PWB Warpage Analysis and Verification Using an AP210 Standards-based Engineering Framework and Shadow Moiré

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1 Abstract

Thermally induced warpage of printed wiring boards (PWB) and printed wiring assemblies (PWAs) is an increasingly important issue in managing the manufacturing yield and reliability of electronic devices. In this paper, we introduce complementary simulation and experimental verification procedures capable of investigating warpage at the local feature level as well as the global PWB level. Simulation within a standards-based engineering framework allows efficient introduction of detailed feature information into warpage models of varying fidelity. Experimental results derived from temperature-dependent shadow moiré provide a rapid high resolution picture of local warpage in critical regions. We describe initial results for two unpopulated PWB test cases which indicate a promising outlook for the methodology.

2 Keywords

PWB / circuit board warpage analysis, stackup, standards-based framework, AP210, STEP, multi-representation architecture, shadow Moiré, phase stepping

3 Nomenclature

AP210	STEP Application Protocol 210 standard for electronics (ISO 10303-210)
ABB	Analysis Building Block
APM	Analyzable Product Model
CTE	Coefficient of Thermal Expansion
ECAD	Electronics Computer-aided Design
ISO	International Organization for Standardization
JSDAI	Java-based implementation of Standard Data Access Interface (ISO 10303-27)
MPM	Manufacturable Product Model
PWA	Printed Wiring Assembly
PWAF	PWB Warpage Analysis Framework
PWB	Printed Wiring Board
SMM	Solution Method Model
STEP	STandard for the Exchange of Product model data (ISO 10303)

4 Introduction

Warpage is the out-of-plane deformation of an artifact (PWB in our case). In this paper, we focus on thermally induced warpage, i.e. warpage of the artifact when it is subjected to thermal loading, caused by differential thermo-mechanical properties of elements composing the artifact. Figure 1 shows some basic scenarios, exemplifying warpage measurement.

Increasingly, local warpage, e.g. warpage in the region of a critical component footprint, is a more critical issue than global warpage, the warpage of the PWB as a whole [16]. Changes in the contour of the component footprint can create shorts or opens in the PWB-component solder joints during reflow soldering or build stresses into the assembly that appear as later reliability problems.

Simulation of local warpage must consider key local features such as conductive traces, vias, tooling holes, etc. yet simulation models cannot effectively include these details fully for typical PWA/Bs. Thus, efficient transfer and appropriate idealization of design data from proprietary electrical and mechanical CAD formats to model-soluble form is required.

In this paper, we put forth the ideas and development aspects of an AP210 (ISO 10303-210) standards-based engineering framework, known as the PWB Warpage Analysis Framework (PWAF). First, we present the model-based conceptual architecture of the PWAF. Thereafter, we describe the actual implementation of the PWAF in terms of the nature and scope of particular models and the associated transformations.

Experimentally, classic warpage measurements performed with pin gauges on the PWB perimeter no longer provide sufficient information to diagnose potential manufacturing or reliability issues for typical designs. In this paper, we describe the Shadow Moiré technique as the basis for experimental warpage measurements. Further, we discuss the experimental configuration and warpage results for two PWB designs, as obtained from this technique. Future work is anticipated to verify and validate the above simulation models via this technique.

5 Conceptual Architecture of PWB Warpage Analysis Framework (PWAF)

We perceive the need for a conceptual architecture, as an aggregation of well connected and high fidelity information models, for the physics-based representation of PWB designs and the analysis of their warpage worthiness. Figure 2 shows the multi-representation architecture [1, 2] view of the subject framework. The PWAF is comprised of five model types. First, we describe the need and the nature of each of these model types.

5.1 Manufacturable Product Model (MPM)

The manufacturable product model, as the name implies, consists of detailed information concerning the PWA and the associated PWB at the level of richness at which they can be manufactured. Design information is the basic need for any analysis that can be performed at different stages of the life cycle of an electronics product (a PWB in this case). Traditional ECAD tools can represent only a share of this complete information pool for a certain range of electronics products and with varying semantics across them. To answer the needs for intelligent representation of electronics product design information and its usage, we use the STEP AP210 standard (ISO 10303-210) [3, 4]. The manufacturable product model is based on AP210 and shall be referred here on as a 210-based MPM. The 210-based MPM is a higher fidelity product model as compared to the set of information sub-pools that are used to populate it (ECAD tools, auxiliary sources like component databases, etc.). The term "fidelity" here refers to the extent of information coverage and the ability to exchange information with both downstream and upstream information models in the PWAF. Being a standards-based model, the MPM has a greater neutrality with respect to an increasing number of ECAD tools that can generate models conforming to the standard [3,7].

5.2 Analyzable Product Model (APM)

The APM [1] is an analyzable view of an MPM. Only a subset of the information contained in an MPM might be needed for the contexts in which the electronic product needs to be analyzed. For this reason, a view (model in this case) containing the relevant information is generated from the MPM. The APM shall be explained in more depth while discussing the development of the PWAF.

5.3 Analysis Building Block (ABB) Model

The ABB [1] model is an information model that contains the idealized view of the APM for the purpose of the subject analysis. ABBs are product independent analytical objects (e.g. representing physics-based concepts like continuum mechanics bodies and idealized material behavior properties).

