



SMAnalytics – Shape Memory Alloy Test Data Analysis and Reporting Software

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High Temperature and Smart Materials Branch

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What is the Goal?

**Use Shape Memory Materials
for Actuation**

Reliable, traceable shape memory material test data
- Used by designers and engineers



What is the driving need?

Reliable, traceable shape memory material test data

FAA – US Code of Federal Regulations Title 14 Part 25
“the suitability and durability of materials used for parts, the failure of which could adversely affect safety, must be established on the basis of experience or tests; conform to approved specifications that ensure their having the strength and other properties assumed in the design data; and take into account the effects of environmental conditions, such as temperature and humidity, expected in service”



Other Sectors Include:

Automotive



Space



Industrial Valve





Need – Standards for Actuator Materials

Reliable, traceable shape memory material test data

(1) Tested per standard test methods – “conform to approved specifications that ensure their having the strength and other properties assumed in the design data”

- What standards are there for actuator SMAs?

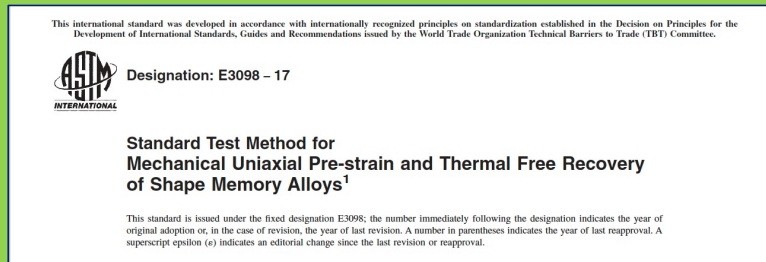
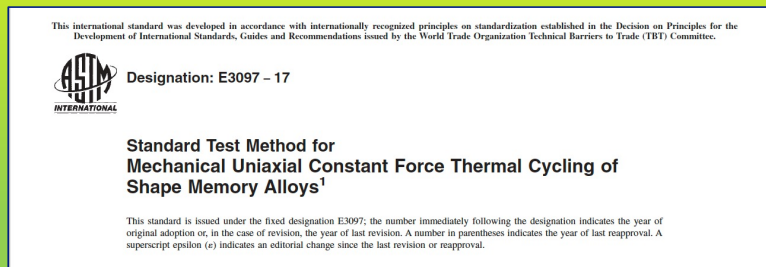




Standardization – Method and Analysis

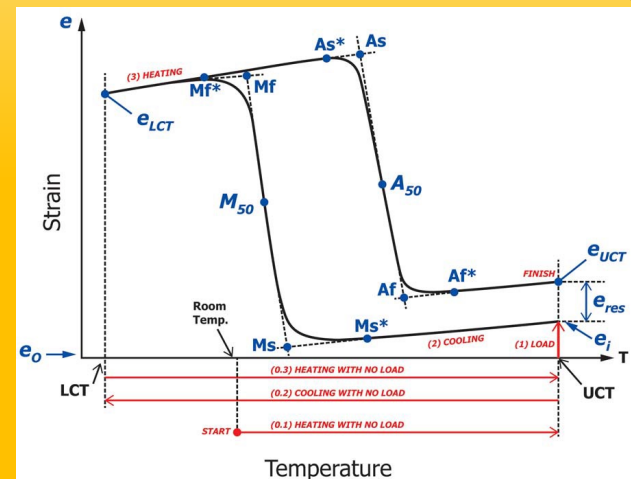
UCFTC and UPFR Style tests have been used for decades to evaluate SMA properties

Only recently standardized: ASTM 2017
Standardize test methods and measured parameters



Analysis methodology is still loosely defined

ASTM E3097: “12.2 Graphically determine A_s , A_f , M_s and M_f by the intersection of tangent lines drawn from the steepest portion of the strain versus temperature curves on heating and cooling and lines tangent to the strain versus temperature slopes near the LCT and the UCT as shown in Fig. 1.”



Reduce Uncertainty in Data

Even out of the same lot of material, there can be many sources of variability in data

Mitigation Strategy: **Reduce, Quantify ...**

Sample Prep and Design



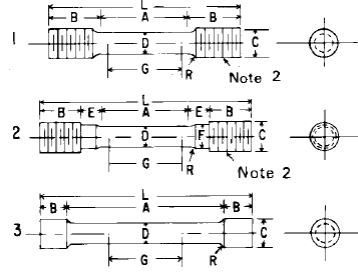
Designation: E 8 - 01

Standard Test Methods for Tension Testing of Metallic Materials¹

This standard is issued under the fixed designation E 8; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.

Reduce



Testing Methodology

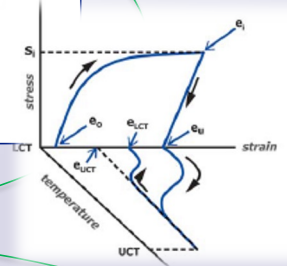


Designation: E3098 - 17

Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys¹

This standard is issued under the fixed designation E3098; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last revision. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

Reduce



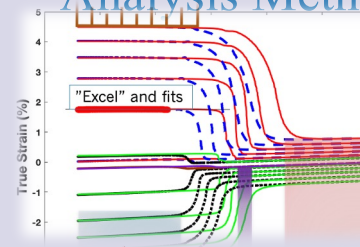
Test Setup/Equipment

Ruggedness, ILS Testing_c

	Strain Rate	Cooling Rate	Heating Rate
-1	0.001 mm/mm per min	1 deg C / min	1 deg C / min
1	0.01 mm/mm per min	4 deg C / min	4 deg C / min
Run #**			
1	1	1	1
2	-1	1	1
3	-1	-1	1
4	1	-1	-1

Quantify

Analysis Method



Analyst



SMAnalytics = **Reduce**

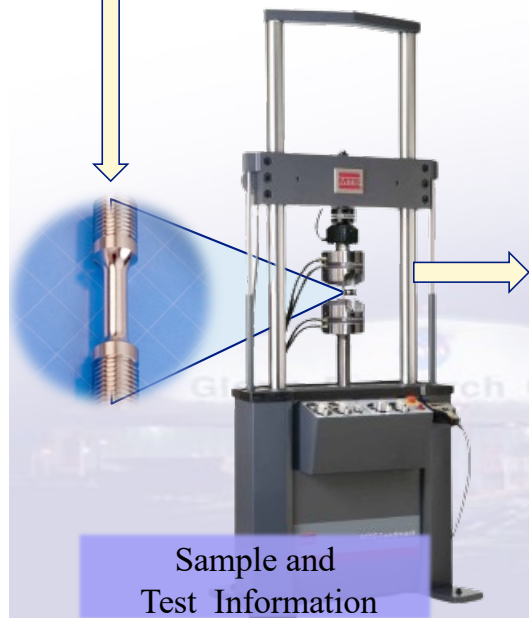
Big Picture – Test Data to Customer/User

ASTM Standard

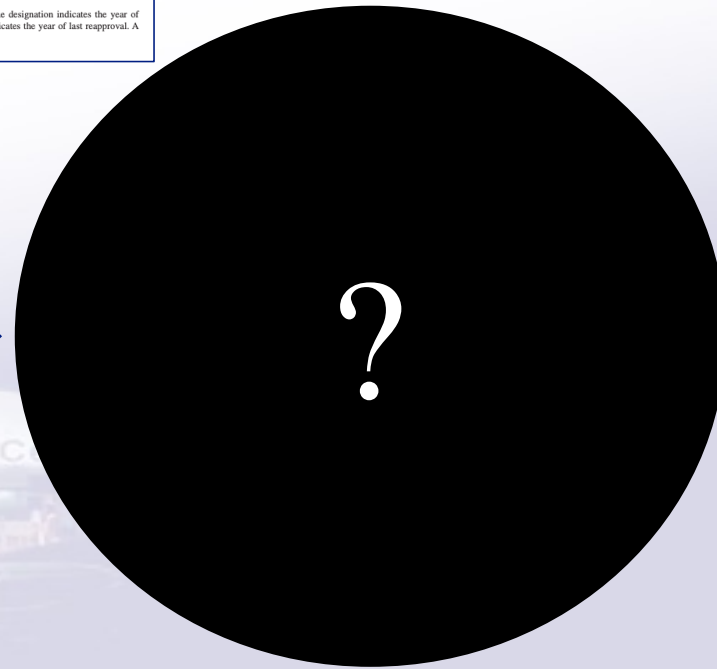
Designation: E3097 – 17

Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys¹

This standard is issued under the fixed designation E3097; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.



Sample and Test Information



ASTM Material Certification Report

Test Note	
Test Date	12/5/17
Lab	NASA-GRC/SHENB
Operator	O. Bonifin
Material	NTI
Sample Identification	
Material Condition	
Specimen Geometry	Cylindrical dogbone ($\Phi = 0.1530$ in, gauge L = 0.5 in)
Lower Cycle Temperature (LCT)	37
Upper Cycle Temperature (UCT)	150
Austenite Start - A _s (Deg C)	117.8771
Austenite Finish - A _f (Deg C)	122.8756
Martensite Start - M _s (Deg C)	70.722
Martensite Finish - M _f (Deg C)	67.642
Austenite Start Strain (ϵ , A _s)	0.06827
Austenite Finish Strain (ϵ , A _f)	0.02175
Martensite Start Strain (ϵ , M _s)	0.001662
Martensite Finish Strain (ϵ , M _f)	0.06902
Strain at Lower Cycle Temp (e, LCT)	0.07035
Strain at Upper Cycle Temp (e, UCT)	0.02033
Cooling Transformation Strain (ϵ , c _t)	0.067358
Heating Transformation Strain (ϵ , h _t)	0.04652
Heating / Cooling Method	Induction
temperature uniformity	
heating rate (Deg C / min)	4
cooling rate (Deg C / min)	4
Strain Measurement Method	Mechanical extensometer with Alumina Rods
Strain Rate (mm/mm per min)	0.01
Hold Time (s)	30

