Use of Lead-Free Laminate DMA and TMA Data to Develop Stress versus Temperature Relationships for Predicting Plated Hole Reliability

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Abstract
Accelerated testing of plated hole life is necessary for economic reasons due to the long time to failure during field operating conditions. One difficulty in performing accelerated testing on plated holes is to decide which acceleration model to use. In the work presented here, we will assume an inverse power law relation of cycles to failure versus stress. Stress versus temperature curves will be derived from TMA and DMA data from over twenty lead-free laminates, before and after reflow thermal stress. We will then compare stress versus cycle to failure data for both the lead-free laminates and the two thermal stress conditions, ATC and IST. Completion of this work will enable prediction of plated hole cycles to failure based upon laminate material properties and help to better understand the key role that laminate materials play in plated hole reliability. Also, the two stress conditions will be compared with respect to field life predictions

Keywords
Cycle to Failure (CTF), ATC, IST, DMA, TMA, T_g, Inverse Power Law (IPL), Stress, Laminates…

Introduction
This paper uses a previously developed method[1] to mathematically combine strain data obtained from thermal mechanical analysis (TMA) and storage modulus data obtained from dynamic mechanical analysis (DMA) to construct a stress versus temperature plot. The stress data obtained using this method then allows us to compare stress versus cycle to failure (CTF) data for 27 combinations of laminate materials and stack-ups tested in this High Density Packaging User Group (HDPUG) Lead-Free 2 project.

The industry wide transition to lead-free solder and the subsequent increase in melt temperature from 183°C for eutectic tin-lead solder to 217°C for SAC 305 alloy has a significant impact on plated hole reliability. Laminate material suppliers have developed many new laminate materials intended to meet these new requirements creating a demand to test these new laminate materials. The MRT-5 test board[2] used in this project is a 5th generation design. One of the enhancements the MRT test board going from the 4th to the 5th generation was the addition of an area without copper. This area of pure laminate material, free of copper was used to obtain samples to test the DMA and TMA properties of the laminate materials.

We used two versions of the MRT-5 test board, a 20-layer construction, a 58% resin construction that is 2.95 +/- 0.30mm thick and a 69% resin construction that is 3.00 +/- 0.30mm thick. The laminate materials used in the Lead-Free 2 project included: FR4, eight laminates with ten stack-ups; Halogen-Free FR4, six laminates with eight stack-ups; and High Speed Materials, six laminates with nine stack-ups. The final total is 20 laminate materials and 27 stack-ups.

It is hoped that the rather easy to obtain thermal mechanical properties DMA and TMA would serve as accurate predictors of a laminate materials plated hole thermal cycle reliability. This question will be investigated in this paper.

Storage Modulus and Strain Plots
After completion of printed board fabrication, 27 each “As Received” board samples without assembly preconditioning were sent for TMA testing and DMA testing. A duplicate set of 27 each “6x SMT Reflow at 260°C” board samples were sent out for assembly preconditioning using a standard multi-zone SMT reflow oven before being sent for TMA testing and DMA testing.

TMA testing used a single temperature sweep from ambient to 260°C (actually 36°C to 258°C) and DMA testing used a single sweep from ambient to 260°C (actually 28°C to 258°C). Both test suppliers used TA Instruments equipment and the DMA testing utilized a cantilever beam test set-up. The data obtained from the TA Instruments equipment is in a binary format that is then converted into an ASCII text format. The DMA data and the TMA data is then read by a Matlab program that was specifically written for this project. The raw DMA and TMA data does not extend all the way to the desired minimum temperature of 25°C or the desired maximum temperature of 260°C so step one is to extrapolate to 25°C and 260°C. Since the test specimens for TMA can have residual internal stresses imparted into them during the process to remove them from the printed board sample, we included an algorithm that ignores the initial erratic data points caused by the residual stress. Next, since the raw DMA and TMA data does not have consistent temperature intervals, the Matlab program uses the raw data to interpolate data points on 1°C intervals for both DMA and TMA. Figure 1 shows one of the 54 plots for this project and includes DMA storage modulus data overlaid with TMA strain data.

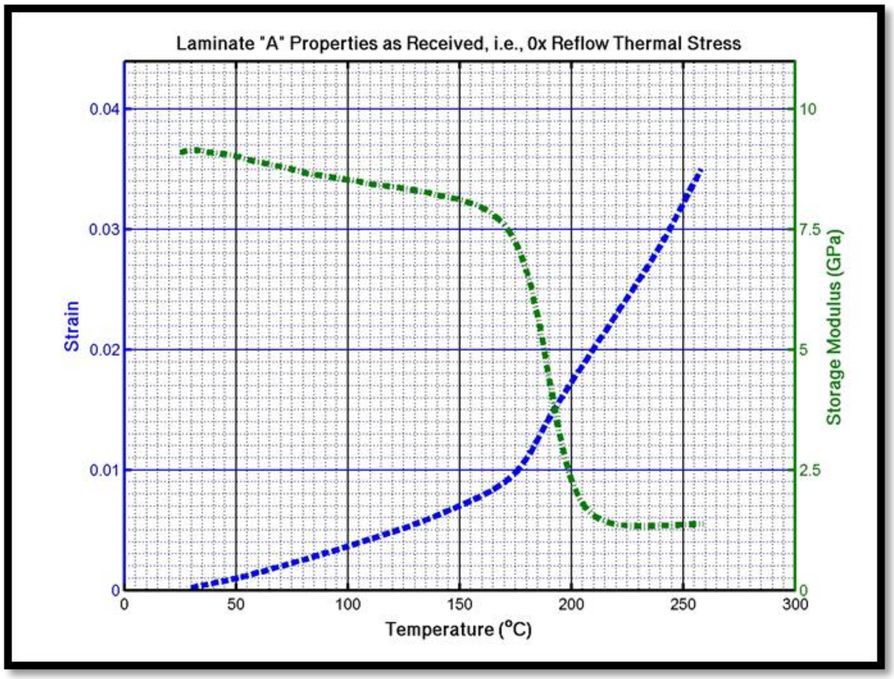

Figure 1 – Typical laminate material properties with a sharp drop in the Storage Modulus after Tg and an increase in the Strain after Tg.

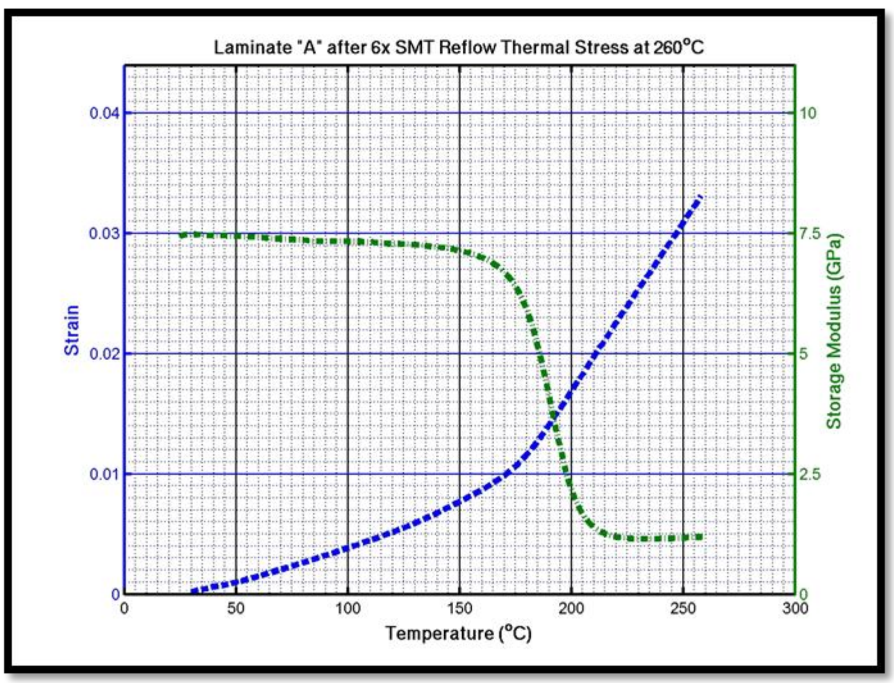

Figure 2 – The same laminate as shown in Figure 1 after 6x SMT thermal stress.

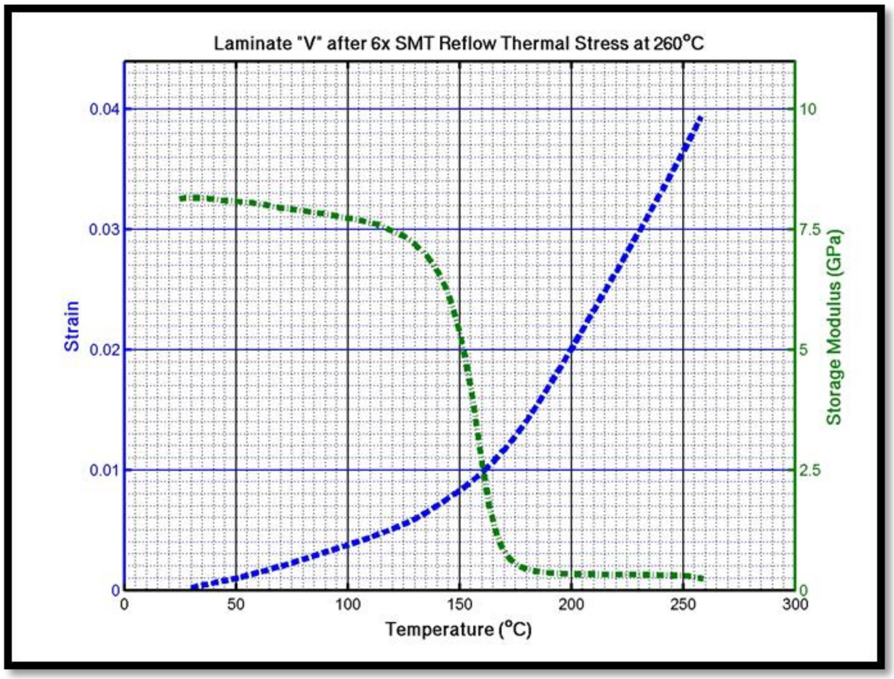

Figure 3 – The typical drop in storage modulus is seen after laminate Tg, but in this case the Storage Modulus above 180°C is unusually low.

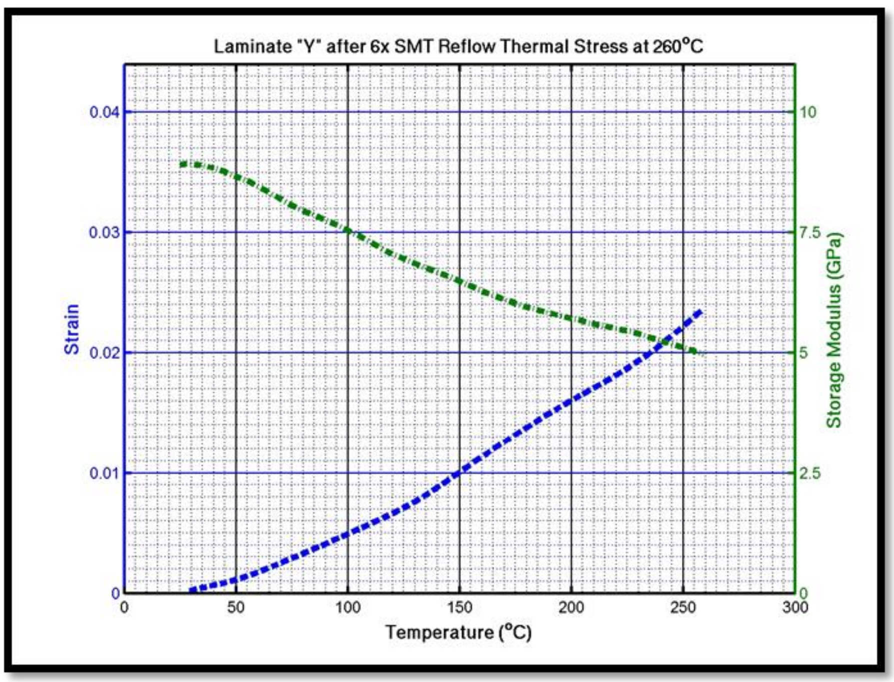

Figure 4 – The mechanical properties of this laminate material are very atypical with an almost linear DMA and TMA plot across the temperature range tested. What is the Tg of this laminate material?

In total there are 54 storage modulus and strain versus temperature plots that were generated. Figures 1 through 4 exhibit a good cross section of those 54 plots. Figures 1 and 2 demonstrate the most common characteristics of the storage modulus and strain versus temperature plots. The storage modulus drops significantly above Tg, typically a 5x or greater drop. Similarly, the strain plot is typical with an increase in the slope of 2-3x above Tg. It should be noted that strain is a dimensionless number and multiplying the value on the plots times 100 results in the expansion percentage that is commonly reported on laminate material data sheets. In the first two plots there was a drop in the storage modulus between "As Received" in Figure 1 and "After 6x SMT Reflow" in Figure 2.

While Figure 3 follows the most common trends for both storage modulus and strain, the drop off in storage modulus is extremely high with a 25x drop. The result, shown later in this paper in Figure 6 is an uncharacteristic drop in the rate of increase in strain above the Tg. The final storage modulus and strain versus temperature plot, Figure 4, shows a fairly linear response for both storage modulus and strain that is distinctive. This plot really makes you wonder what resin system was used in this laminate material.

It is not practical to include all 54 storage modulus and strain versus temperature plots in this paper. Appendix A "As Received" and Appendix B "After 6x SMT Reflow" each have a table with storage modulus, strain, and stress values at important temperatures for all 27 laminate materials and stack-up combinations. The two tables also highlight in **RED** outliers of interest.

