Image Rotation to Mitigate the Fiberweave Effect its Impact on PCB Manufacturing

Jon Kuchy, Intel® Corp.
Jonathan.Kuchy@Intel.com

Jeff Loyer, Intel® Corp.
Jeff.Loyer@intel.com

ABSTRACT

Typical PCB materials have inherent properties (the "Fiberweave Effect") which can be detrimental to the Signal Integrity of the physical link. This presentation describes the effect and a means to mitigate for it (image rotation). The possible effects on PCB fabrication and manufacturing include: dimensional; SMT solder joint; mechanical properties (elastic modulus, warpage, and CTE); and impact to Solder Joint Reliability. A study of those effects is summarized and presented.

INTRODUCTION

Image Rotation was outlined as a mitigation technique for the Fiberweave problem in an earlier Intel White Paper [5]. This paper represents follow-on efforts to analyze the viability of that strategy for High Volume Manufacturing. The intent was to answer the following questions regarding Image Rotation:

1) Are features distorted? E.G.., are trace widths affected?
2) Are features' locations distorted?
3) Are Surface Mount Technology (SMT) structures (solder joints) negatively affected?
4) How are PCB mechanical properties (elasticity, warpage) affected?

FIBERWEAVE BUNDLE EFFECT BACKGROUND

Typical printed circuit boards are constructed from various woven fiberglass fabrics (Figure 1), strengthened and bound together with epoxy resin. The glass and epoxy have relative permittivity's (Er, aka Dielectric Constant, or Dk) of ~6 and ~3.5 [4], respectively, presenting a non-homogeneous medium for signal propagation. Traces running parallel to the board edge (and therefore the weave) are especially susceptible to this non-homogeneity (these will often be referred to as "routed orthogonally" in this paper). For instance, in Figure 2, note the fiber (weave) bundle and epoxy regions. The 2 traces in Figure 2, making up the 2 halves of a differential pair (designated "D+" and "D-"), are running over the different materials (epoxy vs. fiberglass weave), see correspondingly different Er values, and have different propagation properties (velocity and loss primarily).

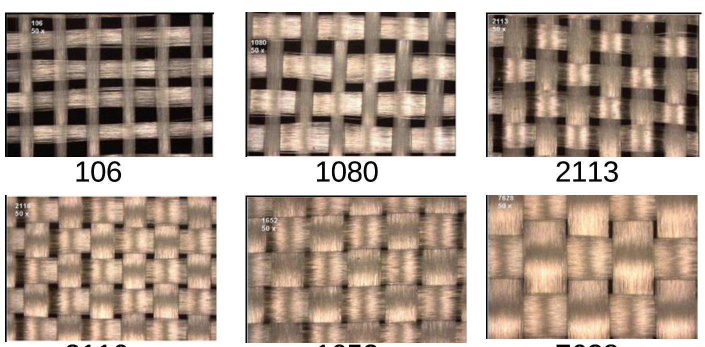


Figure 1: PCB Woven Fiberglass Fabric Constructions

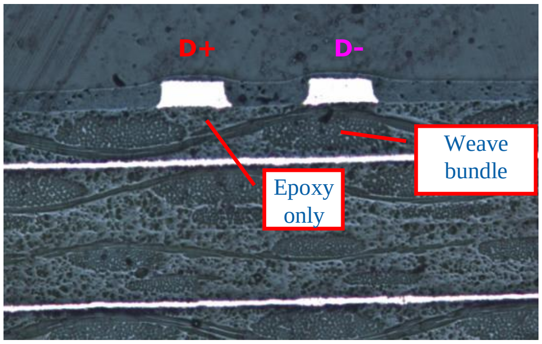


Figure 2: Inhomogeneous nature of a PCB as shown in a cross section

At high data rates the difference in propagation velocities leads to skew between the 2 traces which can amount to a substantial fraction of the transmission unit interval, resulting in an increased common mode voltage (Figure 3) and a correspondingly degraded differential signal (Figure 4) [1]. In addition, the resulting common mode signal can become a source of increased crosstalk and EMI in the system.

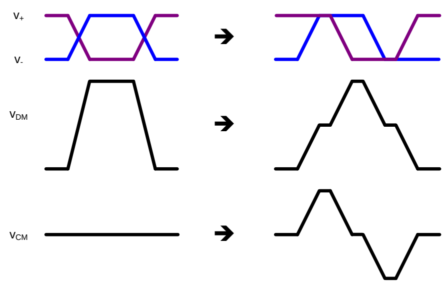


Figure 3: Effect of skew on differential and common mode signals

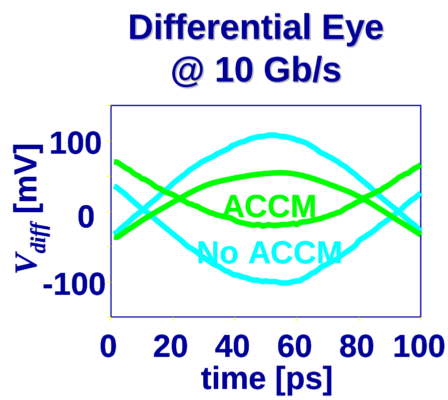


Figure 4: Effect of skew on differential eye

During the past several years, researchers both from within Intel and outside have investigated this effect [1-4], and recently a study was concluded that quantified it, and laid out strategies to deal with it. One of those strategies was to rotate the image at 10 degrees, relative to the fiberglass weave. This paper outlines a consequent study to determine the feasibility of that strategy – can it be supported in an HVM (High Volume Manufacturing) environment?

IMAGE ROTATION DESCRIPTION

To alleviate the effect of the trace alignment to the weave, the traces can simply be angled, relative to the weave, by 10 degrees, as shown in Figure 5.

This rotation can be accomplished in several ways, the 2 studied here are:

1) Rotate the CAD image 10 degrees, relative to the panel edge, when processing the panel
2) Rotate the fiberglass weave 10 degrees, relative to the panel edge, when cutting the panel material

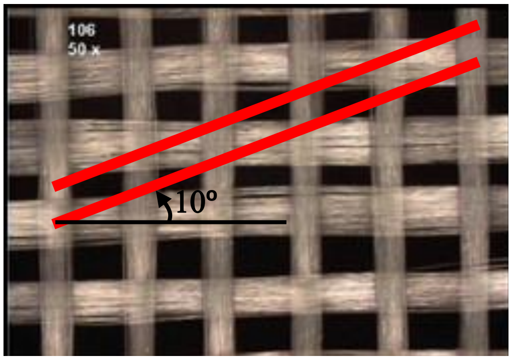


Figure 5: 10º skew of traces, relative to Fiberglass Weave

STUDY'S OBJECTIVES

Adopting either of these methods forces the majority of the copper trace routing out of alignment with the fiberglass weave, which is a large variation from what we've done in the past. Before advocating large scale adoption of the practices, we wanted to ensure there were no hidden (possibly subtle) manufacturing effects that might lead to decreases in yield. Possible manufacturing effects were:

1) Dimensional distortion of features (improper trace width, for instance)
2) Positional distortion of features (placement accuracy)
3) SMT (Surface Mount Technology) joint formation
4) SMT joint strength
5) Elastic Modulus
6) Warpage

STUDY'S METHOD 1: ROTATE PRODUCT DESIGN BOARD

The first test was to take a sample of an existing design, rotate the artwork 10 degrees (see Figure 6), and run those boards through the complete manufacturing, assembly, and test process to see if any problems were encountered. The design was a sophisticated, state-of-the-art, 4-socket server. The only problem encountered was the PCB manufacturer un-rotating the design to force it to fit in the standard panel (see Figure 7). This highlighted some interesting aspects:

1. Rotated artwork would need to be clearly spelled out as a requirement, else the manufacturer might un-rotate it to save money (see Figure 8)
2. Some tools allow easy rotation of the artwork. We don't know what tool this PCB house used, but they appeared to un-rotate the design with a minimum of effort (there was no delay in board manufacturing)

These boards provided anecdotal evidence that rotating the artwork wouldn't have any significant effect on the PCB manufacturing.

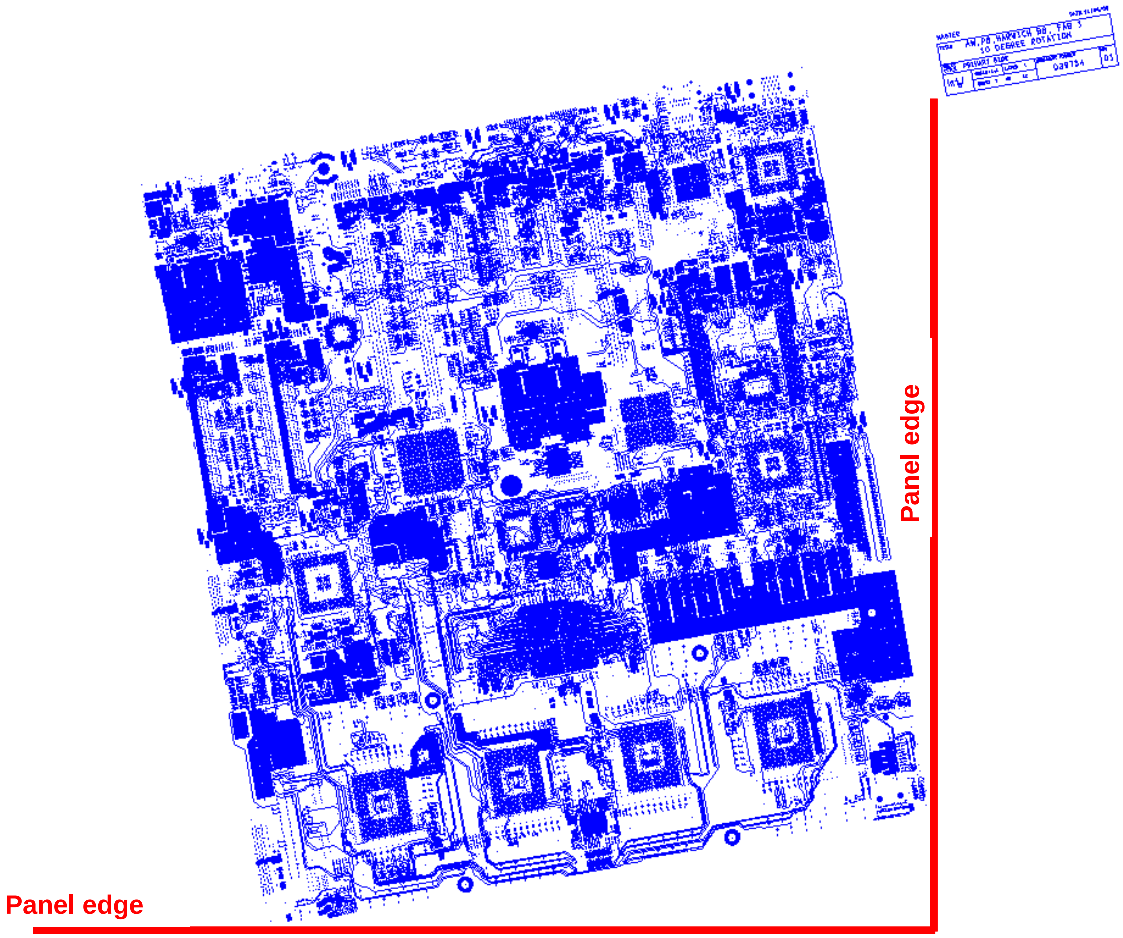
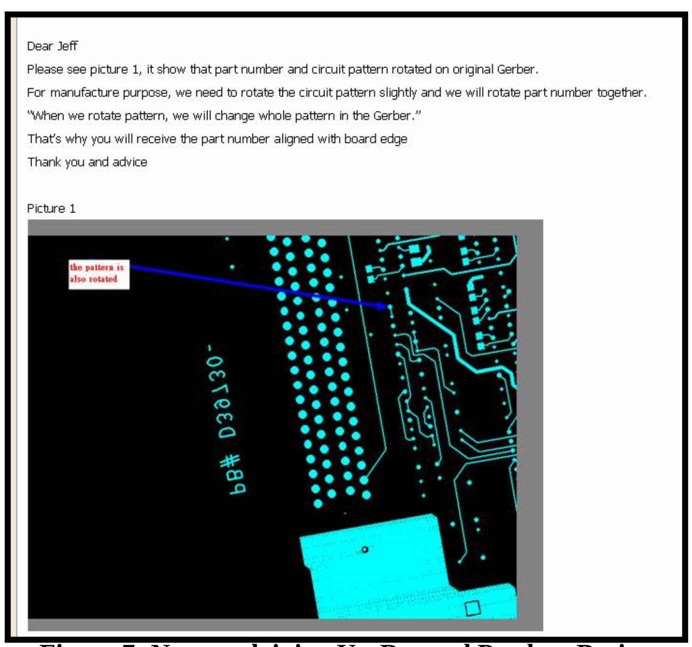


