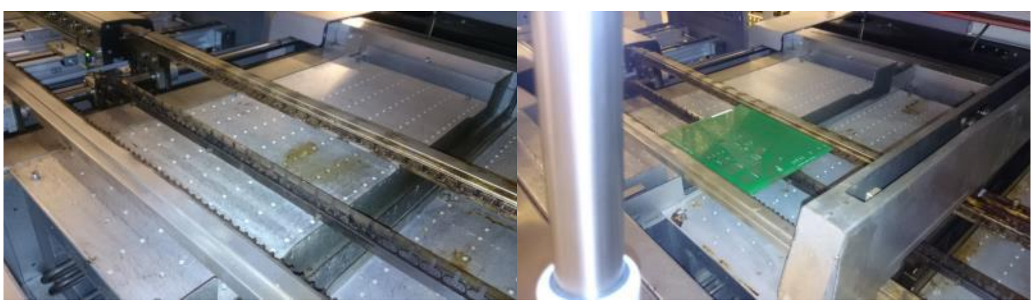

**Figure 2 – Reflow oven conveyor with board support, without board (left) and with board (right).**

When a board is heated above the glass transition temperature (Tg) for its polymers, cooperative movements of tangled polymer molecule chains will take place if sufficient force is applied[1] (e.g. from the weight of the components and from the board's own weight). If this is performed in greater scale, the board will bend or bow. When the temperature decreases below the Tg and the board base material returns to a solid state, the warpage could have become permanent.

According to chapter 9.3 in the standard IPC J-STD-001F, Requirements for Soldered Electrical and Electronic Assemblies [1], the limits after soldering for bow and twist[2] for a board populated with surface mounted components is 0.75% of the diagonal (for twist) or 0.75% of the width or the length (for bow).

[1] Source: Polymers and liquid Crystals, Case Western Reserve University, (http://plc.cwru.edu/).
[2] Bow and/or twist are, most often, called "warpage" in this report.

Illustrations of the bow and twist, from the IPC TM-650, test method 2.4.22 [2], are given in Figure 3.

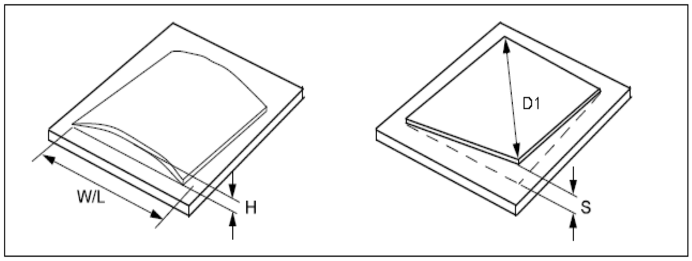


**Figure 3–Illustrations of how to measure bow (left) and twist (right) [2].**

Even board warpage less than 0.75% could give problems during e.g. the assembly of big press fit connectors or just to insert the boards in board magazines or bolting the board into a chassis. When warped boards are straightened during e.g. insertion in magazines, the extra stress and strains applied to the components' solder joints will make the reliability decrease [3]. It is therefore desirable to produce boards that have margins to this warpage limit.

The question that this study aimed to answer was if it could be possible to formulate an easy-to-use guidance rule for when a board support is needed in the reflow oven in order to get boards with a permanent warpage well below 0.75%.

## II. Methodology

This evaluation included two different parts, whereof the first consisted of a study in which warpage on real boards from the production with different designs were documented and a second part that consisted of warpage measurements of simple laminates of different sizes, thicknesses, materials etc.

### *A. Documentation of Real Boards and Their Warpage*

Real warpage data was documented for different kinds of boards; both for boards with much warpage and for boards with nearly no warpage at all. Relevant information about these boards was collected into a table and the headings in the table columns were:

Board part number, R-state, lead-free soldering (yes/no), board length, board width, panel length, panel width, total board thickness, total number of layers, Cu thickness(for all layers), number of power/ground layers, Cu-balance (top/bottom), total weight of components and solder paste, average component weight per square decimeter, weight of board, type of board material, type of prepreg, resin type, warpage before soldering, warpage after soldering and if oven center support was used.

By analyzing all data from these real boards, it was believed that there should be sufficient information in order to formulate guiding principles for when board support would be needed. However, this was not possible, so dedicated tests had to be performed to find out how different parameters affect board warpage.

### *B. Warpage Tests - Laminates*

There was a need to perform simplified tests of the different board parameters that affect warpage. Therefore, tests were performed with laminates of different thicknesses and materials that were cut into various sizes dependent on the type of test. Each laminate was then subjected to different weights which were placed in the center of the laminate or spread evenly over the laminate surface, depending on test.

The following parameters were tested[3]:

- Copper balance
- Warp/weft direction
- Milling
- Board width
- Board thickness
- Mixed base material symmetry
- Glass/epoxy class (density and thickness of glass fibers bundles in weave)
- Base material (type of resin)

[3]Parameters that could affect board warpage according to, among others, the document ”Vad göra med buktning och vridning av mönsterkort” by Esbjörn Johansson, Capinor AB, 2009 [4].

### III. Real Board Warpage Data

Different kinds of boards that had been designed by various design units were chosen in order to get an understanding of how design and materials could affect board warpage. In this collection of boards, there were those with much warpage, but also boards that would have been expected to have significant warpage, but that did not have this.

The following data from 30 boards was collected:

Board Part number, R-state, Lead-free soldering (yes/no), board length, board width, panel length, panel width, total board thickness, total number of layers, Total Cu thickness(all layers), number of power/ground layers, Cu-balance (top/bottom), total weight of components and solder paste, component weight per square decimeter, weight of board, type of board material, type of prepreg, resin type, warpage before soldering, warpage after soldering and if oven center support was used.

An example of how the data collection could look is shown for 11 of the 30 studied boards in Table 1 and Table 2 (the original table had to be divided into twoin order to fit into this report).

The rows in the table with data for boards that have a warpage well below the 0.75% limit have green color. If the warpage is close to 0.75%, the rows are colored in orange and the rows in the tables for boards with more than 0.75% warpage are colored in red.

**Table 1–Real Board Data - 1**

| Board[4] | Leadfree soldering [yes/no] | PCB Length [mm] | PCB Width [mm] | Panel Length [mm] | Panel Width [mm] | Total Board thickness [mm] | Total number of layers | Total Cu thickness, all layers [µm] | Number of power/ground layers | Cu balance Top/Bottom |
|---|---|---|---|---|---|---|---|---|---|---|
| A | No | 366 | 264 | 366 | 289 | 1.8 | 10 | 274 | mixed layers | 65/76 |
| B | Yes | 366 | 264 | 366 | 289 | 1.6 | 8 | 202 | mixed layers | 64/68 |
| C | Yes | 274 | 311 | N/A | N/A | 2.3 | 20 | 504 | 8 | 45/43 |
| D | Yes | 244 | 311 | N/A | N/A | 1.4 | 6 | 275 | mixed layers | 86/89 |
| E | Yes | 210 | 265 | N/A | N/A | 1.9 | 12 | 260 | mixed layers | 71/70 |
| F | Yes | 207 | 265 | N/A | N/A | 1.5 | 2 | 80 | 0 | 11/4 |
| G | Yes | 207 | 265 | N/A | N/A | 1.5 | 6 | 148 | 4 | 62/60 |
| H | Yes | 207 | 265 | N/A | N/A | 2.0 | 8 | 182 | 6 | 69/67 |
| I | Yes | 207 | 265 | N/A | N/A | 2.5 | 10 | 216 | 8 | 72/71 |
| J | Yes | 210 | 265 | 210 | 265 | 2.2 | 20 | 406 | 10 | 25/24 |
| K | Yes | 201 | 90 | 275 | 201 | 0.9 | 4 | 135 | mixed layers | 84/88 |

**Table 2–Real Board Data -2**

| Board | Total weight components + solder paste [g] | Average component weight/area [g/ $dm^2$] | Weight of PCB [g] | Type of PCB material | Bow & twist before soldering [mm] | Bow & twist after soldering [mm] | Center support used (yes/no) |
|---|---|---|---|---|---|---|---|
| A | 805 | 82 | 461 | HFFR4[5] | ~0 | 1.8 | Yes |
| B | 750 | 78 | 348 | HFFR4 | ~0 | 1.7 | Yes |
| C | 774 | 91 | 250 | HFFR4 | ~0 | max 1.0 | No |
| D | 555 | 73 | 319 | LH[6]+HFFR4 | 0 to 0.2 | 0.9 | Yes |
| E | 423 | 76 | 280 | HFFR4 | ~0 | ~0.4 | No |
| F | 169 | 31 | 141 | FR4 | ~0 | 1.9 | No |
| G | 169 | 31 | 184 | FR4 | ~0 | 1.6 | No |
| H | 169 | 31 | 247 | FR4 | ~0 | 1.1 | No |
| I | 169 | 31 | 310 | FR4 | ~0 | 0.4 | No |
| J | 35 | 6 | 320 | HFFR4 | ~0 | 0.3 | Yes |
| K | 63 | 35 | 120 | LH+HFFR4 | ~0 | 1.5 | Yes |

[4]The real board part numbers and revisions have been removed from the tables.

[5] HFFR4 = Halogen-Free Flame Retardant 4.