Temperature versus Stress Plots

Once the DMA and TMA data is available on 1°C intervals from 25°C to 260°C, the Matlab program calculates the incremental strain for each 1°C interval…

Incremental Strain at T_1 = (Dimension Change from T_1 to T_2) / Thickness at T_1

…and from this we can calculate the incremental stress…

Incremental Stress at T_1 = Incremental Strain at T_1 * Storage Modulus at T_1

Once the incremental stress has been obtained for each 1°C interval, it is straightforward to sum, i.e., integrate the incremental stress at each temperature resulting in the cumulative stress versus temperature plot shown in Figure 5. As a quality control measure, the Matlab analysis programming code was developed in parallel with an Excel spreadsheet approach. By doing this extra step, we were able to validate the Matlab program code.

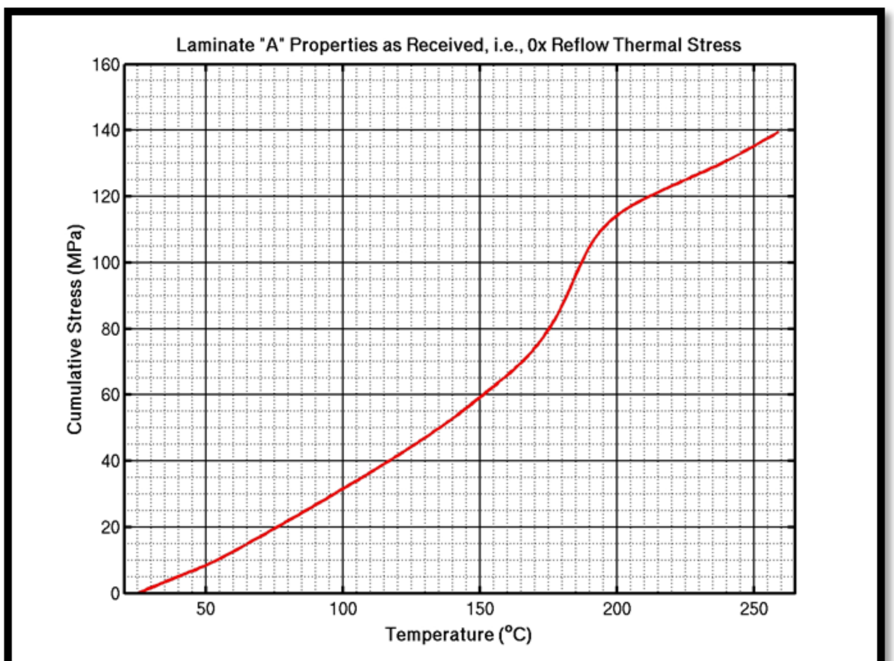

Figure 5 – Stress plot resulting from the laminate material properties shown in Figure 1.

Figure 5 is a good example of what most of the laminate materials cumulative stress versus temperature plots look like, i.e., a flat linear increase in stress up to the laminate material Tg, a discontinuity through the Tg transition, then a return to a flat linear increase in stress above Tg. In most cases the slope after Tg is lower than below Tg. Basically, the magnitude of the drop in storage modulus after Tg is more than the increase in the strain. Figure 6 shows this same trend, but the decrease in the slope of the stress above Tg is unusual compared to the typical laminate materials due to the extremely large drop in the storage modulus.

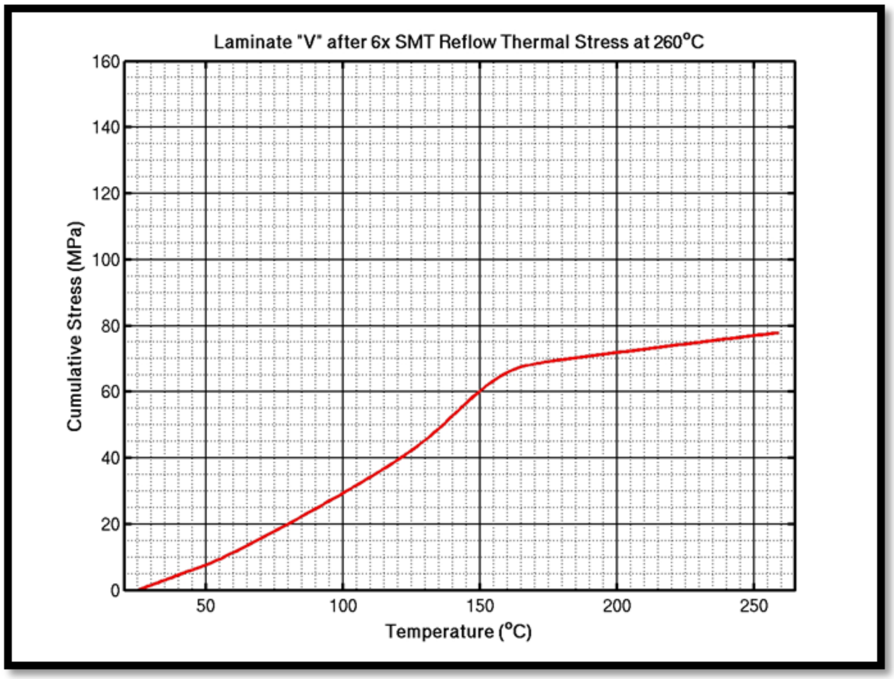

Figure 6 - Stress plot resulting from the laminate material properties shown in Figure 4.
The very low Storage Modulus above 180°C also results in low stress above 180°C.

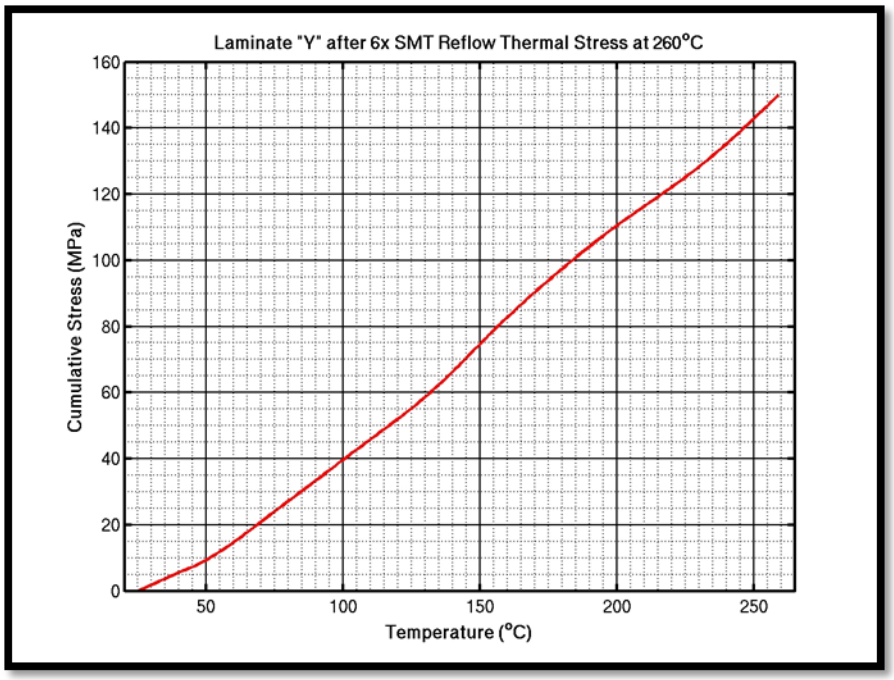

Figure 7 - Stress plot resulting from the laminate material properties shown in Figure 6.

Finally, there is Figure 7 that is very atypical compared to the other laminate materials. The stress versus temperature is linear through the ambient to 260°C temperature range. This laminate is certainly unusual resulting a number of RED entries for outliers on the tables in Appendix A and B. In particular, the stress at 135°C is high compared to the other laminates.

Stress versus Cycle to Failure

Developing the stress versus temperature relationship for a laminate material is a next important step. Since copper is a ductile metal, it is known to follow an Inverse Power Law (IPL). For any repeated stress that exceeds the elastic region, the cycles to failure (CTF) will follow a log-log relationship versus the stress. As a practical matter, the copper plated hole connections does not care how that stress is applied. If we could easily remove the plated hole and cycle it on an easy to calibrate machine it would be easy to option the cycles to failure versus stress relationship. Since we cannot do that, this explains the need for our first step, to develop the stress versus temperature curves to "calibrate" the stress we apply.

Over the range of temperatures used in electronic assembly and in the field use of assembled electronic systems, copper sees insignificant changes in its mechanical properties. With a melting point of 1085C, copper exhibits minor property changes in the temperature range of ambient to 260°C. In comparison, the Tg transition seen in most laminates materials results in significant changes in mechanical properties that effect the suitability of use of any particular laminate and these changes in properties must be accounted for in accelerated testing. The reason to focus on the laminate material properties is that it is the expansion of the laminate material is what causes the stress on the copper plated hole that ultimately results in damage accumulation and fatigue failure of this interconnects.

As these three stress versus temperature plots show, there is significant difference from one laminate material to another. There have also been a number of studies and papers written over the years comparing the results from some of the commonly used accelerated life test methods in use. In the HDPUG Lead-Free 2 project we used two of these accelerated test methods, air-air thermal cycle test (ACT) using the test conditions of -40°C to 135°C and interconnect stress test (IST) using the test conditions of ambient to 150°C. One implicit assumption in our work is that any cold cycle temperature excursion below ambient results in a compressive stress on the plated hole that does not result in fatigue damage and therefore does not contribute to the cycles to failure. We will reevaluate that assumption later in the paper.

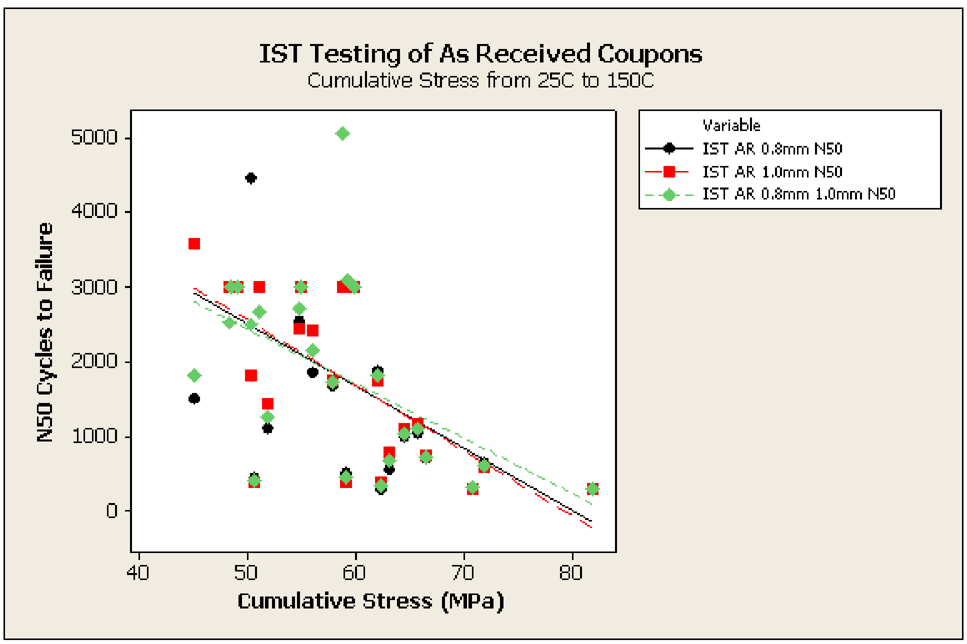

Figure 8 – IST N50 cycle to failure plot versus stress at 150°C of as received IST coupons. The close match of 0.8mm pitch failures to 1.0mm failures is a surprise.

Figure 8 is the first of two plots of the "As Received" IST coupon cycles to failure data versus the "As Received" laminate material stress data. It is good to see that the three different IST test coupon designs result in a close match in their respective best-fit regression lines. Nonetheless there is still a fair amount of scatter in the data and the adjusted R^2 that measure the correlation ranges from 0.235 to 0.428, which is relatively low. Figure 9 is the same data as Figure 8 plotted using an inverse power law, log-log plot. While there is still a fair amount of scatter in the data, the adjusted R^2 has improved somewhat on average and ranges from 0.313 to 0.384. So, what does this tell us? The fact that the best-fit regression line is a close match for all three IST coupon designs shows consistency. The moderately low values for R^2 indicate that there are other factors in addition to the stress caused by the laminate material expansion that also effect the cycles to failure. For reference, Table 1 has a complete listing of the adjusted R^2 values for all the cycle to failure versus stress plots including some plots that are not shown in this paper.