5.4 Context-based Analysis Model (CBAM)

A CBAM [1] enables us to map the behavior to the ABB model for a particlar kind of analysis and fidelity (e.g. 2D PWB warpage analysis). The physical structure of the actual electronic product is usually complex. It might be sufficient to analyze (within the limits of significance) a much simpler structure by eliminating non-contributing features, calculating effective material properties for some constituents, etc. This simpler structure is the idealized behavior model for the analysis template as represented by the ABB model. CBAMs capture the knowledge and the decision to derive a particular ABB model, for analyzing the APM in a given context. Rightly so, the "context" is the identifying entity in a CBAM. As an example, for thermo-mechanical warpage analysis of a given PWB, we might select a set of plane-stress ABBs or 3D continuum ABBs, depending upon the nature of the loading and the structure of the product itself. In this case, the thermal loading and the structure of the electronic product are the "context". The CBAM captures the actual idealizations that are needed to generate the ABB model from the APM, in this context. A given product can have multiple CBAMs (product-specific analysis templates) for other fidelities and behaviors.

5.5 Solution Method Model (SMM)

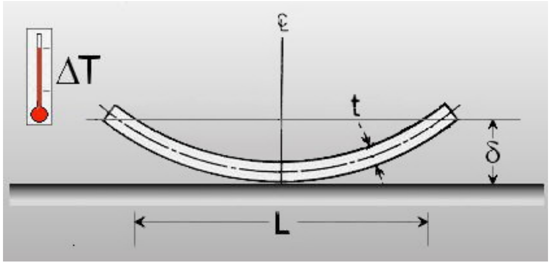
The SMM [1] contains information pertaining to the specific solution strategy applied to the ABB model. For example, an ABB model can be developed into a finite element-based SMM or a finite difference-based SMM for solution purposes. The information contained in the SMM is in a ready-for-interpretation state by the traditional analysis tools (e.g. ANSYS [10] for finite element analysis, etc.).

5.6 PWAF Architecture Overview

Now, we discuss the specific architecture of the PWAF, as comprised of the above model types. The navigation map for the conceptual architecture is comprised of a series of model transformations, as shown in Figure 2. The basis for developing this stepping-stone architecture (multiple transformations as opposed to one) is to be able to provide greater flexibility in the framework, hence addressing a wider range of designs and different analysis theories. The transformation function (as a conglomerate of parameter-based associativity) [1, 2] is derived based on the decision made by an analyst (an experienced engineer) in dealing with the particular design. The same design might be idealized differently based upon the context of the problem. Hence, the possibilities and the range for a particular transformation function expand as we move from the left to the right in Figure 2.

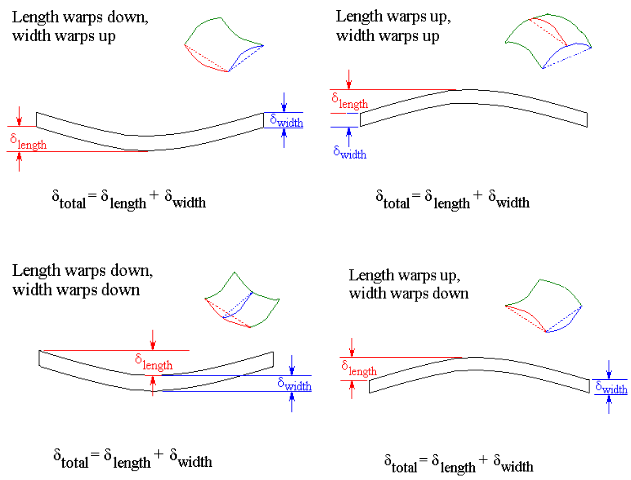
Information captured by traditional ECAD tools and enhanced by gap-filling tools [5] is integrated to develop the 210-based MPM. Thereafter the APM is derived from the MPM by extracting an information pool relevant to the particular analysis at hand. Further, based upon the context of the analysis (physical and functional structure of the product, boundary conditions, loading etc.) the corresponding CBAM is generated for a particular analysis. The CBAM then enables the derivation of a ABB model from the APM. Lastly, the SMM is generated from the ABB model in a ready-to-solve state and is interpreted by traditional analysis tools (example: ANSYS for finite-element analysis etc.). Overall this approach increases modularity and resuability as well as enhancing knowledge capture and tool independence.

We shall elucidate the navigation map more explicitly in the context of the PWAF.



$\delta = (\alpha_b \, L2 \, \Delta T) / t$ where
L: Undeformed Length; **t**: Undeformed Thickness;
ΔT: Temperature Change; α_b: Specific Coefficient of Thermal Bending

a. Warpage of a 1D linear element due to differential thermal expansion of multi-metallic strips



b. Warpage of planar elements

Figure 1: Warpage (δ) – Basic measurement scenarios for linear and planar elements [17]