NASA Shape Memory Material Database

Shape Memory Alloys

Superelastic Alloys

Quarterly

Multi Element

Shape Element

Big Picture – Test Data to Customer/User



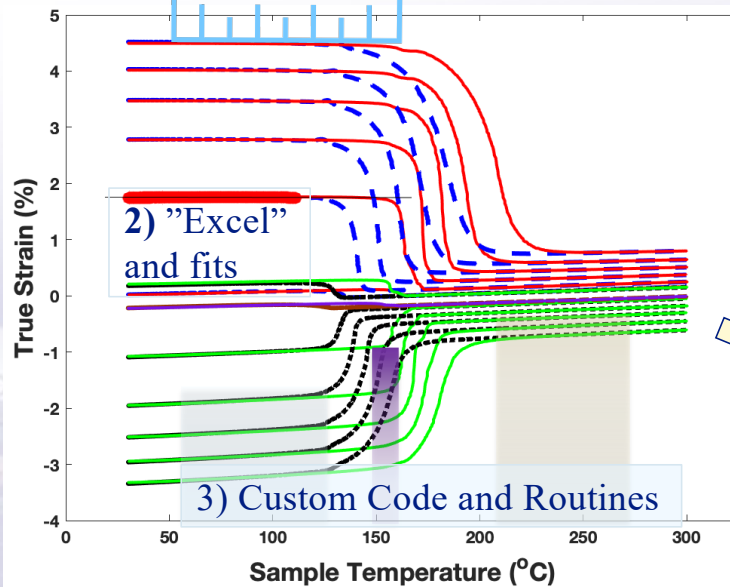
Designation: E3097 – 17

ASTM Standard

Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys¹

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1) Plot and Straight Edge

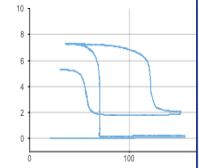


2) "Excel" and fits

3) Custom Code and Routines

ASTM Material Certification Report

Test Type	UC/TC
Test Note	
Test Date	12/5/17
Lab	NASA-GRC-SH3MB
Operator	O. Bonifan
Material	NTI
Sample Identification	
Material Condition	
Specimen Geometry	Cylindrical dogbone ($\Phi = 0.1530$ in, gauge L = 0.5 in)
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Hold Time (s)	30



NASA Shape Memory Material Database



Sample and Test Information



SMAAnalytics was designed to fill this gap

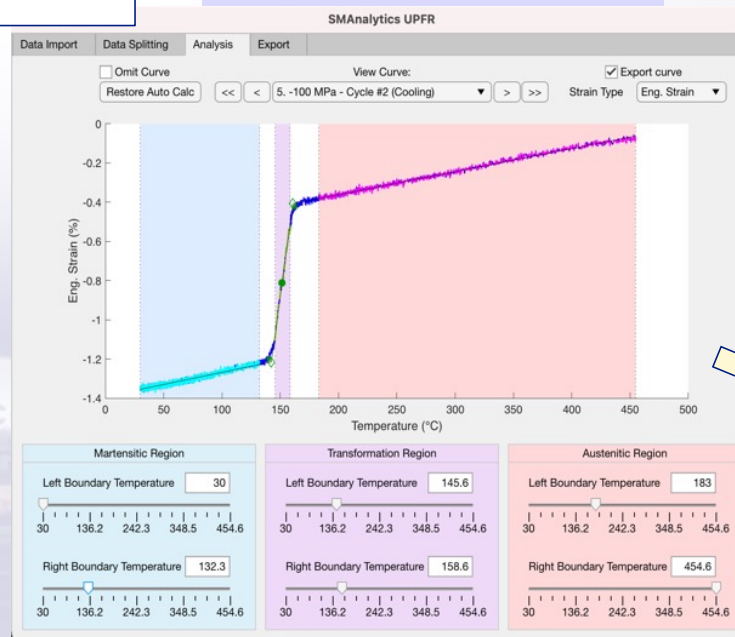


Designation: E3097 - 17

ASTM Standard

Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys¹

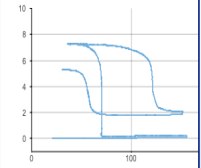
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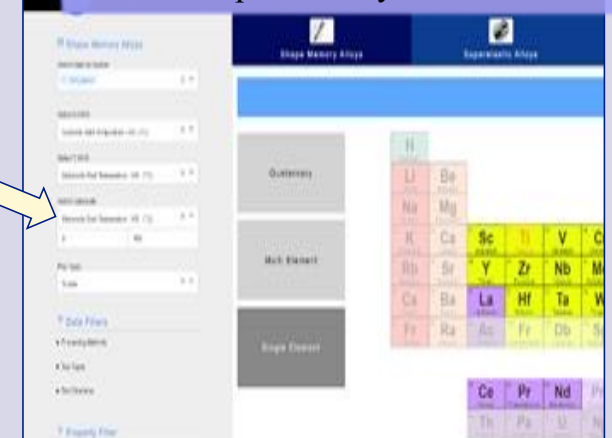
Sample and Test Information

ASTM Material Certification Report

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Austenite Start Strain (e _{AS})	0.06827
Austenite Finish Strain (e _{AF})	0.02175
Martensite Start Strain (e _{MS})	0.001662
Martensite Finish Strain (e _{MF})	0.06902
Strain at Lower Cycle Temp (e _{LCT})	0.07035
Strain at Upper Cycle Temp (e _{UCT})	0.02033
Cooling Transformation Strain (e _{CT})	0.067358
Heating Transformation Strain (e _{HT})	0.04652
Heating / Cooling Method	Induction
Temperature Uniformity	
Heating rate (Deg C / min)	4
Cooling rate (Deg C / min)	4
Strain Measurement Method	Mechanical extensometer with Alumina Rods
Strain Rate (mm/mm per min)	0.01
Hold Time (s)	30



NASA Shape Memory Material Database





SMAanalytics addresses 3 common SMA tests

(1) Differential Scanning Calorimetry - DSC

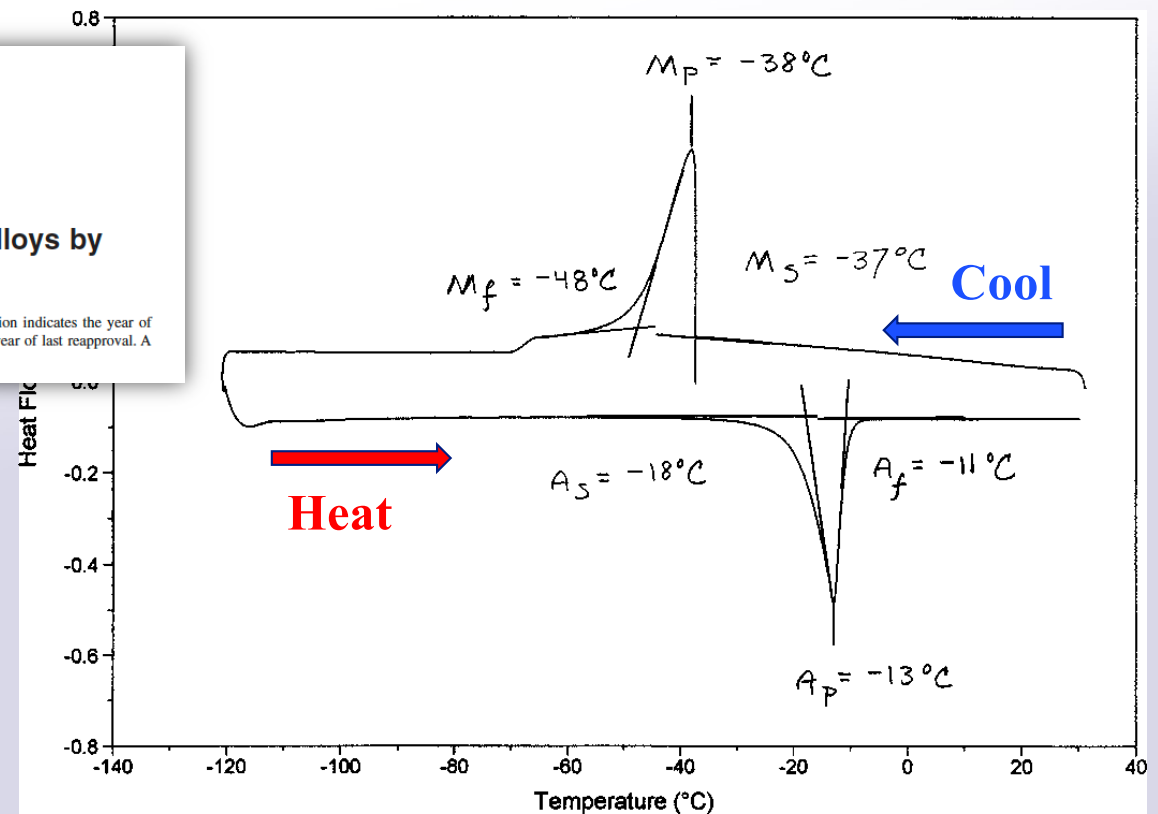
Designation: F 2004 – 05

Standard Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis¹

This standard is issued under the fixed designation F 2004; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