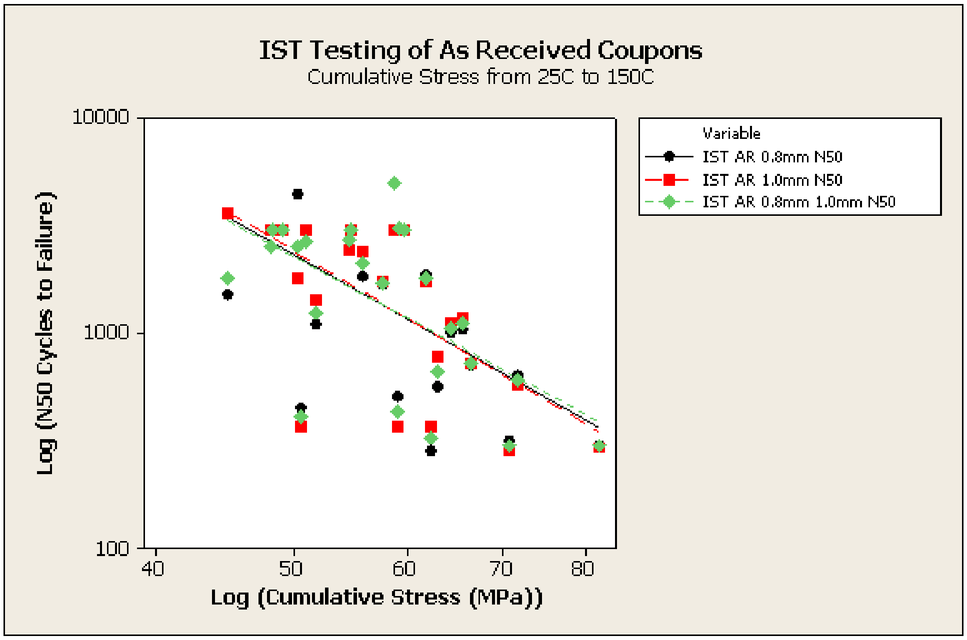

Figure 9 – Inverse power law, i.e., a log-log plot of IST N50 cycle to failure data versus stress at 150°C. While the correlation coefficient is similar to Figure 8, a log-log relationship is the proper analysis method for a ductile metal.

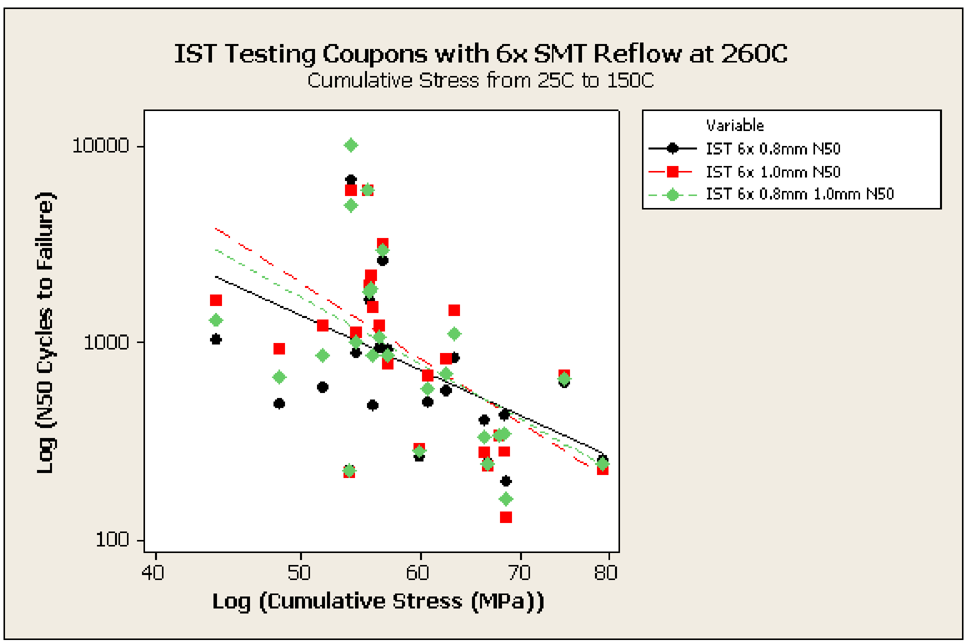

Figure 10 – Inverse power law log-log plot of IST N50 cycle to failure data versus stress at 150°C of IST coupons that have received 6x SMT thermal stress at 260°C.

Figure 10 plots the "6x SMT Reflow" IST coupon cycle to failure data versus the "6x SMT Reflow" laminate material stress data using an inverse power law, log-log plot. There is a decrease in the adjusted R^2 fit coefficients to the range of 0.185 to 0.330. Nonetheless, the best-fit regression lines once again show consistency. The drop in adjusted R^2 values is not unexpected since the 260°C peak reflow temperature used for the 6x SMT reflow in extremely demanding on laminate materials. During the HDPUG Lead-Free project cross section analysis that was performed did reveal a number of defects after 6x SMT reflow including eyebrow cracks, hole wall separation, damage in Zone A, and delamination in the majority of the laminate materials.

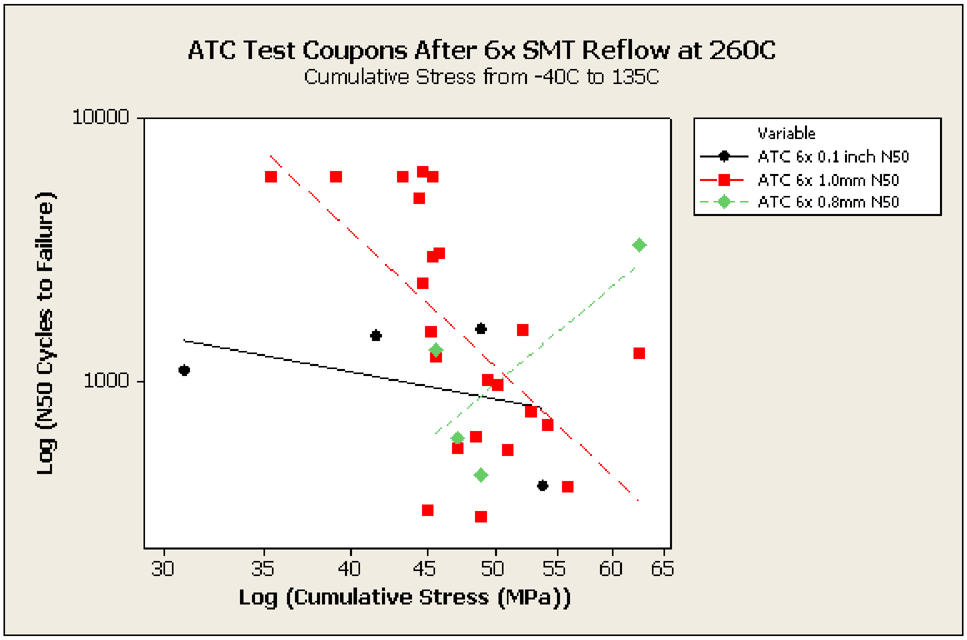

Figure 11 - Inverse power law log-log plot of ATC N50 cycle to failure data versus stress at 135°C of ATC coupons that have received 6x SMT thermal stress at 260°C. The erratic behavior of 0.10-inch pitch and 0.8mm pitch plots is due to the small sample size of four ATC coupons.

All of the previous cycle to failure versus stress plots used data from IST coupons. Figure 11 uses ATC coupons and shows very erratic behavior, which is due to the small sample size. Both the 0.100-inch pitch ATC coupons and the 0.8mm pitch ATC coupons have only four samples. The cycle to failure versus stress plot for the 1.0mm pitch ATC coupons has a sufficient sample size of 23 and exhibits a best-fit consistent with the IST coupons cycle to failure versus stress plots. The remainder of the cycle to failure versus stress plots use 1.0mm pitch IST and ATC data.

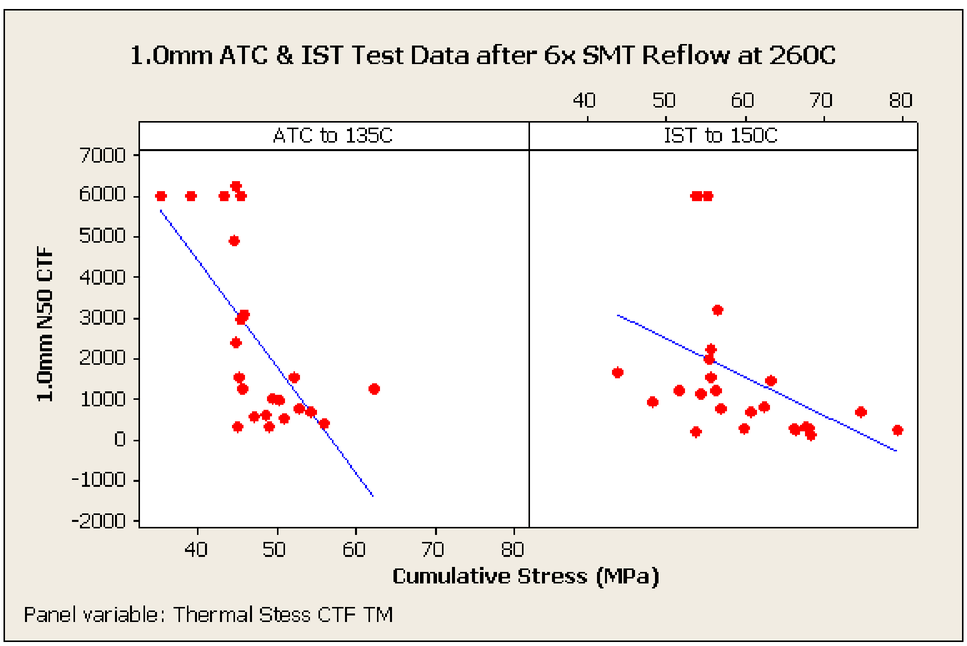

Figure 12 – Comparison of ATC to IST using N50 CTF data versus stress data is interesting since the range of different stresses due to different strain and storage moduli is further widened by the difference in peak temperature used by the two test methods.

Figure 12 does not use an inverse power law, log-log plot. By plotting this way it is easy to see the difference in slopes due to the lower stress applied to the ATC coupons from ambient to 135°C compared to the higher stress applied to the IST coupons from ambient to 150°C. For the ATC coupons we are only using the tensile stress imposed on the plated hole from ambient to 135°C and ignoring the compressive stress from -40°C to ambient. Figure 13 uses the appropriate inverse power law, log-log plot and the close match of the slope of the ATC plot on the left to the IST plot on the right confirms that the compressive stress below ambient on the ATC coupons can be ignored. Both Figure 12 and 13 use the same scale on the left and right graphs to aid in their comparison. Figure 14 combines the 1.0mm pitch cycle to failure versus stress data for ATC and IST on to one plot. The excellent overlap of these two different thermal cycle temperature ranges validates the use of stress versus temperature data to normalize and combine data from the two test protocols.

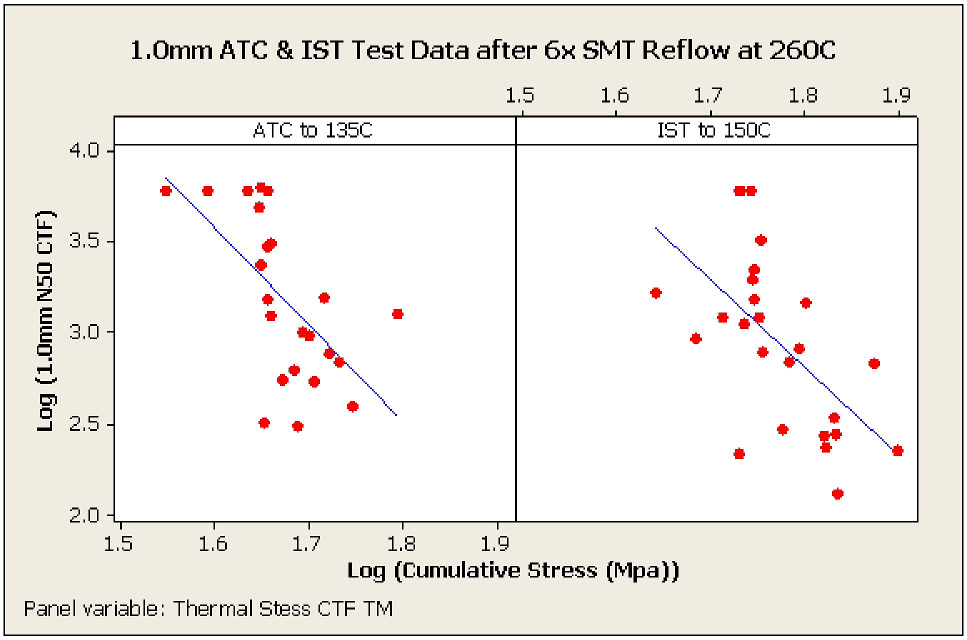

Figure 13 – The same data as Figure 12 using an Inverse Power Law Log-Log plot. As expected, the IST data is shifted to a higher stress than the ATC due to the higher test temperature of IST. Slopes are comparable indicating a good fit between to two test methods.

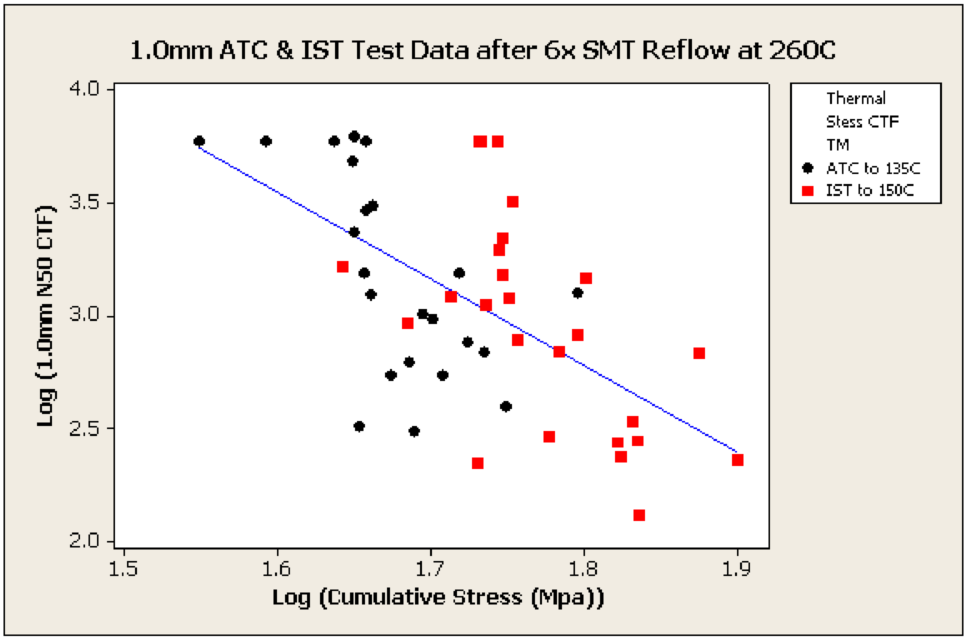

Figure 14 – The same data as Figures 12 and 13 using an Inverse Power Law Log-Log plot. As expected, the IST data is shifted to a higher stress than the ATC due to the higher test temperature of IST. Slopes are comparable indicating a good fit between to two test methods.