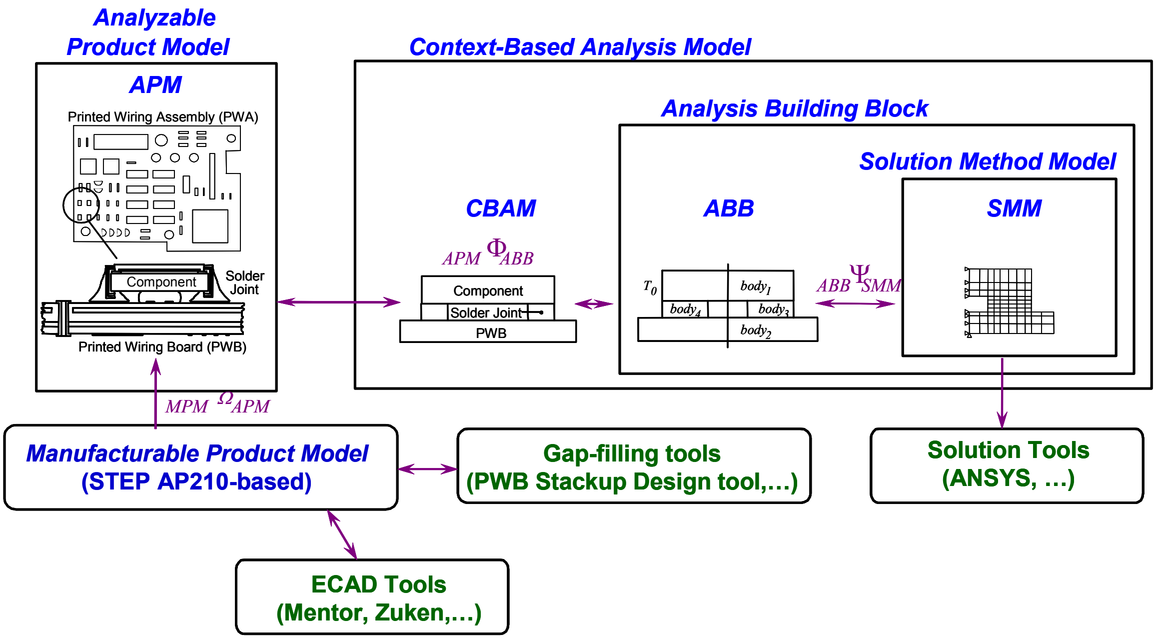


Figure 2: Multi-representation architecture (MRA) view of PWAF [1, 2]

6 Realization of PWB Warpage Analysis Framework (PWAF)

The PWB Warpage Analysis Framework is a realization of the conceptual architecture proposed in the previous section. We now elucidate the navigation map for this architecture, the detailed contents of the stepping stone models, and the associated transformations.

6.1 Creating the Manufacturable Product Model – a normalization and enrichment process

The first step in the PWAF navigation map is the normalization of information captured in disparate sources to a unified and rich AP210-based MPM. In a typical engineering environment (as in an electronics design enterprise), information about the PWA and the PWB is contained in the ECAD tools and other auxiliary data sources (e.g. component databases). However, the extent of ECAD information coverage concerning the PWB is usually insufficient for the evaluation of the warpage worthiness of the subject design. But, before we can fill these information gaps, this design information is normalized to create an AP210-based model using the *LKSoft Design Integrator* (commercially, also referred as an AP210 converter) [6, 7, 12]. The normalized AP210-based model is then imported into an AP210 standards-based *PWB Stackup Design Tool* [5, 8]. In this environment, information specific to the PWB stackup, such as layer thickness, material, layer constituents etc. can be captured and communicated. This provides a platform for the design engineer to add missing pieces of information concerning the PWB stackup details that are not supported by the traditional ECAD tools. Thereafter, an enriched AP210 based design model is generated from this environment. This enriched model is the *Manufacturable Product Model*.

Figure 3 shows a snapshot (with different examples) of the state of information captured in a typical ECAD tool in (a). It also shows a view of the board stackup information as viewed from the *PWB Stackup Design Tool* environment in (b). Snapshots (c) and (d) show the 2D and 3D views of an enriched and normalized AP210-based MPM.

6.2 Extracting an Analyzable Product Model from the MPM

For the purpose of thermo-mechanical warpage analysis of the subject design, we need a subset of the information pool captured in the MPM. The next navigation step in the PWAF is to generate an APM from the MPM. Figure 4 shows the specific design objects that are of key concern for warpage analysis. We are interested in certain key features on each stratum (layer) of the PWB stackup and the shape of the PWB itself (outline, mechanical tooling holes, etc.). These specific features on a stratum are the conductive traces and islands of metallization (example: lands around vias and plated through holes and constituting component footprints, etc.), mostly providing electrical connectivity between different points. The APM is comprised of these design objects and is generated from the MPM using a Java [9]-based tool communicating with the MPM using STEP standard JSDAI libraries [7].

6.3 Generating the Analysis Building Block from the APM and the CBAM

Navigating further on the PWAF architecture map, the next step is the generation of an Analysis Building Block (ABB) model. However, the context of the problem needs to be highlighted before we proceed. For the subject analysis, the thermal loading profile and the boundary conditions are provided for the problem. Also, the thickness of the PWB is very small compared to its length and breadth and we consider it to behave structurally as a layered shell. This defines the context of the given problem and is captured as a CBAM.

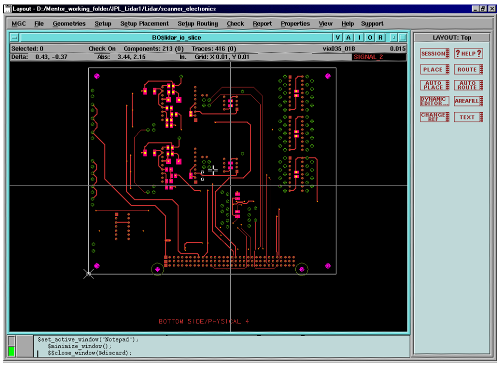
From the expertise of design engineers and analysts, for the given context, it is within the limits of reasonable significance to analyze the PWB as a grid of elements with effective material properties as opposed to dealing with the exact layout of metallization on each stratum. We intend to capture this expertise in our architecture. The ABB model specifically does this. The ABB model in the PWAF is a grid of elements with effective material properties, as computed from the APM. Figure 5 shows the nature of the ABB model as generated from the APM in the context represented by the CBAM. The effective material properties are computed using geometric algorithms developed by GIT which utilize Java 2D [9] and LKSoft's geometric processing libraries.

