Experimental Technique for Monitoring Fatigue Crack Growth Mechanisms During Thermomechanical Cycling

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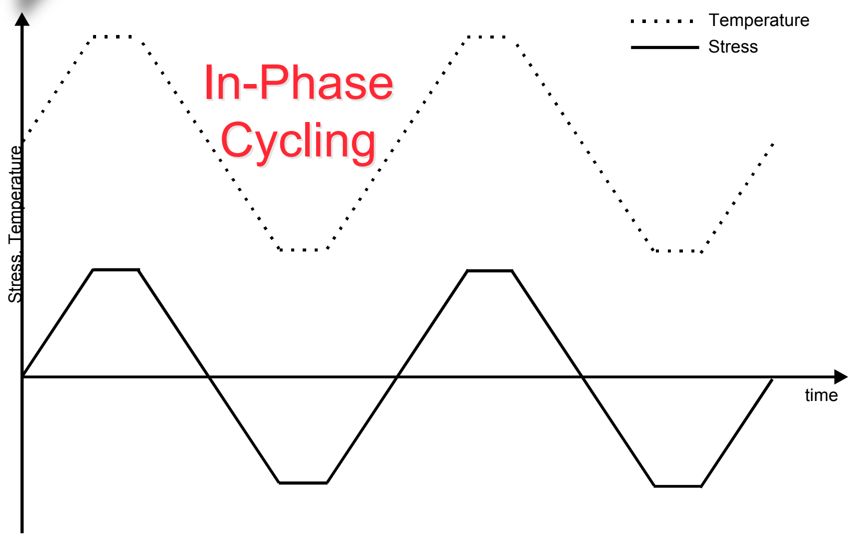
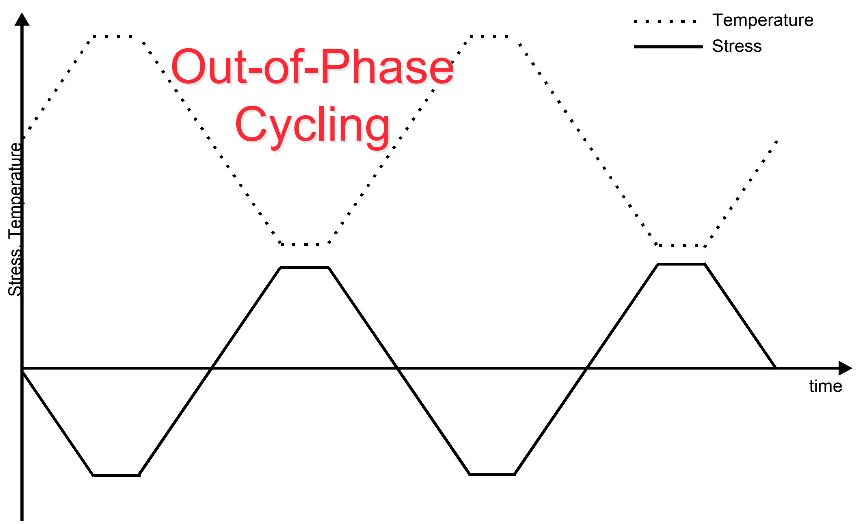
Outline

- *Experimental Definitions*
- *Mechanical Loading System*
- *Temperature Control System*
- *Crack Dimension Measurement System*
- *Test Matrix*
- *Fracture Mechanics Approximations*
- *Isothermal Fatigue Crack Growth Results*
- *Thermomechanical Fatigue Crack Growth Results*
- *Individual Cycle Results*
- *Conclusions*

Experimental Definitions



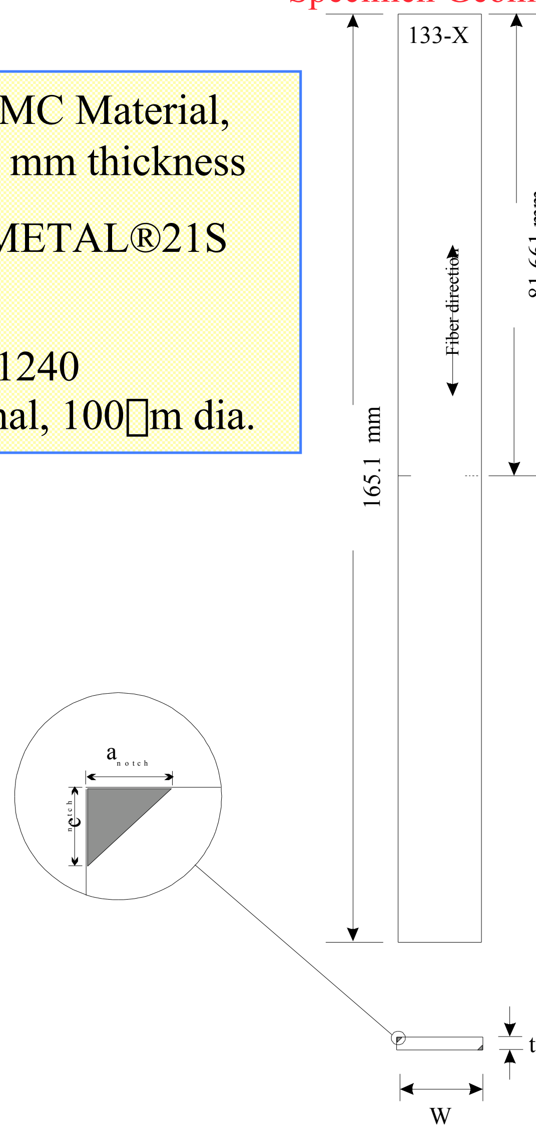


Titanium MMC Material,
16 ply = 2.1 mm thickness

Matrix: TIMETAL®21S
(□-21S)

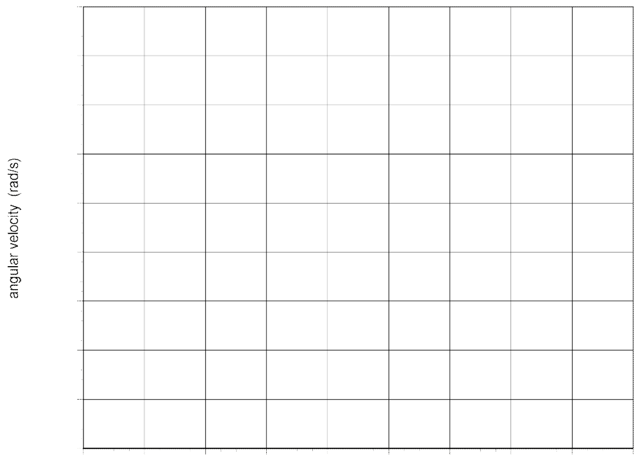
Fibers: SM1240
Unidirectional, 100□m dia.