Table 1 – Correlation coefficients for the Stress versus Cycle to Failure Plots

Stress Condition	Coupon Design	N	Adjusted R^2 for Stress vs CTF	Adjusted R^2 for Log Stress vs Log CTF
IST coupons "As Received" followed by cycle to failure from ambient to 150°C	0.8mm pitch	25	0.330	0.348
	1.0 mm pitch	25	0.428	0.384
	0.8 & 1.0mm pitch	25	0.235	0.313
	Reference Plot		Figure 8	Figure 9
IST coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from ambient to 150°C	0.8mm pitch	25	0.074	0.185
	1.0mm pitch	25	0.144	0.330
	0.8 & 1.0mm pitch	25	0.078	0.258
	Reference Plot			Figure 10
ATC coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from -40°C to 135°C	0.100 inch pitch	4	Insufficient data	Insufficient data
	1.0mm pitch	23	0.406	0.321
	0.8mm pitch	4	Insufficient data	Insufficient data
	Reference Plot			Figure 11
ATC and IST coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from -40°C to 135°C for ATC and ambient to 150°C for IST	1.0mm pitch	48	0.243	0.340
	Reference Plot		Figure 12	Figures 13 & 14

Accessing the stress versus temperature database for the 27 laminate material and stack-up combinations, the stresses range from 16 to 40 MPa at a 90°C maximum field use temperature depending upon the laminate material used. Using Figure 14 and performing a visual extrapolation back to stresses in the 16 to 40 MPa range yields N50 values in the 1,000 to 10,000 cycles to failure range. Assuming one power on off cycle per day this equates to a 3 to 30 year field life. More accurate predictions of life in the field are beyond the scope of this paper. To perform more accurate field life prediction one would need to use a test board with a similar thickness to the actual product, use laminates material with a spread in properties, use the actual cycle to failure data, not the N50 to understand variation, etc. Nonetheless, it looks feasible to dramatically speed up this type testing by selecting a small number of laminate materials, a higher peak temperature like that used in IST testing, and varying the preconditioning levels to better understand to impact of assembly thermal stress on plated hole life. In all cases, an understanding of the stress versus temperature relationship which is relatively easy to obtain can greatly drop the testing that is needed to intelligently make field life predictions. In essence, it is feasible to extrapolate results from tested laminate materials to those, which were not tested using the stress versus temperature plots.

Conclusions and Summary

The authors have expanded upon a previously developed method[1] through access to the large number of laminate materials and stack-up combinations available from the HDPUG Lead-Free 2 project to better understand the stress versus temperature relationships of these combinations. These stress versus temperature plots also provide valuable insight into the respective laminate materials. We have also used that stress versus temperature data to successfully combine cycle to failure data from ATC and IST test methods, which use different temperature ranges. This not only allows the combination of data obtained from these different test methods, but also shows that these different test methods are inherently consistent with each other when properly normalized by using the stress versus temperature relationship.

Future Work

There is still work to be done using the full set of cycle to failure data, not just the N50 summary data to better understand the low adjusted R^2 correlation coefficients. Additionally, due to time constraints we have not investigated other factors that could have reduced the adjusted R^2 from plating conditions to fabrication supplier.

Acknowledgements

HDPUG, for their support of the Lead-Free 2 laminate material testing program.
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James Frei and Jing Shi, Oracle America, writing the Matlab code to calculate the stress versus temperature plots.
Paul Reid, PWB Interconnect Solutions, Inc. obtaining the DMA data.
Kim Morton and Viasystems Guangzhou, obtaining the TMA data.
Leoncio Lopez, Oracle America, consulting on the DMA/TMA method to construct the stress versus temperature plots.

Acronyms Used in this Paper

ATC – Air-Air Thermal Cycling
DMA – Dynamic Mechanical Analysis
HDPUG – High Density Package User Group
IPL – Inverse Power Law
IST – Interconnect Stress Test
Tg – T-sub-g, the laminate phase change from glassy to plastic state
TMA – Thermal Mechanical Analysis

References:

[1] D. Barker, M. Freda, "Predicting Plated Through Hole Life at Assembly and in the Field from Thermal Stress Data," Proceedings of IPC Printed Circuits Expo/APEX, Anaheim, CA, February-2006, S36-01-1.

[2] Joe Smetana, Bill Birch, Wayne Rothschild, "A Standard Multilayer Printed Wiring Board for Material Reliability Evaluation," Proceedings of IPC Printed Circuits Expo/APEX, Las Vegas, NV, April-2011.

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- Introduction
- Storage Modulus and Strain Plots
- Converting DMA + TMA Data into Stress versus Temperature Plots
- Plated Hole Stress versus Cycles to Failure
- Conclusions and Summary
- Future Work

Introduction

- HDPUG Lead-Free 2
  - Board design
    - 20 layer, 254 x 178mm (10.0 x 7.0 inch)
      - Option 1, 58% resin, 2.95mm thick (0.116 inch), 20 of 27
      - Option 2, 69% resin, 3.00mm thick (0.118 inch), 7 of 27
  - Laminates tested
    - FR4, eight stack-ups with 58% resin, two stack-ups with 69% resin
    - Halogen-Free FR4, six stack-ups with 58% resin, two stack-ups with 69% resin
    - High Speed, six stack-ups with 58% resin, three stack-ups with 69% resin
  - LF2 testing
    - 6x SMT at 260° C followed by extensive cross section analysis
    - Testing on as received and 6x SMT reflow boards/coupons
      - ATC, -40° C to 135° C, cycle to failure
      - IST, ambient to 150° C, cycle to failure
        - » Plated hole reliability
        - » Material damage, delamination
      - S-parameter testing
      - CAF

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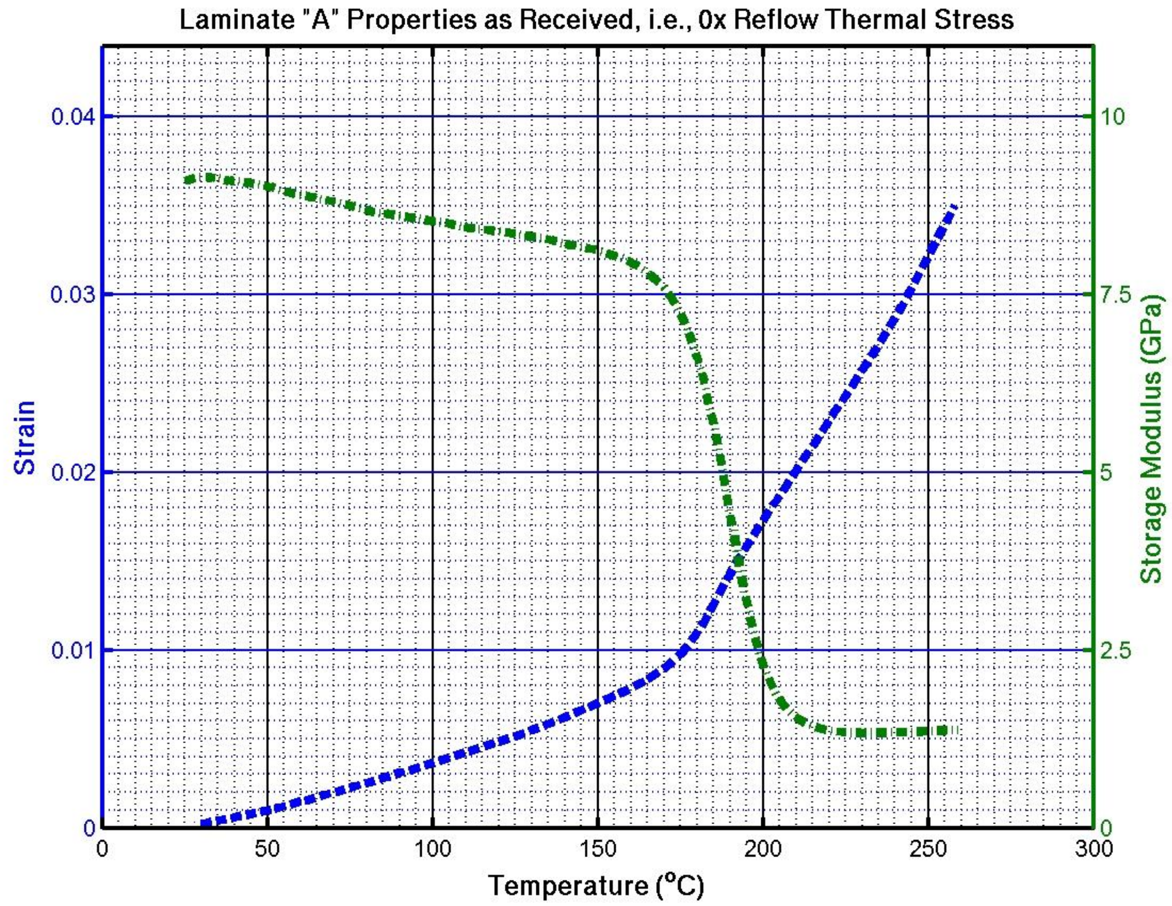
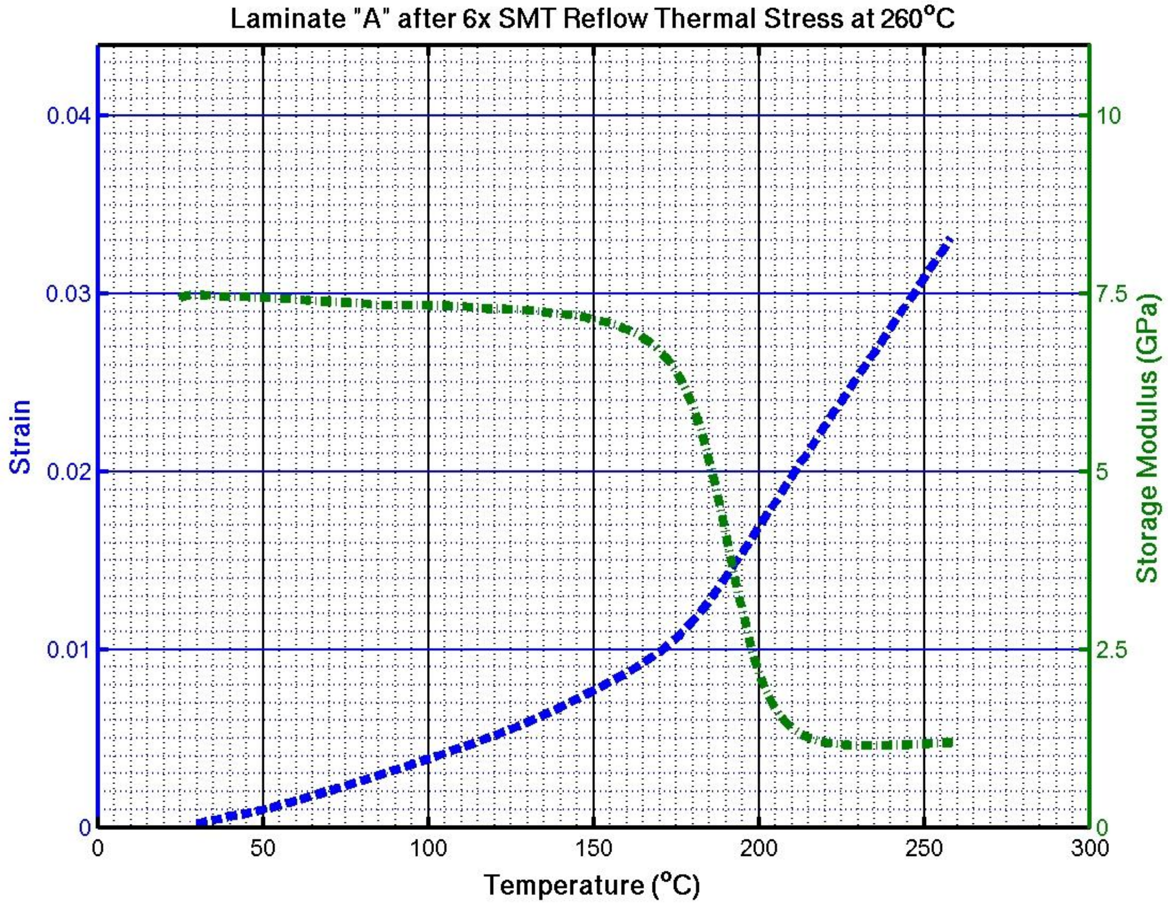
Storage Modulus and Strain Plots

- DMA raw data from 28° C to 258° C on ~0.1° C increments
- TMA raw data from 36° C to 258° C on ~1° C increments
- For both DMA and TMA…
  - Extrapolate to 25° C to 260° C
  - Interpolate to 1° C increments
- Additional step for TMA
  - Ignore some of the early raw data points that might have residual stress from the test sample extraction process
- Four examples plots from the 54 generated follow
  - Strain versus temperature and storage modulus versus temperature overlaid on the same graph