6.4 Deriving the Solution Method Model from the ABB model and its interpretation in a finite element solver

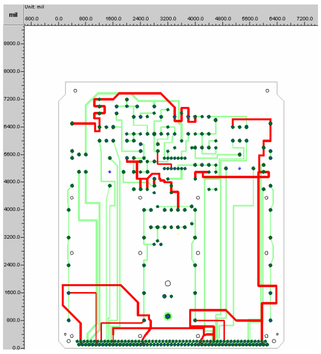
The last navigation step in the PWAF map is the creation and interpretation of a Solution Method Model. As highlighted while describing the conceptual architecture, there may be multiple methods used to solve a physics-based representation of the ABB model. The SMM captures the application of a particular method to the subject problem. In the scenario of PWAF, we use the finite element method to evaluate the warpage and associated thermal stresses in the PWB subjected to the given boundary conditions and thermal loading. In essence, the physics of the problem is captured in the ABB model and the SMM is a solution-specific wrapper to the same. Figure 6 shows an example lexical view of the finite element-based SMM, as generated from the ABB model. In this scenario, the SMM is described using APDL (ANSYS Parametric Design Language) [10].

Thereafter, the subject SMM is interpreted and solved using ANSYS [10]. Figure 7.a shows an example view of the meshed finite-element model of a

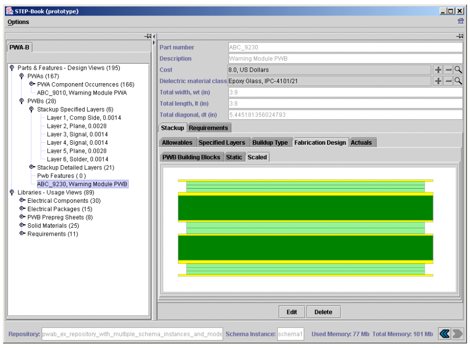
PWB with a single point constraint (locking all degrees of freedom) at bottom left. Figure 7.b shows the warpage profile (out of plane deflection) for the same PWB (with homogenous material properties) when subjected to a linear temperature increase from 25 deg. C to 150 deg. C. As evident, the deflection increases with the radial distance from left-lowermost corner, which is fixed.



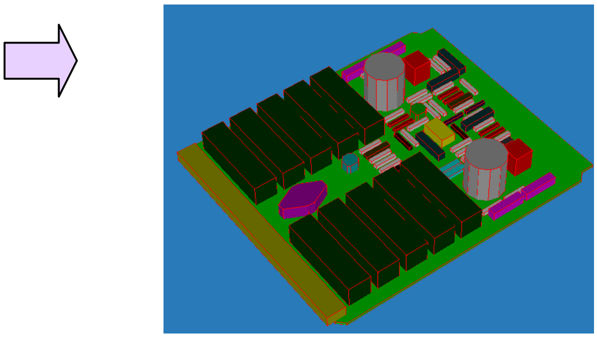
a. *Electronic product design in an ECAD tool*



c. 2D view of AP210-based MPM – shows PWB layer specific features (traces, metallization areas, etc.)

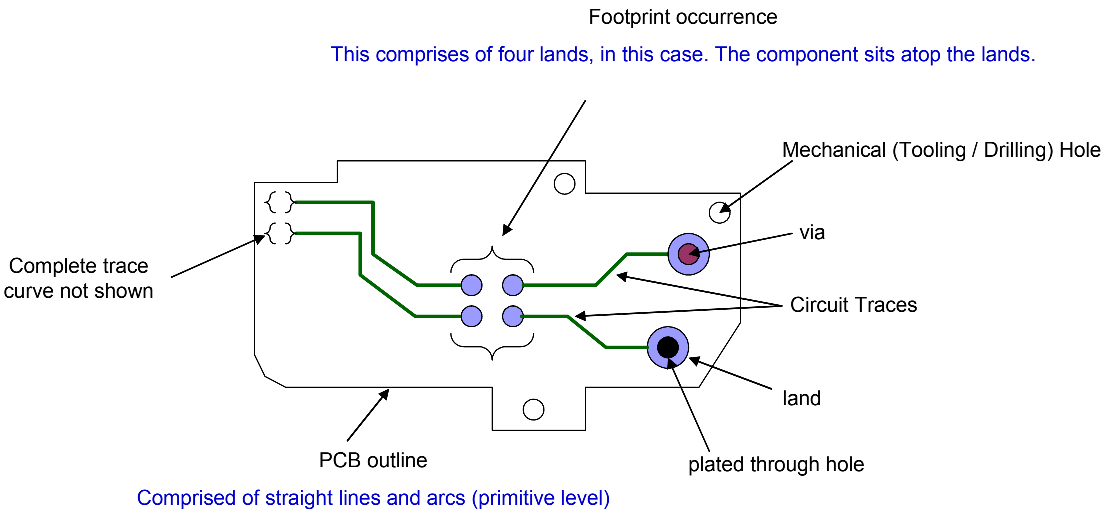


b. *Gap-filling tool for PWB stackup design*



d. *3D view of AP210-based MPM – shows assembly level information (components and their layout, etc.)*

Figure 3: Electronic product design information in traditional ECAD tools and gap-filling tools normalized into an AP210-based manufacturable product model (MPM)



This figure shows the top view of an unpopulated PWA ➔ bare PWB with metallization features. It captures the top two layers of the PWB. The top layer with the metallization (traces, lands, etc.) and the adjacent dielectric layer (area shown above within the PWB outline and not occupied by any metallization)