Transformation Temperatures

- + Any Production Stage
- + Small Sample
- + No Load Conditions





SMAAnalytics addresses 3 common SMA tests

(2) Uniaxial Constant Force Thermal Cycling - UCFTC

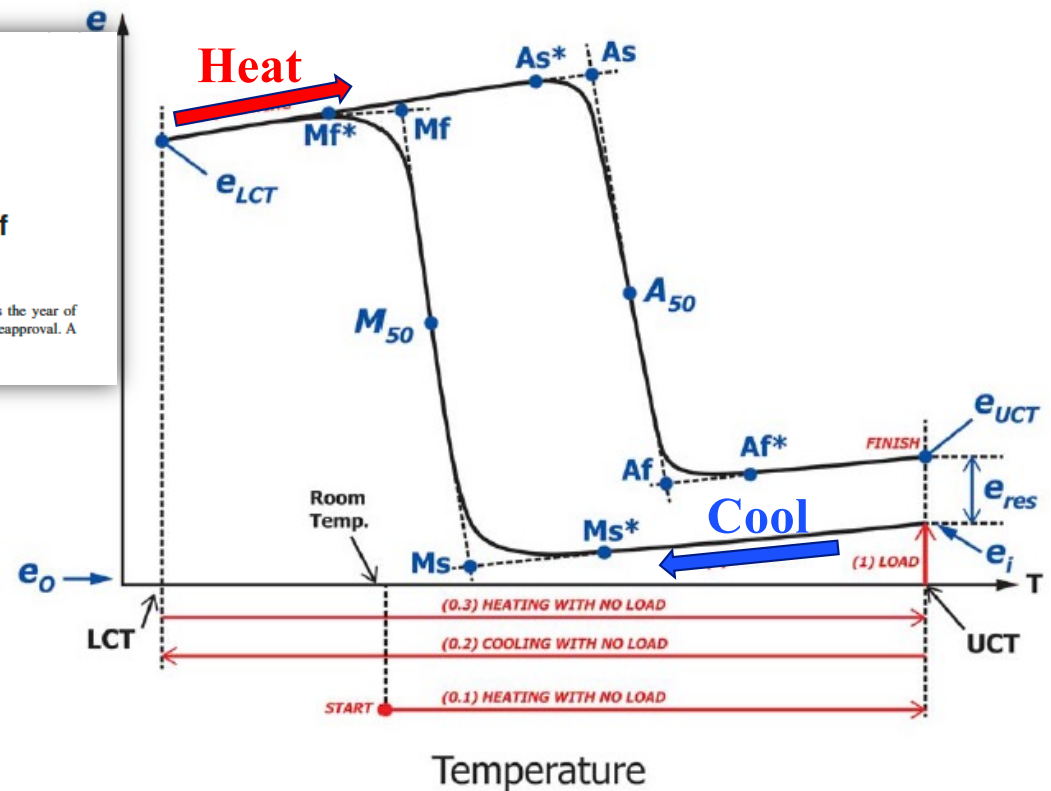
Designation: E3097 – 17

Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys¹

This standard is issued under the fixed designation E3097; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

Transformation Temperatures Transformation Strains

- + Actuation response
- + Under some load, or no-load



SMAnalytics addresses 3 common SMA tests

(3) Uniaxial Pre-strain and Thermal Free Recovery - UPFR

Designation: E3098 – 17

Standard Test Method for Mechanical Uniaxial Pre-strain and Thermal Free Recovery of Shape Memory Alloys¹

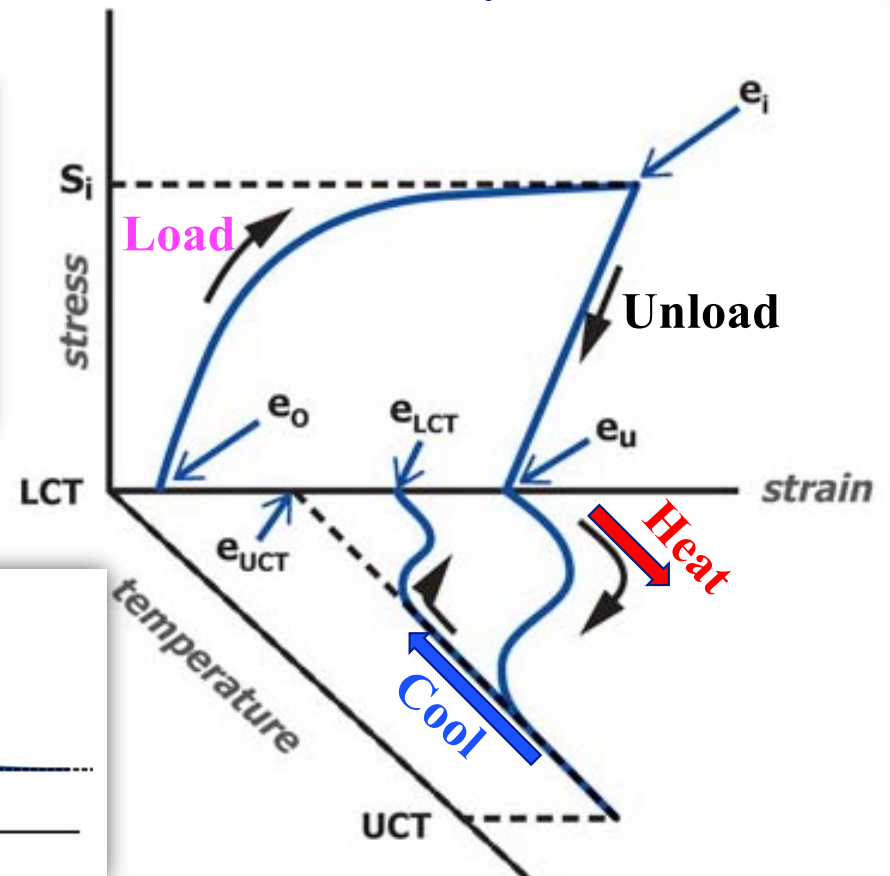
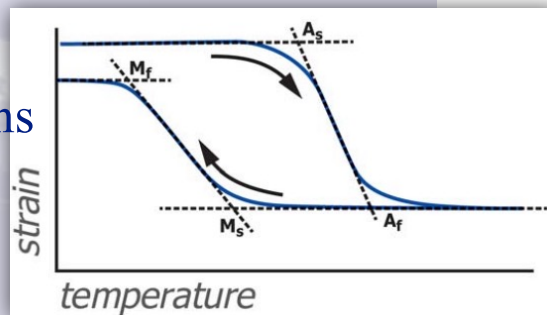
This standard is issued under the fixed designation E3098; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

Transformation Temperatures

Transformation Strains

Strain Recovery

- + Representative conditions
- + Stress Free or Stressed

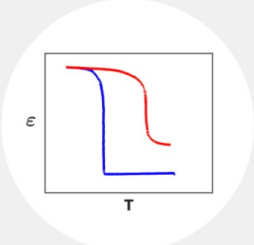




A User-Friendly Graphical Interface Launch Window



The logo for SMAAnalytics with DSCAN features a stylized blue and red line graph with a red star at the origin, followed by the text "SMAAnalytics" in a large, bold, sans-serif font, and "with DSCAN" in a smaller font below it.



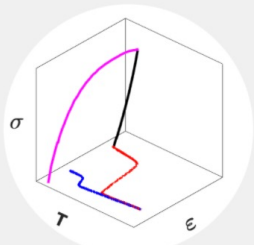
A circular icon containing a graph of strain (ϵ) versus temperature (T). The graph shows a blue curve that remains at a high strain level until a certain temperature, then drops sharply to a lower strain level, and finally levels off at a higher temperature.

UCFTC

New UCFTC Analysis

Load UCFTC Analysis

ASTM E3097



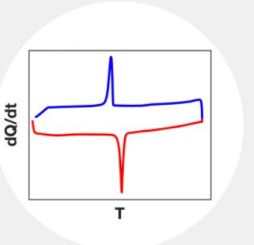
A circular icon containing a 3D plot of stress (σ) versus temperature (T) and strain (ϵ). The plot shows a complex, multi-colored surface representing the relationship between these three variables.

UPFR

New UPFR Analysis

Load UPFR Analysis

ASTM E3098



A circular icon containing a graph of heat flow rate (dQ/dt) versus temperature (T). The graph shows a blue curve with a sharp, narrow peak at a specific temperature, indicating a phase transition.

DSC

New DSC Analysis

Load DSC Analysis

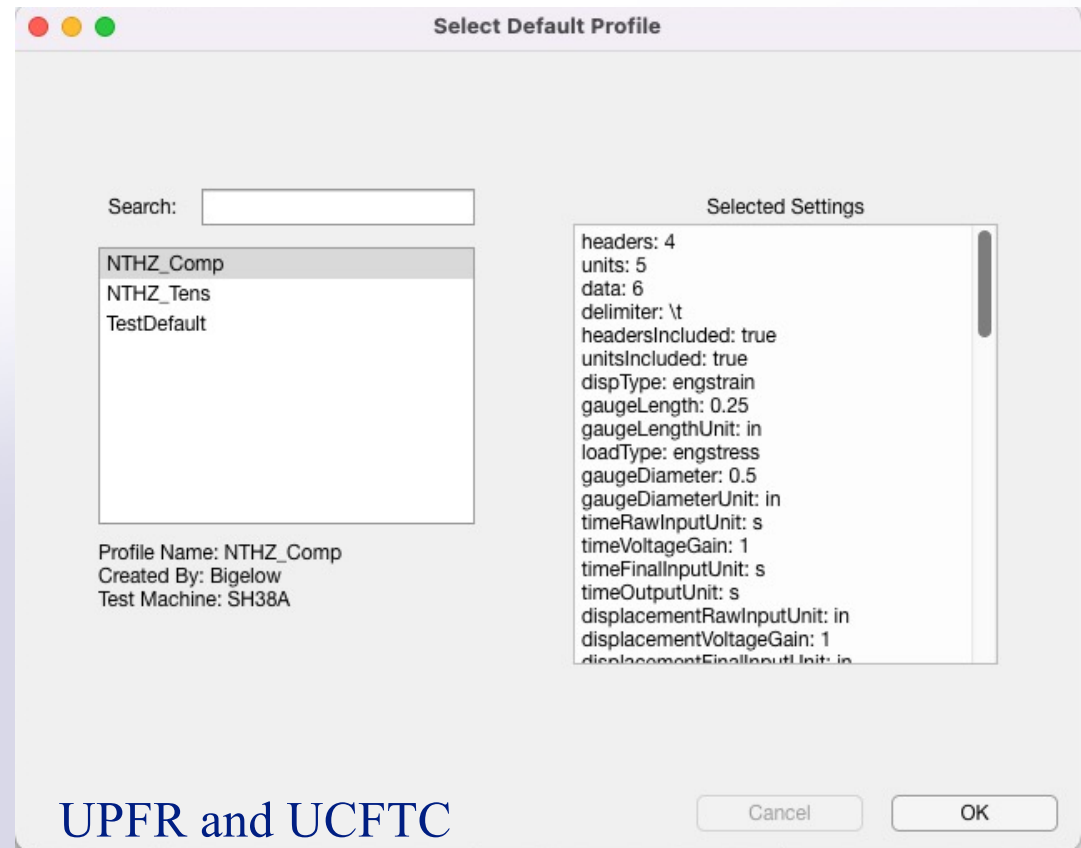
ASTM F2004

Version: 1.0.2 (Released 12/22/2023)