Corner Crack
Specimen Geometry

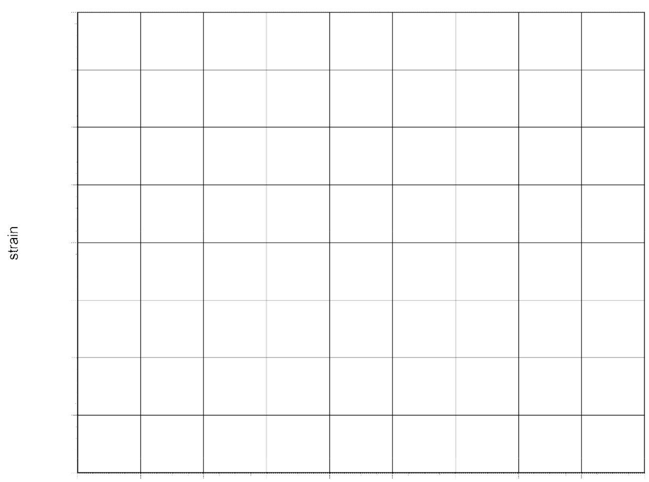


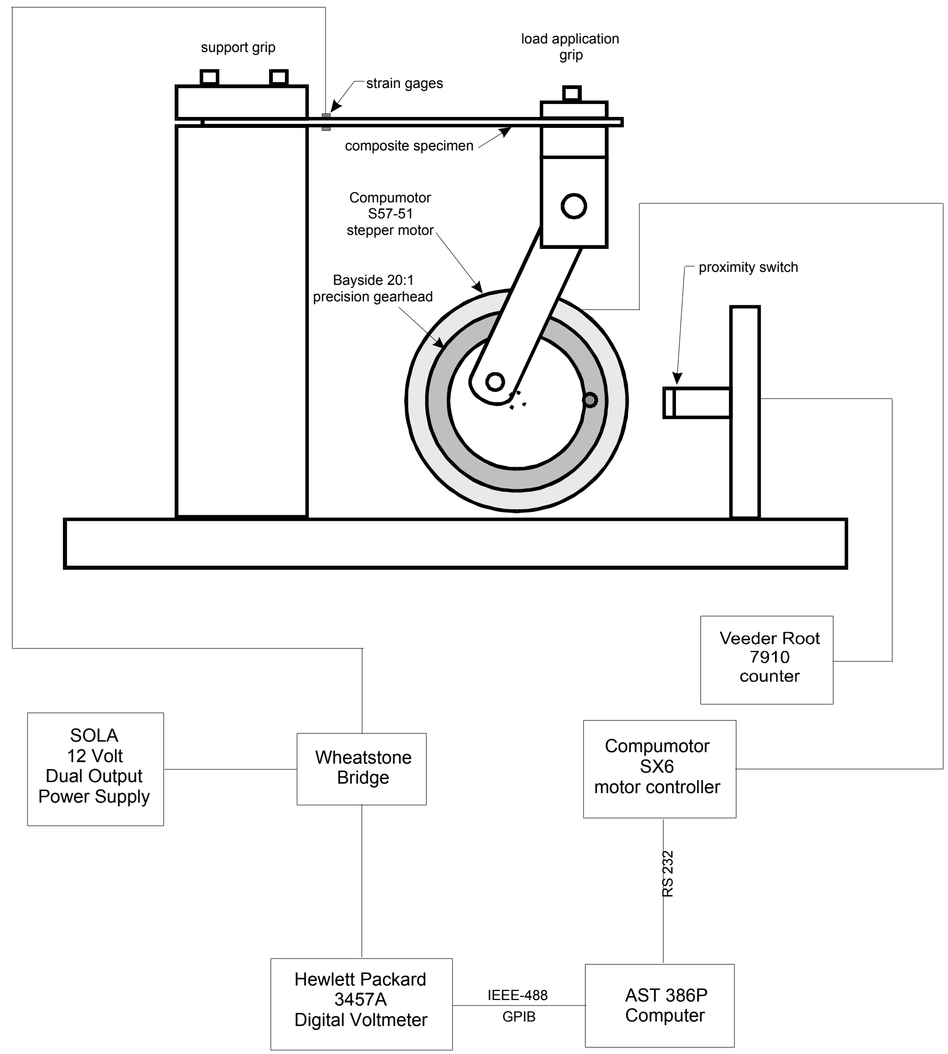
Mechanical Loading System

Angular Velocity Variation



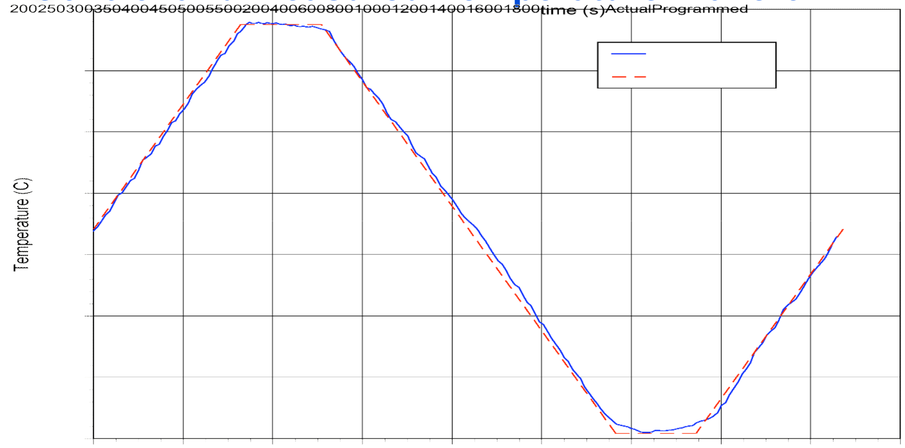
Resulting Loading Waveform



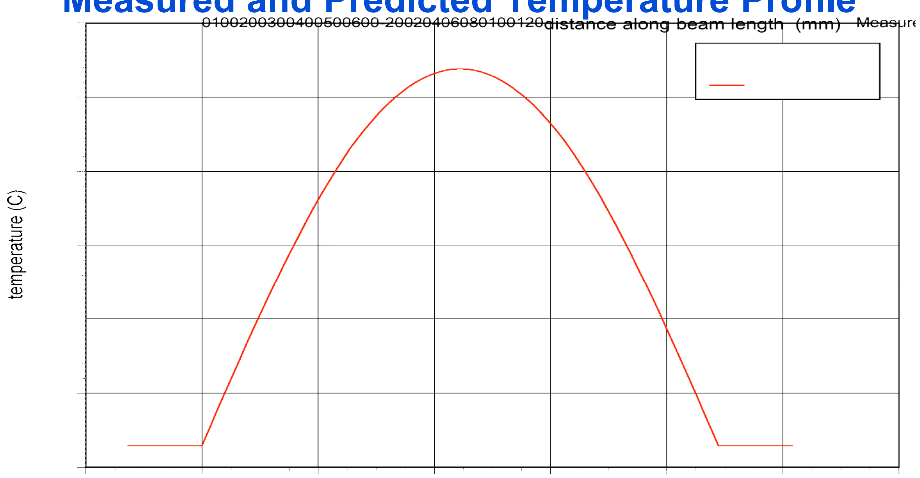


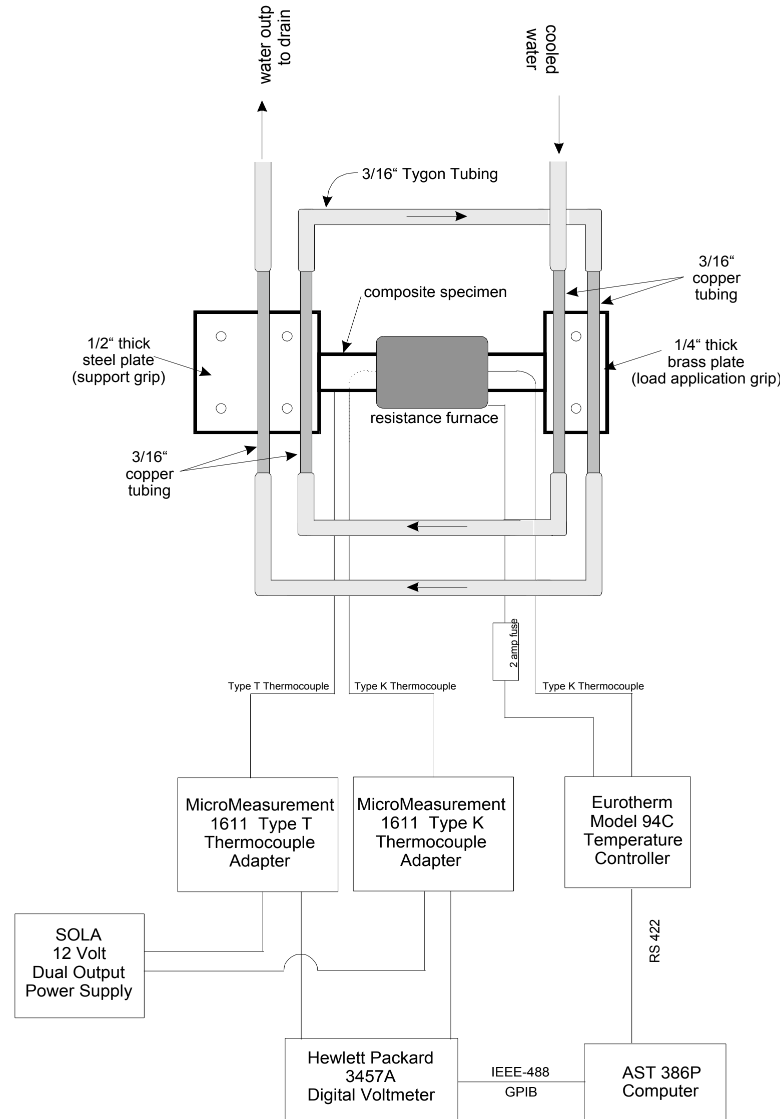
Temperature Control System