Storage Modulus and Strain Plots



Storage Modulus and Strain Plots



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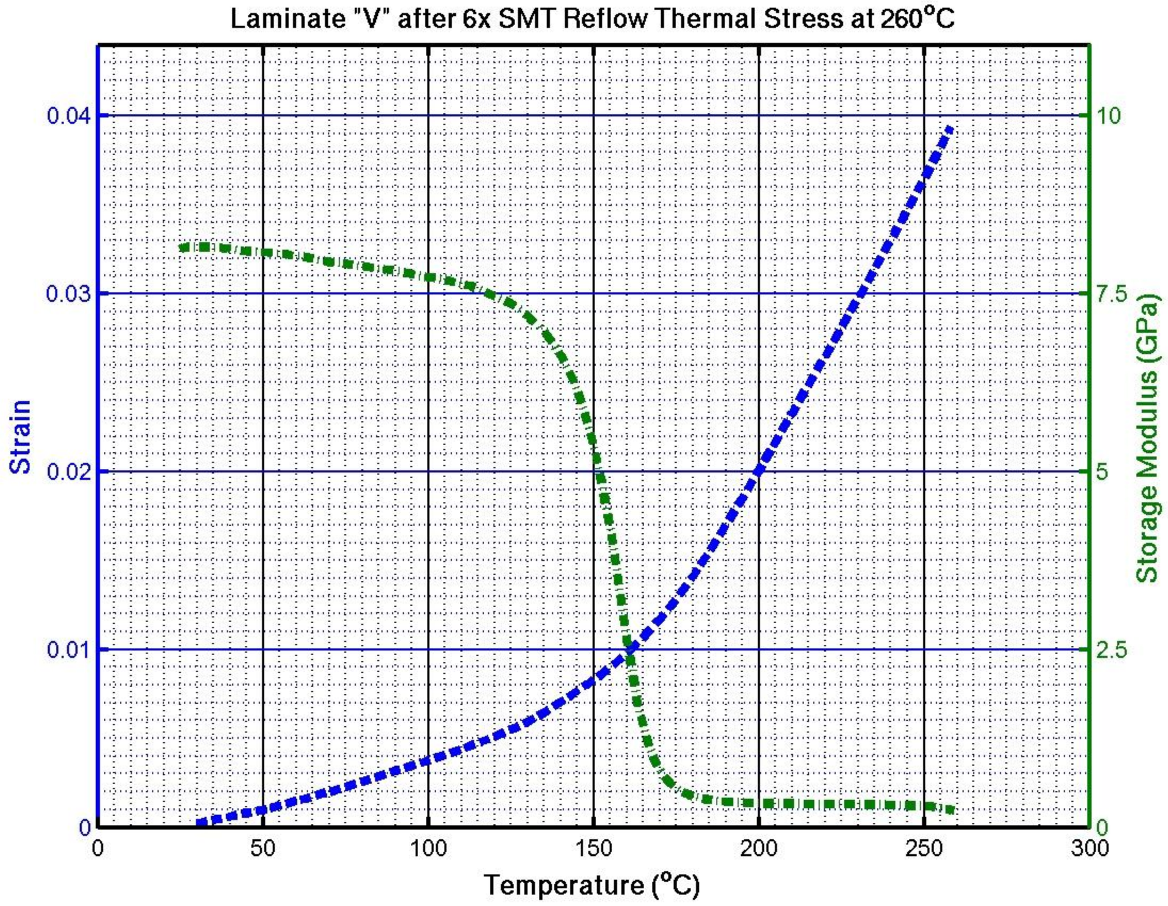
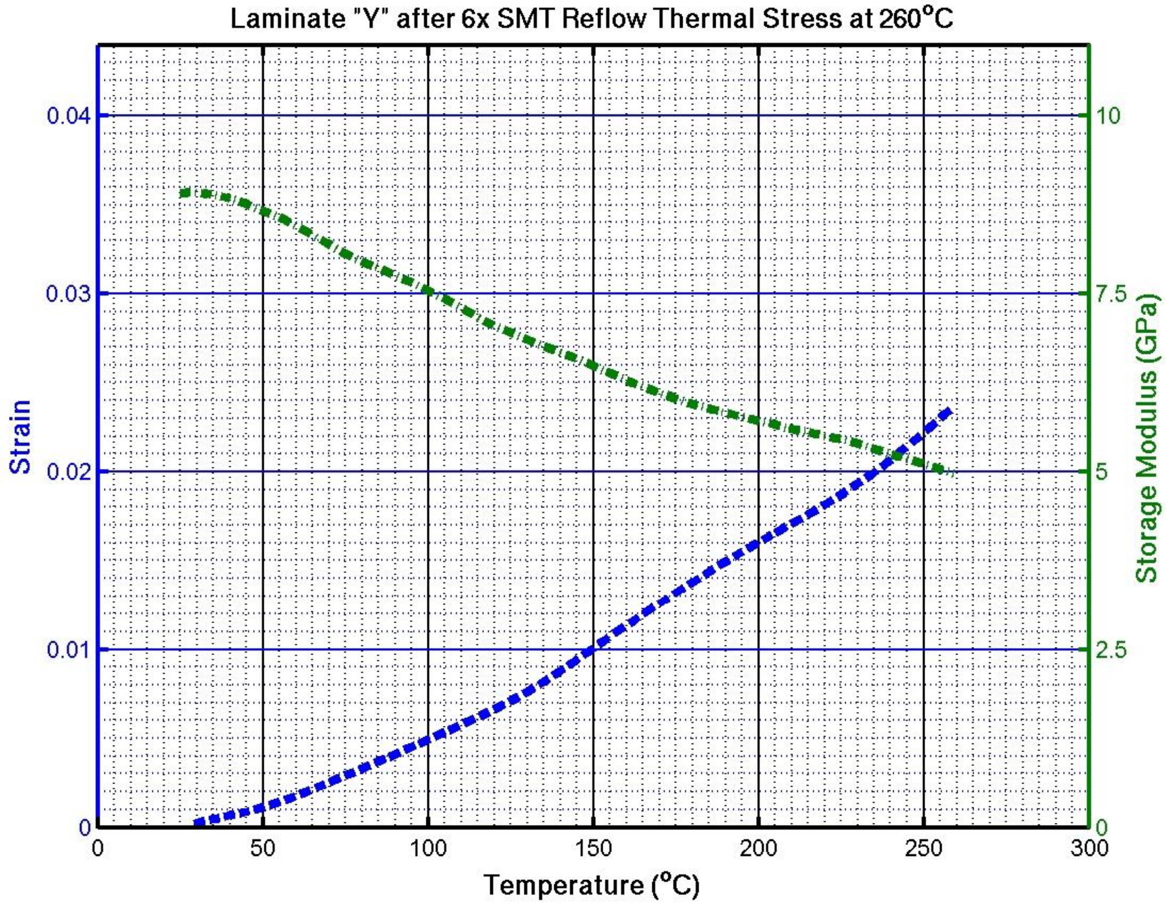


Storage Modulus and Strain Plots



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Converting DMA + TMA Data into Stress versus Temperature Plots

Incremental Strain at T_1 =

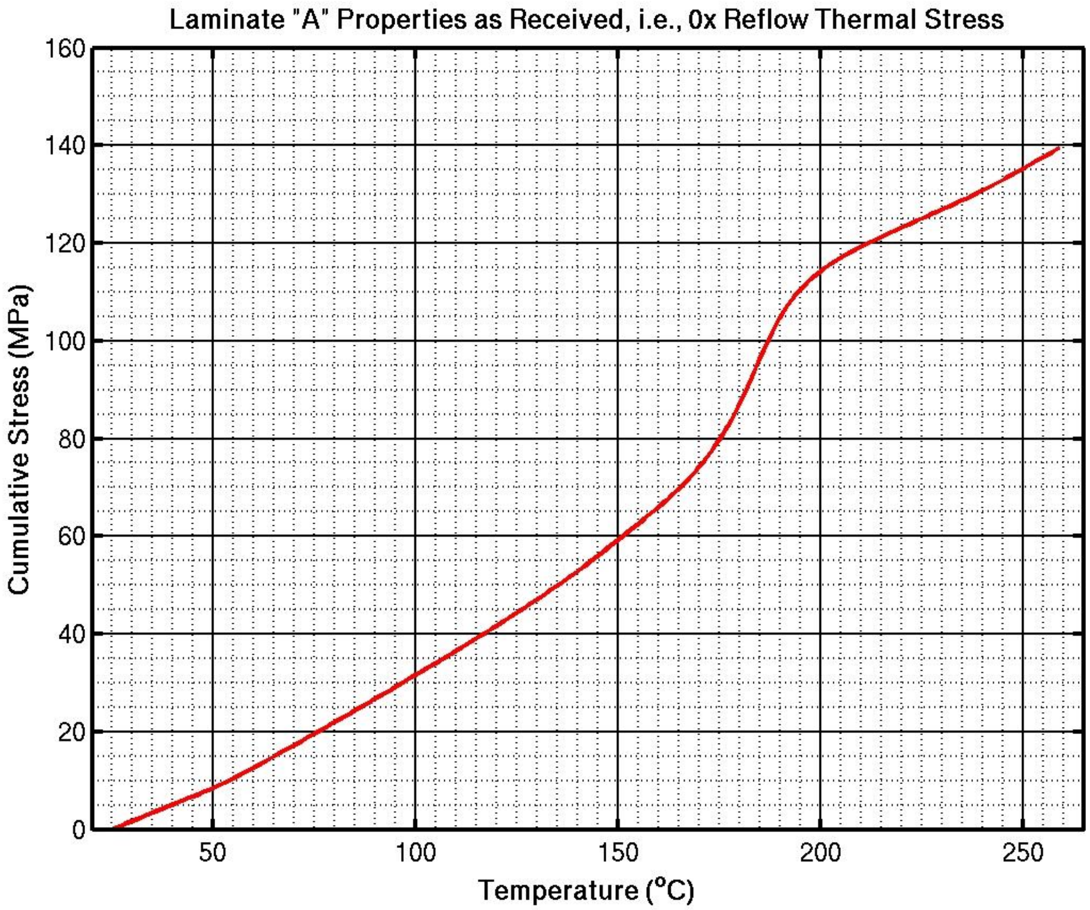
(Dimension Change from T_1 to T_2) / Thickness at T_1