Figure 4: Key design objects (on a PWB stratum) represented by the APM

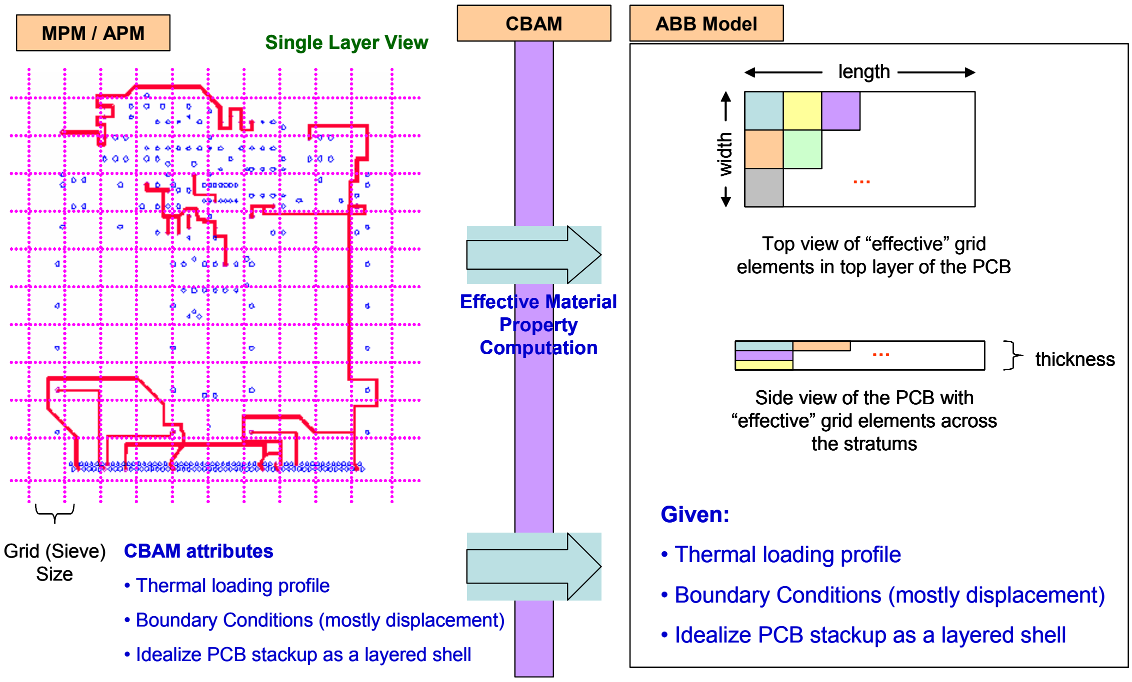


Figure 5: Key aspects of a warpage CBAM (product specific analysis template) and its associated ABB model (generic analysis model)

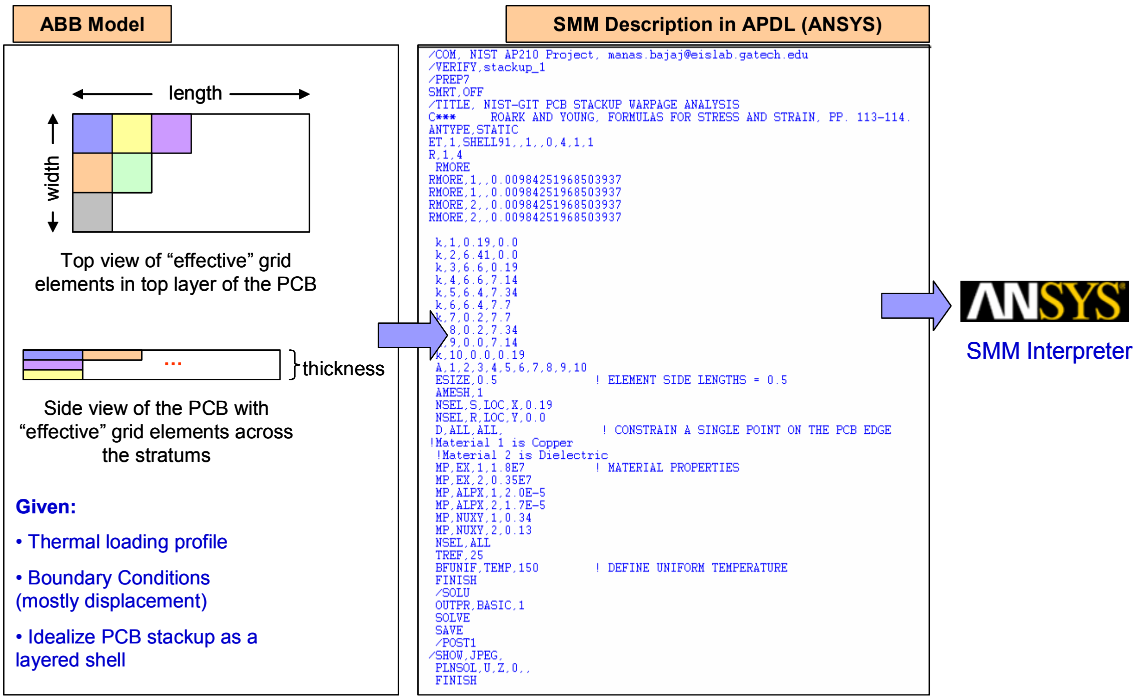
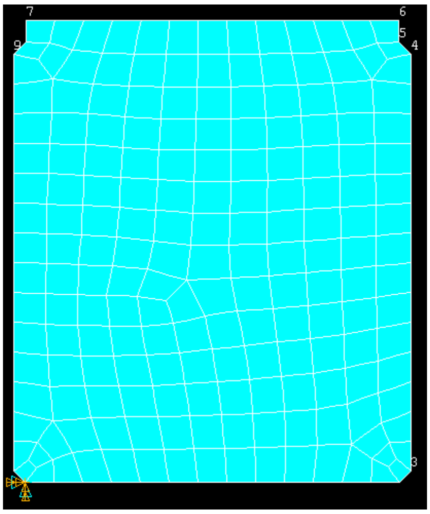
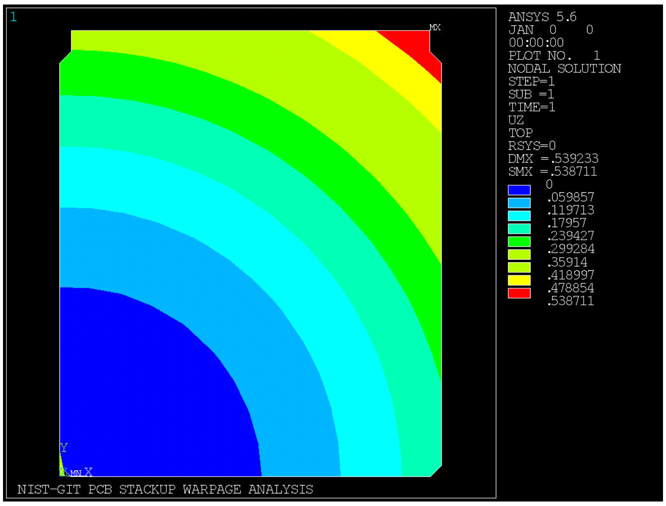