Figure 6: Rotated Product Design


Dear Jeff

Please see picture 1, it show that part number and circuit pattern rotated on original Gerber.

For manufacture purpose, we need to rotate the circuit pattern slightly and we will rotate part number together.

"When we rotate pattern, we will change whole pattern in the Gerber."

That's why you will receive the part number aligned with board edge

Thank you and advice

Picture 1

Figure 7: Note explaining Un-Rotated Product Design

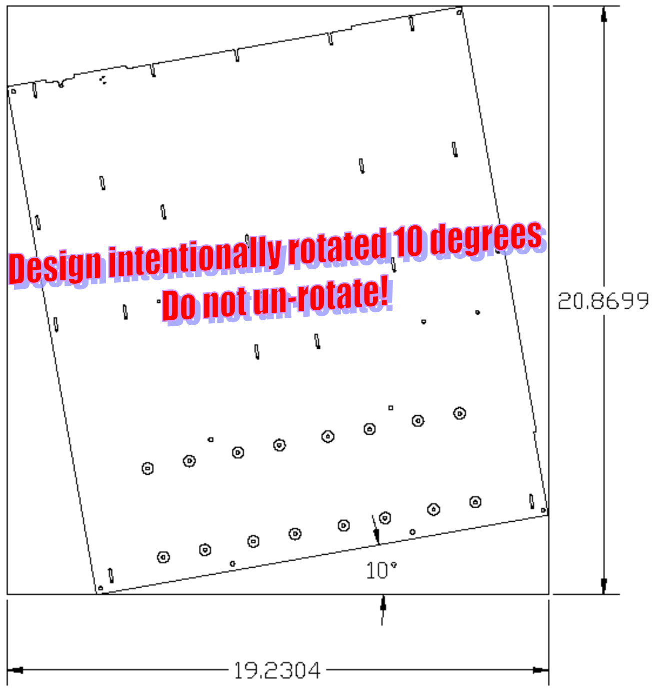


Figure 8: Fab Drawing Highlighting Intentional Design Rotation

STUDY'S METHOD 2: RIGOROUS TEST BOARDS

Test board were designed and built with 3 different weave/design alignments:

1) M0: standard build, no special alignment to weave or design
2) M10: Image rotated 10 degrees on panel
3) A10: Material rotated 10 degrees on panel

The boards were measured appropriately to determine if there was any significant degradation in key metrics of manufacturing effects:

1) Dimensional distortion of features: Trace widths of traces routed at 0, 45, and 90 degrees, relative to the board edge
2) Positional distortion of features: pitch of SMT pads in the Y direction; pitch of vias in the X direction
3) SMT joint formation: Boards were cross-sectioned, and the heights of solder joints measured and analyzed
4) SMT joint strength: a "Dye Penetrant Test" was performed on SMT solder joints
5) Elastic Modulus
6) Warpage

DIMENSIONAL DISTORTION OF FEATURES

Rotating the artwork forces the majority of the copper trace routing out of alignment with the primary axis' of the exposure equipment. There was a question of the effect on feature size: would trace widths remain as originally intended, or be distorted by the rotation.

Traces were laid out in three orientations: Horizontal (X direction), Vertical (Y direction), and diagonal (45 degrees) – see Figure 9.

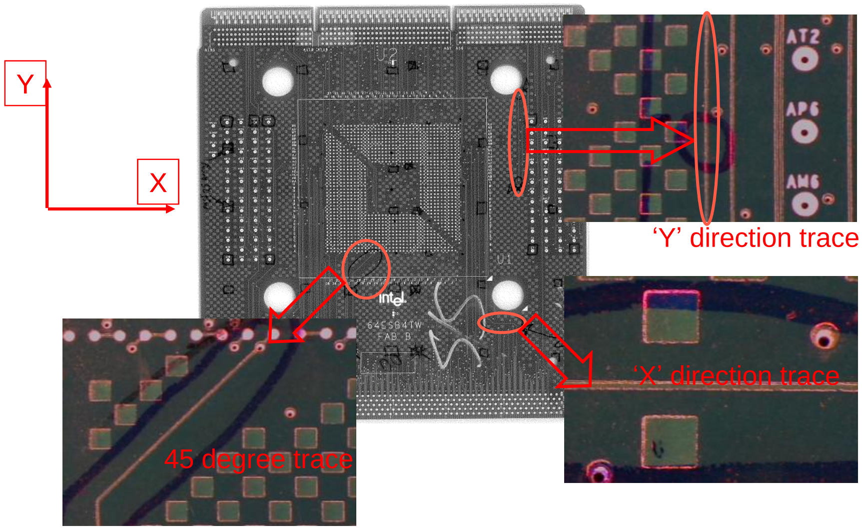


Figure 9: Layout for Dimensional Measurements of Traces

Samples of the 3 orientations were measured on the 3 varieties of boards (un-rotated, rotated artwork, rotated weave), (see Figure 10). Note that it appears the 2 rotated instances have appreciable narrower widths (M0, in the middle, seems wider). But, there is no reason to expect rotated material to have an effect on trace width, so we attribute the slight difference in width of the rotated image material to manufacturing variation.

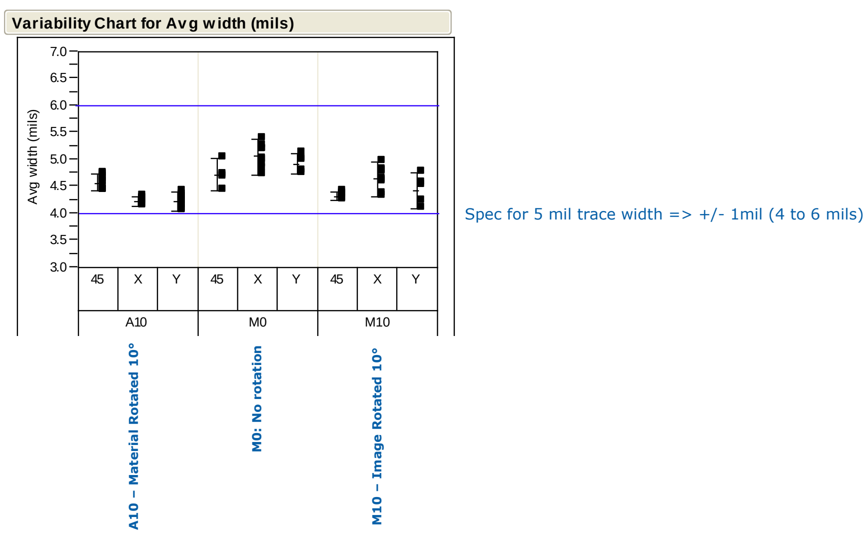


Figure 10: Dimensional Measurements of Traces Results

POSITIONAL DISTORTION OF FEATURES

Rotating the artwork forces the majority of the copper trace routing out of alignment with the primary axis' of the exposure equipment, and rotating the material forces the trace routing out of alignment with the weave. There was a question whether this would cause distortion of feature placement.

Measurements of relative position of key features (BGA pads, vias) were made in the Horizontal (X) and Vertical (Y) directions – see Figure 11.

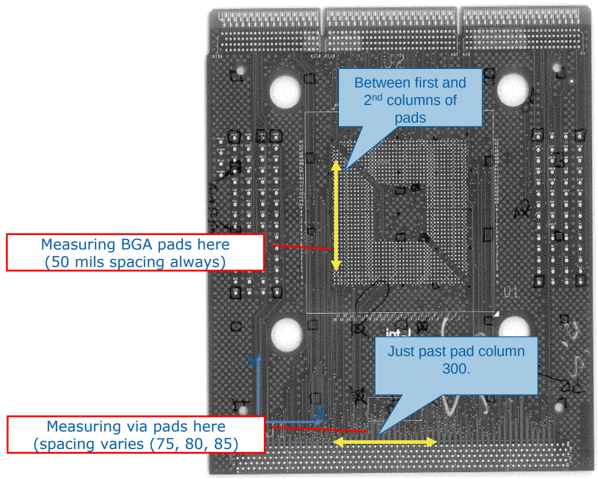


Figure 11: Layout for Measuring Positional Distortion

The X & Y position of the features were measured on the 3 varieties of boards (un-rotated, rotated artwork, rotated weave), (see Figure 12 for X direction measurements). The pitch of the measured points in the Y-direction was consistent and as a result showed an insignificant deviation from the design point. The graphical representation is not included. Note that there is no significant variation from expected position in either case.