Create, save, and reuse Profiles: Streamline Analysis

- **Test type profiles**
 - Compression
 - Tension
 - Cyclic
- **Lab based profiles**
 - My lab
 - Your lab
- **Data characteristic profiles**
 - Noisy load
 - Fast vs slow heat/cool





1b

Accepts many file formats and allows easy parsing

Text File Settings

Data Settings

Selected Data File
Run 1 Transcribed New.txt

Raw Data File

Import Results

	seconds	C	MPa	%
	time	temperature	stress	strain
0	37.48305	0.98703	0	
1	37.43973	0.98603	0	
2	37.44081	0.98473	0	
3	37.41177	0.98069	0	
4	37.34543	0.97924	0	
5	37.38213	0.97868	0	
6	37.43492	0.98315	0	
7	37.51518	0.98686	0	
8	37.5504	0.99174	0	
9	37.54662	0.99404	0	
10	37.47446	0.99913	0	
11	37.54822	1.00222	0	
12	37.62576	1.01105	0	
13	37.67821	1.02244	0	

Line Selected: 1

Update Import Parameters (Row #)

Column Headers Units First Data Line

☐ Not Included ☒ Not Included

File Delimiter

Update Default Settings

OK

Text File Settings

Data Settings

Selected Data File
Run 1 Transcribed New.txt

Raw Data File

Import Results

	Column 1	Column 2	Column 3	Column 4
Row 1	seconds	C	MPa	%
Row 2	time	temperature	stress	strain
Row 3	0	37.48305	0.98703	0
Row 4	1	37.43973	0.98603	0
Row 5	2	37.44081	0.98473	0
Row 6	3	37.41177	0.98069	0
Row 7	4	37.34543	0.97924	0
Row 8	5	37.38213	0.97868	0
Row 9	6	37.43492	0.98315	0
Row 10	7	37.51518	0.98686	0
Row 11	8	37.5504	0.99174	0
Row 12	9	37.54662	0.99404	0

Line Selected: 1

Update Import Parameters (Row #)

Column Headers Units First Data Line

☐ Not Included ☐ Not Included

File Delimiter

Update Default Settings

OK



1b

Data Import Controls – Classifying

- Handles raw data (e.g., force, displ.) or calculated data (e.g., stress, strain)
- Data Column Titles transfer over automatically from Column Headers
 - Uses your headers for easy identification
- Unit conversion to meet different needs



Data File

Text File Settings | **Data Settings**

Displacement Data Type

☐ Gauge Displacement

☒ Engineering Strain

☐ True Strain

Specimen Gauge Length: 0.25 in

Load Data Type

☐ Force

☒ Engineering Stress

☐ True Stress

Specimen Diameter: 0.5 in

	Data Column	Raw Input Unit	Time Step	Time Zero Offset	Final Input Unit
Time	time (seconds)	s	1	0	s

	Data Column	Raw Input Unit	Voltage Gain	Voltage Offset	Final Input Unit
Eng. Strain	strain (%)	%	1	0	%
Eng. Stress	stress (MPa)	MPa	1	0	MPa
Temperature	temperature (C)	°C	1	0	°C

Data Column	Import?
time (seconds)	☒
temperature (C)	☒
stress (MPa)	☒
strain (%)	☒

Select All Clear All

Output Unit

Time: min

Eng. Strain: %

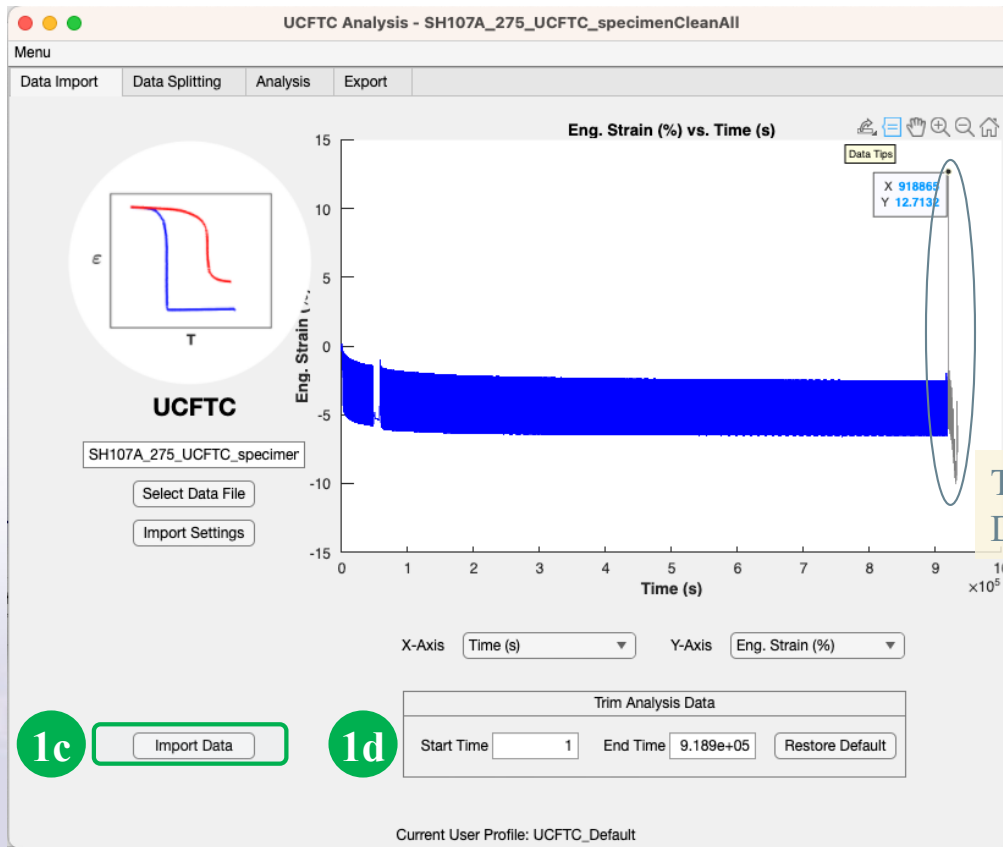
Eng. Stress: MPa

Temperature: °C

Update Default Settings OK



Trim un-needed pre-test or post-test data



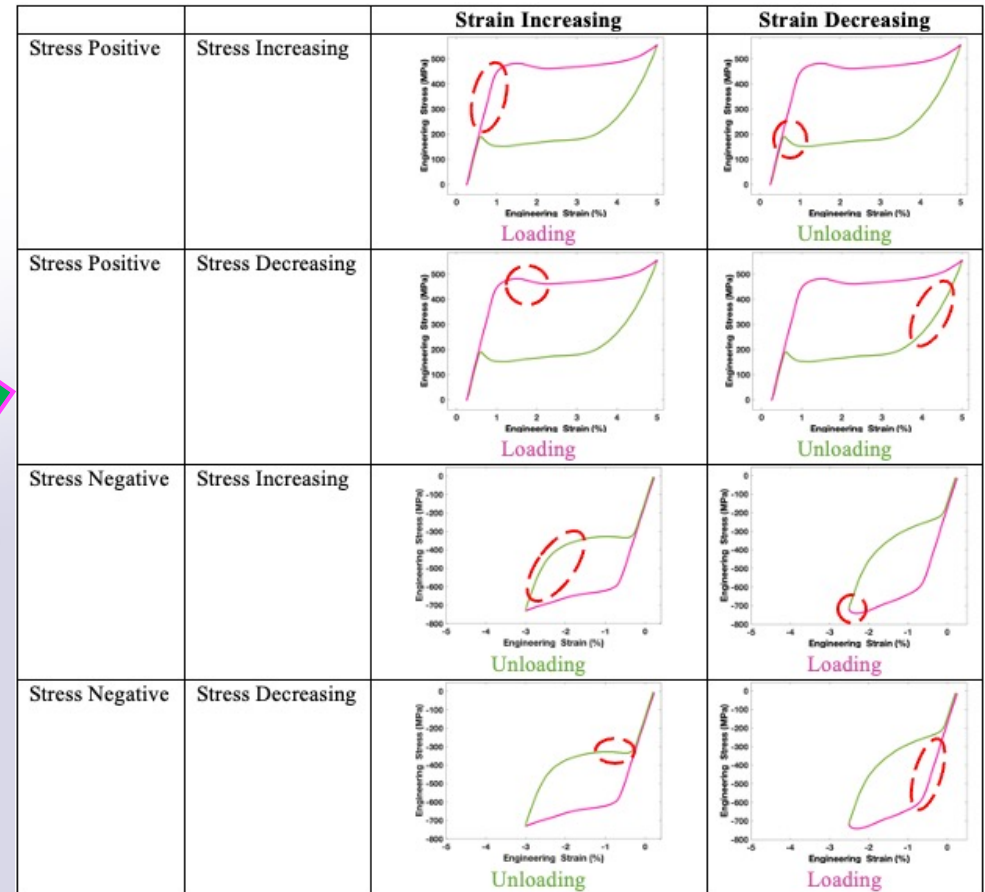
Reduce data pre-processing requirements

- Extra heat/cool cycles in UPFR
- Data Spikes
- Strain Resets



Auto-detects segments to facilitate data splitting

- **Heat:**
 - Stress Constant
 - Temperature $\uparrow$
- **Cooling:**
 - Stress Constant
 - Temperature $\downarrow$
- Loading, Unloading