Figure 6: Lexical view of the SMM model generated from the ABB model



a. Meshed finite element model of an example PWB



b. Warpage profile results for the example PWB

Figure 7: PWB finite element model processed in ANSYS

7 Physical Measurement via Shadow Moiré Technology

7.1 Context

This section overviews an experimental technique to measure the warpage flatness of physical PWB samples. The next two sections then highlight test results. We anticipate future efforts will compare analysis results from the preceding sections with these test results.

7.2 Overview

Shadow moiré [14] is an optical method for measuring relative vertical displacement of (semi-) continuous opaque surfaces. It is a full-field technique, i.e. it acquires the optical data with a video camera across the entire sample simultaneously. Shadow moiré is based on the geometric interference of a shadow grating projected on the sample surface and a real grating on a flat reference surface. The principle optical elements are shown in Figure 9 - a white light source, a Ronchi-rule grating suspended above the sample, and a video camera interfaced to a microcomputer. The Ronchi-rule grating is a sheet of clear, low coefficient of thermal expansion (CTE) glass with a photo-lithographically patterned chrome thin film on the bottom surface. The pattern has parallel opaque and clear lines of equal width and constant pitch, P.

As shown in Figure 8, light passes through the reference grating at an oblique angle, *a*, typically around 45° in our designs, and casts a shadow of the grating on the sample.

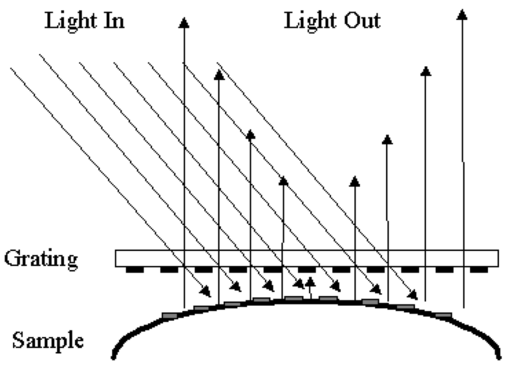


*Figure 8: **Principles of Shadow Moiré***

This shadow grating is observed back through the reference grating at a different angle, *b*, typically 0° (normal). The overlap of the shadow and real gratings is a periodic function of the distance between them. Each successive fringe represents a height change of the sample surface of W, the height per fringe. W can be calculated with the following equation:

$$W = \frac{P}{\tan a + \tan b}, \qquad \textit{Equation 1}$$

The relative height of any two points in the fringe image can be calculated by counting the number of fringes between them and multiplying by the height per fringe, W.

7.3 Phase Stepping Enhancements

Fringe counting analyses offer low vertical resolution and do not automatically order the fringes, making shadow moire analysis very slow, labor-intensive, and subject to error. In an improved procedure called phase stepping [14], three or more fringe images are obtained as part of each measurement. Between each successive image, the sample is translated uniformly away from the grating by a fixed distance or phase step. By fitting the multiple intensity values measured at each pixel to a sinusoidal function, the phase of the periodic variation, which is proportional to the height at that pixel, can be separated from brightness and contrast parameters that are dependent on the illumination and reflectivity of the sample.

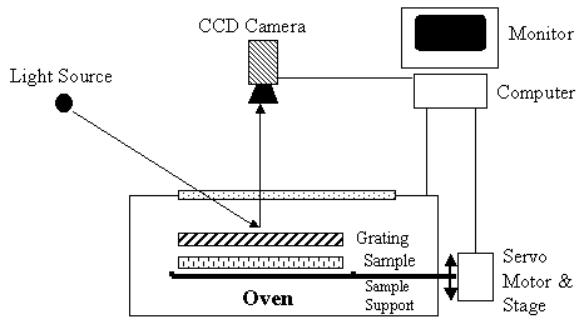


Figure 9: Elements of a Phase Stepping, Temperature-Dependent Shadow Moiré System

Phase stepping requires an important new feature to the system hardware. As shown in Figure 9, the sample support is now attached to a high resolution vertical stage, so that the sample may be translated up and down with respect to the fixed grating.