[6] LH = Low Loss High Performance material (glass fiber reinforced hydrocarbon ceramics), especially used for boards subjected to high frequency signals.

Drawings of each layer for each board and also Shadow Moiré warpage measurements, if this existed, were collected for the analysis and understanding of the warpage results.

Two examples of copper balance data are given in Table 3.

**Table 3–Example of copper balance for a 10 layer and a 6 layer board.**

| Board I | Percentage copper | Board D | Percentage copper |
|---|---|---|---|
| Layer_1 | 11 % | Layer_1 | 84 % |
| Layer_2 | 88 % | Layer_2 | 89 % |
| Layer_3 | 88 % | Layer_3 | 86 % |
| Layer_4 | 88 % | Layer_4 | 95 % |
| Layer_5 | 88 % | Layer_5 | 81 % |
| Layer_6 | 88 % | Layer_6 | 95 % |
| Layer_7 | 88 % | N/A | N/A |
| Layer_8 | 88 % | N/A | N/A |
| Layer_9 | 88 % | N/A | N/A |
| Layer_10 | 4 % | N/A | N/A |
| Top 5 | 72 % | Top 3 | 86% |
| Bottom 5 | 71 % | Bottom 3 | 89% |

An example of Shadow Moiré warpage measurements during heating and cooling of a small board is given below.

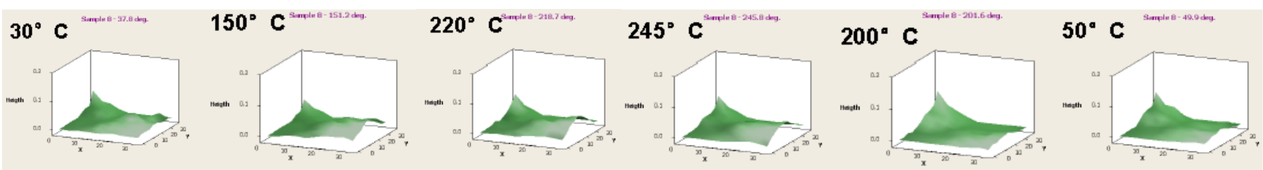


**Figure 4 – Example of a Shadow Moiré warpage measurement during board heating and cooling[7].**

The collected data from the 30 boards gives hints about when board support is needed, but in order to formulate an easy-to-use guidance rule, the data collection was not regarded as sufficient.

**IV. Laminate Warpage Tests**

A great amount of laminate reflow tests were performed in order to get a basic understanding of how different parameters affect warpage during reflow soldering. By using simple laminates, different board parameters could easily be varied and compared to each other.

In these tests, laminates of different thicknesses and materials were bought and cut into various sizes dependent on the type of test.

The laminates have been subjected to different weights that have either been placed in the center of the laminate or spread evenly over the laminate surface. The most common weight per area used in these tests (100 $g/dm^2$) was chosen to be slightly higher than the weight per area on the analyzed real boards with heaviest components per board area.

After initial warpage measurements, the laminates were subjected to an ordinary Pb-free reflow soldering cycle and after this, the final warpage was measured.

[7]Picture source: Sony Ericsson

Initial warpage was, most often, measured with weight on the laminate, see Figure 5.

**Figure 5 - Measurements of laminate with weight prior to reflow[8]**

The measuring equipment used in this study is shown in Figure 6.

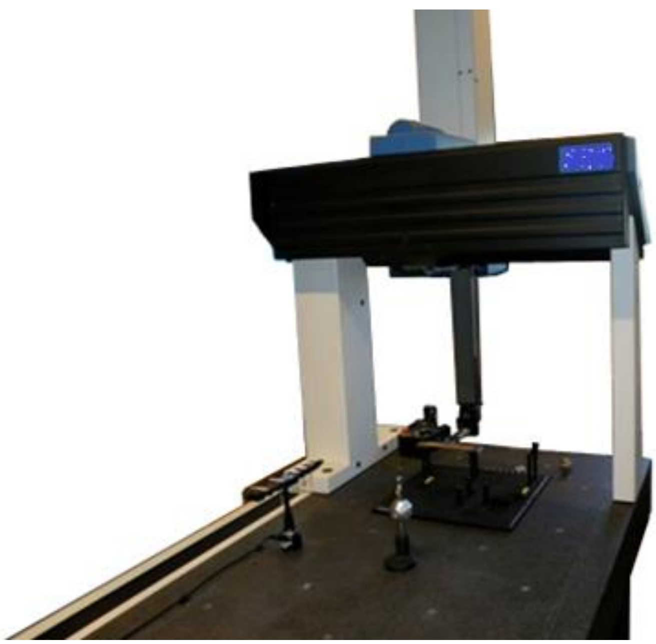

**Figure 6–The measurement equipment used in the study[9].**

[8]Picture source: Ove Isaksson, Ericsson in Kista

[9] Ibid.

After the initial measurements, the laminates were placed in a fixture, see Figure 7.

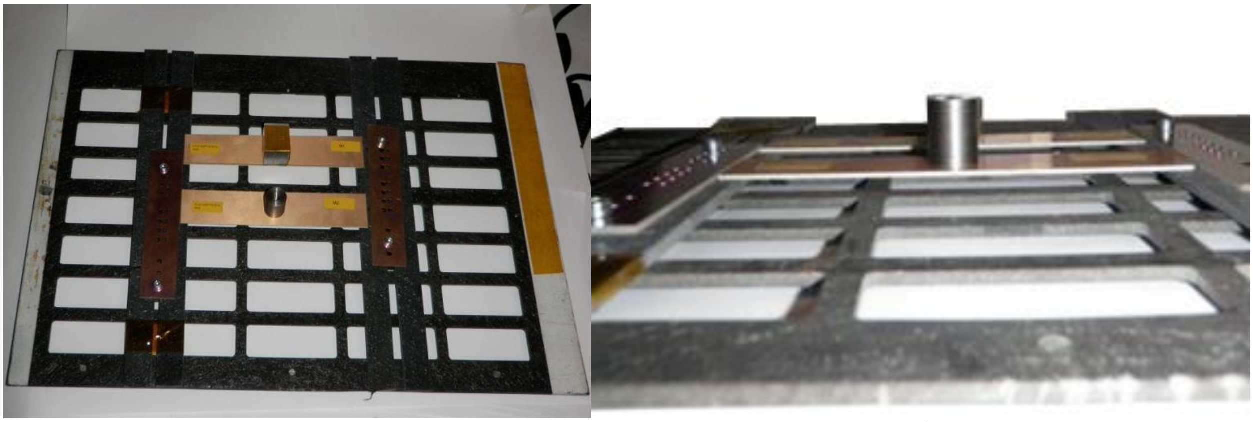

**Figure 7 - Reflow fixture with laminates and weights[10].**

The distance between the side-supports in the fixture has been varied from 100 mm to 400 mm in different tests, see Figure 8.

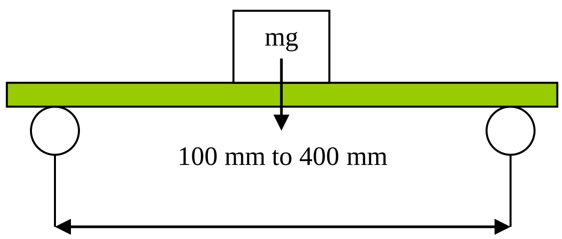


**Figure 8 - Side-view of the fixture used during reflow[11].**

The fixture with the laminates was sent into reflow soldering. A production reflow oven with the settings shown in table 4 was used for the reflow soldering. These settings resulted in an ordinary Pb-free reflow profile with a peak temperature of about 240°C and a time over liquidus of about 60s.

**Table 4 - Oven settings for the laminate warpage test.**

| **Zone** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Top [°C]** | 95 | 140 | 160 | 180 | 200 | 220 | 250 | 270 | 240 | 95 | 60 | 40 |
| **Bottom[°C]** | 95 | 140 | 160 | 180 | 200 | 220 | 250 | 270 | 240 | 95 | 60 | 40 |

After reflow soldering, the laminates’ warpages were measured again according to the IPC TM-650, test method 2.4.22 [2], see the previously shown Figure 3.

[10]Picture source: Ove Isaksson, Ericsson in Kista
[11]Ibid.

## V. Tested parameters and test results

The following parameters have been tested regarding how they affect board warpage [4]:

- Copper balance
- Warp/weft direction
- Milling
- Board width
- Board thickness
- Mixed base material symmetry
- Glass/epoxy class (density and thickness of glass fibers in weave)
- Base material (type of resin)

The author of this report is aware that the results from these simplified laminate tests can not directly be translated into real, complex multi-layer board warpages. However, some knowledge of the parameters relative importance can be estimated by these tests.

The warpage results from the tests can be found below.

### *A. Copper Balance*

In this test, the warpage dependence on copper trace directions and copper symmetry in X-, Y- and Z-direction have been investigated.

#### *A.1–Trace Direction*

A test that should confirm that copper actually strengthens the boards was performed. In this test, laminates with continuous traces (1 mm wide with 1 mm gap) parallel or orthogonal to the reflow oven's conveyors were tested.

A photo of the test laminates can be seen in figure 9. The laminates have the same pattern on both their primary and secondary side.