Control and Measured Temperature Waveform



Measured and Predicted Temperature Profile





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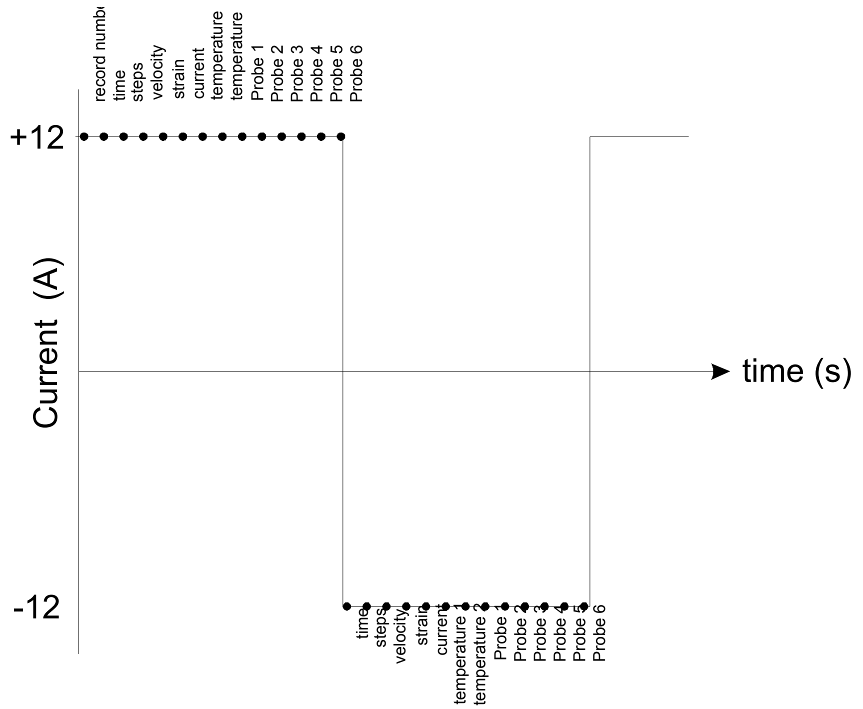
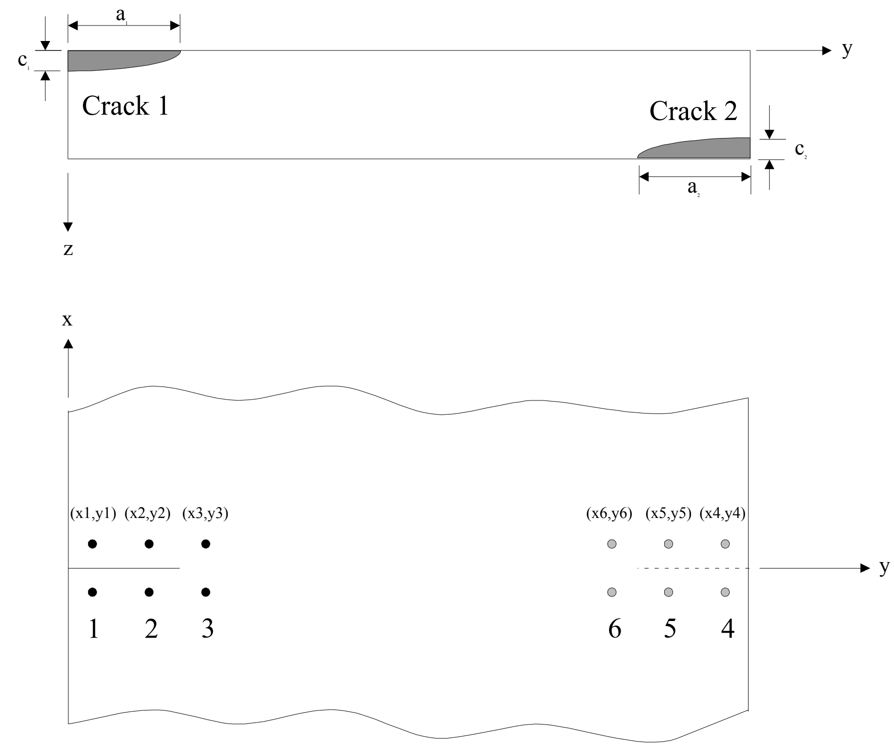
Reversing Electrical Potential Measurements Used for Inverse Solution Fit to Quarter-Ellipse Shaped Cracks