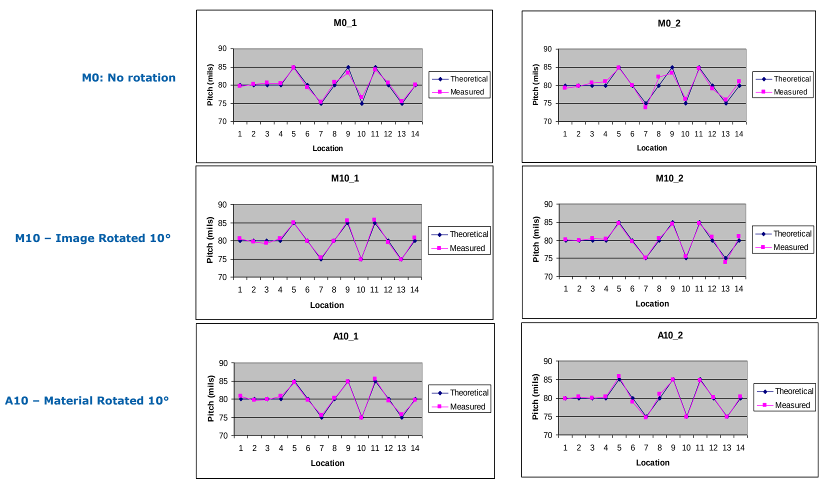


Figure 12: Positional X Distortion Measurement Results

SMT JOINT FORMATION: CROSS-SECTION BOARDS, MEASURE HEIGHTS OF SOLDER JOINTS

To investigate the effect of rotating the material on SMT joint formation, rotated and un-rotated boards were assembled with BGA devices and then cross-sectioned to carefully examine the SMT joint height (see Figure 13) of 6 representative locations (A1, A19, A38, AU1, C1, U1).

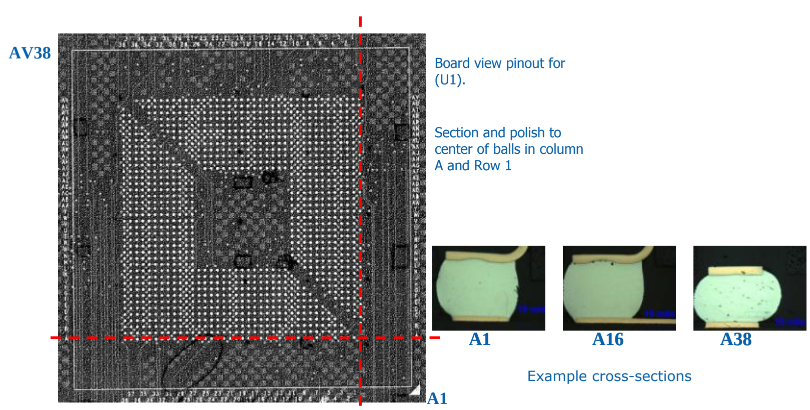


Figure 13: Layout for Measuring SMT Joint Height

The heights of the joints were measured on the 2 varieties of boards (un-rotated, rotated weave), (see Figure 14). Note that there is no significant difference in the solder-joint height for the rotated case.

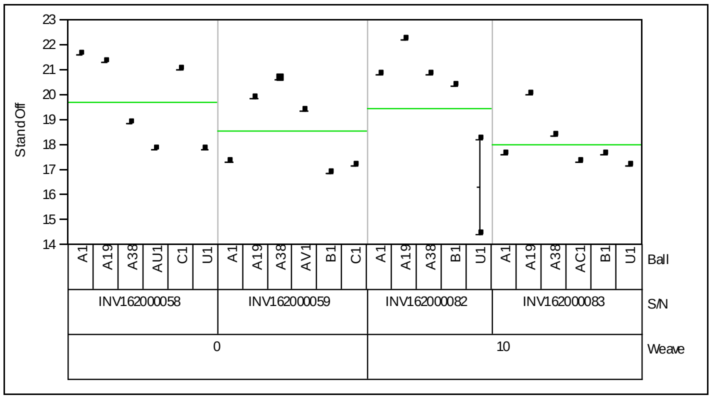


Figure 14: SMT Joint Height Measurement Results

SMT Joint Formation: Dye Penetrant Test

To further investigate the effect of rotating the material on SMT joint formation, rotated weave and un-rotated boards were assembled with BGA devices. In order to evaluate whether the rotated fiber weave influenced the strength of the board level interconnect a Dye Penetrant Test was used. The area of interest is cut from the remainder of the PCB, in this case the CPU socket and PCB material under the socket. The specimen is immersed in dye and then placed in a vacuum chamber so that the dye can be pulled into any cracks or voids present in the interface. The sample is then allowed to dry, prepped in a fixture and the component is pulled away from the PCB using a screw driven static loading machine.

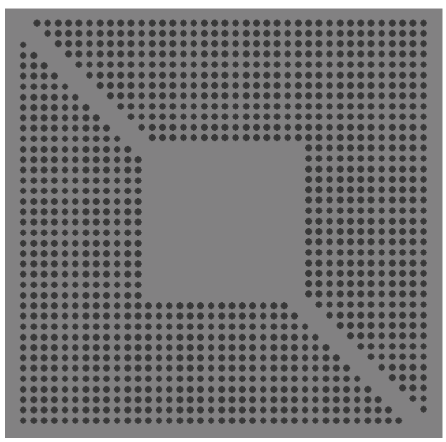


Figure 15: Map of BGA for Dye Penetrant Test

The PCB surface is then mapped utilizing a high resolution optical microscope. The amount of stain present in the joints is used as an indication of crack %.

S/N	Type	Qty 1-25%	Qty 26—50%	Qty 51-75%	Qty 76-100%
0062	U1 (0-degree)	0	0	0	0
0086	U1(10-degree)	0	0	0	0

Figure 16: Initial Dye Penetrant Test Results

As was expected in a Time 0 joint there was no indication of crack formation which is indicated by the 0% staining area. The next step is to map the fail type. The PCB surface is also examined for the interface that failed at each location. The interfaces are listed in Figure 17 and 1 – 4. The critical measure is whether more “Type 4” cracks occur, indicating weaker bonding of the pad to the PCB. The 10-degree rotation appears better, but we believe that is due to the small sample size.

S/N	Type	% Type 1	% Type 2	% Type 3	% Type 4
0062	U1 (0-degree)	0	50.5	7.1	42.4
0086	U1(10-degree)	0	86.1	2.0	11.9

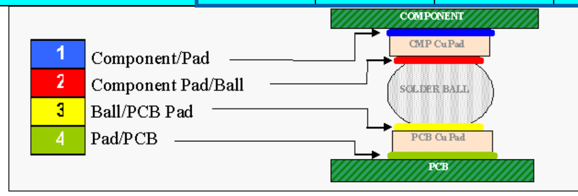


Figure 17: Dye Penetrant Test Results

INFLUENCE OF ROTATED FIBERWEAVE ON ELASTIC MODULUS

To evaluate whether the effect of rotating the material had any effect on mechanical properties of a PCB, the PCB was submitted to a bend test which measured the load required to flex a board to a prescribed deflection point. Both non-rotated and rotated image boards were used in this evaluation. In order to check the weave influence in both the X and Y direction the measurements were taken first with the PCB at a 0 degree angle and then rotated 90 degrees and measured again.

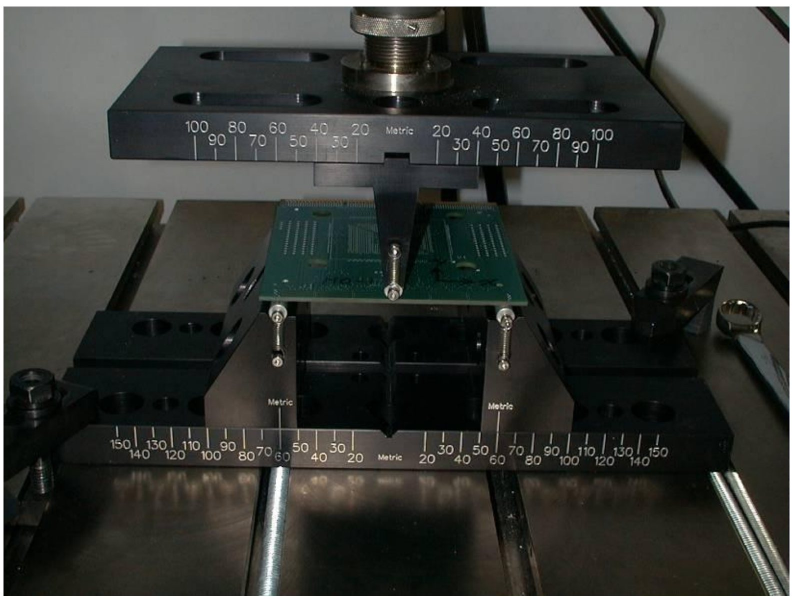
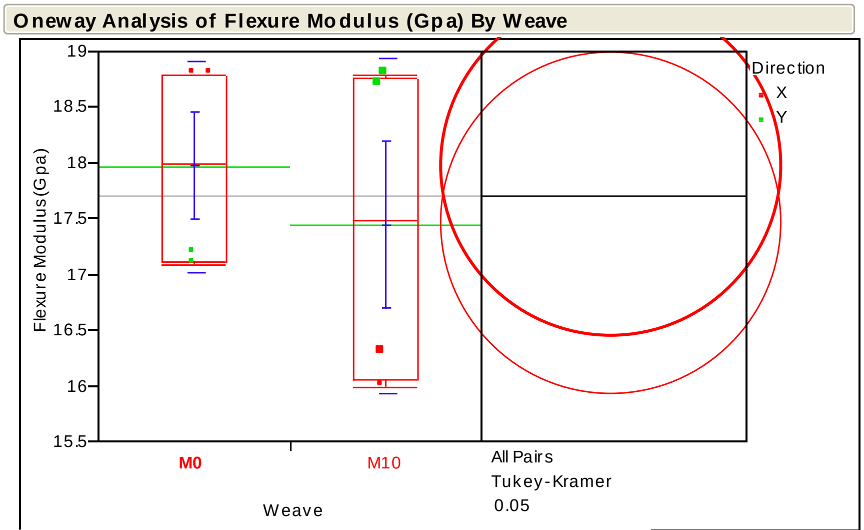


Figure 18: PCB in the Board Bending Fixture

No significant difference was noted in the overall measured Flexural Modulus of the 2 test panels as shown in Figure 19.