**Figure 9–Copper trace direction on test laminates; length direction (top), crosswise direction (bottom)[12].**

[12]Picture source: Ove Isaksson in Kista

There were two thicknesses on these laminates; 0.8 mm thick laminates with the unsupported width in reflow oven of 100 mm and 1.6 mm thick boards with 200 mm unsupported width in oven. All laminates were tested with 100 g/dm$^2$ weights evenly distributed on their board surfaces.

The test showed that the trace direction matters and that continuous traces, orthogonal to the conveyors, help to decrease the warpage, especially for the 200 mm free length laminates, which is shown in Table 5.

**Table 5–Copper trace direction – warpage.**

| Laminate | Thickness [mm] | Glass type | Material | Warpage before reflow with weight [mm] | Weight | Warpage after reflow with weight [mm] | Warpage after reflow with weight |
|---|---|---|---|---|---|---|---|
| 1 L[13] | 1.60 | 7628 | FR4 | -0.27 | 60 g | -0.65 | -0.3% |
| 2 L | 1.60 | 7628 | FR4 | -0.40 | 60 g | -0.92 | -0.5% |
| 3 L | 1.60 | 7628 | FR4 | -0.23 | 60 g | -0.82 | -0.4% |
| 4 L | 1.60 | 7628 | FR4 | -0.03 | 60 g | -0.95 | -0.5% |
| 5 L | 1.60 | 7628 | FR4 | -0.27 | 60 g | -0.81 | -0.4% |
| 6 L | 1.60 | 7628 | FR4 | -0.24 | 60 g | -0.88 | -0.4% |
| | | | | | | | |
| 1 T[14] | 1.60 | 7628 | FR4 | 0.11 | 60 g | -1.49 | -0.7% |
| 2 T | 1.60 | 7628 | FR4 | -0.01 | 60 g | -1.33 | -0.7% |
| 3 T | 1.60 | 7628 | FR4 | -0.95 | 60 g | -1.90 | -1.0% |
| 4 T | 1.60 | 7628 | FR4 | -1.00 | 60 g | -1.89 | -0.9% |
| 5 T | 1.60 | 7628 | FR4 | 0.00 | 60 g | -1.23 | -0.6% |
| 6 T | 1.60 | 7628 | FR4 | 0.13 | 60 g | -1.41 | -0.7% |

*A.2–Asymmetric copper distribution*

Another test was performed with the following laminates:

- Symmetrical, 2 layers, 100% copper on both layers
- Asymmetric, 2 layers, 100% copper on layer 1, 50% copper on layer 2 with diamond pattern (the “diamonds” did not have any connection to each other)[15].
- Asymmetric, 1 layer with 100% copper

All the laminates had a bow of 0 to 0.05mm before soldering with no weight applied and the soldering was performed without weight on the laminates.

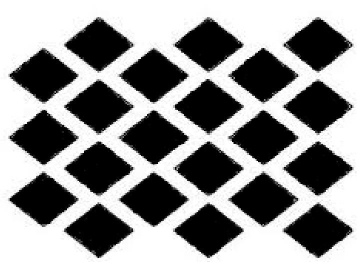

**Figure 10 –Complementary diamond shape pattern.**

[13]L = Traces orthogonal to reflow oven conveyors.
[14]T = Traces parallel to reflow oven conveyors.
[15]The diamond shaped copper layer that covered 50% of the layer 2 area on this test laminate could be considered as an example of a complementary pattern that often are used on real board areas with, originally, little or no copper.

This test showed that copper symmetry is important and that complementary copper pattern does strengthen the board, see Table 6.

**Table 6–Asymmetrical laminate test – 150mm unsupported width.**

| Thickness | Glass type | Copper | Up | Warpage after reflow with no weight |
|---|---|---|---|---|
| 1,6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 2 x 17 µm | | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm+ 1 x 50 % Cu | 1 x 50 % Cu | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | 0.05-0.1 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | 0.10-0.15 mm |
| 1.6 mm | 7628 | 1 x 17µm + 1 x 50 % Cu | 1 x 50 % Cu | >+0.15 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.100 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.25-0.30 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.25-0.30 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.30-0.40 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.30-0.40 mm |
| 1.6 mm | 7628 | 1 x17 µm | No Cu | +0.40-0.45 mm |

A real example of a board that has no complementary copper pattern and that does warp too much after the first reflow pass so that a Pin-in-Paste process could not be used for some of its connectors was studied. This board is symmetrical in Z-direction but has an area with no, or nearly no, copper on the same position on all six layers. This absence of copper made the board warp too much in the reflow process.

Layer 6 of this board is shown below. The lower part of the board in this drawing has very little copper and it is the same for all layers.

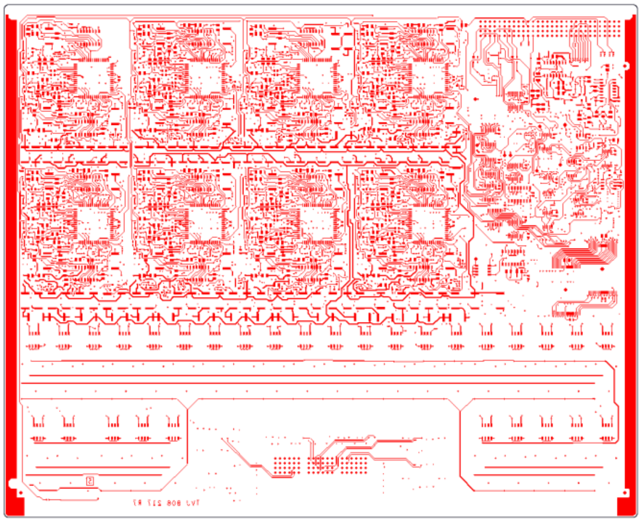

**Figure 11–Layer 6 on asymmetric board.**

*A.3–Conclusion – Copper Symmetry*

The general conclusion regarding copper in boards is that copper strengthens the boards and that it has much impact on board warpage in the reflow process. It is very important to have a good copper symmetry in **all** directions. Too asymmetrical copper may lead to extensive warpage even when board support is used in the reflow oven.

*B. Warp and Weft Direction*

Laminates with the side lengths 30 x 150mm and with 2 layers of 17.5µm copper were tested with different weights and with different warp and weft[16] directions in the reflow oven.

The test showed that the warp and weft direction did not significantly affect warpage during the reflow soldering process, see Table7.

**Table 7–Warp and weft test – laminates turned 90° to change warp and weft direction.**

| Warp | Weft | Thickness | Glass type | Tg | Mtrl | Warpage before reflow with weight | Weight | Warpage after reflow without weight [mm] | Warpage after reflow without weight [%] |
|---|---|---|---|---|---|---|---|---|---|
| | x | 1.6 | 7628 | High | FR4 | 0.3 | M0[17] | -0.12 | 0.1% |
| | x | 1.6 | 7628 | High | FR4 | 0.3 | M | -0.2 | 0.1% |
| | x | 1.6 | 7628 | High | FR4 | -0.07 | M1 | -0.4 | 0.3% |
| | x | 1.6 | 7628 | High | FR4 | -0.33 | M1 | -0.42 | 0.3% |
| | x | 1.6 | 7628 | High | FR4 | -0.29 | M1 | -0.47 | 0.3% |
| | x | 1.6 | 7628 | High | FR4 | -0.48 | M2 | -0.74 | 0.5% |
| | x | 1.6 | 7628 | High | FR4 | -0.48 | M2 | -0.73 | 0.5% |
| | x | 1.6 | 7628 | High | FR4 | 0.05 | M2 | -0.65 | 0.5% |
| | x | 1.6 | 7628 | High | FR4 | -0.15 | M2 | -0.65 | 0.5% |
| | | | | | | | | | |
| x | | 1.6 | 7628 | High | FR4 | 0.34 | M0 | -0.12 | 0.1% |
| x | | 1.6 | 7628 | High | FR4 | 0.22 | M | -0.29 | 0.2% |
| x | | 1.6 | 7628 | High | FR4 | -0.05 | M1 | -0.42 | 0.3% |
| x[18] | | 1.6 | 7628 | High | FR4 | -0.47 | M1 | -0.77 | 0.6% |
| x | | 1.6 | 7628 | High | FR4 | -0.46 | M1 | -0.73 | 0.5% |
| x[19] | | 1.6 | 7628 | High | FR4 | Resoldering 077 up | M1 | -0.64 | 0.5% |
| x | | 1.6 | 7628 | High | FR4 | Resoldering 0.73 up | M1 | -0.51 | 0.4% |
| x[20] | | 1.6 | 7628 | High | FR4 | Resoldering 0.64 down | M1 | -1.3 | 0.9% |
| x | | 1.6 | 7628 | High | FR4 | Resoldering 0.51 down | M1 | -1.23 | 0.9% |
| x | | 1.6 | 7628 | High | FR4 | -0.23 | M2 | -0.53 | 0.4% |
| x | | 1.6 | 7628 | High | FR4 | -0.07 | M2 | -0.19 | 0.1% |
| x | | 1.6 | 7628 | High | FR4 | -0.27 | M2 | -0.52 | 0.4% |
| x | | 1.6 | 7628 | High | FR4 | -0.07 | M2 | -1.01 | 0.7% |
| x | | 1.6 | 7628 | High | FR4 | -0.23 | M2 | -1.08 | 0.8% |

The test also showed that several reflow soldering cycles increase the warpage.