7.4 Displacement Determination Algorithms

Converting the phase data to displacement data requires an additional analytical step called “unwrapping”. Unwrapping converts phase data, which is discontinuous between fringes of different order, to a smooth continuous curve by adding or subtracting multiples of 2π to each successive fringe. This process is repeated for each pixel across the two-dimensional image and the “unwrapped” phase surface is multiplied by the height per fringe, W, to give the displacement data at each point.

Real PWBs are characterized by interruptions in the surface continuity, such as registration holes and pre-routes. Phase stepping also offers the ability to do quality mapping, a procedure to identify pixels on which the fringes are weak or non-existent

Because of the irregular array of masked pixels, the unwrapping process is carried out most efficiently with a region-filling algorithm, in which the path across the fringes is not predetermined. Instead, it is created during analysis by queuing qualified pixels around the already unwrapped region, which allows it to fill in around excluded regions. The data shown in the following section shows an extensive outline of pre-route segments around the board within the panel, which could nevertheless be analyzed with the software able automatically to recognize regions within the image that may cause problems in the analysis and exclude those data points from the analysis. The amplitude of the intensity variation at each pixel, i.e. the fringe contrast, can be compared to a threshold value and the pixel is masked from analysis in regions where contrast is below the threhsold.

8 Experimental Configuration

The system used for the experimental measurements is the AkroMetrix TherMoire PS88+. Two unpopulated PWB designs from Rockwell Collins [10] were measured in this project. Design 1 is a 180 x 137 x 1.2 mm thick multilayer circuit board. Its appearance and orientation are shown in Figure 10. Design 2 is 228 x 85 1.9 mm thick and is shown in Figure 11. Both samples were supported during the temperature cycle warpage measurements by metal rails under the top and bottom edges, as shown. Because of the high baseline warpage in both samples, all measurements were performed with a 50 line per inch grating, which provides a vertical displacement resolution of 5 micrometers with phase stepping. Lateral resolution was .37 mm for both designs.

The samples were cooled from room temperature to –50 C by flowing liquid nitrogen-cooled dry nitrogen within the system oven. Warpage measurements were made at 25 degree intervals as the sample was heated to 150 C. The system heat source is an infra-red radiant heater with direct heating of the bottom side of the sample. To minimize the temperature gradient between sample top and bottom created by the radiant heating, temperature points above 25 C were reached by heating the sample above the target temperature and allowing the sample to cool to the target temperature with the heater turned off. This procedure allowed temperature uniformity within 5 degrees C across the sample to be achieved.

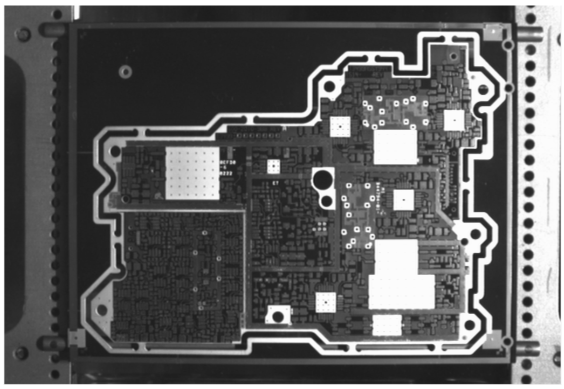


Figure 10: PWB Design 1

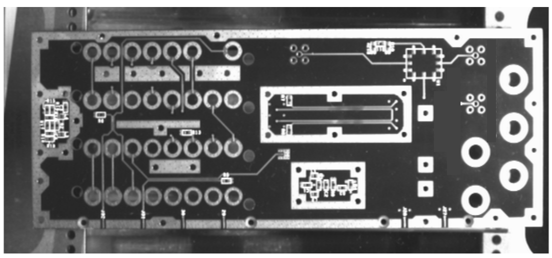


Figure 11: PWB Design 2

9 Experimental Results

Table 1 provides the absolute and relative coplanarity values for one unit of Design 1. Absolute coplanarity is the range from highest to lowest point of the surface contours, where the zero reference plane is chosen as the linear least squares fit to the displacement values. Table 2 shows the same data for Design 2.

Both samples showed a high level of initial warpage. Changes in warpage over the –50 to 150 C temperature range in this study were an order of magnitude smaller than the baseline warpage, so the experimental results presented in Figures 12-16 are all displayed as the change in warpage relative to the sample at 25 C. Relative coplanarity is the range of the difference values between the surface contours at two different temperatures.

Table 1: Measurements for Design 1

Temperature (Degrees C)	Absolute Coplanarity (micrometers)	Relative Coplanarity vs. 25 C (micrometers)
-50	6751	765
-25	6634	493
0	6581	272
25	6505	0
50	6447	175
75	6383	231
100	6309	320
125	6218	409
150	6099	544

Table 2: Measurements for Design 2

Temperature (Degrees C)	Absolute Coplanarity (micrometers)	Relative Coplanarity vs. 25 C (micrometers)
-50	3261	351
-25	3137	208
0	3086	130
25	2995	0
50	2860	140
75	2789	249
100	2675	371
125	2540	488
150	2357	650