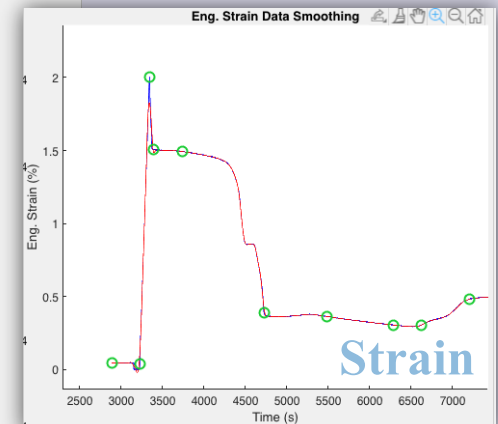
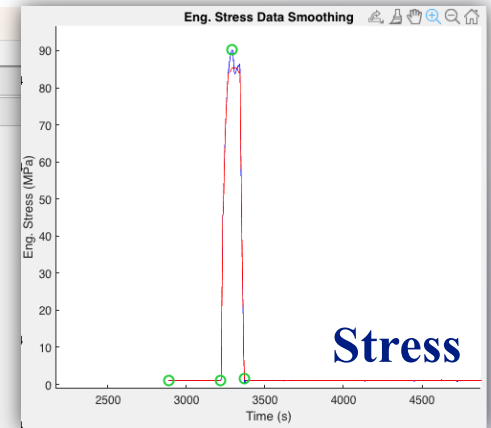
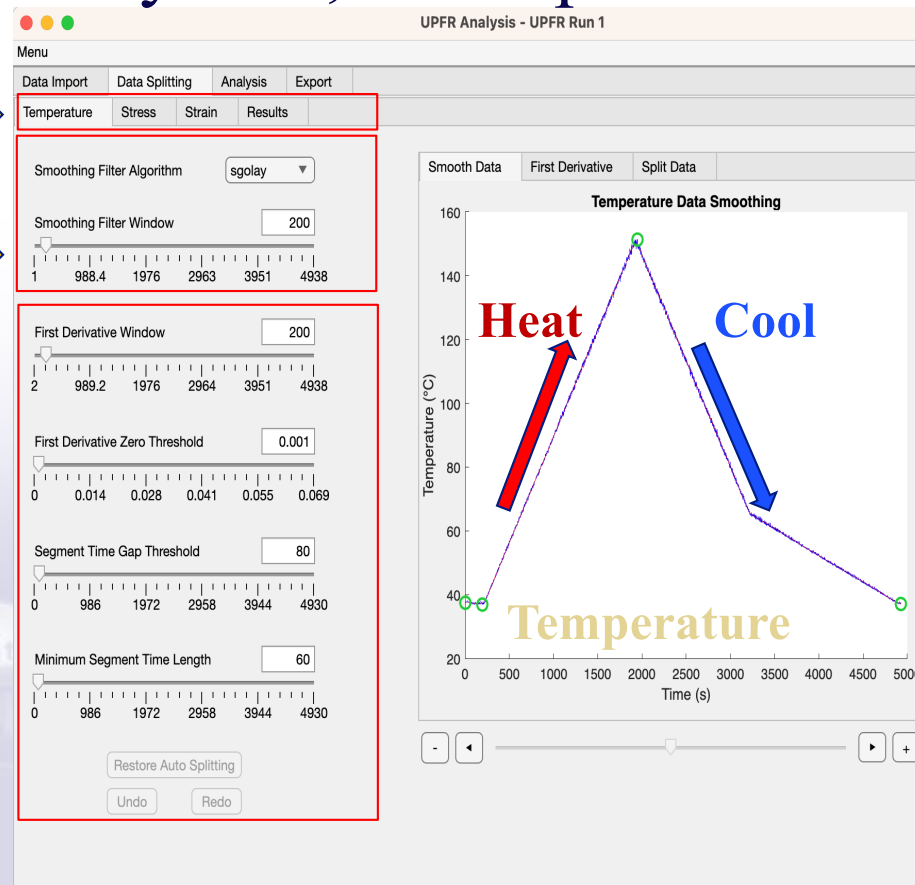


Customizable filters and thresholding to split clean data, noisy data, incomplete data