*C. Milling*

Milling in the board surface could seriously weaken the board. One example of this is the board called J in the real board warpage study, see table 1 and table 2. This is a 20 layer board with a good Z-direction copper balance (top 10 layers = 25% Cu, bottom 10 layers = 24% Cu).

[16] The terms ***warp*** and ***weft*** refers to the threads that make up a woven fabric. *Warp* threads are the vertical threads that run along the length of the loom. *Weft* threads are the horizontal threads that run from side to side.

[17]M0 = no weight, M = 35 g weight, M1 = 100 g weight, M2 = 200 g weight

[18]Grey = Boards that later on were turned upside-down and tested again. See the "green" boards in the table.

[19]Blue = Tests where the "grey" boards have been turned upside-down and then tested again in the reflow oven.

[20]Green = Tests where the "blue" boards have been reflowed again in the reflow oven. Same side up as for the "blue" boards.

Board J has a U-shape, as can be seen in Figure 12.

**Figure 12–The U-shaped board J.**

In the first revision of this board, the U-shape was pre-milled with few and small break-away-tabs between the milled channels. This milling was the main reason for very extensive warpage during reflow soldering. A drawing of this first revision is shown in Figure 13.

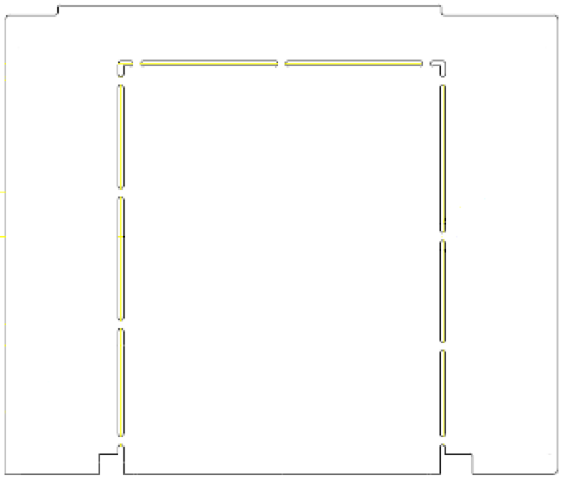

**Figure 13–Panel drawing, board J, Revision A.**

In order to improve the strength of the board, the pre-milling was changed from long to very short and few tracks, just enough for the final milling tool to enter, see Figure 14.

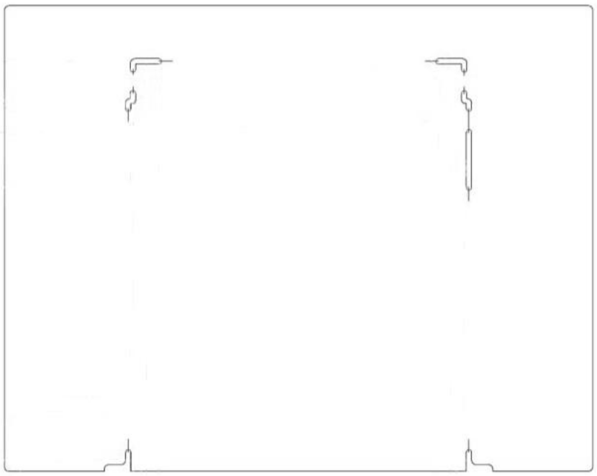

**Figure 14–Panel drawing, board J, Revision G.**

The warpage decreased significantly after this design change.

*D. Board Width*

Several tests where the laminate width was varied have been performed. All these tests show that width is a very important parameter regarding reflow soldering warpage.

The result from one of these tests is shown below in Table 8.In this test, 1.6 mm thick laminates with the unsupported widths in oven of 200 mm (laminate 1), 300 mm (laminate 2) and 400 mm (laminate 3) were used.

The applied weight on all the test laminates was 100 g/dm$^2$ evenly distributed over the laminate surfaces.

The result in this test showed that the 400 mm unsupported width gave way too much warpage and that 300 mm unsupported width gave a slightly better result. The laminates with 200 mm unsupported width in the reflow oven managed to support 100 g/dm$^2$ without much warpage at all.

**Table 8–1.6mm thick laminates, 200mm (1), 300mm (2) and 400mm (3) widths – Component pressure = 100 g/dm$^2$.**

| Laminate | Thickness [mm] | Glass type | Tg | Material | Warpage before reflow with weight [mm] | Weight | Warpage after reflow with weight [mm] | Warpage after reflow with weight [%] |
|---|---|---|---|---|---|---|---|---|
| 1-1 | 1.6 | 7628 | High | FR4 | 1.25 | 60 g | 0.66 | 0.3% |
| 1-2 | 1.6 | 7628 | High | FR4 | 1.23 | 60 g | 0.66 | 0.3% |
| 1-3 | 1.6 | 7628 | High | FR4 | 1.25 | 60 g | 0.62 | 0.3% |
| 1-4 | 1.6 | 7628 | High | FR4 | 1.28 | 60 g | 0.48 | 0.2% |
| 1-5 | 1.6 | 7628 | High | FR4 | 1.13 | 60 g | 0.61 | 0.3% |
| 1-6 | 1.6 | 7628 | High | FR4 | 1.26 | 60 g | 0.67 | 0.3% |
| | | | | | | | | |
| 2-1 | 1.6 | 7628 | High | FR4 | -0.18 | 90 g | -2.38 | -0.8% |
| 2-2 | 1.6 | 7628 | High | FR4 | -0.08 | 90 g | -2.37 | -0.8% |
| 2-3 | 1.6 | 7628 | High | FR4 | -0.04 | 90 g | -2.00 | -0.7% |
| 2-4 | 1.6 | 7628 | High | FR4 | -0.17 | 90 g | -2.14 | -0.7% |
| 2-5 | 1.6 | 7628 | High | FR4 | -0.1 | 90 g | -2.45 | -0.8% |
| 2-6 | 1.6 | 7628 | High | FR4 | 0 | 90 g | -2.20 | -0.7% |
| | | | | | | | | |
| 3-1 | 1.6 | 7628 | High | FR4 | -2.56 | 120 g | -8.96 | -2.2% |
| 3-2 | 1.6 | 7628 | High | FR4 | -3.24 | 120 g | -8.88 | -2.2% |
| 3-3 | 1.6 | 7628 | High | FR4 | -3.07 | 120 g | -9.40 | -2.4% |
| 3-4 | 1.6 | 7628 | High | FR4 | -2.82 | 120 g | -9.21 | -2.3% |
| 3-5 | 1.6 | 7628 | High | FR4 | -3.24 | 120 g | -9.54 | -2.4% |
| 3-6 | 1.6 | 7628 | High | FR4 | -2.45 | 120 g | -8.03 | -2.0% |

This was just one of several examples that showed how important the free width in the reflow oven is during the soldering process.

*E. Board Thickness*
Another very important board parameter is the thickness. Many of this study's tests confirm this.

A comparison between 200mm wide 0.8mm, 1.0mm and 1.2mm thick laminates loaded with 100 g/dm$^2$ is shown in Table 9.

**Table 9–0.8mm, 1.0mm and 1.2mm thickness – 200mm wide and a surface pressure of 100 g/dm$^2$.**

| Thickness [mm] | Glass type | Tg | Material | Warpage before reflow with weight [mm] | Weight | Warpage after reflow with weigh [mm] | Warpage after reflow with weight [%] |
|---|---|---|---|---|---|---|---|
| 0.8 | 7628 | High | FR4 | -2.60 | 60 g | >-3.3[21] | >-1.7% |
| 0.8 | 7628 | High | FR4 | -2.40 | 60 g | >-3.3 | >-1.7% |
| 0.8 | 7628 | High | FR4 | -2.44 | 60 g | >-3.3 | >-1.7% |
| 0.8 | 7628 | High | FR4 | -2.70 | 60 g | >-3.3 | >-1.7% |
| 0.8 | 7628 | High | FR4 | -2.38 | 60 g | >-3.3 | >-1.7% |
| 0.8 | 7628 | High | FR4 | -2.41 | 60 g | >-3.3 | >-1.7% |
| | | | | | | | |
| 1.0 | 7628 | High | FR4 | -0.88 | 60 g | -2.45 | -1.2% |
| 1.0 | 7628 | High | FR4 | -1.10 | 60 g | -2.69 | -1.3% |
| 1.0 | 7628 | High | FR4 | -0.90 | 60 g | -2.45 | -1.2% |
| 1.0 | 7628 | High | FR4 | -1.00 | 60 g | -2.84 | -1.4% |
| 1.0 | 7628 | High | FR4 | -1.07 | 60 g | -2.61 | -1.3% |
| 1.0 | 7628 | High | FR4 | -1.00 | 60 g | -2.83 | -1.4% |
| | | | | | | | |
| 1.2 | 7628 | High | FR4 | -0.60 | 60 g | -1.69 | -0.8% |
| 1.2 | 7628 | High | FR4 | -0.63 | 60 g | -1.75 | -0.9% |
| 1.2 | 7628 | High | FR4 | -0.50 | 60 g | -1.66 | -0.8% |
| 1.2 | 7628 | High | FR4 | -0.60 | 60 g | -1.81 | -0.9% |
| 1.2 | 7628 | High | FR4 | -0.51 | 60 g | -1.62 | -0.8% |
| 1.2 | 7628 | High | FR4 | -0.42 | 60 g | -1.55 | -0.8% |

The results in the table above can be compared to a test with the same load per surface area (100 g/dm$^2$) with 300mm unsupported width on 2.4mm thick boards, see Table 10.