…and from this we can calculate
the incremental stress…

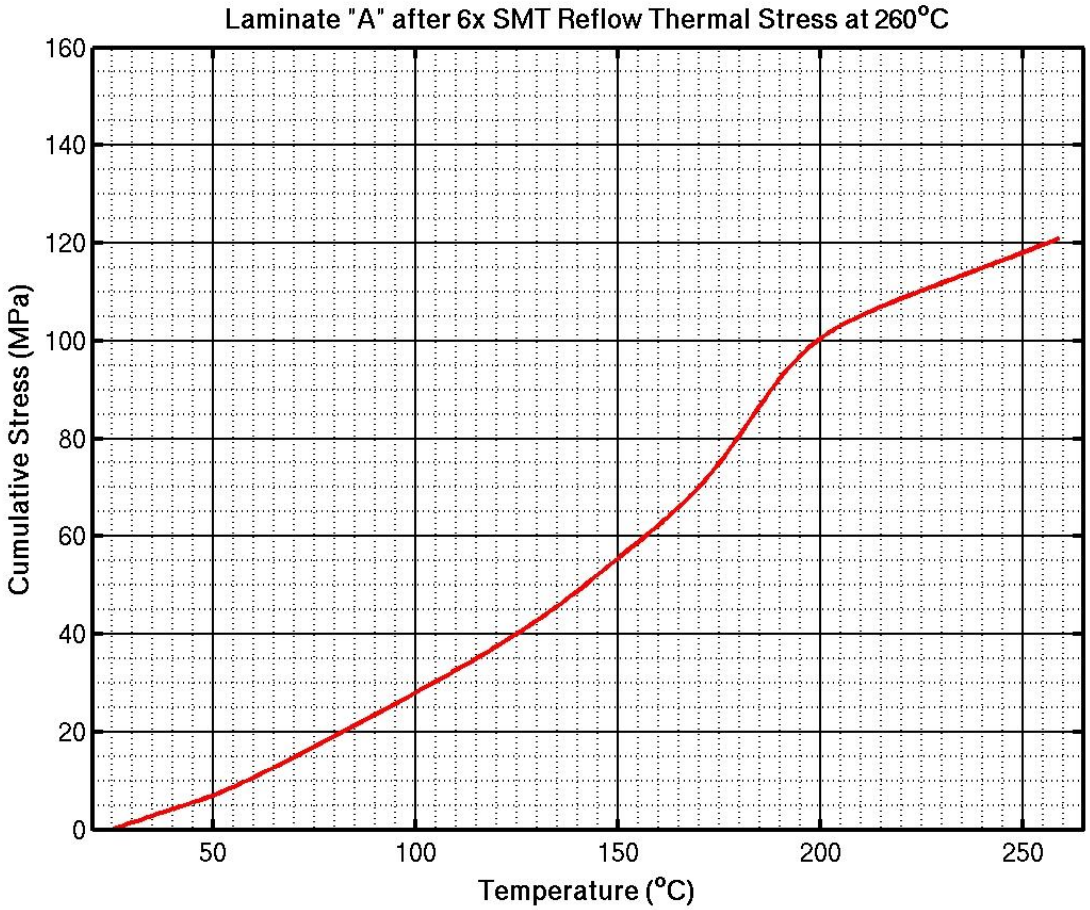
Incremental Stress at T_1 =

Incremental Strain at T_1 * Storage Modulus at T_1

Converting DMA + TMA Data into Stress versus Temperature Plots



Converting DMA + TMA Data into Stress versus Temperature Plots



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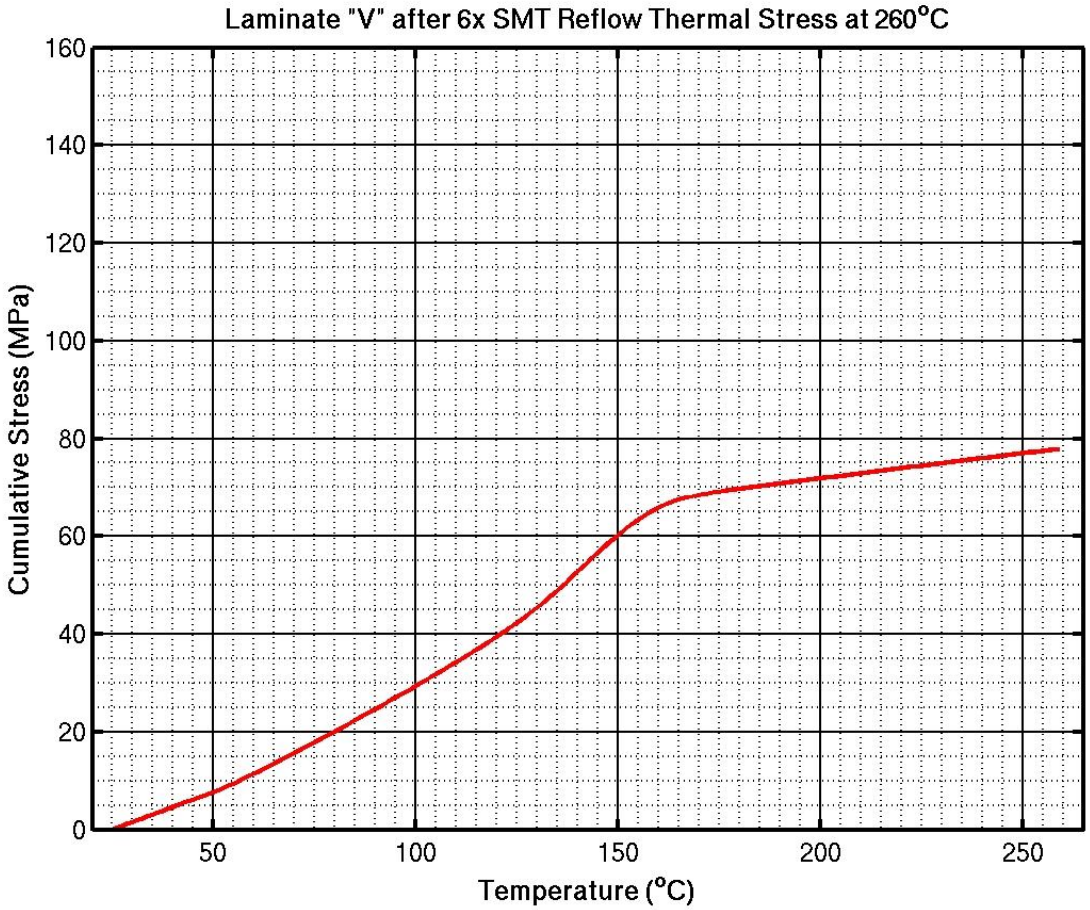
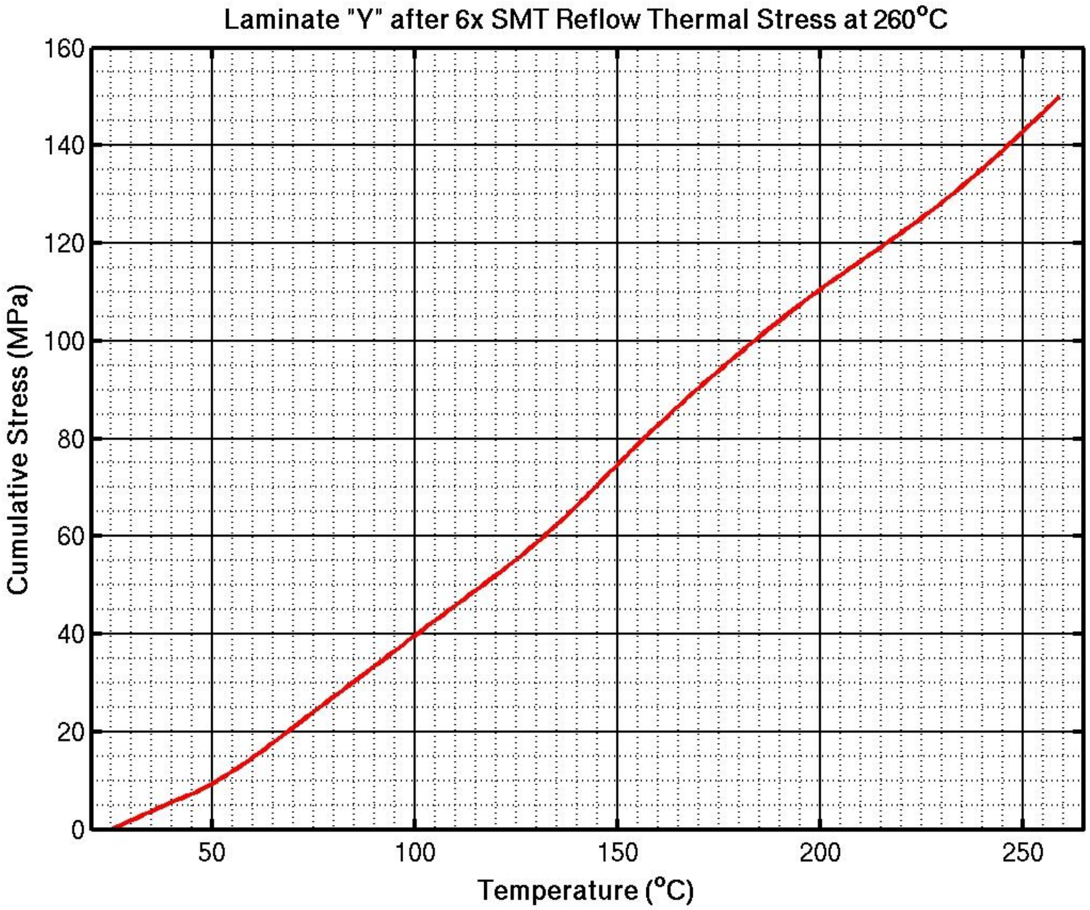


Converting DMA + TMA Data into Stress versus Temperature Plots



Use of Lead-Free Laminate DMA and TMA Data to Develop Stress versus Temperature Relationships for Predicting Plated Hole Reliability

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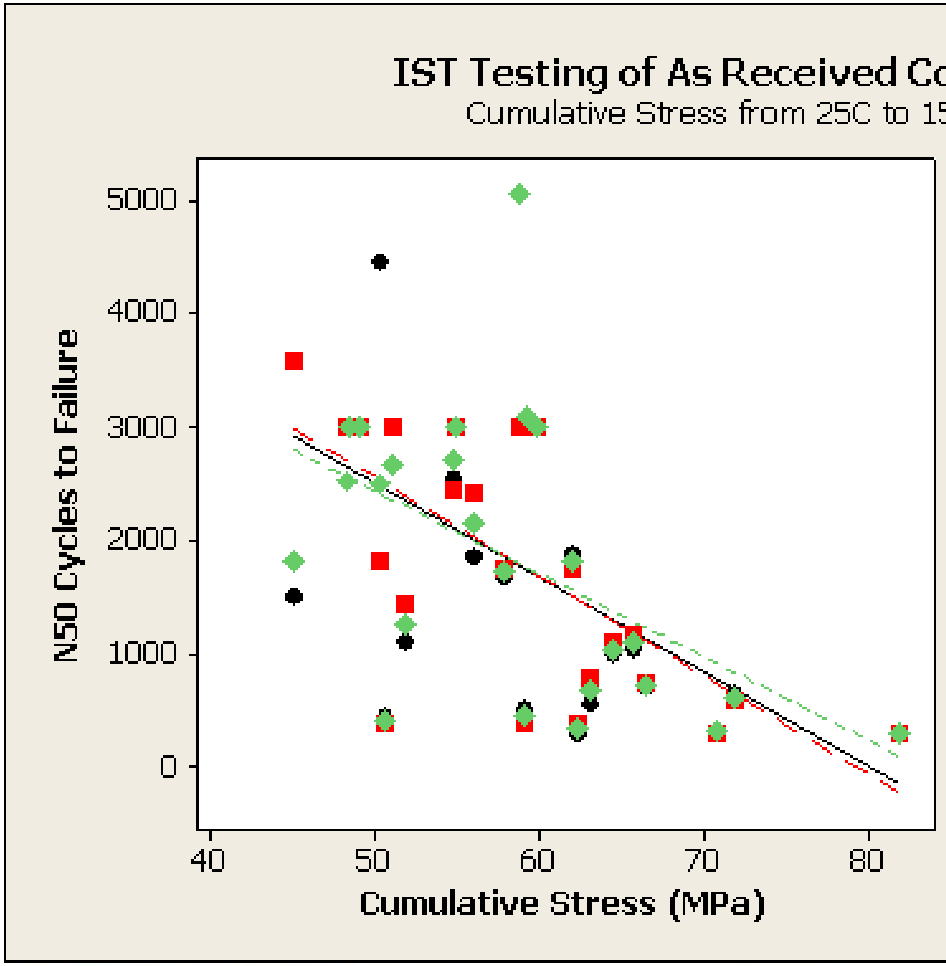
Plated Hole Stress versus Cycles to Failure

- Stress obtained from the stress versus temperature curves derived from the DMA and TMA raw data
  - Stress versus cycle to failure plots
  - Inverse Power Law plots
    - Log (stress) versus Log (cycle to failure)
- Cycle to failure data obtained from two different thermal stress profiles
  - ATC thermal cycle from -40° C to 135° C
    - Use the tensile ATC stress from ambient to 135° C
    - Ignore the compressive ATC stress from -40° C to ambient
  - IST thermal cycle from ambient to 150° C
    - Only tensile IST stress from ambient to 150° C

Plated Hole Stress versus Cycles to Failure



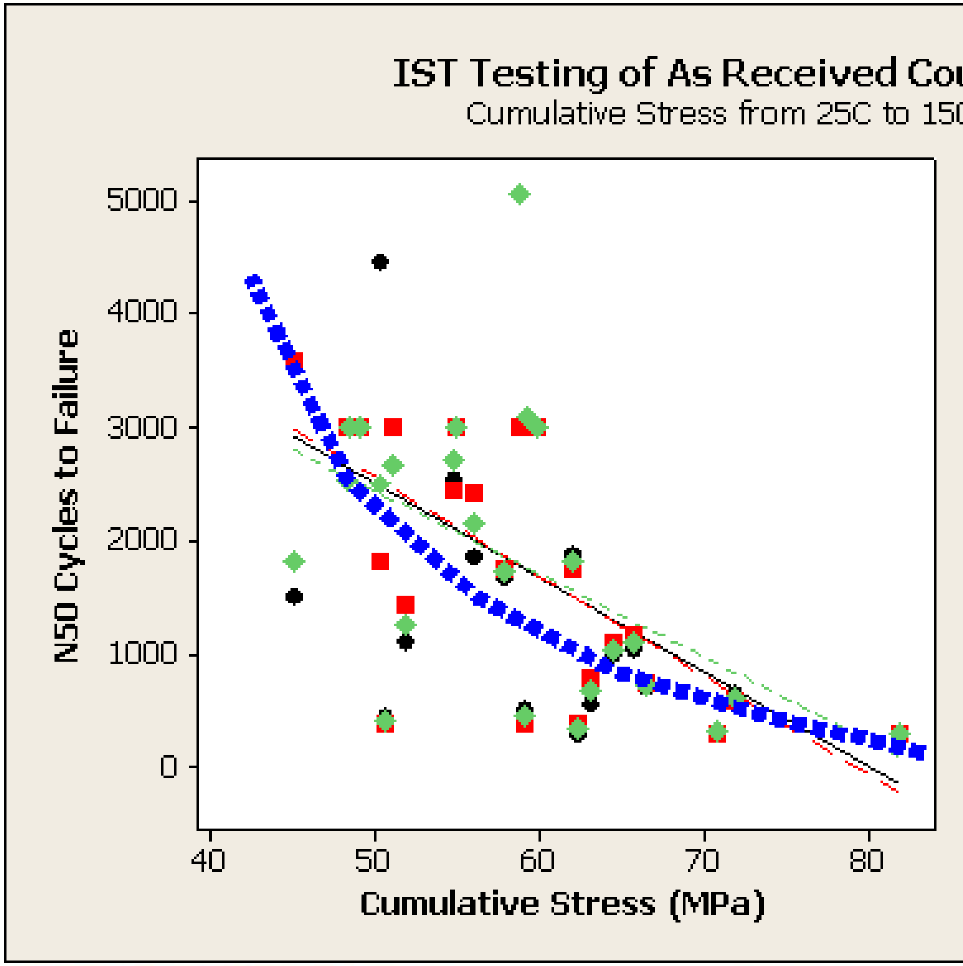
Adjusted R^2 (N)

0.330 (25)

0.428 (25)

0.235 (25)