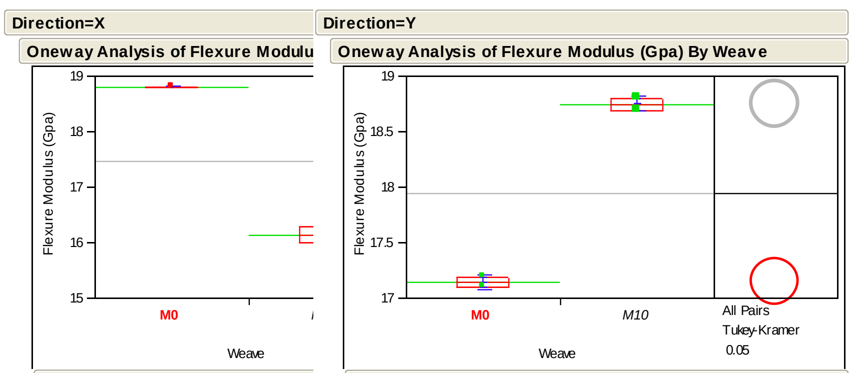


Means and Std Deviations

Level	Numbe	Mean	Std Dev	Std Err Mear	Lower 95%	Upper 95%
M0	4	17.9750	0.95350	0.47675	16.458	19.492
M10	4	17.4500	1.50665	0.75333	15.053	19.847

Figure 19: Overall Flexure Modulus Response

A difference was noted between the X and Y measured responses as shown in Figure 20. While the measured response showed no significant difference, there was an inversion of the responses between the 2 PCB's.



Means and Std Deviations (Direction=X)

Level	Number	Mean	Std Dev	Std
M0	2	18.8000	0.000000	
M10	2	16.1500	0.212132	

Means and Std Deviations (Direction=Y)

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
M0	2	17.1500	0.070711	0.05000	16.515	17.785
M10	2	18.7500	0.070711	0.05000	18.115	19.385

Figure 20: 0 and 90° Test Results

The most popular explanation for this inversion was that it is an artifact of the PCB manufacturing process where the glass weave may have been placed down at different rotations. No further investigation of this was performed due to this being a typical manufacturing process and has not driven any influence of failure modes prior to this investigation.

INFLUENCE OF ROTATED FIBERWEAVE ON WARPAGE

To evaluate whether the 10° Fiber Weave rotation would influence PCB warpage direction during the various reflow cycles in the assembly process, a Shadow Moiré measurement was taken of the PCB's. Shadow Moiré is a metrology that allows us to measure the amount and direction of warpage during a typical reflow cycle in a lab environment. Boards are measured using a camera system and a striated glass panel at room temperature and then at set points as the temperature is raised to a typical reflow temperature (240°C) and then cooled again to room temperature.

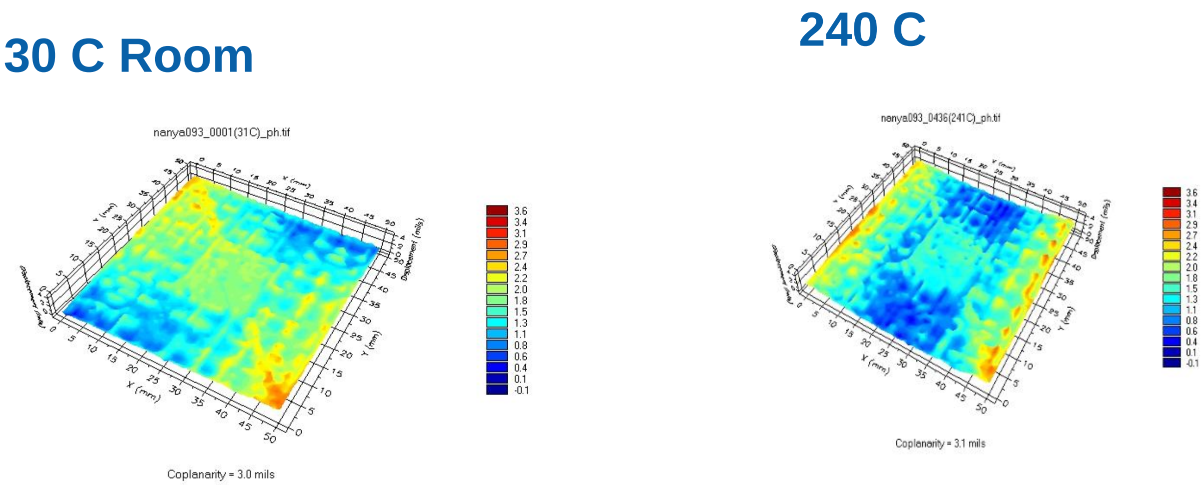


Figure 21: Shadow Moiré Measurement Results of a Normal Test Coupon

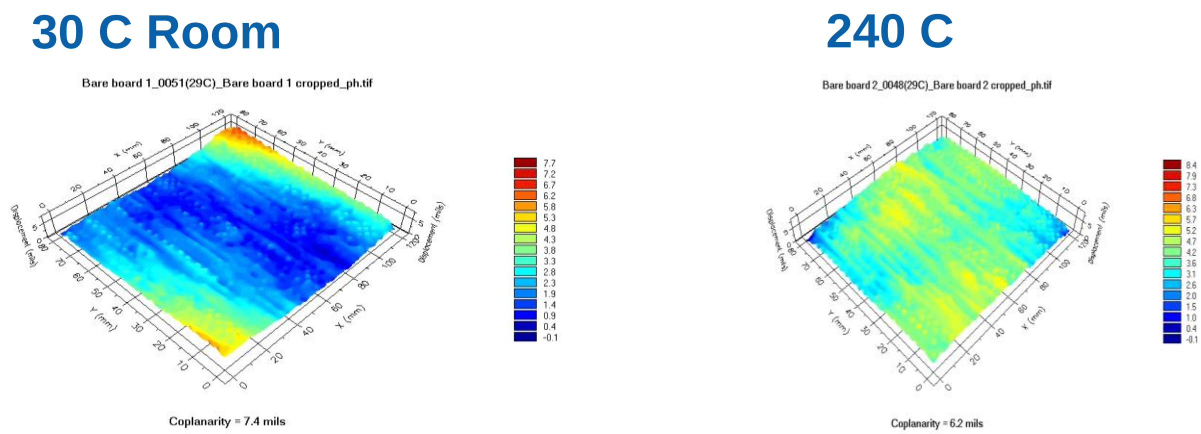


Figure 22: Shadow Moiré Measurement Results of a Test Coupon with 10° Fiber Rotation

No significant influence of the rotation of the fiber weave to warpage was noted. The differences that were noted i.e. relaxation or "potato chipping" were deemed as typical noise within the PCB manufacturing process.

CONCLUSIONS

There was no indication of any problems induced in manufacturing due to rotating either the artwork or the material.

SUMMARY

The fiberweave effect must be comprehended and properly accounted for in future high speed bus designs. Rotating the artwork or material remains an effective means of mitigating the effect, with no impact to manufacturing. The most significant impact is expected to be in cost, due to increased panel size. That cost increase would be less for the case of rotated glass, since it involves an increase only in the size of the raw glass.

ACKNOWLEDGMENTS

Special thanks are due Lori Avishan, Todd Embree, Paul Hamilton, Ife Hsu, Julia Martinez, Satish Parupalli, Gary Shade, and Brandon Draper for invaluable contributions to the Work Group investigating the manufacturing effects.

BIBLIOGRAPHY/REFERENCES

1. Howard Heck, Steve Hall, Bryce Horine, Tao Liang; "AC Common Mode Conversion in Multi-Gb/s Differential Printed Circuit Boards"; DTTC 2004 Paper
2. Dave Coleman, Scott Gardiner, Mohammad Kolbehdari, Stephen Peters; PCI Express Electrical Interconnect Design"; Intel Press Book, 2004
3. Stephen Hall; "Requirements for Multi-GHz Transmission Line Modeling"; IEEE Workshop Paper; 26-May-05

4. Scott McMorrow and Chris Heard; “The Impact of PCB Laminate Weave on the Electrical Performance of Differential Signaling at Multi-Gigabit Data Rates”; DesignCon 2005 Paper
5. Jeff Loyer, Richard Kunze, Xiaoning Ye; “Fiber Weave Effect: Practical Impact Analysis and Mitigation Strategies”; DesignCon 2007 Paper

PCB Image Rotation to Mitigate the Fiberweave Effect – Impact to PCB Assembly

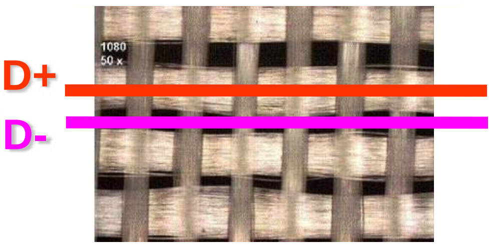
Jon Kuchy, Jeff Loyer

Intel Corp.

Root Cause of Fiberweave Problem

The 2 halves of a differential pair see different effective dielectric constants (and corresponding velocities) due to the difference in Er of the Fiberglass Weave (Er ~6) and Epoxy (Er ~3).

FR4 Glass Cloth w/ Differential Signals



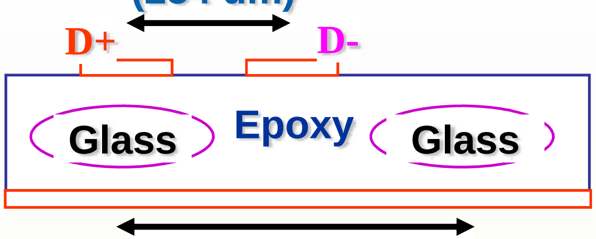
High ε_r (over glass)

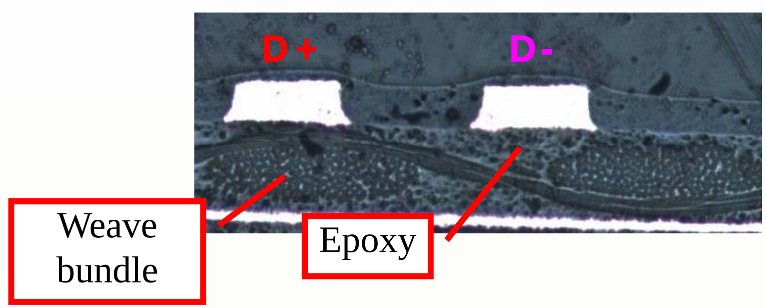
Low ε_r (over epoxy)