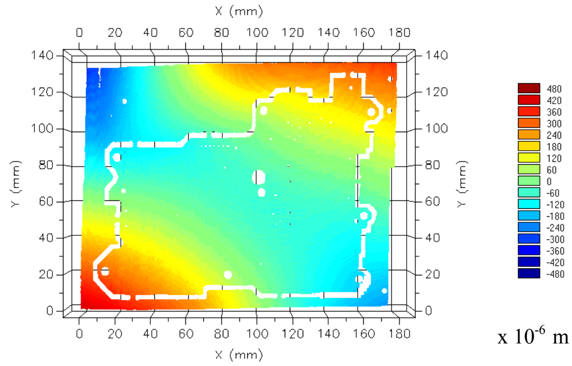


Figure 12: Design 1 warpage, -50 C relative to 25 C

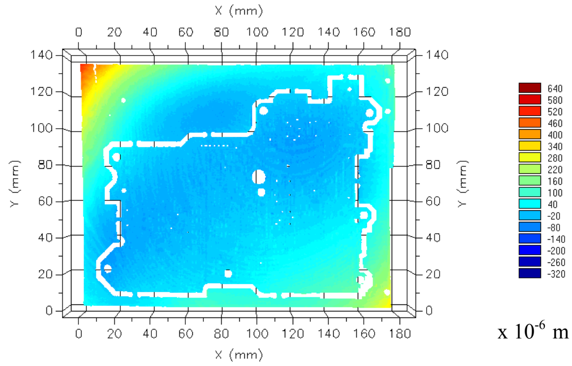


Figure 13: Design 1 warpage, 150 C relative to 25 C

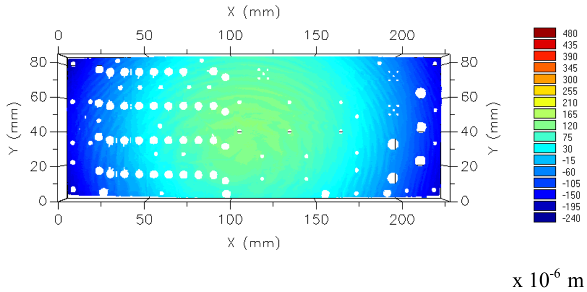


Figure 14: Design 2, -50 C relative to 25 C

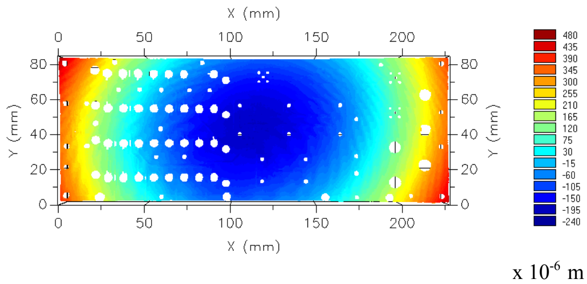


Figure 15: Design 2 warpage, 150 C relative to 25 C

Design 1 shows thermomechanical warpage commonly characterized as "twist", i.e. opposite edges are skewed rather than parallel, and both the sign and magnitude of the skewness changes with temperature. This effect may be related to the assymetry of the prominent pre-routed outline of the PWB within the panel. Twist has also been related to non-orthogonal glass fiber orientation within the FR-4 laminate [15].

Design 2 shows "bow" type warpage, where curvature exists along the edges, but with the four corners remaining substantially co-planar. The baseline warpage at room temperature is convex (domed), so the sub-room temperature measurements show increased warpage, while the higher temperature measurements show a slight flattening out of the PWB.

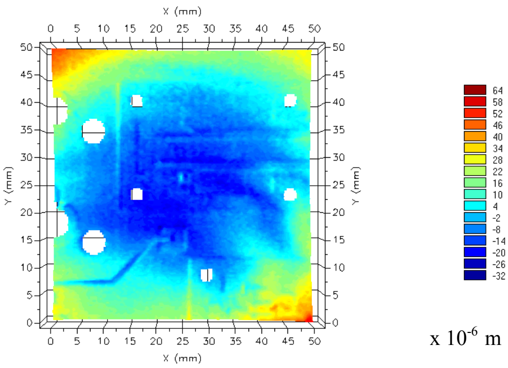


Figure 16: Design 2 local warpage, 150 C relative to 25 C, 50 x 50 mm region at center of PWB

Figure 16 illustrates the application of shadow moire to the measurement of local warpage. A subset of the relative data plotted in figure 15, spanning a region of the sample 50 x 50 mm centered on the PWB shows traces of the circuit pattern as well as several component mounting holes. The relative change in warpage from 25 C to 150 C shows both bow and twist behavior, with a relative change in coplanarity of 86 micrometers.

10 Summary

In this paper, we have pointed out the necessity for detailed simulation and experimental verfication for ascertaining local and global warpage of PWB designs.

Thereafter, we discuss the inability of traditional ECAD tools to capture stackup details in PWB designs (which are necessary for warpage simulation) and their lack of richer semantic representation. We also point out the ability of the AP210 standard for answering these needs for representing information in an intelligent manner. Further, we develop the idea of a conceptual model-based architecture for a PWB warpage analysis framework (PWAF) and elucidate it by navigating it for a specific warpage problem. During this navigation, we also highlight the nature of the subject information models and needs for using the multi-representation architecture e.g. increased modularity and idealization knowledge capture, and reduced vendor-specific dependence.

From the perspective of experimental warpage evaluation, we discuss the detailed experimental setup using the Shadow Moiré technique for full-field warpage measurements. We also discuss the results obtained for two unpopulated designs using this technique.

This paper presents the PWAF methodology and initial results from the first phase of a project sponsored by NIST [13]. The corelation of results obtained from simulations and experiments is one of the goals for the next phases of this project. These evaluation and verification phases will likely involve experimenting with various fidelities of idealizations (i.e., CBAM-based APM-ABB associativities). For example, to achieve increased simulation accuracy, we may need to include factors like specific prepeg sheet structure and orientation and temperature-dependent material properties.

Results to date indicate the described approach is promising and has potential to help designers reduce PWB warpage via highly automated analysis.

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12 Disclaimer

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