**Table 10–2.4mm thick laminates, 300mm width, 100 g/dm$^2$.**

| Thickness [mm] | Glass type | Material | Warpage before reflow with weight [mm] | Weight | Warpage after reflow with weight [mm] | Warpage after reflow with weight [%] |
|---|---|---|---|---|---|---|
| 2.4 | 7628 | FR4 | -0.46 | 90 g | -1.20 | -0.4% |
| 2.4 | 7628 | FR4 | -1.07 | 90 g | -1.50 | -0.5% |
| 2.4 | 7628 | FR4 | -0.72 | 90 g | -1.34 | -0.4% |
| 2.4 | 7628 | FR4 | -0.44 | 90 g | -1.16 | -0.4% |
| 2.4 | 7628 | FR4 | -0.95 | 90 g | -1.46 | -0.5% |

The 2.4 mm thick laminates in Table 10 had about half the percentage of warpage compared to the 1.2 mm thick laminates in table 9, even though the unsupported width in the reflow oven for the 2.4 mm thick laminates was 300 mm instead of 200 mm as it was for the 1.2 mm thick laminates.

The board thickness is a very important parameter for the ability to withstand warpage.

*F. Mixed Base Material Symmetry*
Regarding mixed base material symmetry, there are two examples of this in the study of real boards' warpage and these are the boards D and K in Table 1 and Table 2.

Board D is 311mm wide, has a good copper balance, only 1.4mm thickness and quite heavy components so a center support should be used in the oven. This is also the case, but the board warps a lot anyway. The board has the base materials

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[21] All the 0.8 mm thick laminates touched the bottom of the fixture used in the reflow soldering and could therefore not warp more.

Halogen-Free FR4 and a low loss high performance material(glass fiber reinforced hydrocarbon ceramic material) arranged asymmetrically in different layers of laminates and prepregs.

Board K is 201 mm wide, has a good copper balance, only 0.9 mm thickness and not so heavy components, but a center support should generally be used in the oven. This is normally not the case and the board warps very much during reflow soldering. The board has a low loss high performance base material and Halogen-Free FR4 arranged asymmetrically in different layers of laminates and prepregs.

The boards above are the only examples of boards with different types of base materials, asymmetrically arranged, that have been compared in this project. These boards are quite wide and thin which will contribute to their warpage. However, their warpage, especially board D that uses board support during reflow, indicates that asymmetrically arranged layers of different types of base materials could, not surprisingly, affect warpage negatively.

*G. Glass Fiber/Epoxy Class*

Most of the tests in this project have been performed on laminates with the glass/epoxy class 7628, but in order to get information about if the glass/epoxy class affects board warpage, a test that included the classes 1080 and 2116 was performed.

Photos of the fiber weaves of glass/epoxy class 1080, 2116 and 7628 are given in Figure 15.

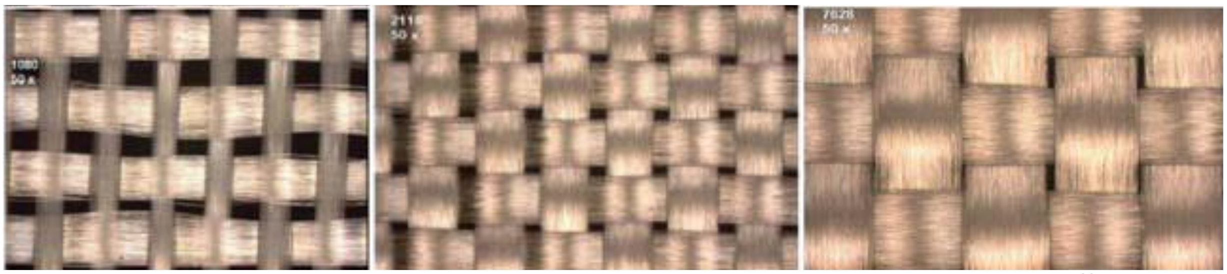

**Figure 15–Different types of fiber weaves, 1080 (left), 2116 (middle) and 7628 (right)[22].**

As can be seen in figure 15, the fiber weaves 2116 and 7628 are much denser than the sparse weave 1080.

In this test, 0.6 mm thick laminates of different sizes were subjected to 100 g/dm$^2$ load during reflow soldering.

An example from this test is the result from 140 mm free board width, which is shown in the table below.

**Table 11–0.6mm thick laminates, 100 g/dm$^2$ weight, 2116 and 1080 glass/epoxy class.**

| Thickness | Glass type | Material | Warpage before reflow with weight [mm] | Weight | Warpage after reflow with weight [mm] | Warpage after reflow with weight [%] |
|---|---|---|---|---|---|---|
| 0.6 | 2116 | FR4 | -0.81 | 42g | -1.59 | -1.14% |
| 0.6 | 2116 | FR4 | -0.51 | 42g | -1.46 | -1.04% |
| 0.6 | 2116 | FR4 | -0.95 | 42g | -1.48 | -1.06% |
| 0.6 | 2116 | FR4 | -0.82 | 42g | -1.53 | -1.09% |
| 0.6 | 2116 | FR4 | -0.76 | 42g | -1.42 | -1.01% |
| 0.6 | 2116 | FR4 | -0.68 | 42g | -1.36 | -0.97% |
| | | | | | | |
| 0.6 | 1080 | FR4 | -1.18 | 42g | -2.68 | -1.91% |
| 0.6 | 1080 | FR4 | -0.72 | 42g | -2.01 | -1.44% |
| 0.6 | 1080 | FR4 | -0.50 | 42g | -1.40 | -1.00% |
| 0.6 | 1080 | FR4 | -0.50 | 42g | -1.55 | -1.11% |
| 0.6 | 1080 | FR4 | -0.55 | 42g | -1.58 | -1.13% |
| 0.6 | 1080 | FR4 | -0.36 | 42g | -1.04 | -0.74% |

Even if there have not been extensive tests performed on many different glass/epoxy classes in this project, the conclusion is that the choice of glass fiber/epoxy class does not have a major impact on board warpage.

*H. Base Material*

Only a very limited comparison between FR4 and low loss high performance base materials has been performed in this study and this comparison was too small in order to be able to draw secure conclusions on the difference in ability to withstand warpage between these two base materials. However, the used low loss high performance materials seem to be very stable.

[22]Picture source: Altera, report AN-528-1.1

It is very likely that the type of base material does matter. However, the type of base material is, most often, very difficult for the production departments to influence so this is not a parameter that often has to be counted for.

**VI. Conclusions and Recommendations**

The tests above show that the following board parameters affect warpage significantly:

- Amount of copper and copper balance
- Thickness
- Width
- Component weight
- Mixed base material and symmetry
- Milling

In order to create a simple rule for when board support is needed during reflow soldering; it was found that the copper symmetry, amount of copper, milling, component weight and mixed base material symmetry could not easily be included.

It is very difficult to estimate how different kinds of asymmetries will affect board warpage and also to include this information into a simple guidance formula.

The problem with component weight (and component distribution) was handled by using a high weight on the board surface (100 g/dm$^2$) in most of the performed tests. The reason to choose this weight per board area was that an investigation showed that the heaviest boards used at the time of this study had about 90 g/dm$^2$ average component weight on their board surfaces. By using an even heavier weight while creating the formula for board warpage, there will be a tolerance for some copper asymmetries and small millings in the boards. The formula is, in other words, conservative.

The expected warpage when on the limit of the suggested formula below would be about 0.4% to 0.5% warpage if no center support is used in the reflow oven.

The simple formula for when board support is needed for a board in order to avoid too much warpage in the reflow soldering process was chosen to:

**W > T x 150 [mm]**

where:

**W** = board width [mm]
**T** = board thickness [mm]

The distance from the board support to the conveyor in the reflow oven is not allowed to be greater than T x 150 mm on any side.

This formula has been verified on real boards in the production and nearly all boards follow the rule in the formula. The only boards that did not follow this guidance rule had severe copper or mixed base material asymmetries or had been weakened by long milled tracks.

The formula above might need to be “calibrated” for other companies’ standard boards, but can be regarded as a good starting point for this work.

## VI. References

[1] IPC J-STD-001F, Requirements for Soldered Electrical and Electronic Assemblies

[2] TM-650, Test Method 2.4.22, Test Methods Manual, Bow and Twist (Percentage)

[3] Thermal Cycle Reliability Assessment of Bowed PCB Assemblies, 2012, Michael Meilunas, Process Research Engineer, Universal AREA Consortium

[4] Vad göra med buktning och vridning av mönsterkort? Esbjörn Johansson, Capinor AB, 2009

## VII. Acknowledgements

The author would like to give a special thanks to Ove Isaksson at Ericsson in Kista who has suggested and performed most of the tests in this evaluation.