Signals travel faster when Er is lower

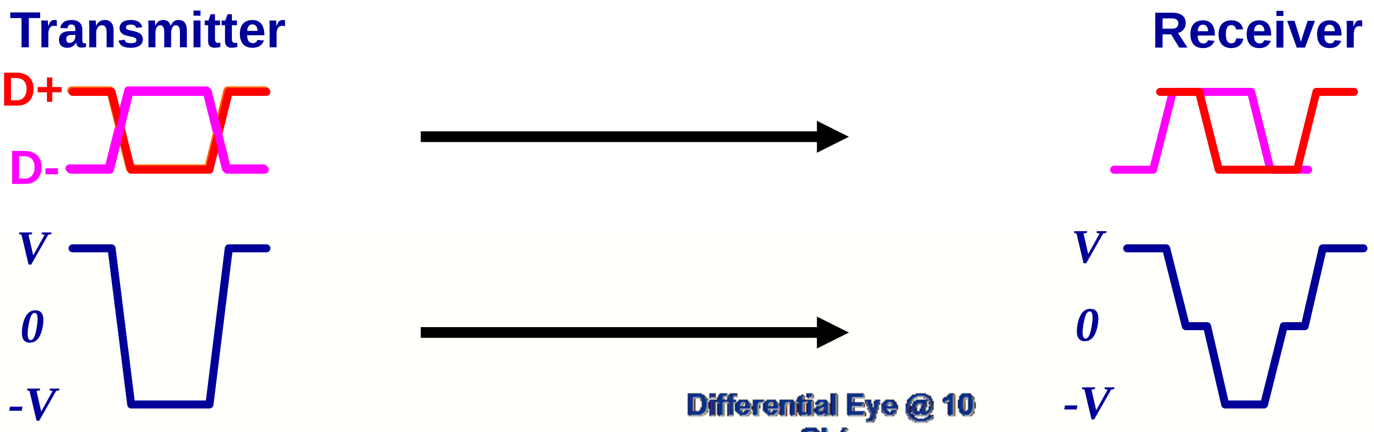
A line routed over a glass bundle travels more slowly due to the higher er

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

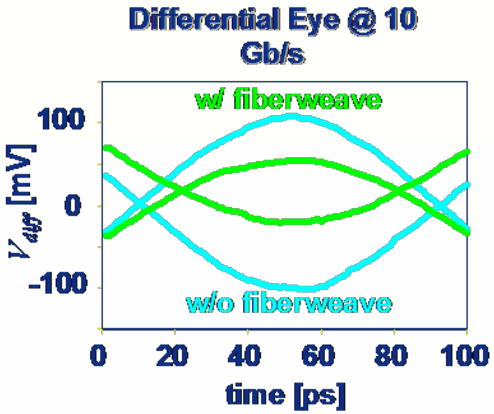




Fiberweave Problem Overview



$$V_{diff} = D^{+} - D^{-}$$



Can cause significant degradation of differential "eye"

$$V_{comm} = \frac{D^{+} + D^{-}}{2}$$

Can also cause significant "ACCM" (AC Common Mode) voltage: noise and EMI concerns

Problem Solutions: Many Possibilities Investigated

Investigated 17 possible approaches:

1) Offset "jog" routing per weave pitch
2) offset "jog" routing per pair spacing
3) zigzag
4) Angled routing
5) PCB vendor rotates image
6) Designer Rotates Image
7) Rotate Glass
8) Advanced materials: Nelco – SI material (NE glass)
9) Specify tighter (or coarser) weaves
10) Adjust trace spacings for weave
11) Electric deskew
12) Random weave (matte?)
13) Subtract from margin
14) Floorplan design for 45 degre
15) Glass-less materials: polyimide, speedboard
16) Multi-ply w/ different pitches
17) Multi-ply w/ different pitches (2)

Focus of today's presentation

Eliminated non-practical approaches, decided on those preferred:

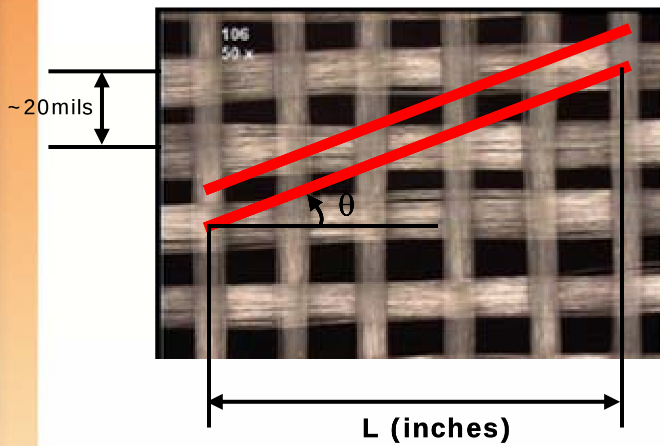
1) Determining that the effect isn't a problem at a particular bus' frequency and lengths per slide 8.
2) Absorbing the impact to eye height, width, and ACCM.
3) Special layout and routing
   a) Floorplan design for 45 degrees
   b) Require <4" (102mm) orthogonal routing
   c) Zigzag or angled routing
4) Designer rotates image
5) Rotate Glass

perhaps PCB vendors will rotate the image in the future

Note: any solution that required specifying weave type was rejected

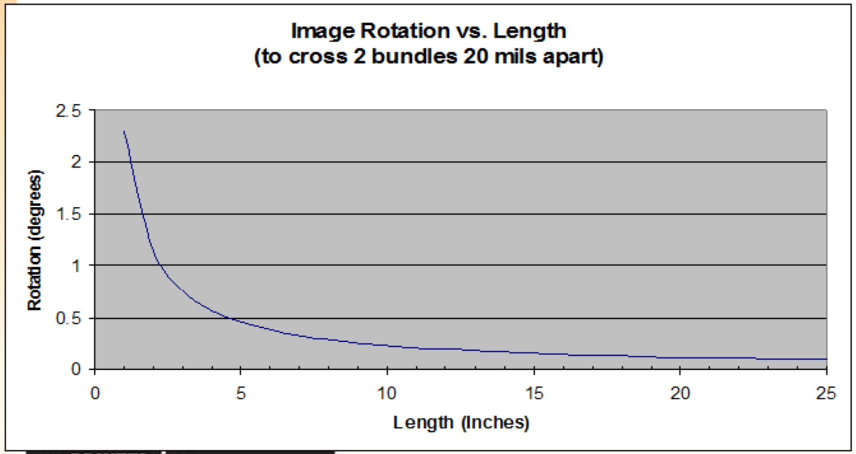
How Much Rotation is Enough?

If a differential pair crosses 2 weave bundles along its length, fiberweave effect should be cancelled



$\theta = \tan^{-1}(0.04/L)$
(L in inches)

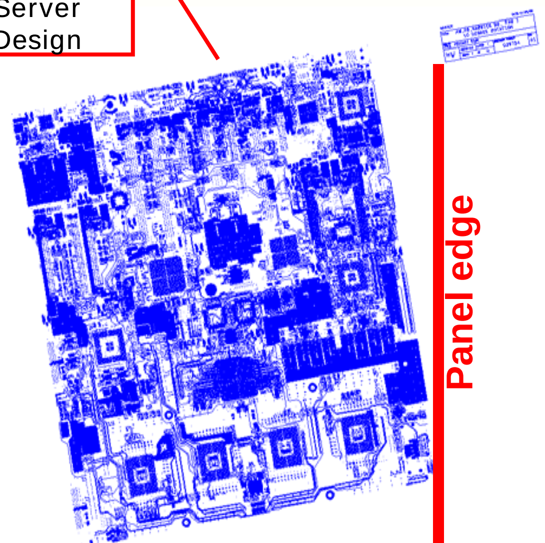
- **<u>1-2 degree rotation</u>** (relative to the fiberweave) is all that's needed to mitigate the effect
- BUT: cross-sectioning of test boards and PCB vendors' experience indicates the fiberweave can be skewed as much as **<u>5 degrees</u>**, relative to the board edge
- **<u>10 degree rotation</u>** should solve the problem for all cases



- Knowing exact fiberweave cloth skew could have significant benefit, but is very difficult to obtain
- 10 degree rotation is conservative, but is required without knowing the fiberweave skew number betters
- Test boards showed that 10° rotation solves the problem

First Test of Image Rotation – Rotated State-of-Art Server Design 10˚

Intent: Rotated Server Design



Note from vendor explaining why design wasn't rotated!

Dear Jeff

Please see picture 1, it show that part number and circuit pattern rotated on original Gerber.

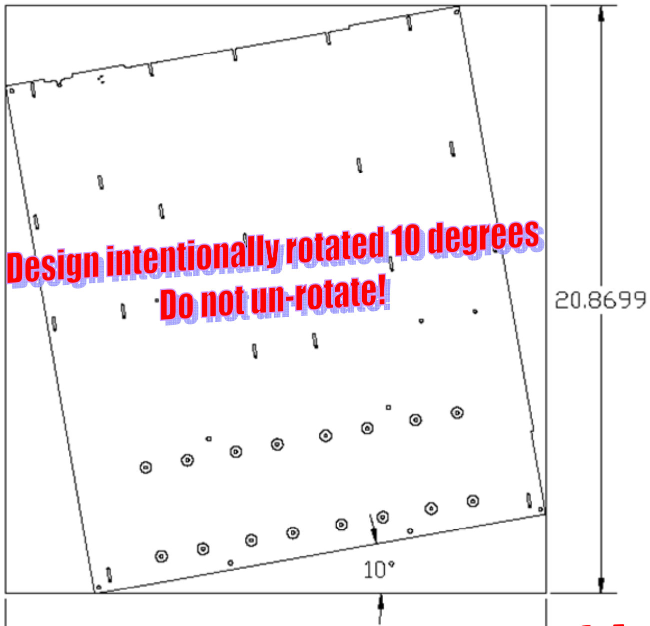
For manufacture purpose, we need to rotate the circuit pattern slightly and we will rotate part number together.

"When we rotate pattern, we will change whole pattern in the Gerber."