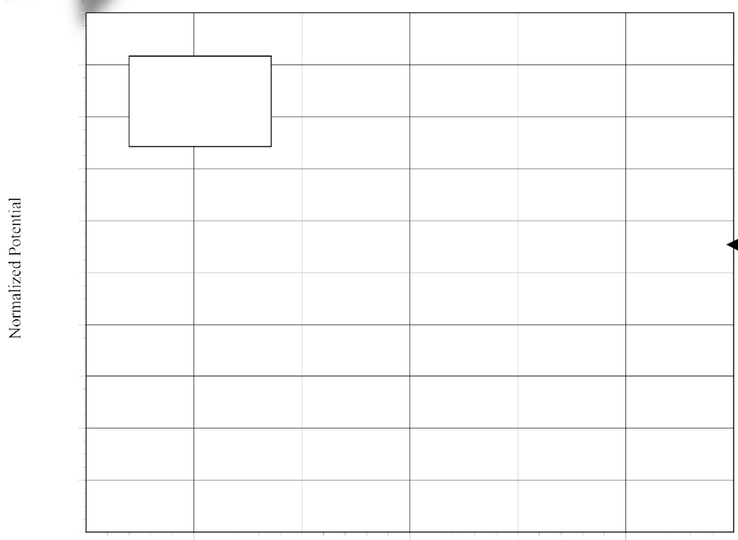


Sequence of Measurements Taken During a Current Reversal

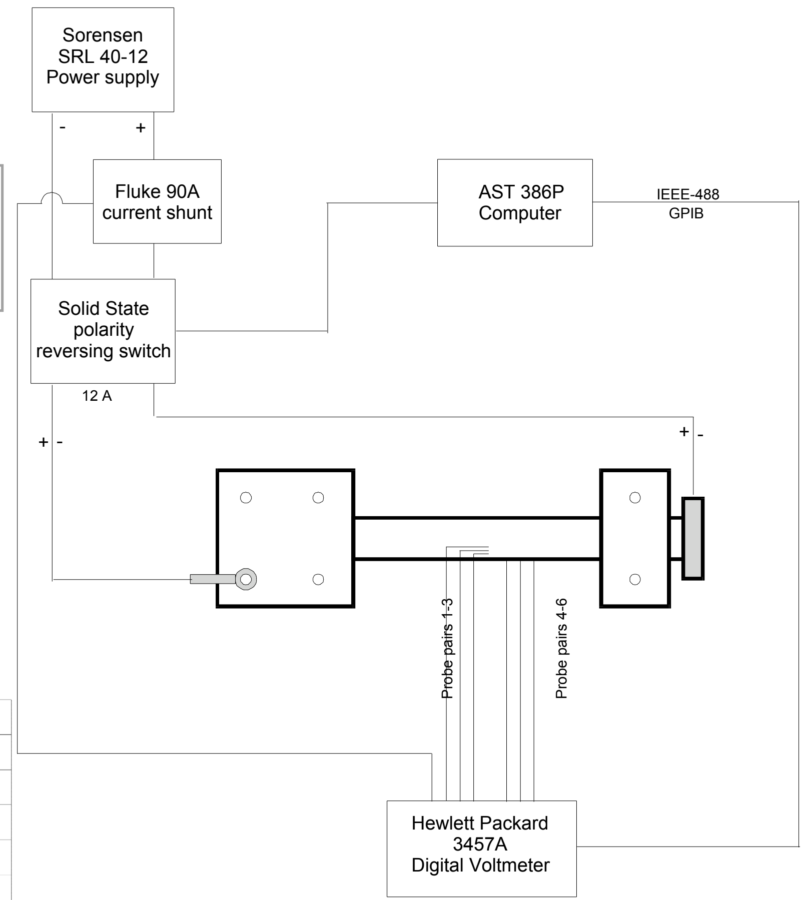


Electrical Potential Probe Pair Locations

Crack Dimension Measurement System: Reversing Electrical Potential Method



Normalized EP data for 3 probe pairs (1 crack)

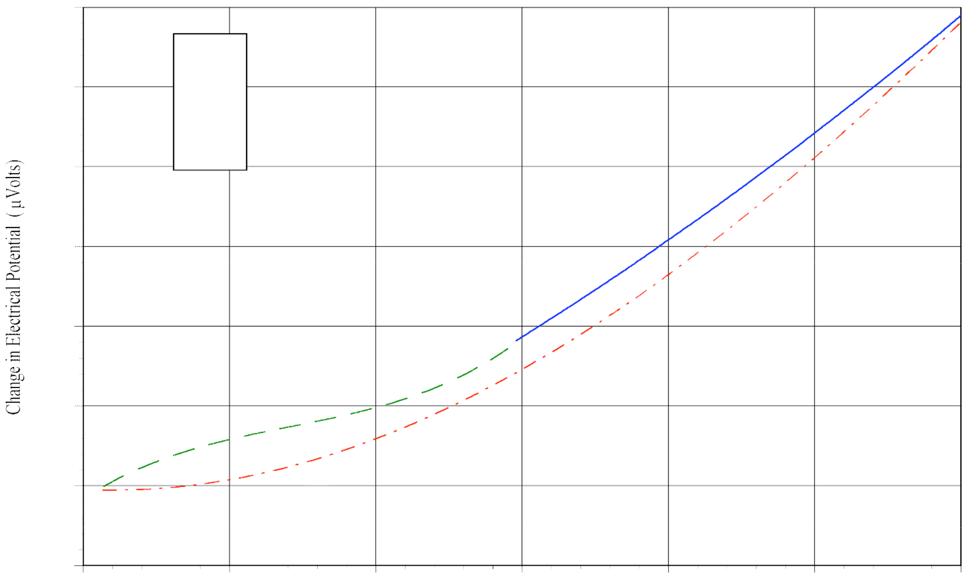


Crack Length Prediction

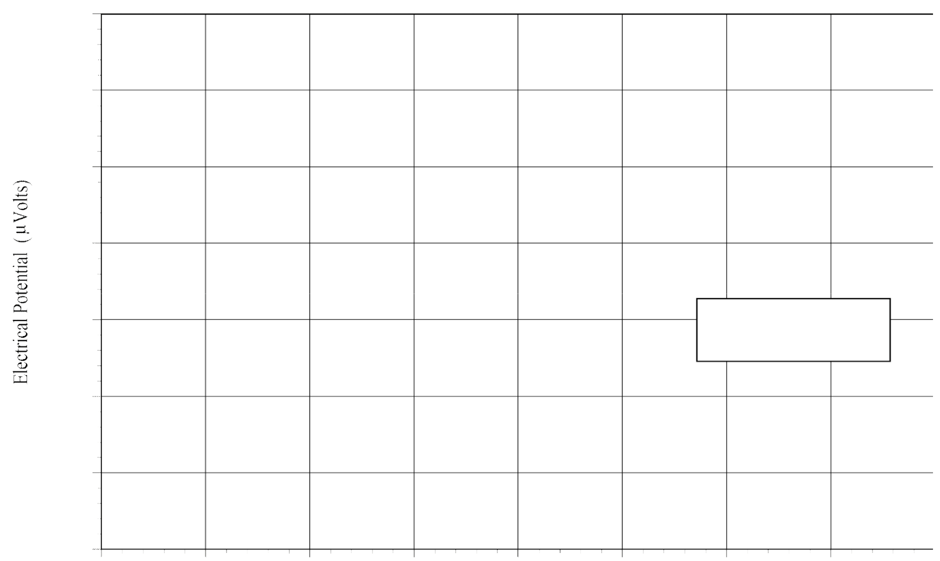
Crack Depth Prediction

Electrical Potential Correction for Changes During Thermal Cycling (Non-Isothermal Tests)