The author is also grateful to the following colleagues that have contributed to the development of methods, performed measurements and reviewed the paper:

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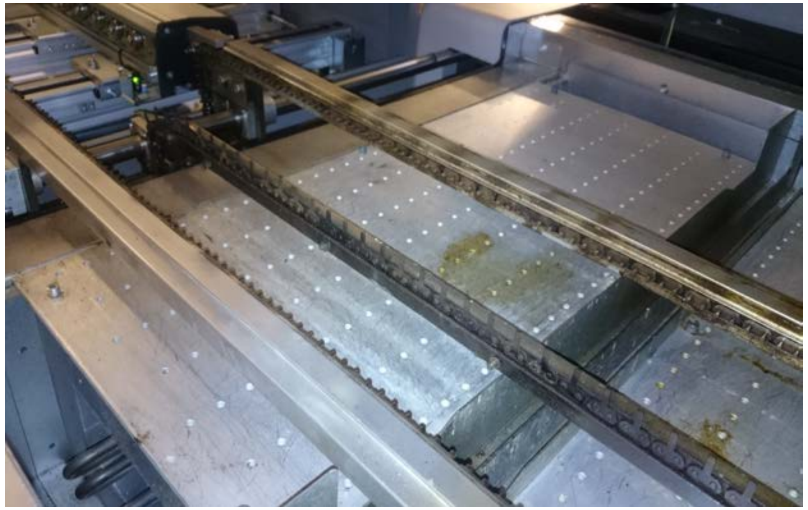
Ericsson AB, Katrineholm: Mikael Hertzman, Åse Ljungdahl
Ericsson AB, Borås: Jonny Rindevad

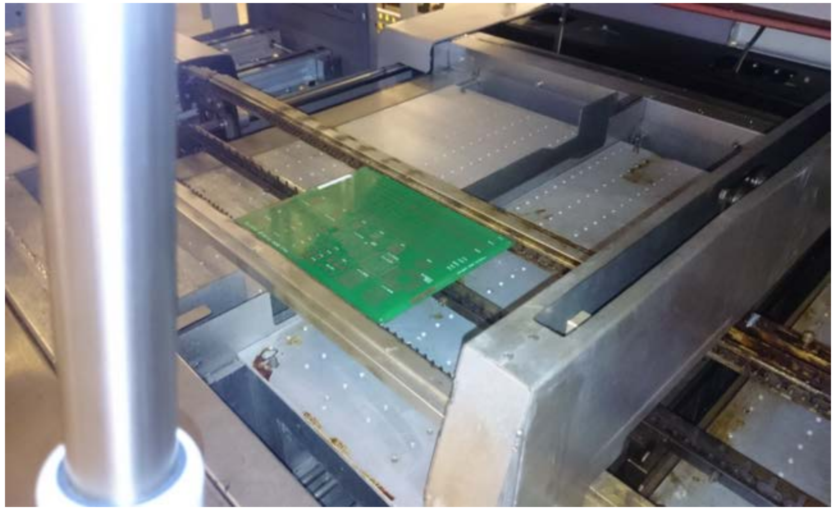
# Board Warpage during Reflow Soldering
# Need for Board Support?

Lars Bruno, Ericsson AB

# Purpose

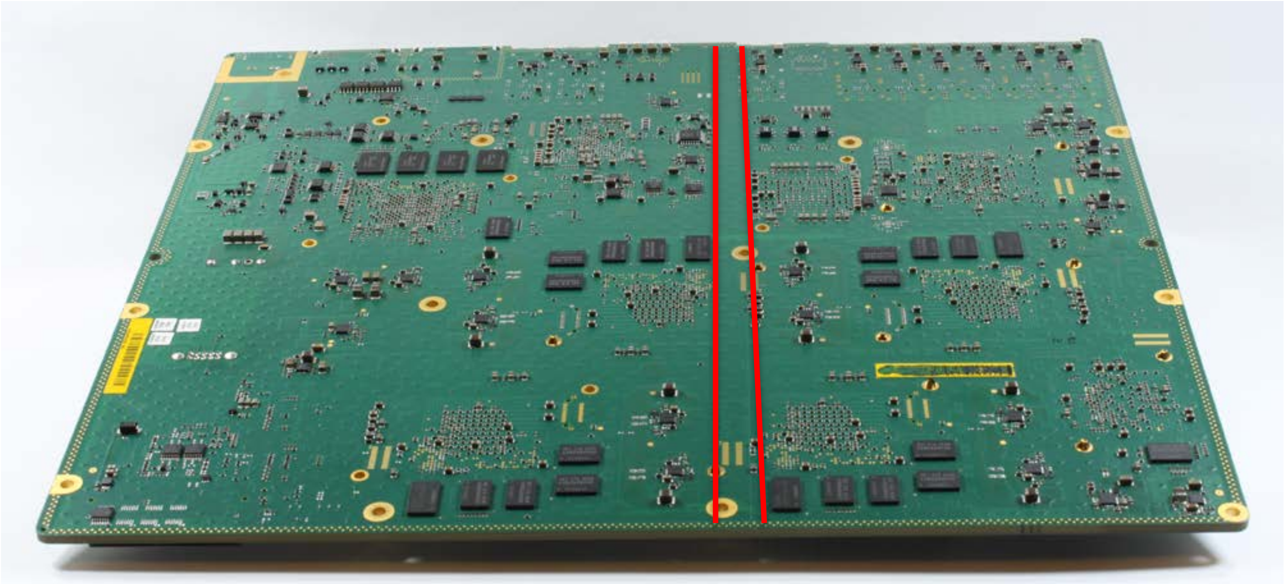
- To find an easy-to-use guidance rule for when board support is needed during reflow soldering in order to mitigate board warpage





# Background

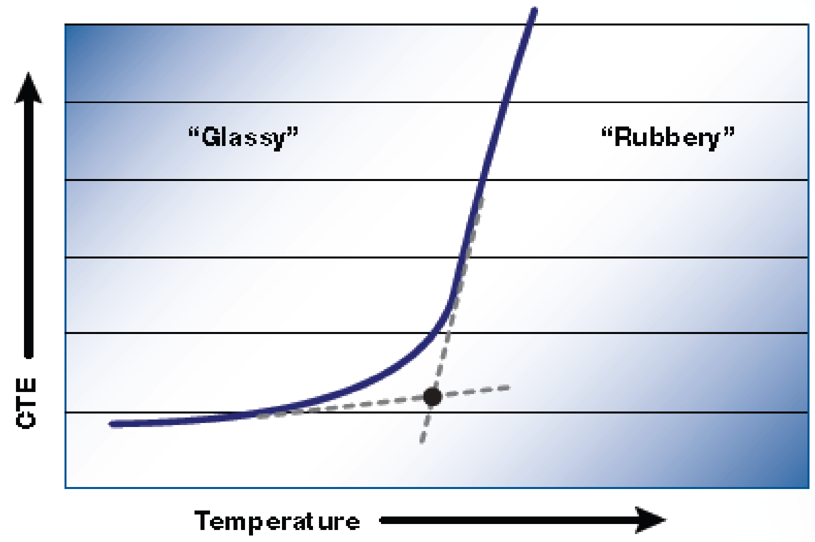
- Difficult for board designers to know when an area on secondary side has to be left free of components in order to give place for board support during reflow soldering



Area intended for board support (~10 mm wide)

# Permanent Warpage

- During reflow soldering, temperature over PCB polymer materials' glass transition temperature (Tg) makes the material to:
  - Soften
  - CTE Increase
  - Modulus drop
  - Lower tensile and shear strength



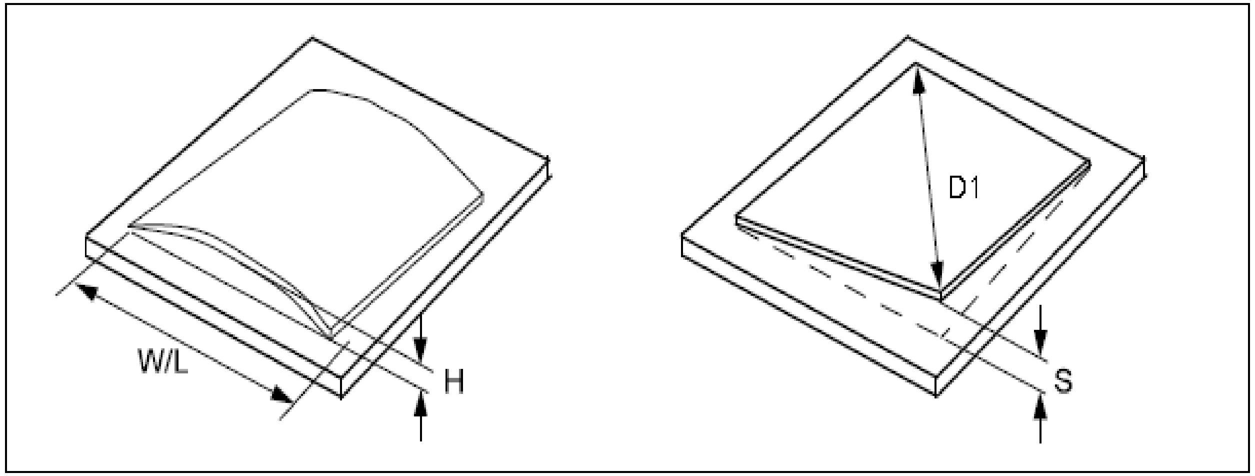

Picture source: Epoxy Technology Inc.