That's why you will receive the part number aligned with board edge

Thank you and advice

Future solution: unambiguous addition to Fab drawing



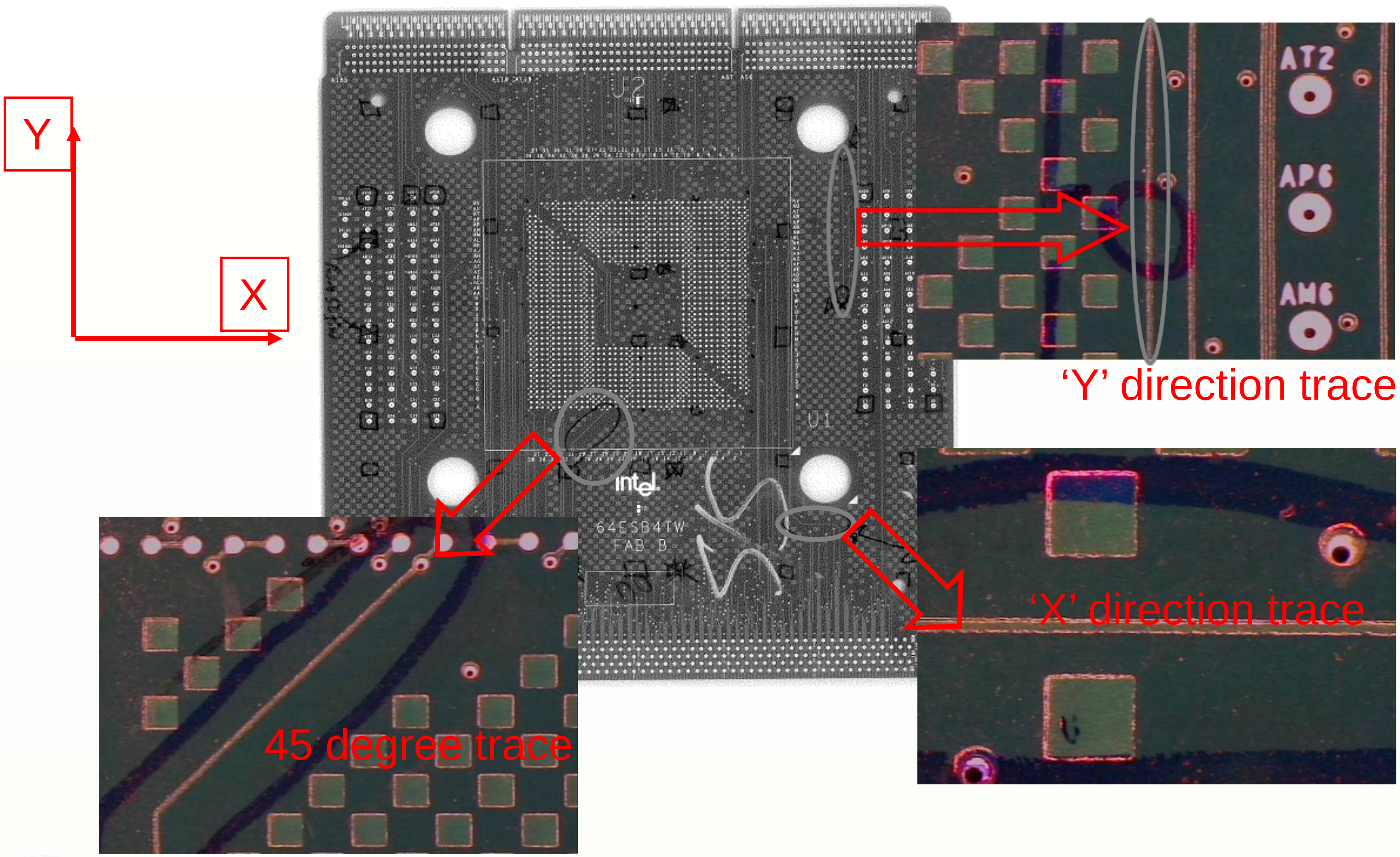
Boards were built to prove existing design could be easily and accurately rotated without any unforeseen manufacturing problems.

This was attempted, but the 1st boards that came back were not rotated. Investigation shows that the <u>manufacturer un-rotated the design</u>; this highlights the difficulty in rotating a design until the process becomes more commonplace.

2nd Round of Rotated Boards came back successful

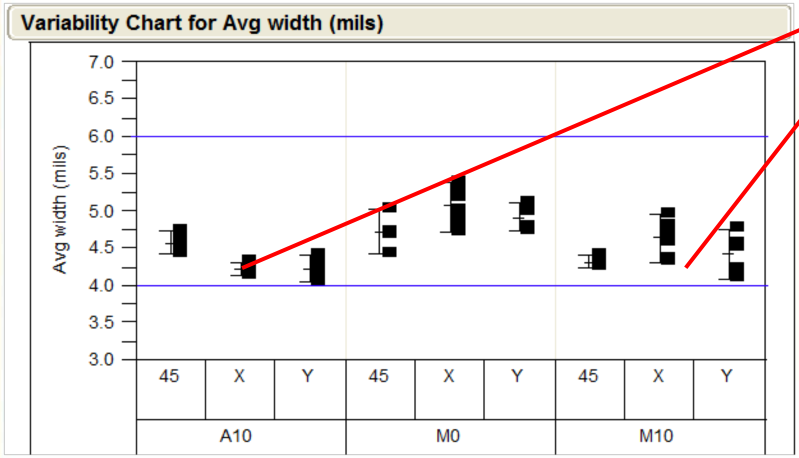
Mfg. effects of skewed fiber weave

Dimensional Measurements of key features (Traces, TP's, Pads,…)



Mfg. effects of skewed fiber weave

Dimensional Measurements of key features (Traces, TP's, Pads,…)



A10 – Material Rotated 10°

M0: No rotation

M10 – Image Rotated 10°

There seems to be a regular difference between no rotation and the 2 rotated instances (rotated trending lower), but still within spec. A10 is lower, but that can only be due to standard mfg variation. Thus, variation of M10 is probably std manufacturing variation

Spec for 5 mil trace width => +/- 1mil (4 to 6 mils)

No significant statistical difference observed between A10, M0 & M10 boards' trace widths

Mfg. effects of skewed fiber weave

True position measurements of key features (Via's, TP's,....)

<u>Measurements:</u>

a) Hole center-center distance (pitch)

b) X,Y coordinates of center for each hole

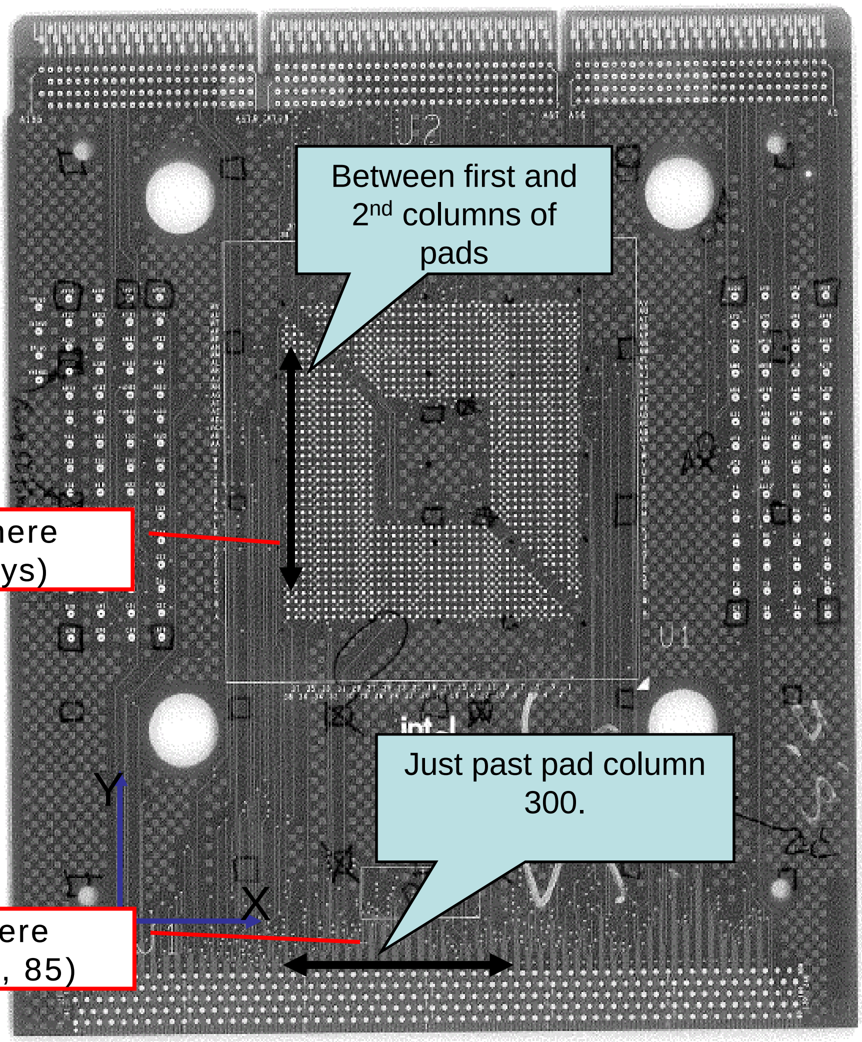
* Measure rows of holes (15) as shown in adjacent figure

* 3 board types (M0, M10, A10)

* 2 samples per each board type

* Nominal pitch values:

- X direction => 75, 80, 85 mils
- Y direction => 50 mils



Mfg. effects of skewed fiber weave

True position measurements of key features (Via's, TP's,….)

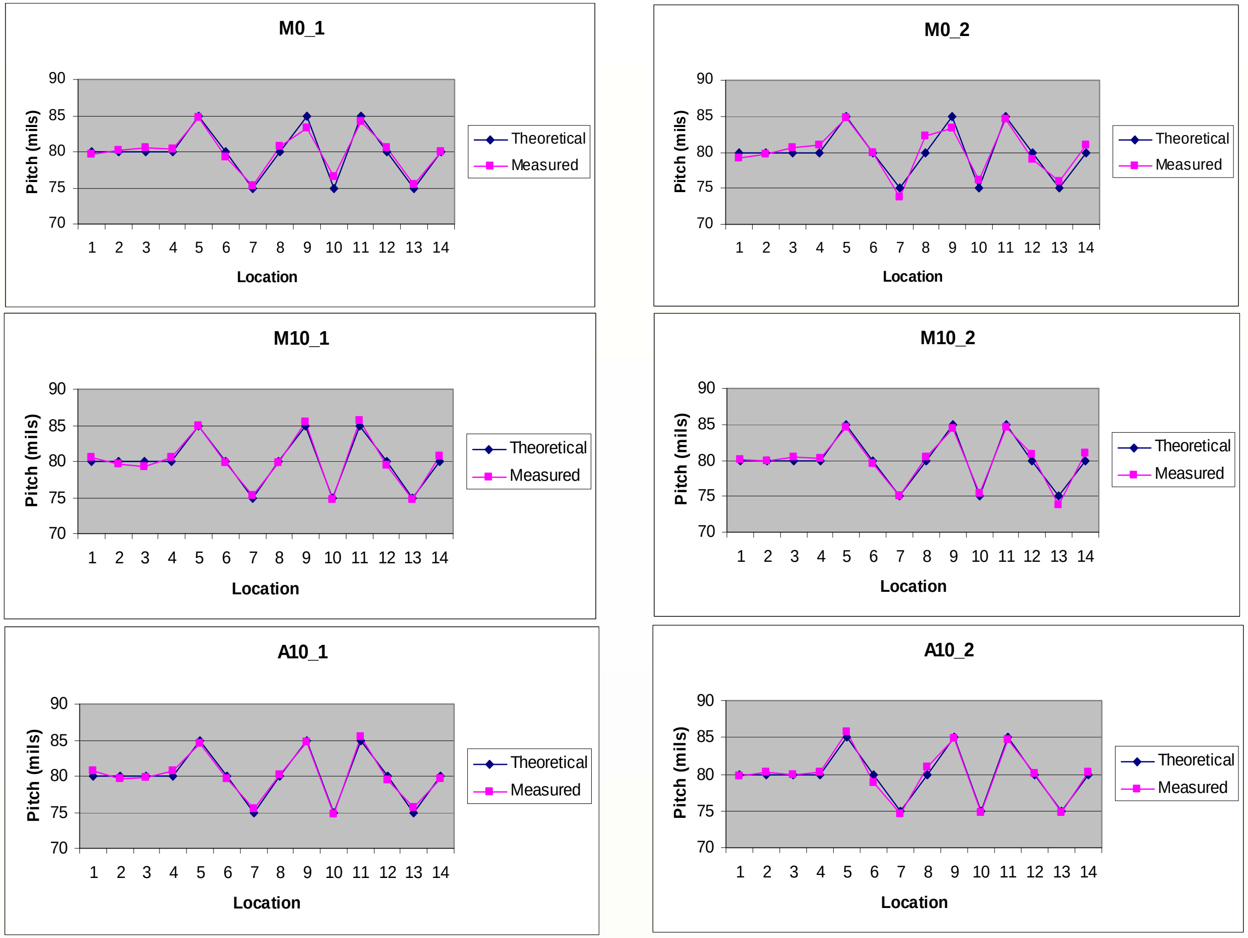
(Y had similar results)