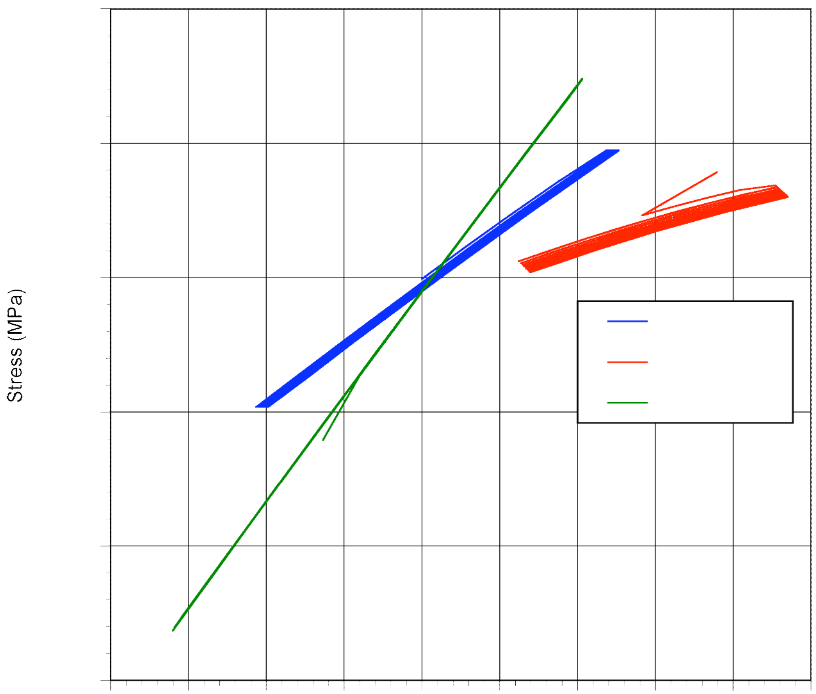
Electrical Potential Change During Thermal Cycle

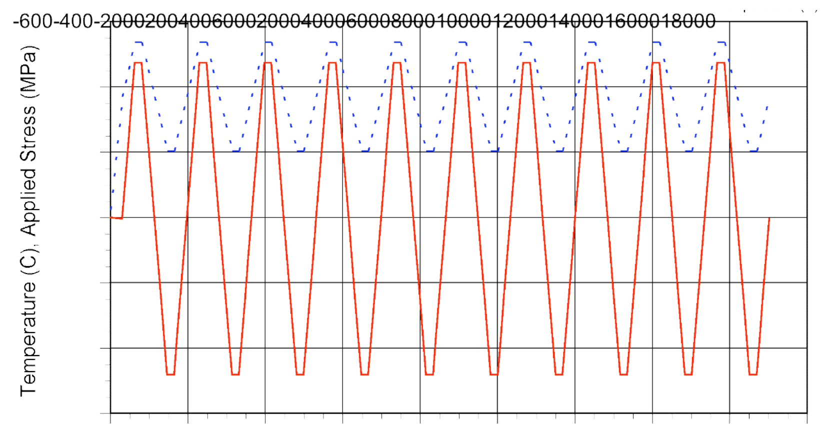


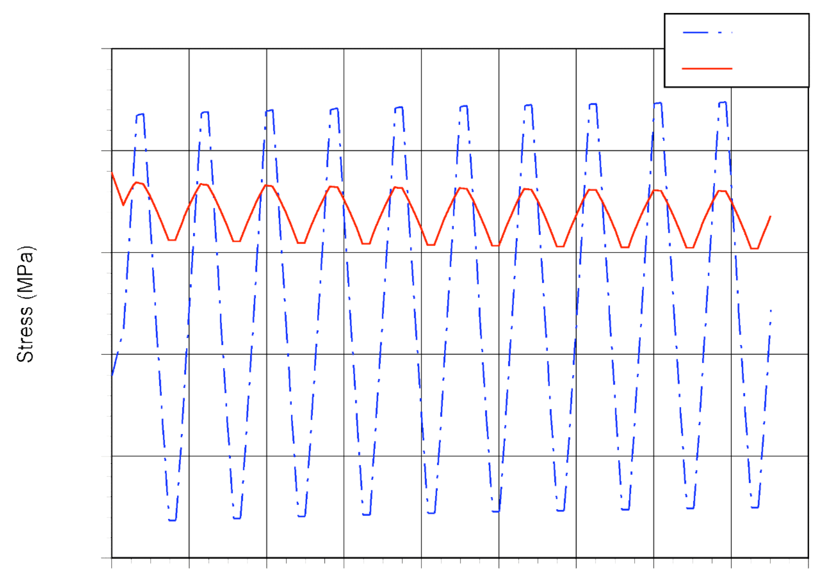
Electrical Potential Before and After Thermal Correction



Applied Loading and Predicted Constituent Axial Stresses for Test 133-5-1 (In-Phase TMF)







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Test Matrix

Test TypeTmax(ºC)Tmin(ºC)T(ºC)Tmean(ºC)max min CyclePeriod (s)AppliedCycles

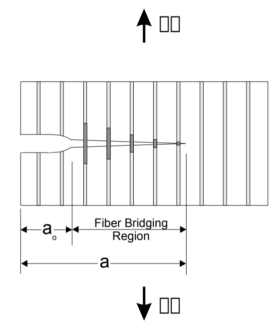
▯ ▯ ▯

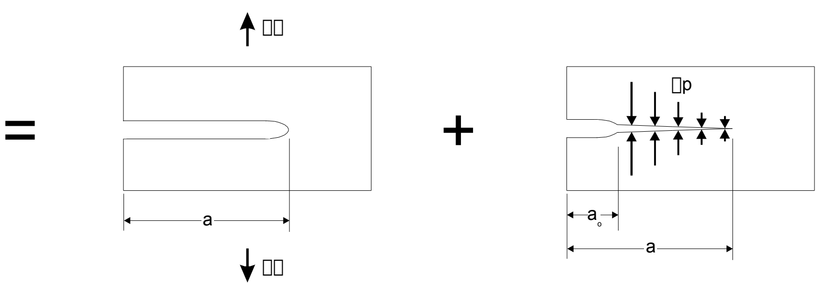
•10 Specimens: 5 Isothermal Fatigue, 5 Thermomechanical Fatigue

•Loading in bending, so top and bottom surfaces were subjected to equal but opposite stresses during cycling. Resulting in two fatigue crack growth experiments with different loading conditions simultaneously on each specimen = 20 experiments.

•The effect of hold times in tension and compression and wave shapes on crack growth rates were also studied.