Operate on any test variable →

Filter options →

Thresholds for optimal fits, smoothing and data splitting →





Processing Algorithms – Mathematically based

Derivatives

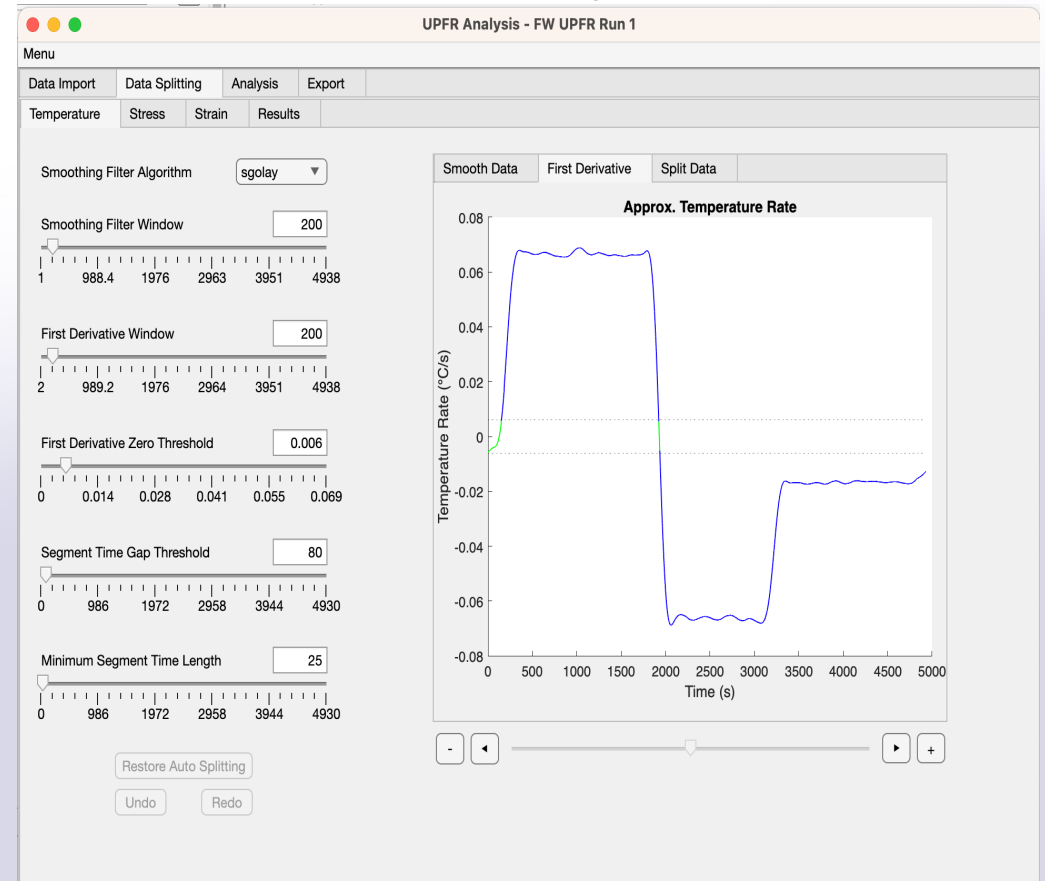
Splitting

Transformation Temperatures

2nd Derivatives

Transformation Region

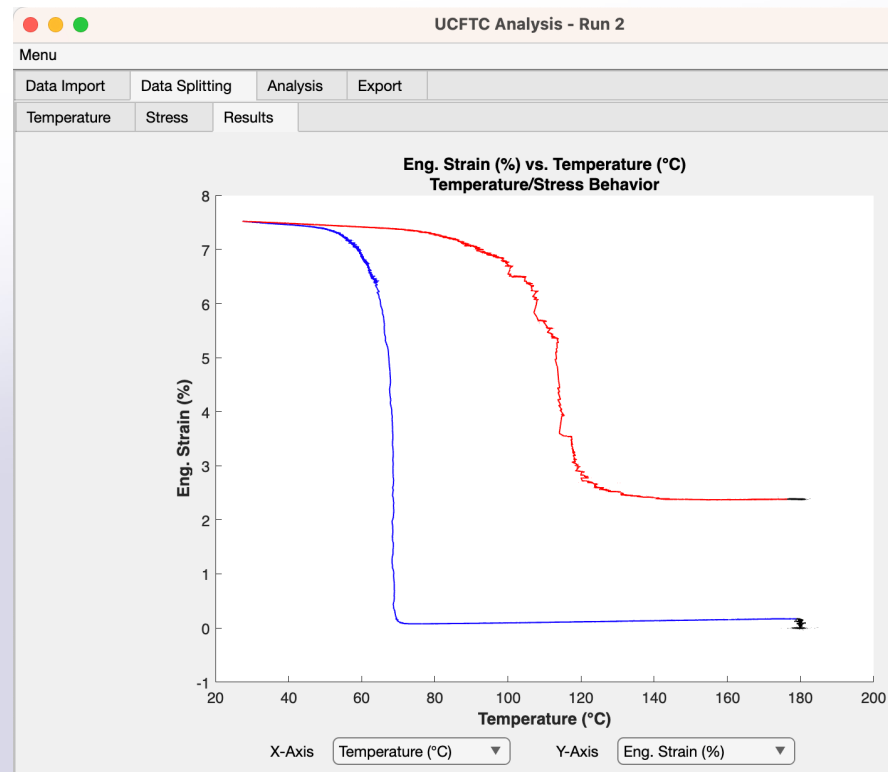
Star Temperatures





UCFTC Results: Software can identify key data segments during splitting

- Heating
- Cooling
- Loading Δ
- Unloading ∇





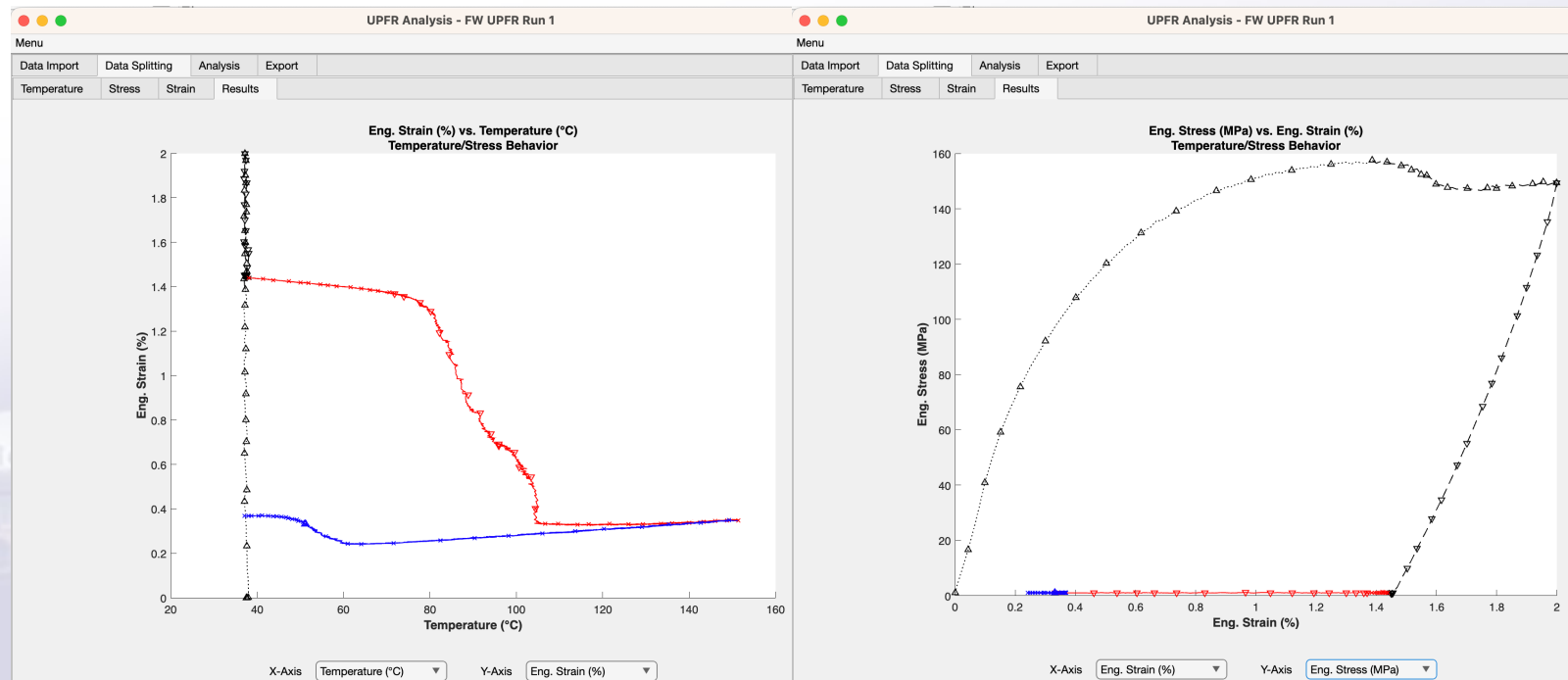
UPFR Results: Software can identify key data segments

Heating

Cooling

Loading Δ

Unloading ∇

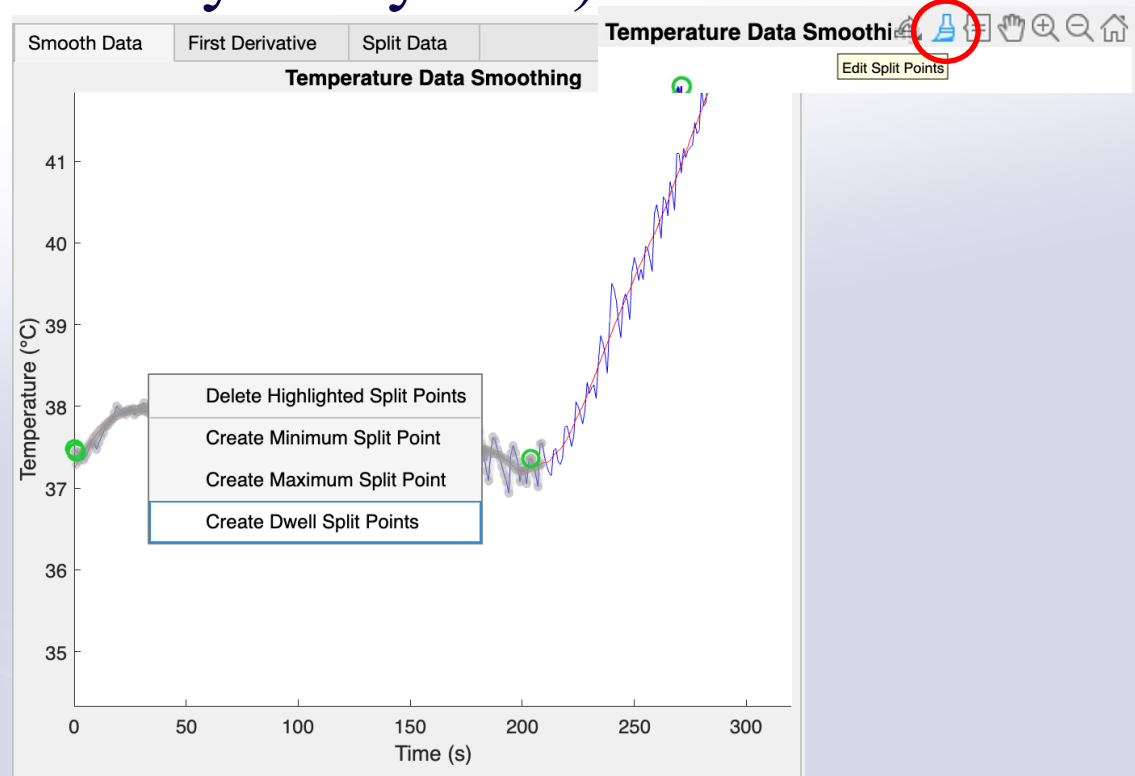




Manual editing available

when automated fitting needs adjusted to get split points
(example: very noisy data)

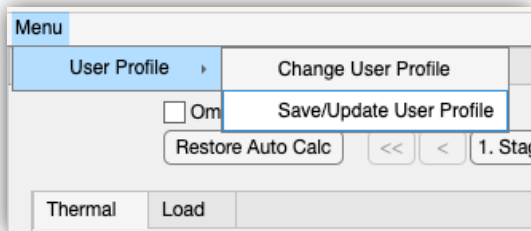
- Use Brush Tool in Toolbar
 - “Edit Split Points”
- Select (Box) data of interest
 - Few points for Max/Min
 - Range of points for Dwell
- Select Desired Action





Creating/Updating Profiles

- Profiles save settings from import and splitting
- Reduces need for user input during import and splitting



Save/Update User Profile

Save As New Profile Update Existing Profile

Save As New Profile

User Profile Name:

Creator:

Test Machine:

Cancel OK

Save/Update User Profile

Save As New Profile Update Existing Profile

Update Existing Profile

Search:

UPFR_Default

Profile Name: UPFR_Default
Created By: UPFR_Default
Test Machine: UPFR_Default

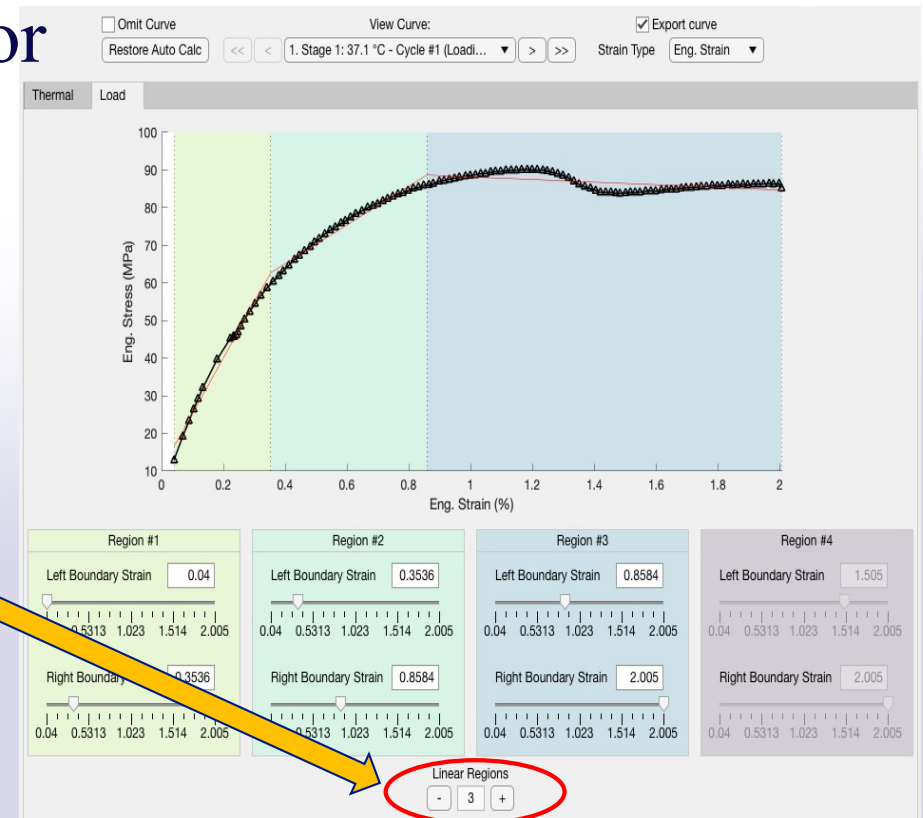
Selected Settings

headers: 4
units: 5
data: 6
delimiter: \t
headersIncluded: true
unitsIncluded: true
dispType: engstrain
gaugeLength: 0.25
gaugeLengthUnit: in
loadType: engstress
gaugeDiameter: 0.5
gaugeDiameterUnit: in
timeRawInputUnit: s
timeVoltageGain: 1
timeFinalInputUnit: s
timeOutputUnit: s
displacementRawInputUnit: in
displacementVoltageGain: 1
displacementFinalOutputUnit: in