X direction pitch measurements

M0: No rotation

M10 – Image Rotated 10°

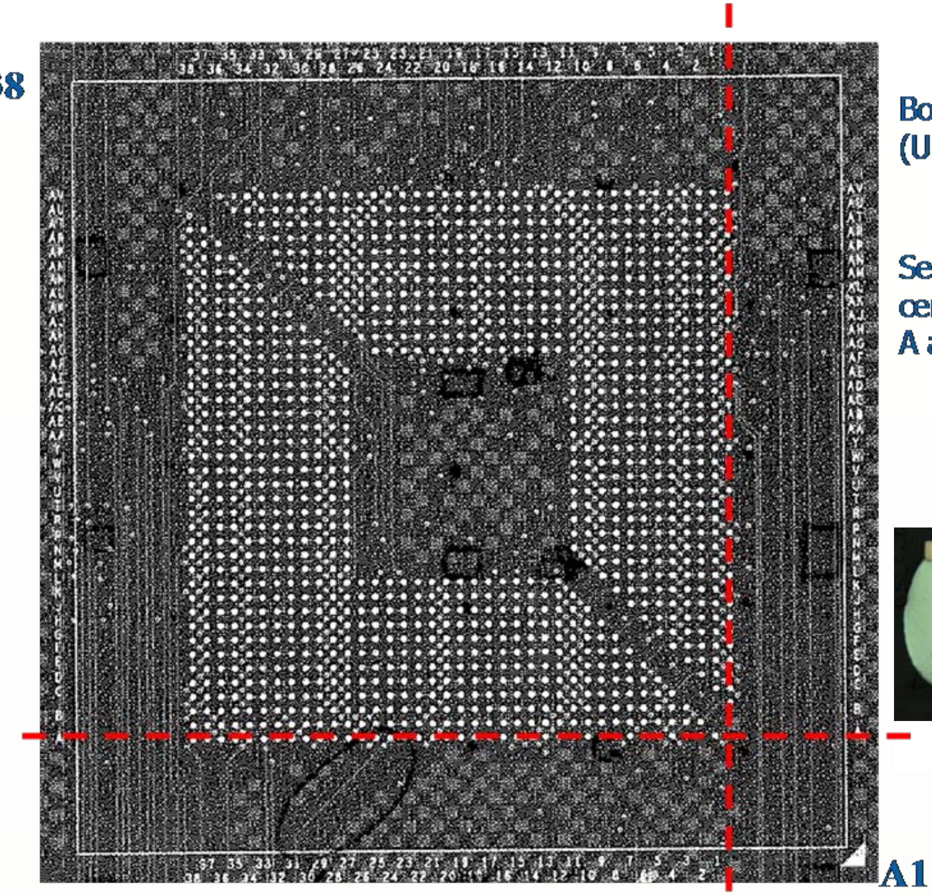
A10 – Material Rotated 10°



- **No significant difference in pitch measurements (Y direction measurements had similar results)**

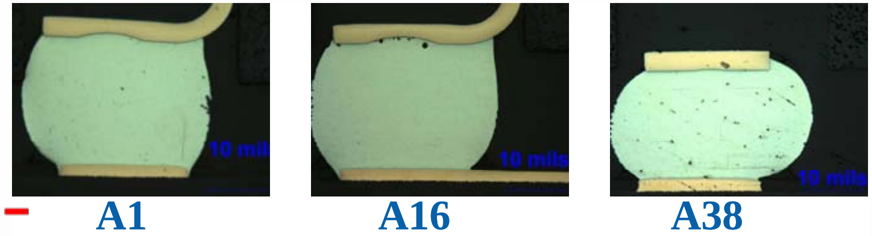
Investigate impact to SMT

Evaluate T0 solder joint formation



Board view pinout for (U1).

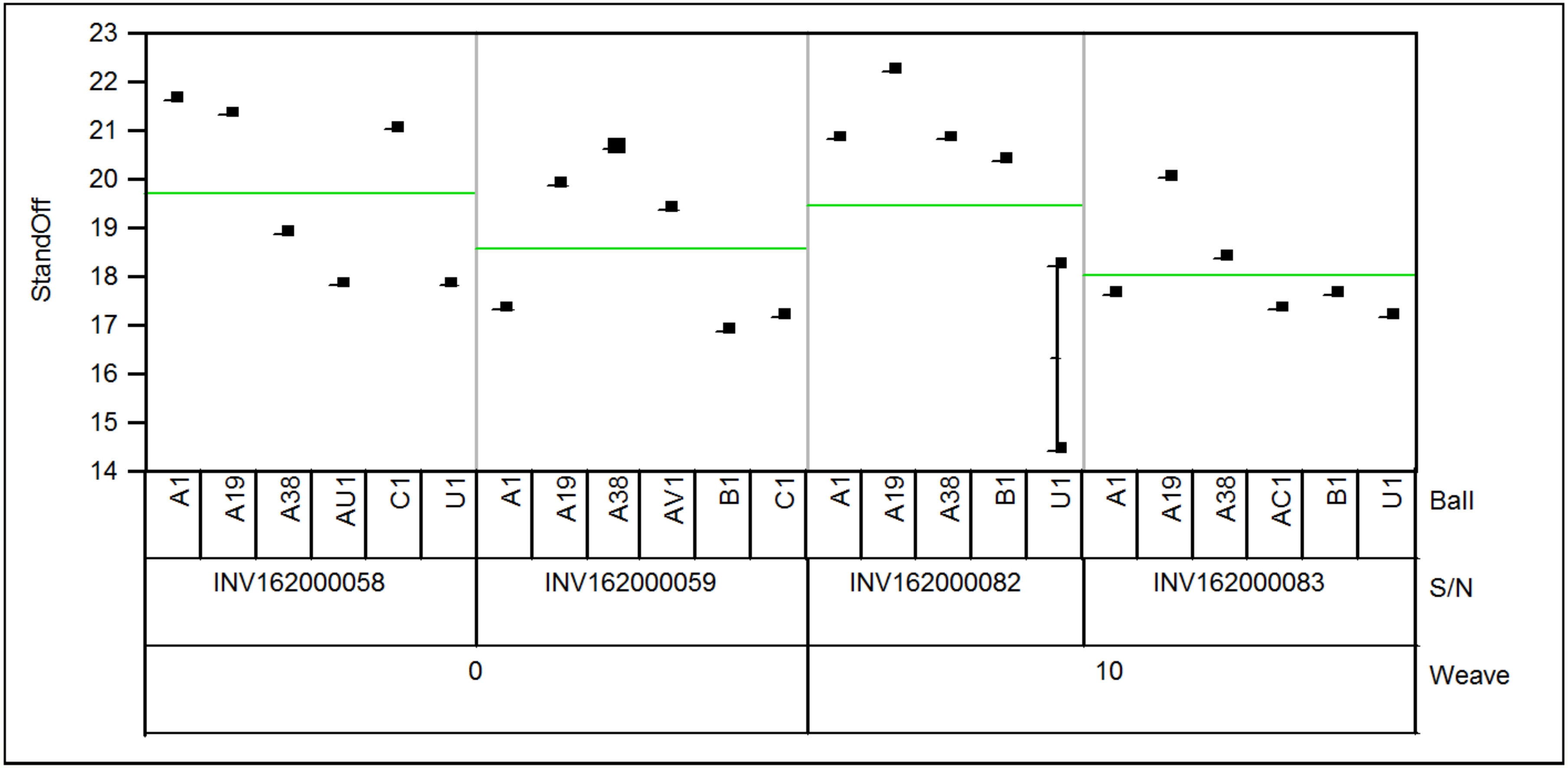
Section and polish to center of balls in column A and Row 1



Example cross-sections

Investigate impact to SMT

Evaluate T0 solder joint formation



No significant difference in Solderjoint standoff

Impact to Solder Joint Reliability (SJR)

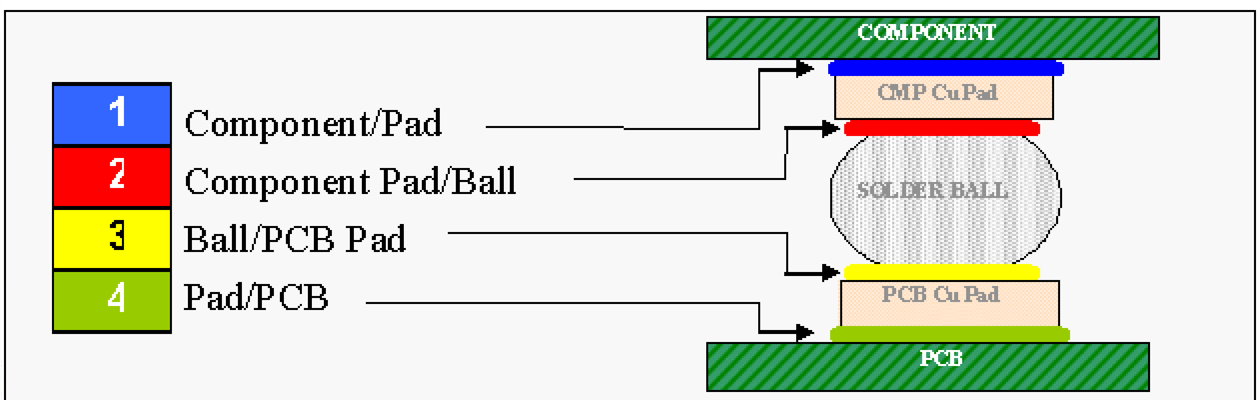
Dye Penetrant Test

S/N	Type	Qty 1-25%	Qty 26—50%	Qty 51-75%	Qty 76-100%
0062	U1 (0-degree)	0	0	0	0
0086	U1(10-degree)	0			