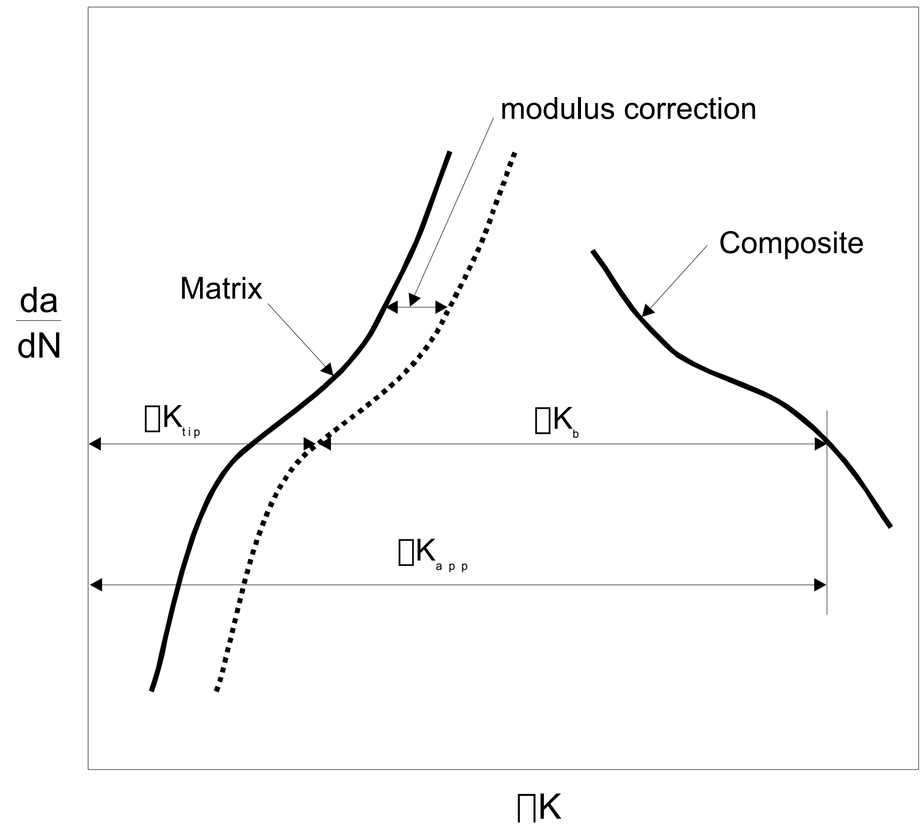
Fracture Mechanics Approximation of Fiber Bridging





$$\Delta K_{tip} = \Delta K_{app} - \Delta K_b$$

$$\Delta K_m = \sqrt{\frac{E_m}{(1 - v_f)E_L}}\,\Delta K_{tip}$$



Schematic of the Bridging and Modulus Corrections to the Stress Intensity Factor Range

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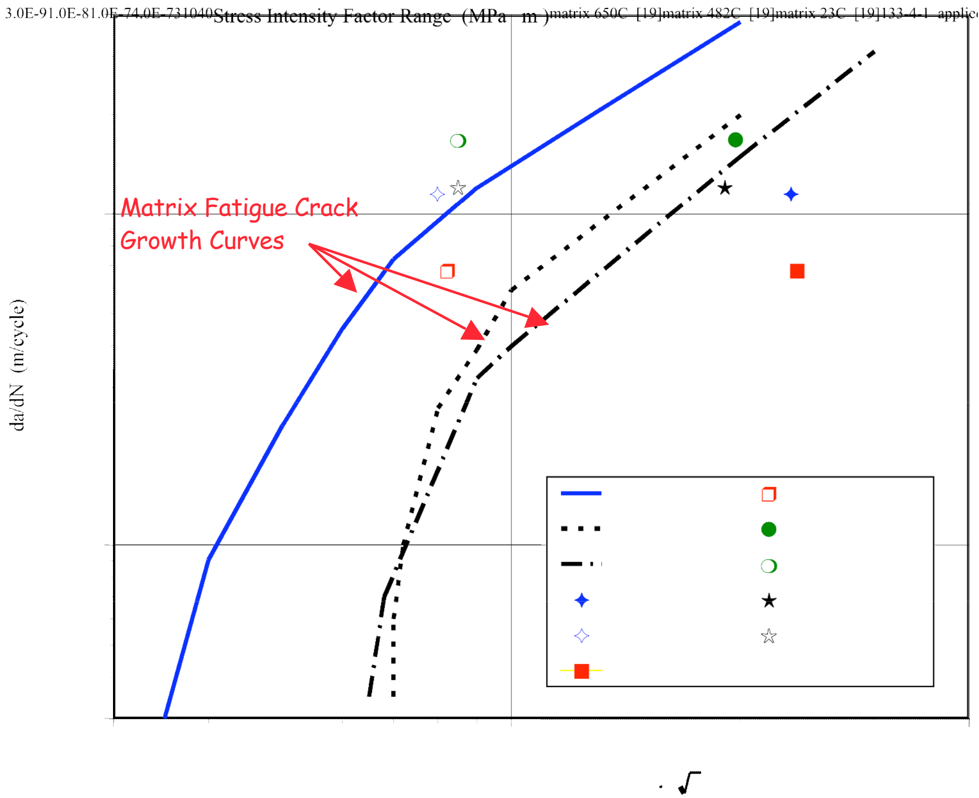
Comparison of 538C Isothermal Crack Growth Results with Matrix Fatigue Crack Growth Data



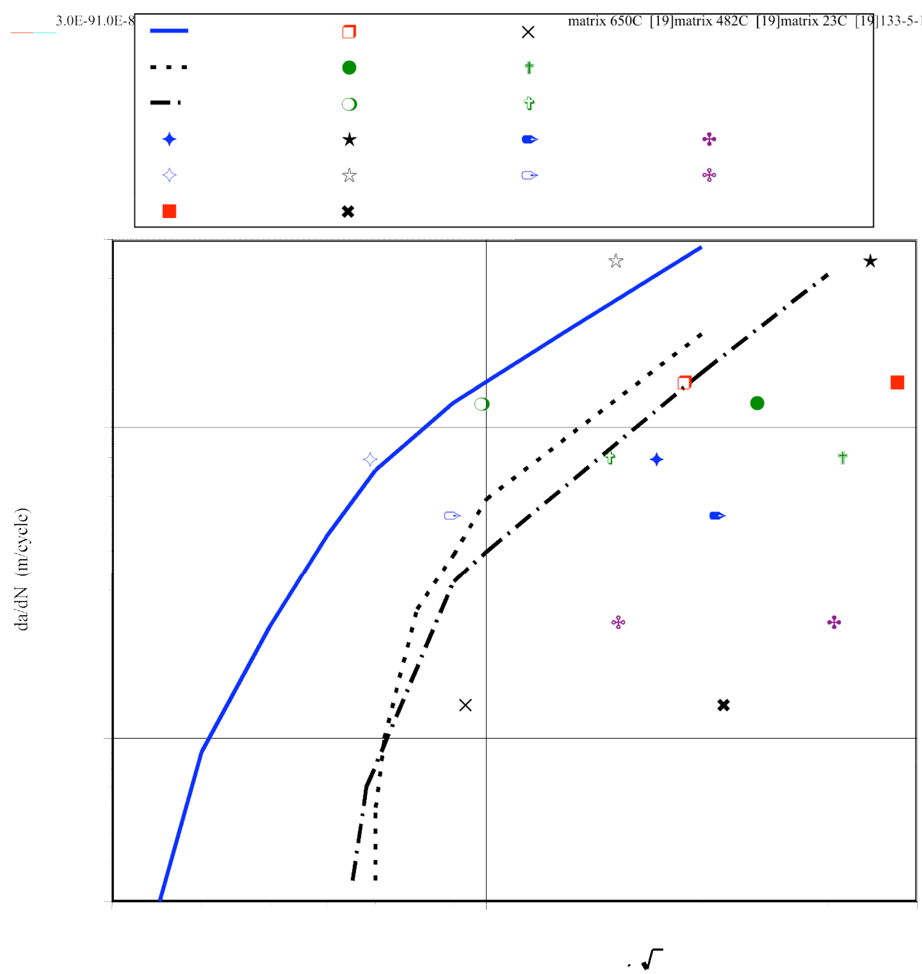
- Composite at 538C exhibits a significant reduction in crack growth rate from the matrix material, equivalent rates to matrix at 23C.