- An applied force could give cooperative movement of the entangled polymer molecule chains
  - Force by components and by the board's own weight
    - Twist and bow of board
- When lowering temperature below Tg the warpage could become permanent

# Warpage Limits

- Twist and bow limits after soldering for surface mounted boards (IPC J-STD-001F):
  - – 0.75% of diagonal for twist
  - – 0.75% of width or length for bow

- Measurements according to IPC TM-650, Test Method 2.4.22



# Methodology

1. Collect data of real boards in the production regarding
   - Material and design
   - Warpage after reflow soldering

2. Simplified tests of different parameters that affect warpage
   - Use of laminates of different thicknesses and materials that have been cut into different sizes

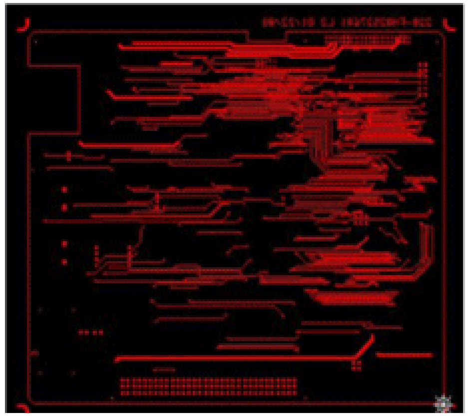
# Real Board Data

- Real board data
  - Examples from 11 of 30 boards shown below

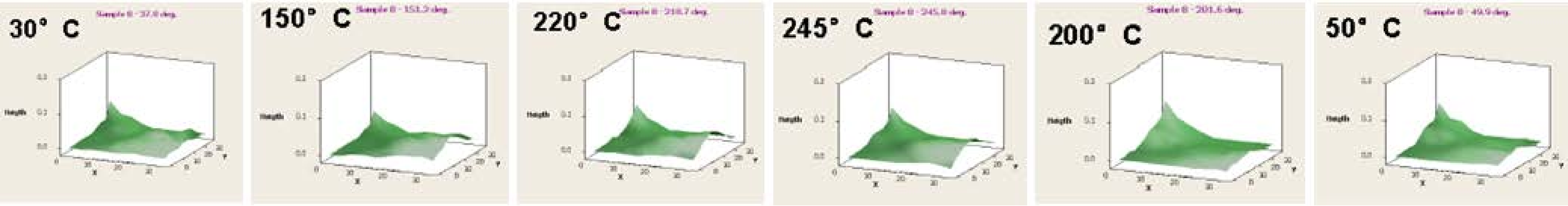
| Board | Lead-free soldering [yes/no] | PCB Length [mm] | PCB Width [mm] | Panel Length [mm] | Panel Width [mm] | Total Board thickness [mm] | Total number of layers | Total Cu thickness, all layers [µm] | Number of power/ground layers | Cu balance Top/Bottom | Total weight components + solder paste [g] | Average components weigh/area [g/ dm$^2$] | Weight of PCB [g] | Type of PCB material | Bow & twist before soldering [mm] | Bow & twist after soldering [mm] | Center support used (yes/no) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | No | 366 | 264 | 366 | 289 | 1.8 | 10 | 274 | mixed layers | 65/76 | 805 | 82 | 461 | HFFR4 | ~0 | 1.8 | Yes |
| B | Yes | 366 | 264 | 366 | 289 | 1.6 | 8 | 202 | mixed layers | 64/68 | 750 | 78 | 348 | HFFR4 | ~0 | 1.7 | Yes |
| C | Yes | 274 | 311 | N/A | N/A | 2.3 | 20 | 504 | 8 | 45/43 | 774 | 91 | 250 | HFFR4 | ~0 | max 1.0 | No |
| D | Yes | 244 | 311 | N/A | N/A | 1.4 | 6 | 275 | mixed layers | 86/89 | 555 | 73 | 319 | LH+HFFR4 | 0 to 0.2 | 0.9 | Yes |
| E | Yes | 210 | 265 | N/A | N/A | 1.9 | 12 | 260 | mixed layers | 71/70 | 423 | 76 | 280 | HFFR4 | ~0 | ~0.4 | No |
| F | Yes | 207 | 265 | N/A | N/A | 1.5 | 2 | 80 | 0 | 11/4 | 169 | 31 | 141 | FR4 | ~0 | 1.9 | No |
| G | Yes | 207 | 265 | N/A | N/A | 1.5 | 6 | 148 | 4 | 62/60 | 169 | 31 | 184 | FR4 | ~0 | 1.6 | No |
| H | Yes | 207 | 265 | N/A | N/A | 2.0 | 8 | 182 | 6 | 69/67 | 169 | 31 | 247 | FR4 | ~0 | 1.1 | No |
| I | Yes | 207 | 265 | N/A | N/A | 2.5 | 10 | 216 | 8 | 72/71 | 169 | 31 | 310 | FR4 | ~0 | 0.4 | No |
| J | Yes | 210 | 265 | 210 | 265 | 2.2 | 20 | 406 | 10 | 25/24 | 35 | 6 | 320 | HFFR4 | ~0 | 0.3 | Yes |
| K | Yes | 201 | 90 | 275 | 201 | 0.9 | 4 | 135 | mixed layers | 84/88 | 63 | 35 | 120 | LH+HFFR4 | ~0 | 1.5 | Yes |

HFFR4 = Halogen-Free Flame-Retardant 4
LH = Low Loss High Performance

# Further Information



- Drawings of each layer on each board
- Shadow Moiré warpage measurements, if this existed



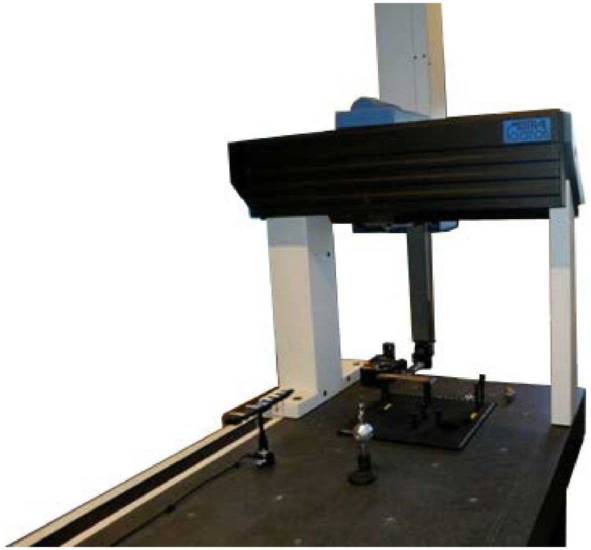

- Not possible to formulate easy-to-use guidance rule ☹
  - Simplified tests necessary to perform

# Parameters to Test

- Tested parameters that are believed to affect warpage
  - Copper balance
  - Warp/weft fiber weave direction
  - Milling
  - Board width
  - Board thickness
  - Mixed base material symmetry
  - Glass/epoxy class (density and thickness of glass fibers in weave)
  - Base material (type of resin)

# Test Procedure

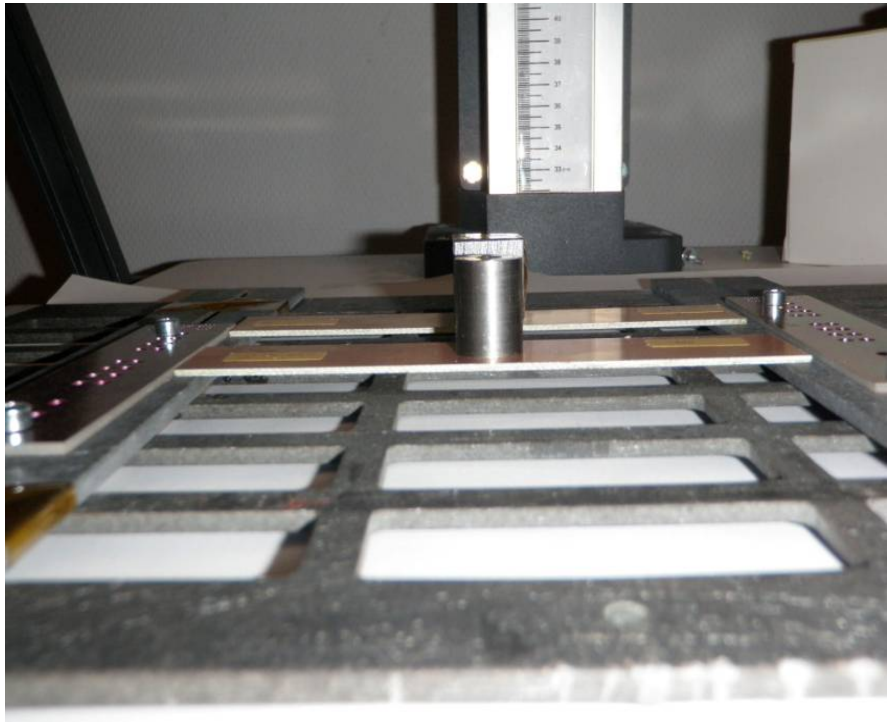
- Used laminates
  - Different materials
  - Different thicknesses
  - Cut into different sizes



- Measure initial warpage
  - With weight (often 100 g/dm$^2$ which is more than analyzed real boards)
    - In center of laminate or evenly distributed
  - Without weight