No cracks found at Time Zero

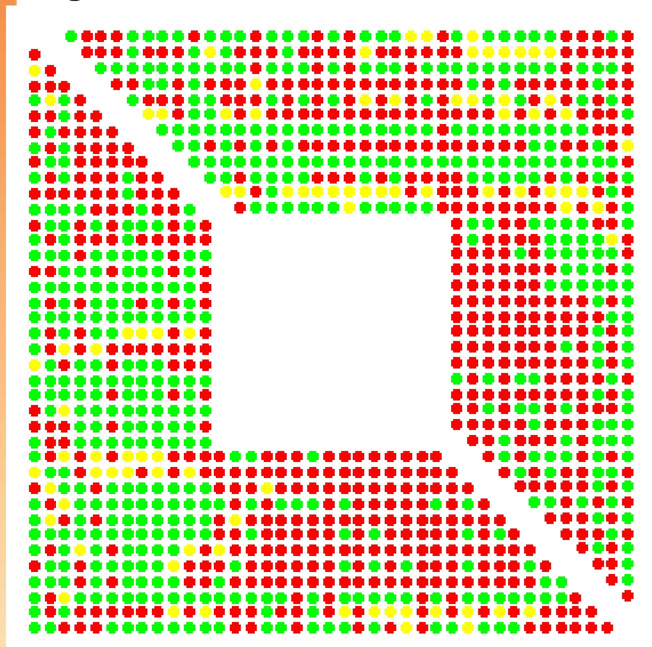
Best case: type 1 (damage component before any other damage)
Next best: joint breaks (type 2 or 3)
Worst: PCB crater (type 4)
10-degree **appears** better, but that is probably mfg variation (invalid sample size)

S/N	Type	% Type 1	% Type 2	% Type 3	% Type 4
0062	U1 (0-degree)	0	50.5	7.1	42.4
0086	U1(10-degree)	0	86.1	2.0	11.9

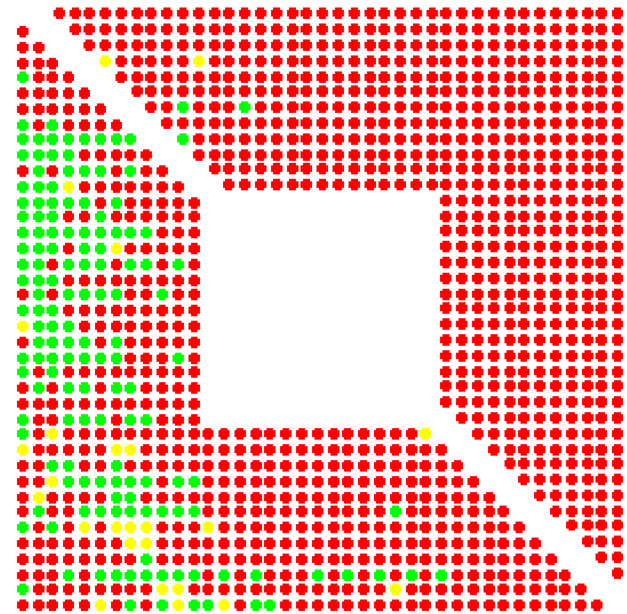


Impact to Solder Joint Reliability (SJR)

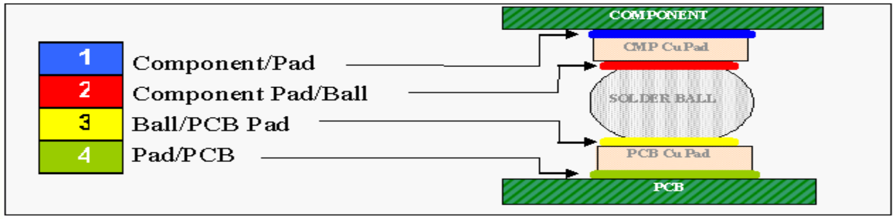
Dye Penetrant Test



0-Degree Disbond Type Map

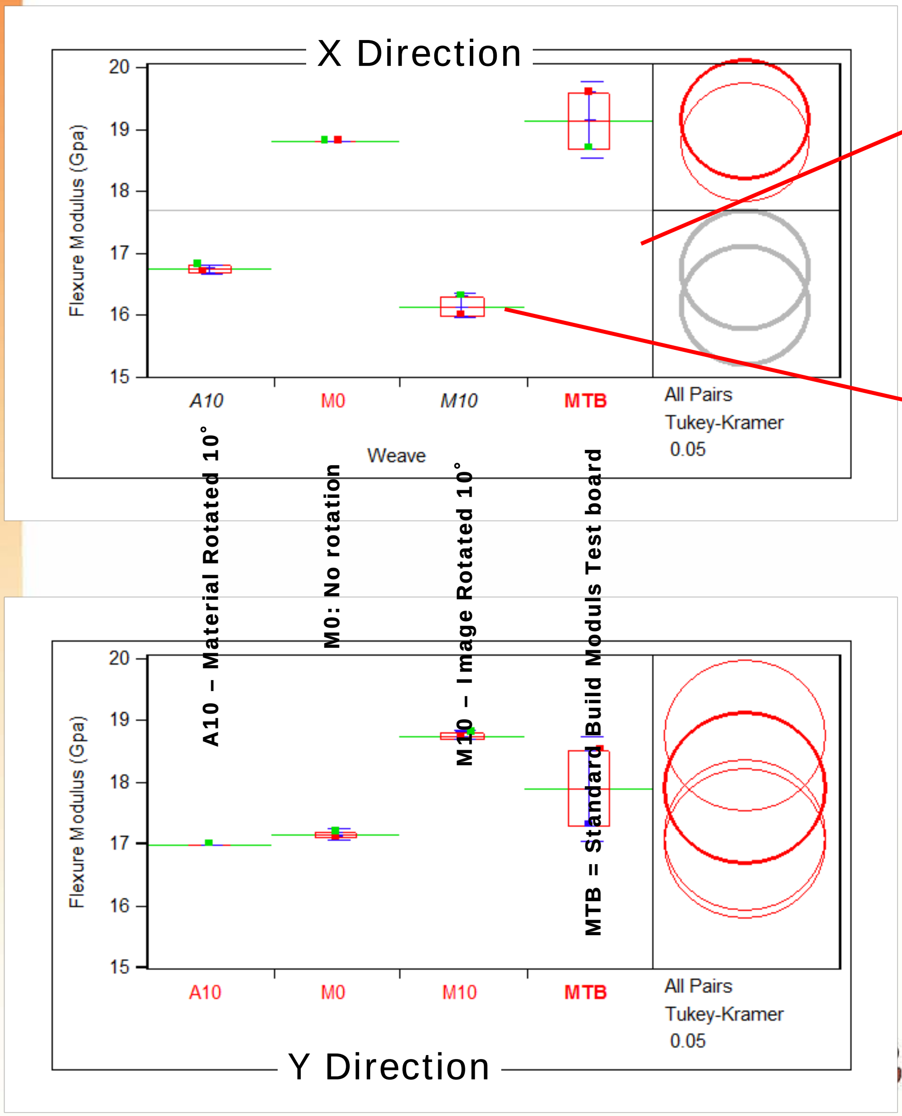


10-Degree Disbond Type Map



Impact to mechanical properties of bds

Elastic Modulus



- X direction top
- Y direction bottom

10 degree more flexible, but in the noise region

- Measurable differences are indicated in X direction only

Manufacturing deviation – panels can be manufactured at 0 or 90 degrees

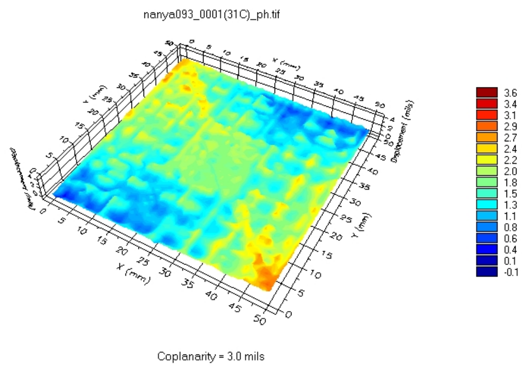
- M0 & M10 Axes appear to be swapped.
- A10 specimen results are inconclusive
- MTB result appears consistent with ETB behavior.

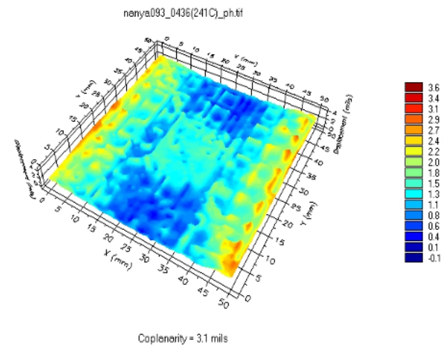
Impact to mechanical properties of bds

Warpage

30 C Room Temp

240 C Peak

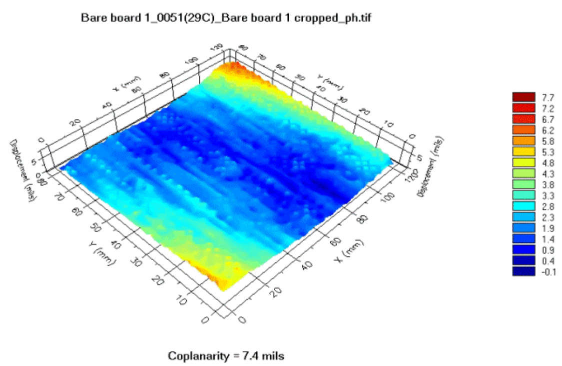


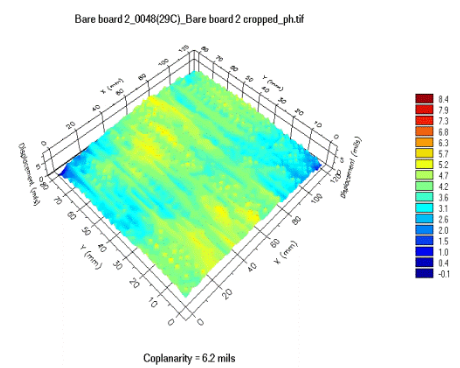


Shadow Moiré Measurement Results of a Normal Test Coupon

30 C Room Temp

240 C Peak





Shadow Moiré Measurement Results of a Coupon with 10° Fiber Rotation

Rotation Process "gotcha's"

Rotating Gerbers is NOT trivial

- Need format with unambiguous rotation direction
- Must rotate Netlist
- Must rotate drill file (which may not be in standard format)
- Must <u>not</u> rotate solderpaste

But, interestingly enough, our HVM vendor <u>un-rotated</u> the design w/o a second thought!

Summary

- Future designs will have to account for the fiberweave effect
- No significant differences were seen for manufacturing boards with rotated image or glass weave
- Rotating the image or weave remain viable alternatives to mitigate the fiberweave effect
  - Cost remains a high concern, with an expected 10% cost adder for rotating the image
  - Cost of rotating the weave is still unknown, though it should be less since less raw material is wasted