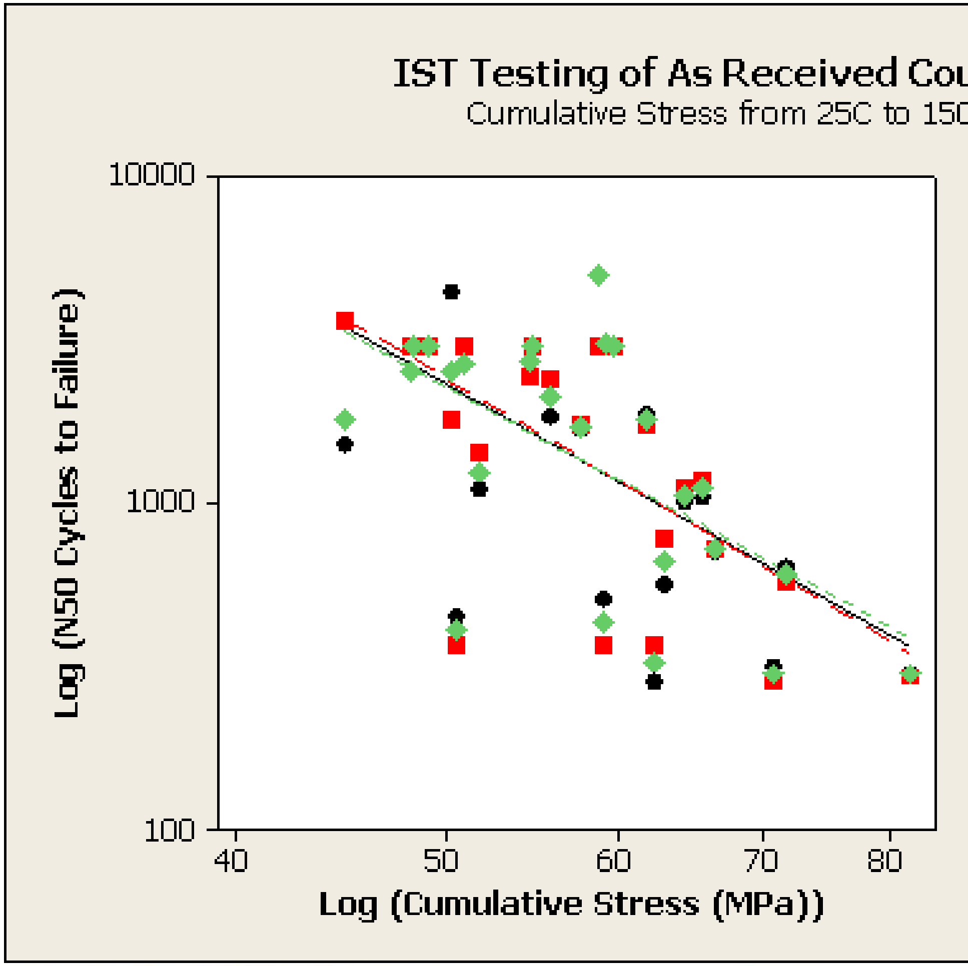
Plated Hole Stress versus Cycles to Failure



Adjusted R^2 (N)

0.330 (25)
0.428 (25)
0.235 (25)

Plated Hole Stress versus Cycles to Failure



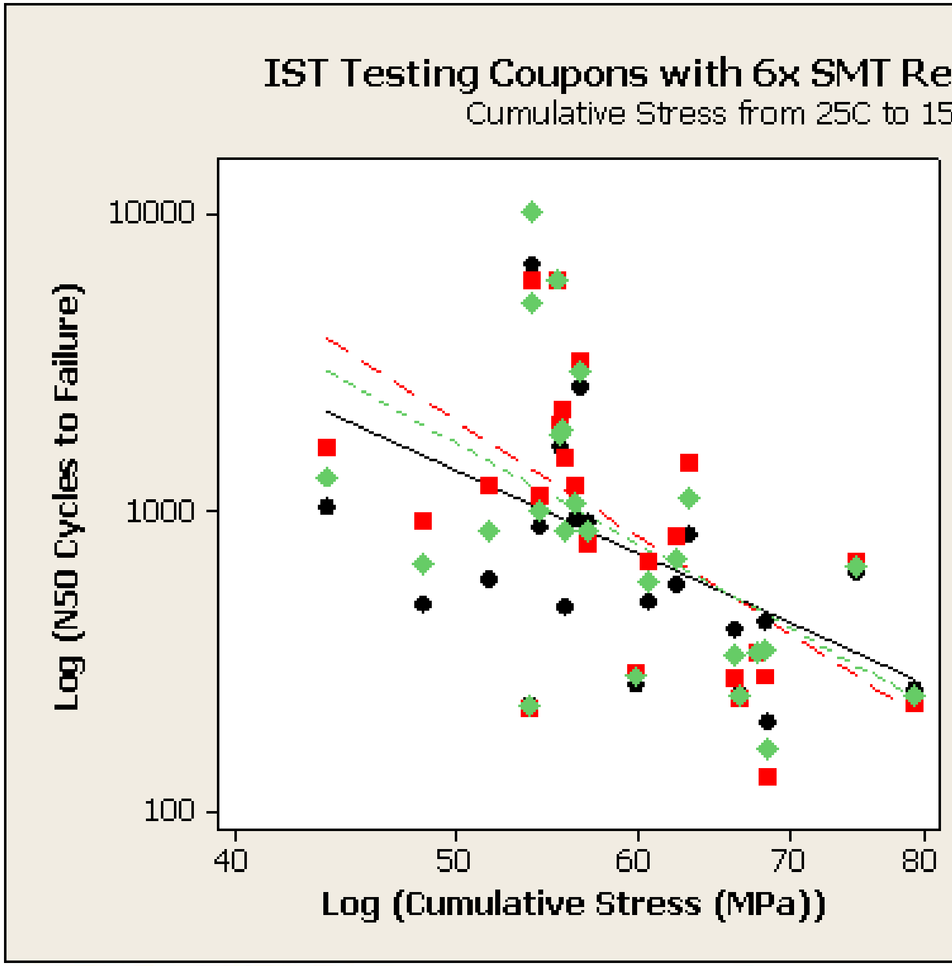
Adjusted R^2 (N)

0.348 (25)

0.384 (25)

0.313 (25)

Plated Hole Stress versus Cycles to Failure



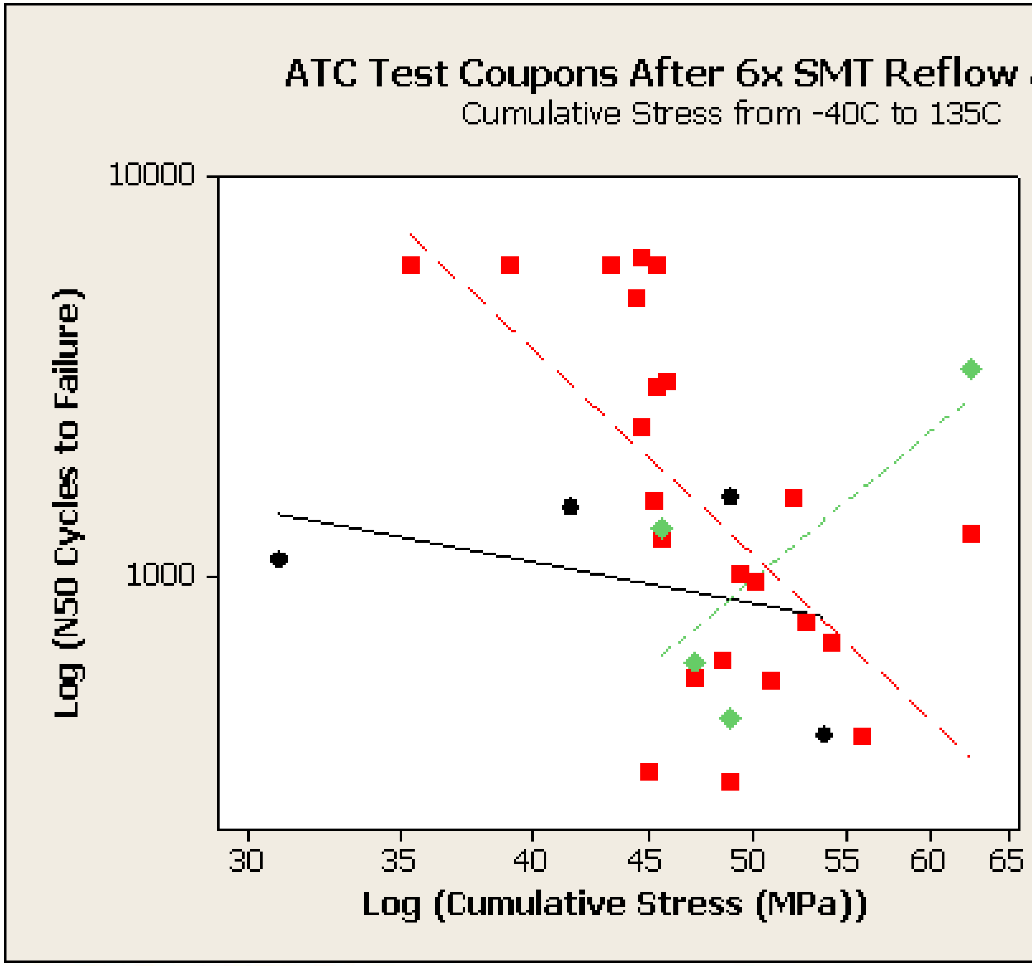
Adjusted R^2 (N)

0.185 (25)

0.330 (25)

0.258 (25)

Plated Hole Stress versus Cycles to Failure



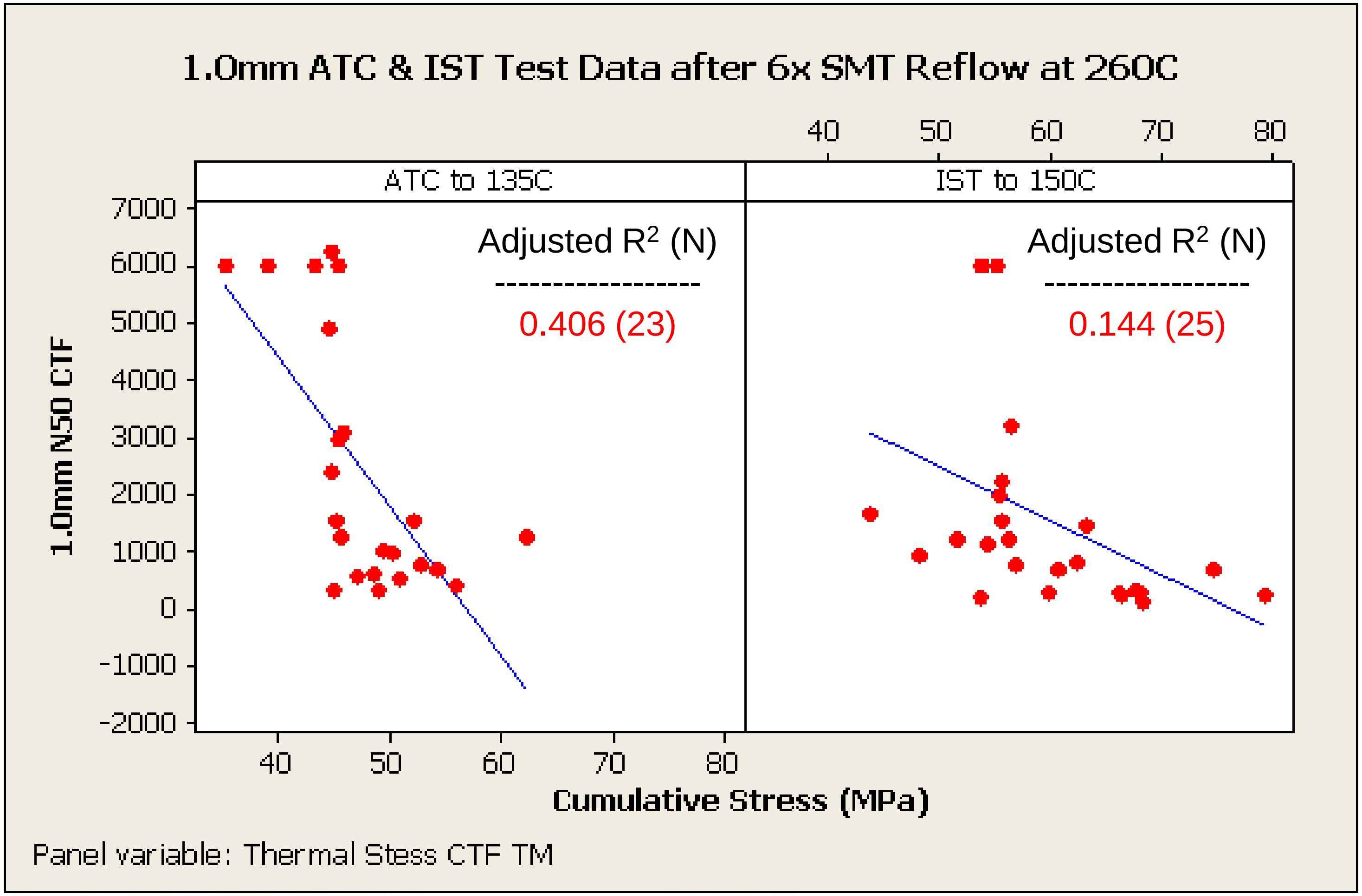
Adjusted R^2 (N)

--- (4)