Cancel OK

UPFR: Editing Load/Unload Segments to account for material behavior

**Splitting the stress-strain curve:
into 1 to 4 segments**



Manually adjust with up to 4 Linear Regions + Adjust Boundary Sliders

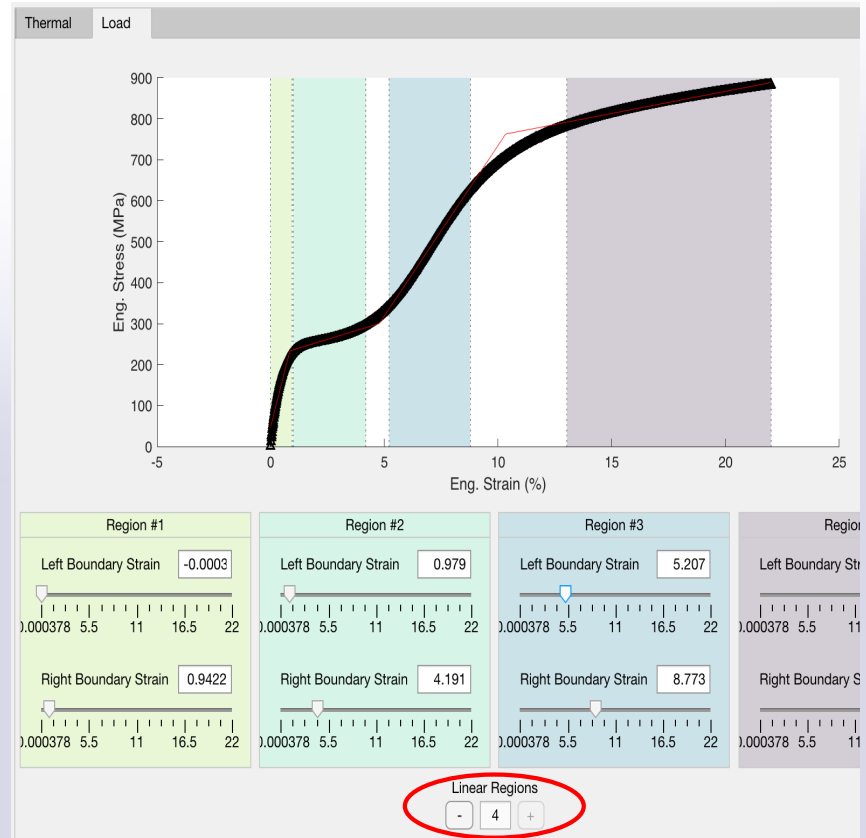
** Mouse over slider and use scroll wheel to fine tune



UPFR: Editing Load/Unload Segments to account for material behavior

To Capture:

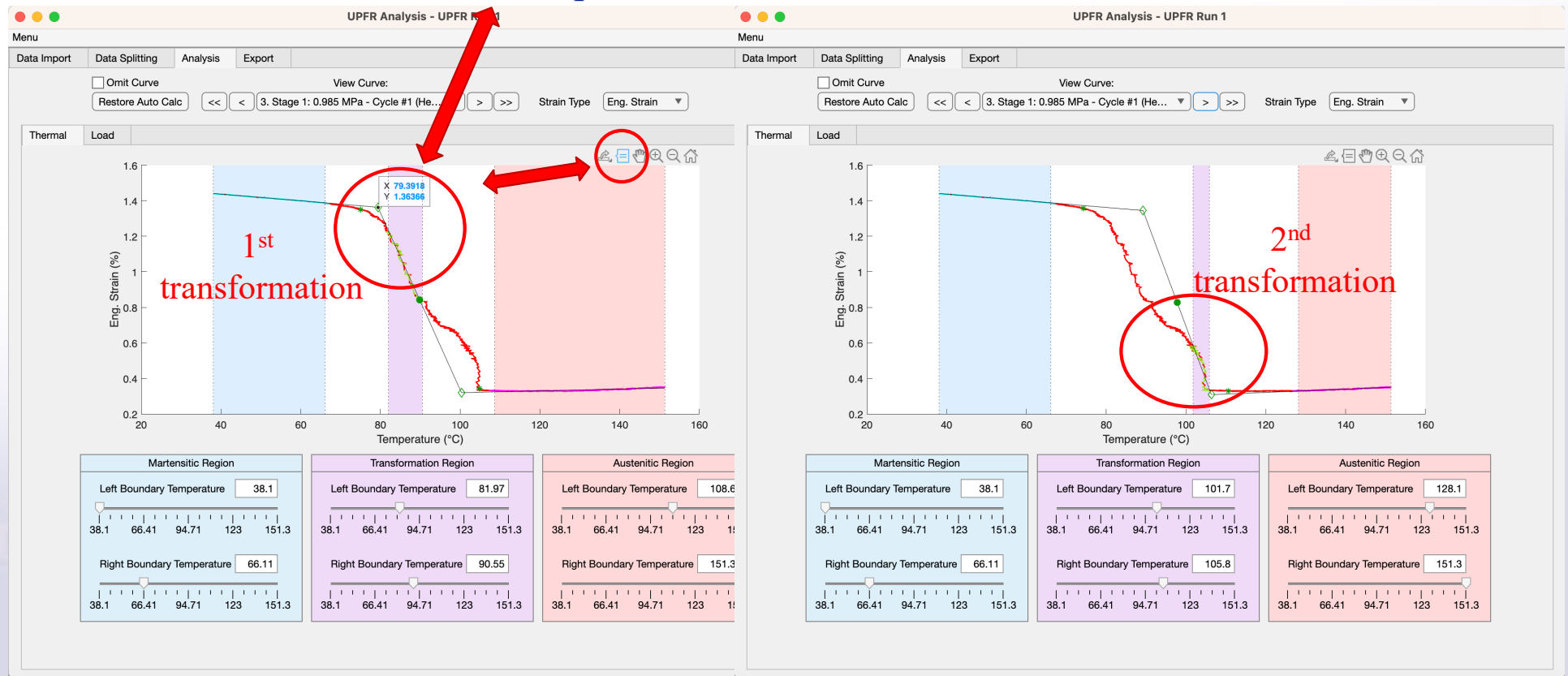
- Slopes/Modulus
- Yield stress (0.2% offset, 0.5%)
- Max stress/strain
- Plateau strain/stress
- Onset of detwinning





Accounting for multiple phase transformations

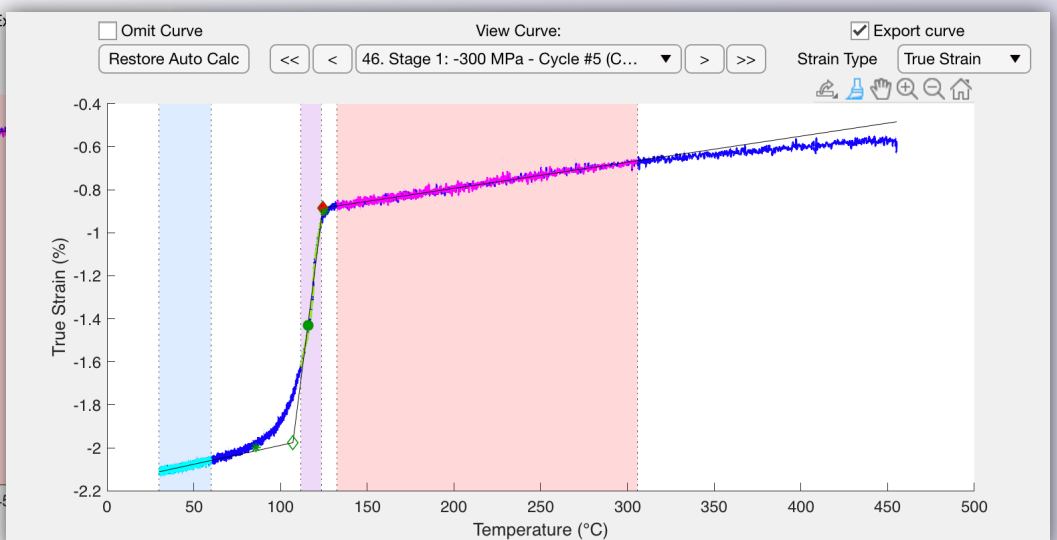
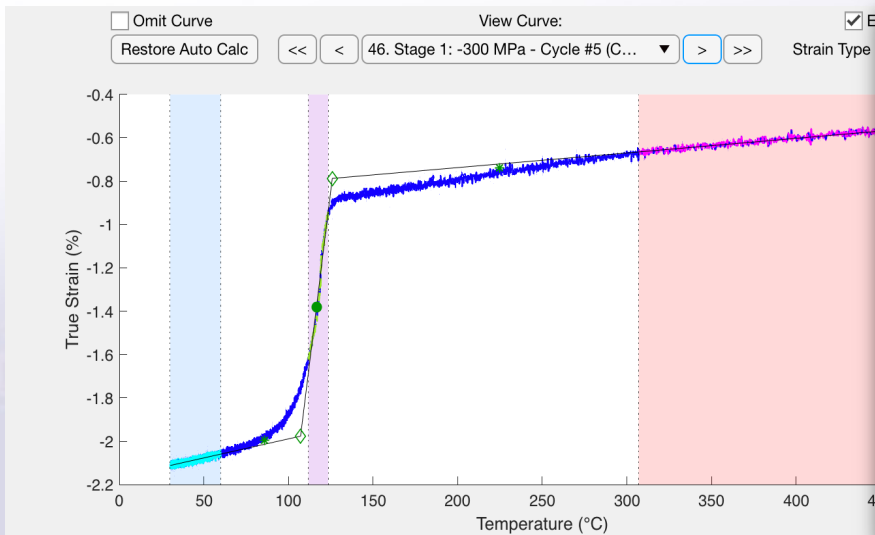
Can use Data Tips to view measured values





Editing Heat/Cool Segments

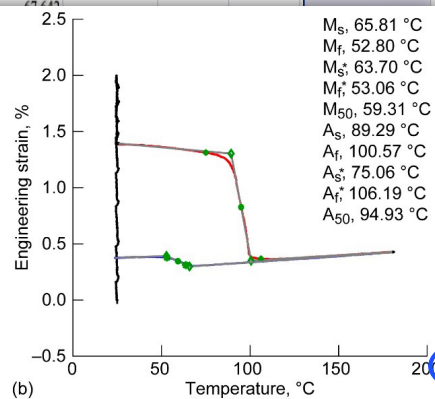
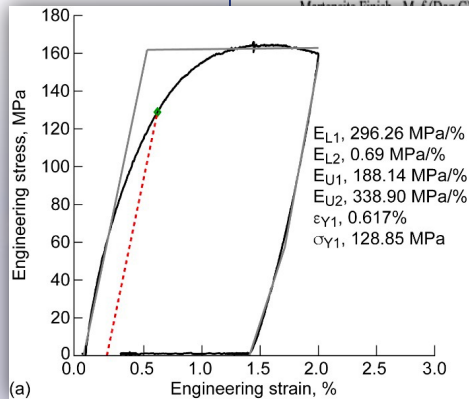
- Can manually adjust any region/fit
- Adjust Boundary Sliders as desired
 - ** Mouse over slider and use scroll wheel to fine tune
- Use Data-Tip to view values if desired





Exporting – ASTM Report

Test Type	UCFTC
Test Note	
Test Date	12/5/17
Lab	NASA-GRC-SH38B
Operator	O. Benafan
Material	NiTi
Sample Identification	
Material Condition	
Specimen Geometry	Cylindrical dogbone (Ø = 0.1530 in, gauge L = 0.5 in)
Lower Cycle Temperature (LCT)	37
Upper Cycle Temperature (UCT)	150
Austenite Start - A _s (Deg C)	117.8771
Austenite Finish - A _f (Deg C)	122.8756
Martensite Start - M _s (Deg C)	70.722
Martensite Finish - M _f (Deg C)	65.81



UPFR Analysis - FW UPFR Run 1

Menu

Data Import Data Splitting Analysis Export

ASTM UPFR Report

Cycle Selection	Raw Data				
Stage #	# of Load Cycles	Mean Temperature (°C)	# of Thermal Cycle	Mean Stress (MPa)	Export UPFR?
1	1	37.4479	1	0.9853	☒

Note: Only stages containing at least one full load cycle and one full thermal cycle may be chosen.