# Test Procedures – Continuation

- Laminates placed in a fixture
  - Distance between support varied between 100 mm to 400 mm
- Sent into reflow soldering
  - Peak 240° Celsius
  - Time over liquidus about 60s
- Final warpage measured after reflow soldering



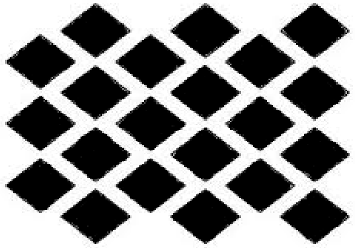
# Copper Balance

- How does copper matter?
- Two different laminates
  - – Copper traces in length direction (both sides)
  - – Copper traces crosswise direction (both sides)


- Copper in length direction gave less than half warpage compared to crosswise copper direction

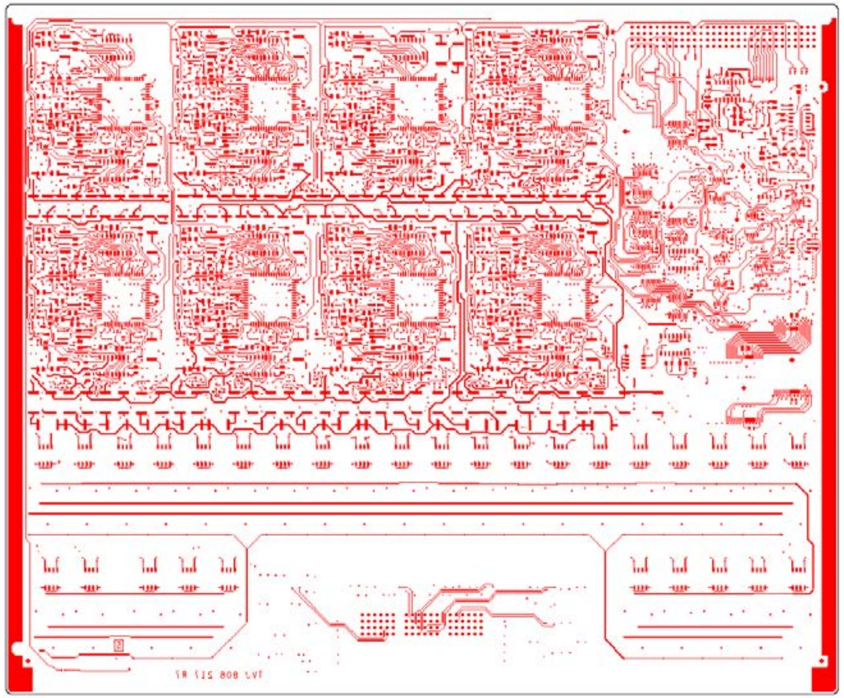
# Copper Balance

- The following laminates were also tested (with no weights)
  - Symmetrical, 2 layers, 100% copper on both layers
  - Asymmetric, 2 layers, 100% copper on layer 1, 50% copper on layer 2 with diamond pattern
  - Asymmetric, 1 layer with 100% copper



- 100%/100% symmetrical and 100%/50% asymmetric laminates
  - similar result (complementary fill-in pattern helps!)
- 100%/0% laminate, 2 to 4 times more warpage!

# Copper Balance

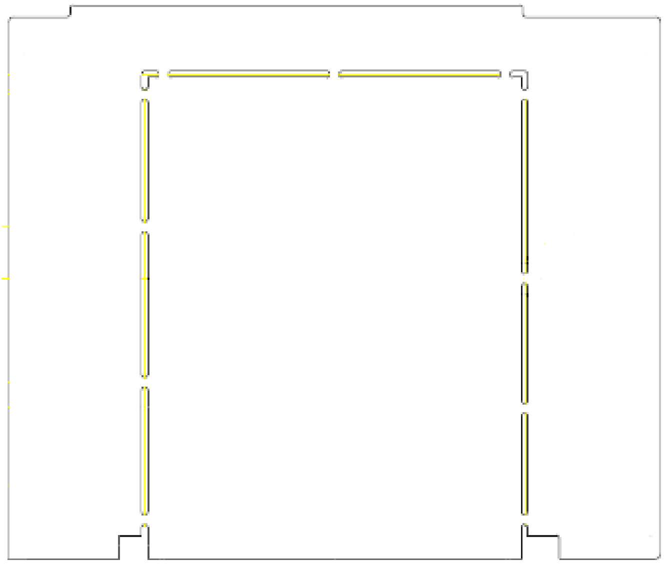


- One 6-layer board studied
  - Symmetrical in Z-direction
  - Lower part of board very little copper
    - Same for all 6 layers
- Extensive warpage
- Conclusion, copper balance
  - Copper strengthen board
  - Important to have good copper symmetry in **all** directions!

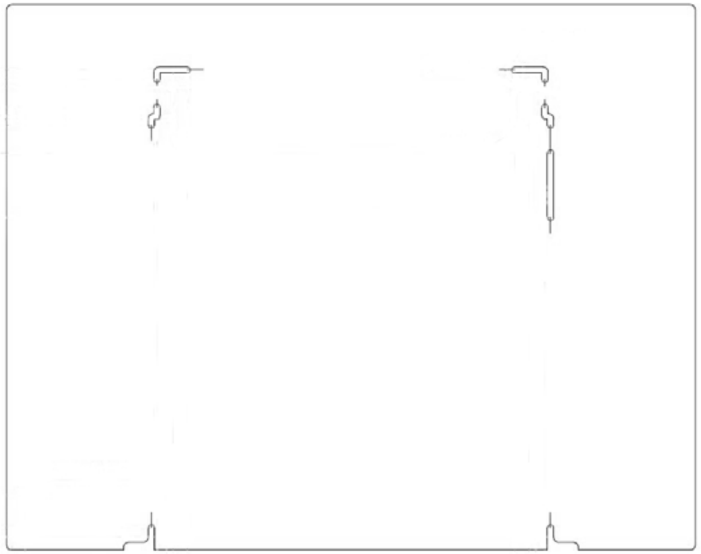
# Milling

- Example of board with long milled tracks in early revisions
  - Extensive warpage
- Short and few milled tracks in later revision
  - Nearly no warpage

U-shaped board



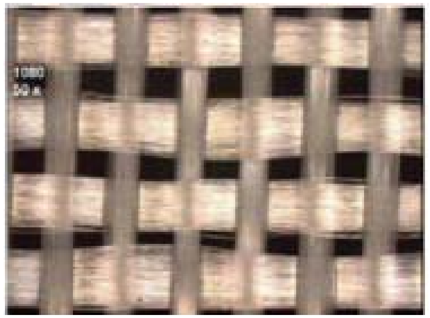
Long milled tracks



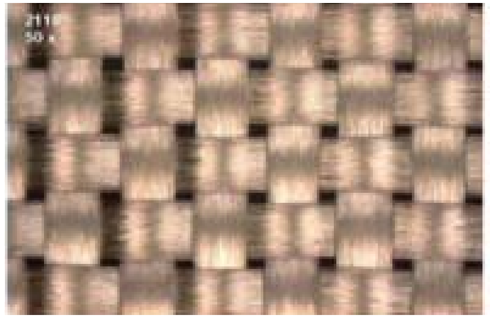
Short & few milled tracks

# Fiber Weave

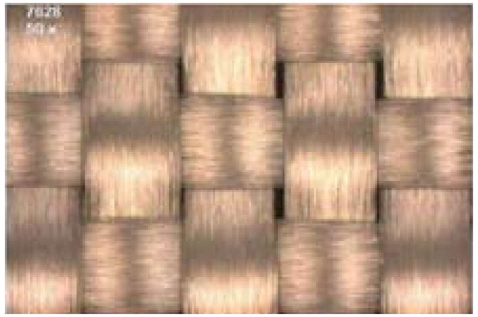
- Laminates with different glass/epoxy classes were compared
  - No significant difference in warpage



1080



2116



7628

- Laminates with same warp and weft direction for all layers of weave and then cut in 90˚ angles towards each others
  - No significant difference in warpage

# Width and Thickness

- Many tests with laminates of different thicknesses were performed
  - Thickness  important parameter
    - Thick laminates give less warpage than thin

- Many tests with laminates of different widths were performed
  - Width in reflow oven is an important parameter
    - Shorter unsupported widths gives less warpage than long unsupported widths

# Significant Parameters

- Of the tested board parameters, the following affect board warpage significantly:
  - Amount of copper and copper balance
  - Thickness
  - Width
  - Component weight
  - Mixed base material and symmetry
  - Milling

# Parameter Discussion

- Very difficult to include copper symmetry, amount of copper, milling and mixed base material symmetry in simple formula
  - Difficult to estimate how and how much different kinds of asymmetries affect board warpage

- These parameters are not included
  - Heavy weights per board area in tests to give a conservative formula
    - Gives some room for asymmetries and small millings

# Easy-to-use Formula

- The following formula for when board support is needed is suggested:

**W > T x 150 [mm]**

Where:

**W = board width**

**T = board thickness**

- Board support offset:
  - The distance from the board support to the conveyor in the reflow oven is not allowed to be greater than this (T x 150 mm) on any side.

# Conditions

- The copper and mixed base material balances have to been reasonable symmetrical
- There should be no, or at least very little, milling in the board
- Not extremely high component weights (= not much more than 100 g/dm$^2$)

# Thank You for Listening!

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