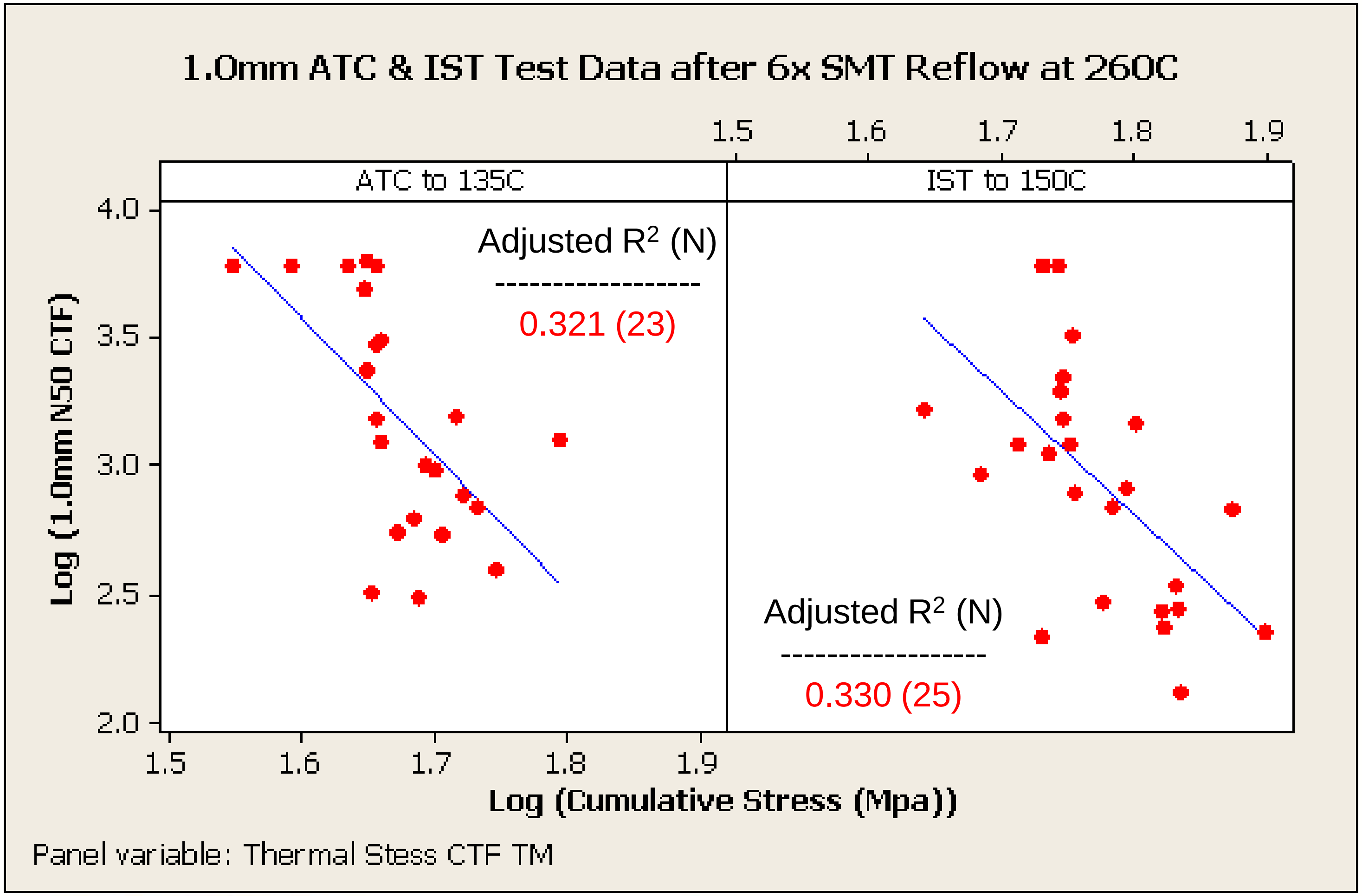
0.321 (23)

--- (4)

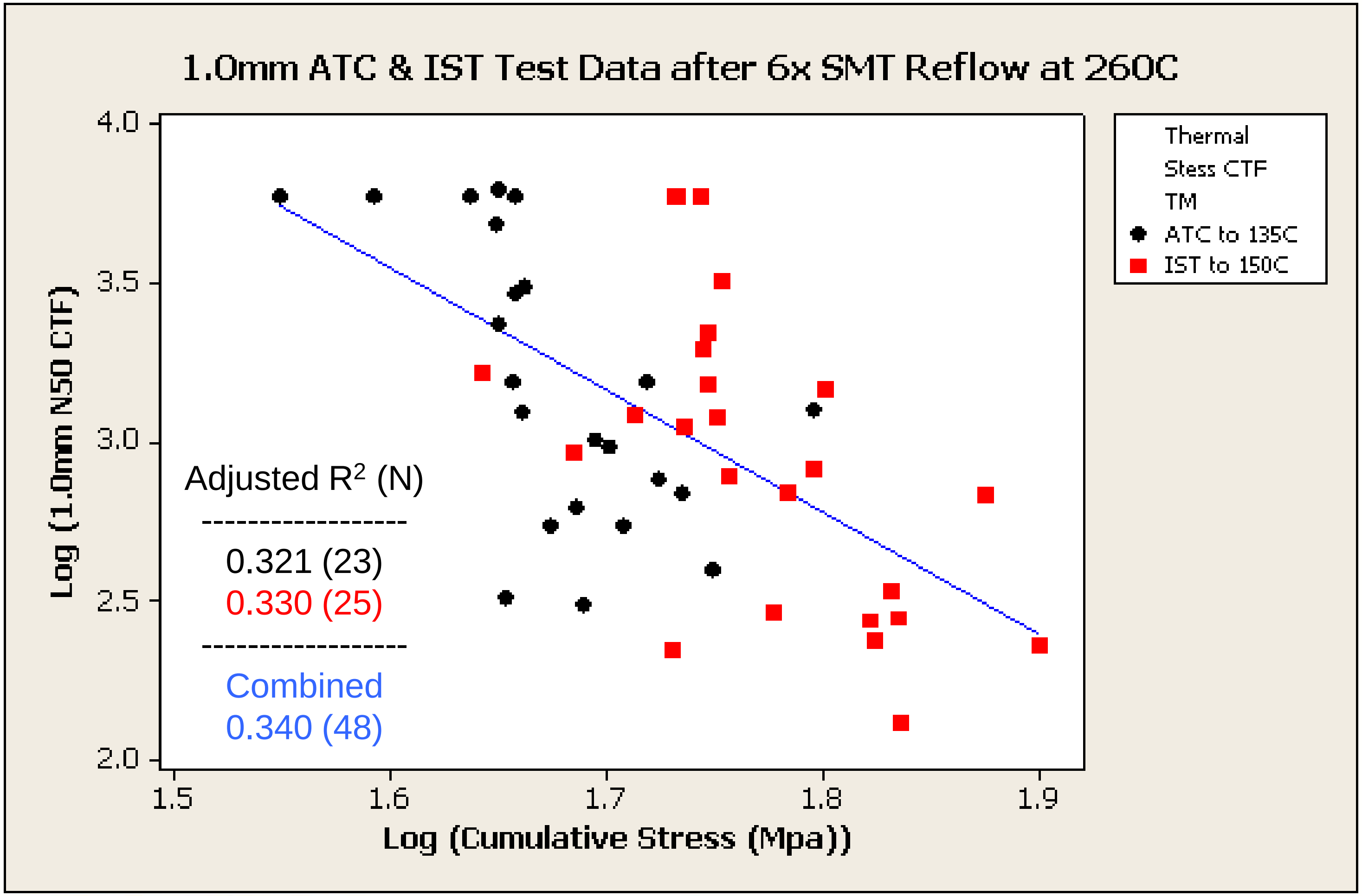
Plated Hole Stress versus Cycles to Failure



Plated Hole Stress versus Cycles to Failure



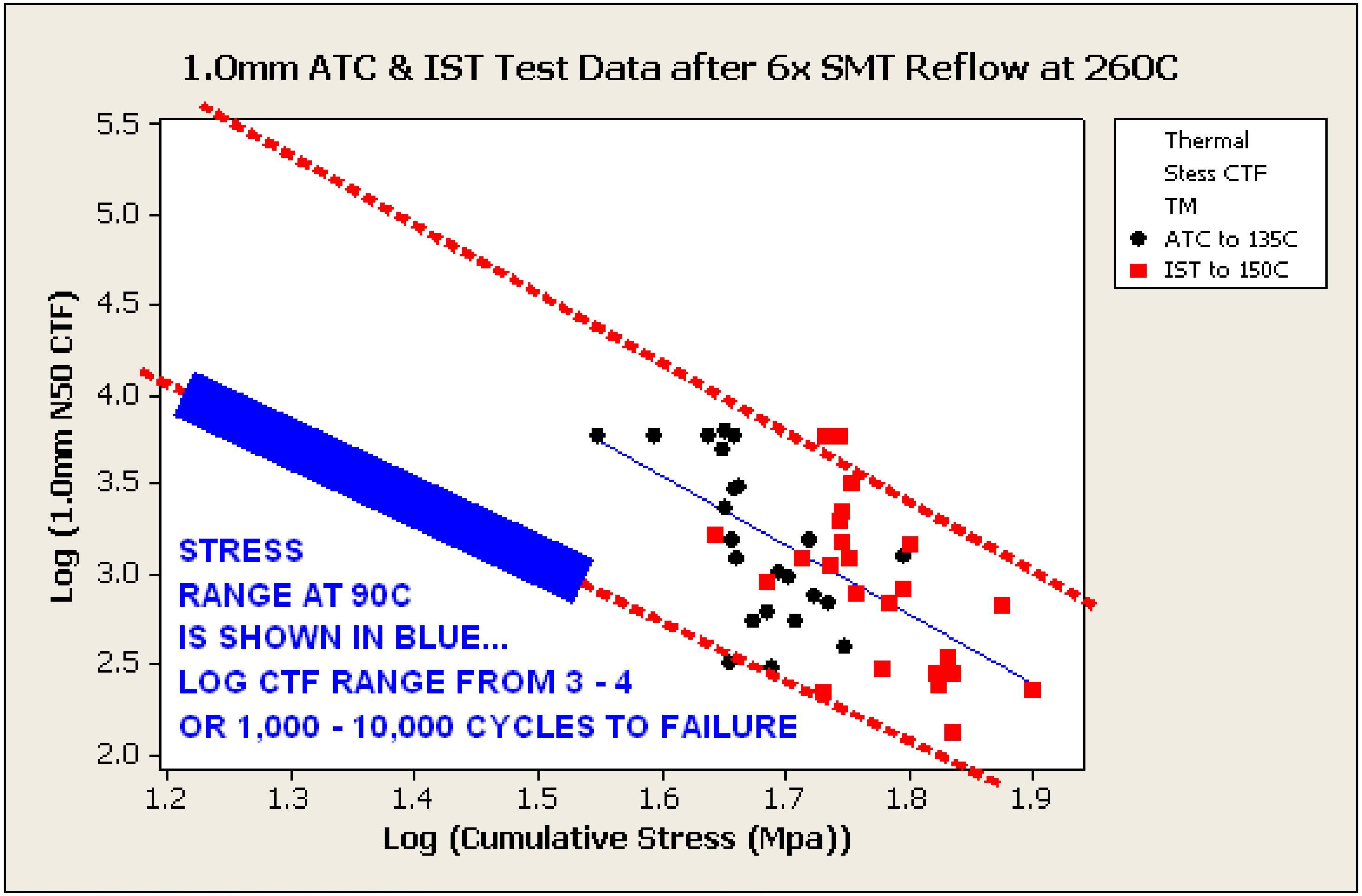
Plated Hole Stress versus Cycles to Failure



Plated Hole Stress versus Cycles to Failure

Stress Condition	Coupon Design	N	Adjusted R^2 for Stress versus CTF	Adjusted R^2 for Log Stress versus Log CTF
IST coupons "As Received" followed by cycle to failure from ambient to 150°C	0.8mm pitch	25	0.330	0.348
	1.0 mm pitch	25	0.428	0.384
	0.8 & 1.0mm pitch	25	0.235	0.313
	Reference Plots	---	Figure 8	Figure 9
IST coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from ambient to 150°C	0.8mm pitch	25	0.074	0.185
	1.0mm pitch	25	0.144	0.330
	0.8 & 1.0mm pitch	25	0.078	0.258
	Reference Plot	---	---	Figure 10
ATC coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from -40°C to 135°C	0.100 inch pitch	4	Insufficient data	Insufficient data
	1.0mm pitch	23	0.406	0.321
	0.8mm pitch	4	Insufficient data	Insufficient data
	Reference Plot	---	---	Figure 11
ATC and IST coupons with "6x SMT Reflow" at 260°C followed by cycle to failure from -40°C to 135°C for ATC and ambient to 150°C for IST	1.0mm pitch	48	0.243	0.340
	Reference Plots	---	Figure 12	Figures 13 & 14

Plated Hole Stress versus Cycles to Failure



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Conclusions and Summary

- Refined our method to produce stress versus temperature curves from DMA and TMA data
  - Automated data analysis with a custom Matlab program
  - Generated “thought-provoking” strain and modulus versus temperature plots of the numerous laminate materials tested
- Stress versus cycle to fail plots
  - Meet expected behavior, decreased CTF at higher stress levels
  - Verified Inverse Power Law, i.e., log-log relationship
  - Adjusted R2 ranging from 0.185 to 0.384 using IPL, log-log plots
    - Stress due to laminate material expansion does not explain all the CTF variation
- ATC and IST cycle to failure data
  - Achieved excellent agreement between these two thermal cycle ranges using “normalized” stress data obtained from laminate material DMA and TMA data
  - Made crude estimates of 3 to 30 year field life after 6x SMT reflow

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Future Work

- Deeper dive into the HDPUG Lead-Free 2 data set…
  - Develop a more comprehensive predictive model with higher adjusted R^2 using more input factors
    - Two resin percentage stack-ups
    - Three fabricators
      - Two sets of plating conditions at one fabricator
    - Cross section factors
      - Eyebrow cracks, hole wall separation, damage in Zone A, delamination, etc.
  - Improved prediction of field life
    - Use full CTF database, not just N50 values
    - 0x and 6x SMT and Miner's Rule

Thank You!

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