- For the same ΔK_{app}, the crack growth rate in the matrix would be about an order of magnitude higher than in the matrix (fiber bridging + stiffness effect reduce crack growth rates).

- Crack growth rates correlate well with predicted ΔK_m, notice that ΔK shifts towards 650C matrix curve after correcting for fiber bridging and modulus.

[19] Ghonem and Zheng, 1993

Comparison of Thermomechanical Fatigue Crack Growth Results with Matrix Fatigue Crack Growth Data



- In-Phase Tests end with -1, out-of-phase tests end with -2.
- For all TMF tests, composite showed a reduction in crack growth rate over the matrix material.
- Out-of-phase TMF tests have a higher □K than their counterpart in-phase TMF tests due to their larger effective applied stress range.
- Calculated □K_{app} gives a correlation between in-phase and out-of-phase data: higher □K is calculated for out-of-phase tests which always have a higher crack growth rate than in-phase tests.
- Crack growth rate increases with applied stress range (133-6-1 vs. 133-10-1), 20% increase in applied stress range results in over an order of magnitude increase in crack growth rate.
- Crack growth rates increase with temperature range and mean temperature.

[19] Ghonem and Zheng, 1993

Individual Cycle Results

•Actual physical increases in crack dimensions can only be accurately measured at maximum load.

•Changes in the predicted crack dimensions during individual loading cycles represent the opening and closing of the crack rather than a physical change in the crack dimension.

133-2 Crack 1
Isothermal 371C, 482C, 538C
30 s Hold in Tension
30 s Hold in Compression

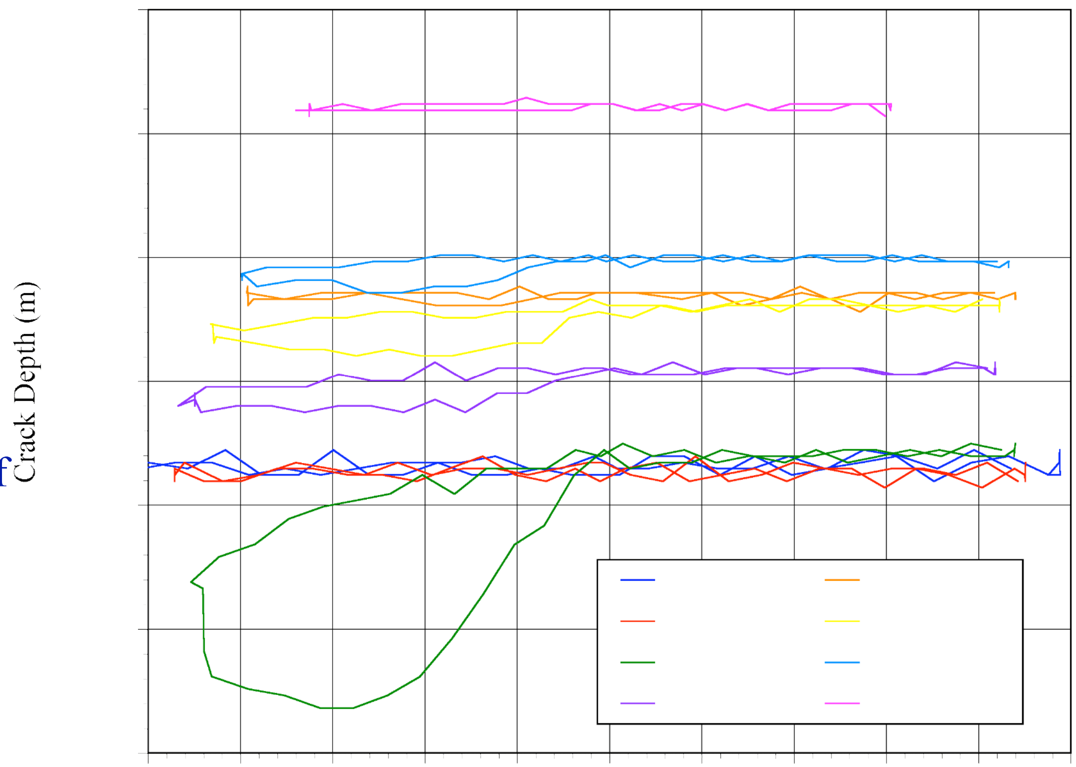
•371C: No crack growth over 2045 cycles

•482C: Immediate change in cycle response, crack closing during compressive hold time. Response loop slowly became smaller until it closed after 500 cycles.

•538C: Immediate change with development of large loop. Response loop slowly closes over next 500 cycles.

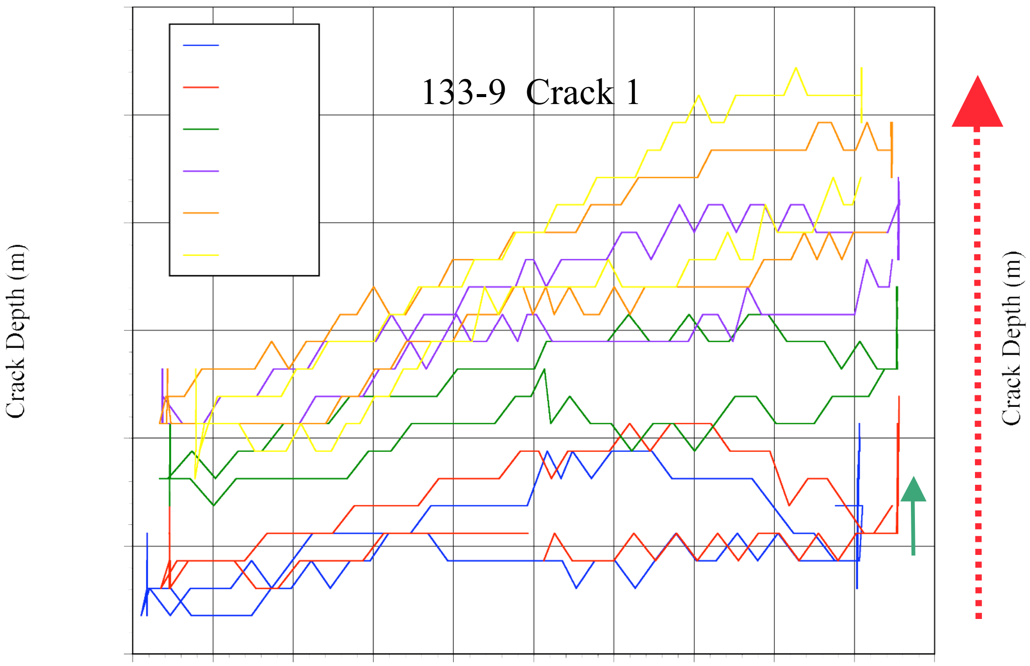
•Higher temperature allows crack to open and close: reduction in compressive stress in fibers that hold crack closed.

•Crack depth is more sensitive due to geometry.

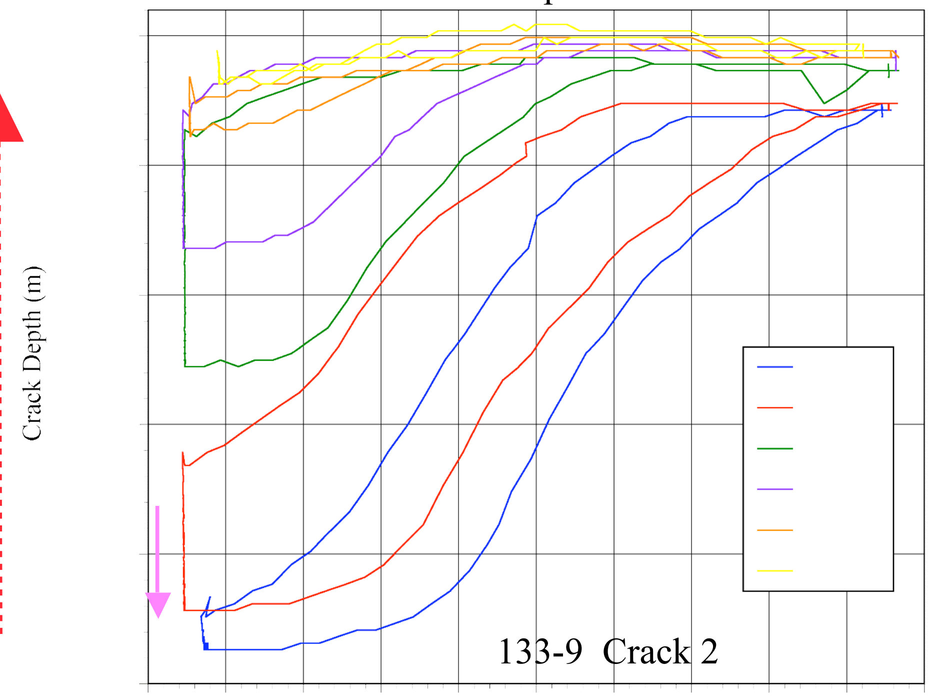


Individual Cycle Results: In-Phase vs. Out-of-Phase

In-of-Phase TMF   288C - 454C
1800 s Hold in Tension
180 s Hold in Compression



Out-of-Phase TMF   288C - 454C
180 s Hold in Tension
1800 s Hold in Compression



Upward shift of Cycle Loops corresponds with crack growth over cycles.

- Small changes in crack depth for in-phase cycling, some crack opening during 1800s hold time in tension.
- Large changes in crack depth for out-of-phase cycling, crack closure during 1800s hold time in compression.

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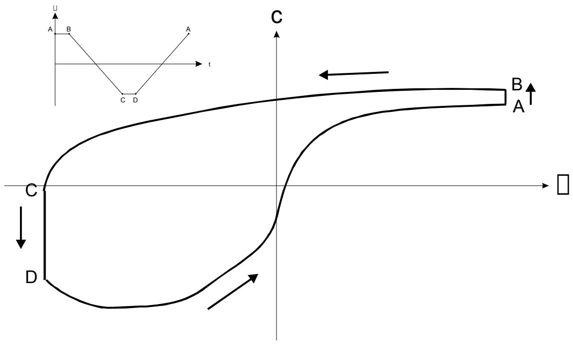
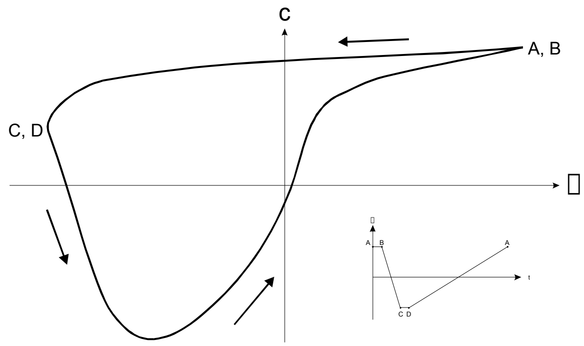
Individual Cycle Responses Show Traits Common to Experiments of a Given Type

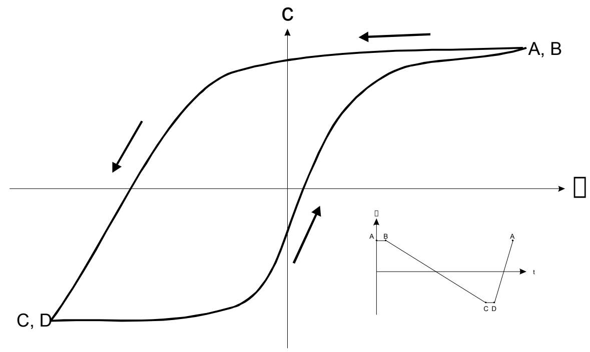
Isothermal



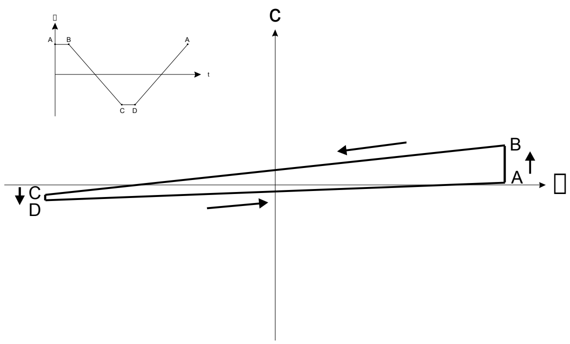
Slow-Fast Isothermal



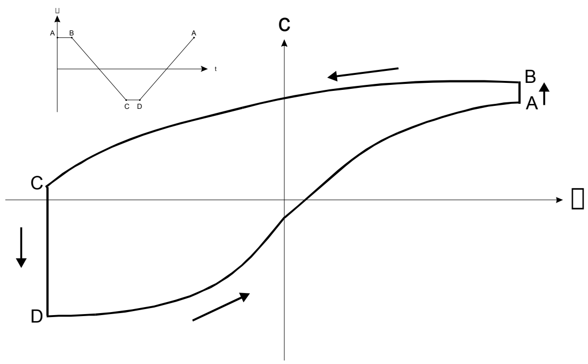
Fast-Slow Isothermal



In-Phase TMF



Out-of-Phase TMF



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Conclusions

- *A fully automated TMF test system capable of extremely sensitive crack growth measurements was developed.*
- *Thermomechanical fatigue crack growth rates correlate with the effective stress intensity factor*
- *Crack growth rates increase with temperature*
- *Higher crack growth rates are observed in out-of-phase TMF tests than in-phase TMF tests*
- *Isothermal tests have crack growth rates higher than in-phase TMF tests but lower than out-of-phase TMF tests*
- *Hold time effects are complex*
  - *hold times in compression increase the crack growth rate more than hold times in tension*
  - *hold times are the most significant factor affecting the opening and closing of cracks during cycling*
- *Loading wave shape effects are apparent in the crack-strain hysteresis loops*
- *Crack opening/closing behavior is complex and changes with cycles*