Export UPFR Report Export Raw Data Export Database

1

View/Edit Sample Info

Sample Info

Open Export Folder



Exporting – Database format available

UPFR Analysis - FW UPFR Run 1

Menu
Data Import | Data Splitting | Analysis | Export

ASTM UPFR Report

Cycle Selection | Raw Data

Raw Data	Export?
time (seconds)	☒
temperature (C)	☒
stress (MPa)	☒
strain (%)	☒

Select All | Clear All

Export UPFR Report | Export Raw Data | Export Database

Open Export Folder

Sample Info

View/Edit Sample Info

Automatic 3

Test Information

Test Type	UPFR
Sample ID	FW UPFR Run 1
Test Date	9/5/23 0:00
Operator	
Laboratory	
Test Rig	
Material	
Specimen Geometry	
Heating Method	
Cooling Method	
Strain Measurement Method	
Method for Calculating A ₅₀ /M ₅₀	(A _f M _f + A _s M _s)/2
Test Notes	

Stage # Load Cycle Type Load Cycle Temperature Initial Strain

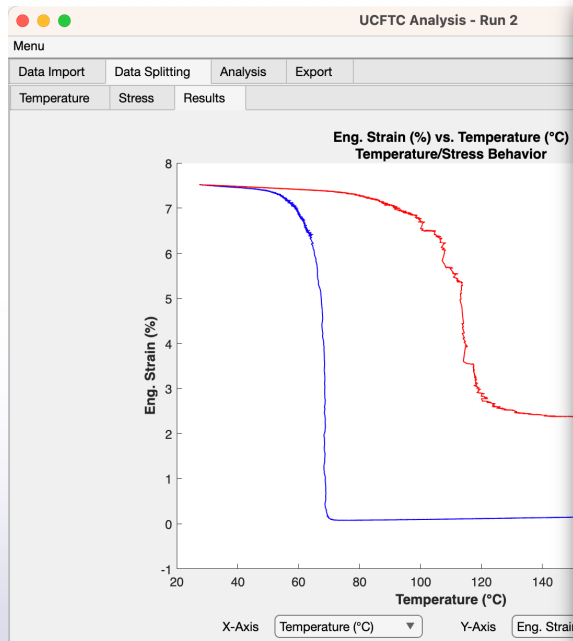
Stage #	Load Cycle Type	Load Cycle Temperature °C	Initial Strain % (Eng.)
1	Loading-Unloading	37.43296558	

Eng. Stress (MPa) vs. Eng. Strain (%)

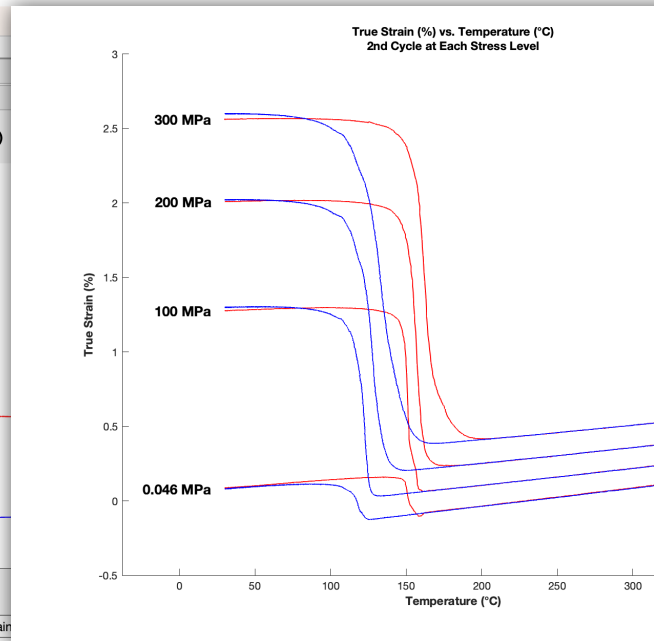
True Strain (%) vs. Temperature (°C) 2nd Cycle at Each Stress Level



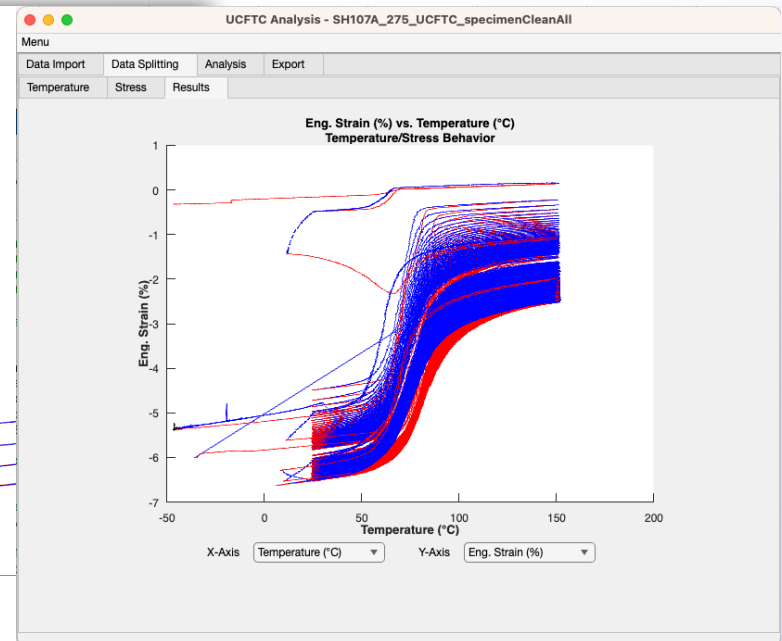
Powerful, robust algorithm can handle different “flavors” of UCFTC



Standard Test Method



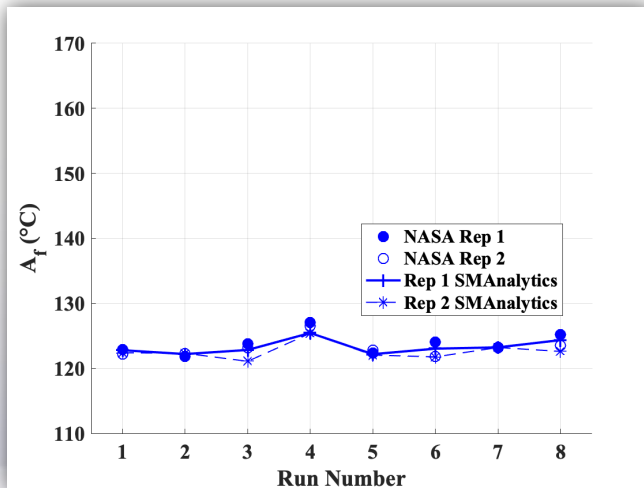
Multiple Stress Levels



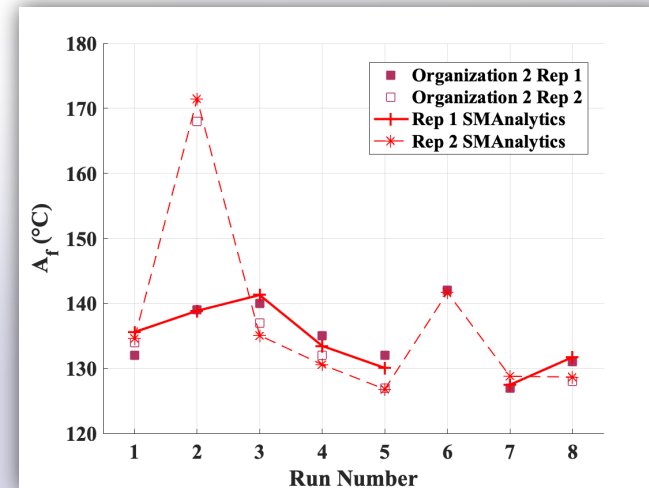
High Cycle (eg. Durability)
*even with “dirty” data
3min to process 1000cycles



SMAnalytics Analysis Matches Human Analysis Automatically



Clean Data



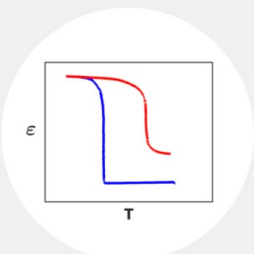
Noisy Data

Data from ASTM Ruggedness Software Validation



Launch Window

**SMAAnalytics**
with DSCAN

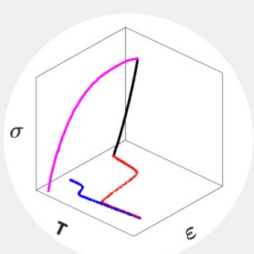


UCFTC

New UCFTC Analysis

Load UCFTC Analysis

ASTM E3097

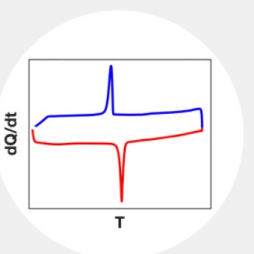


UPFR

New UPFR Analysis

Load UPFR Analysis

ASTM E3098



DSC

New DSC Analysis

Load DSC Analysis

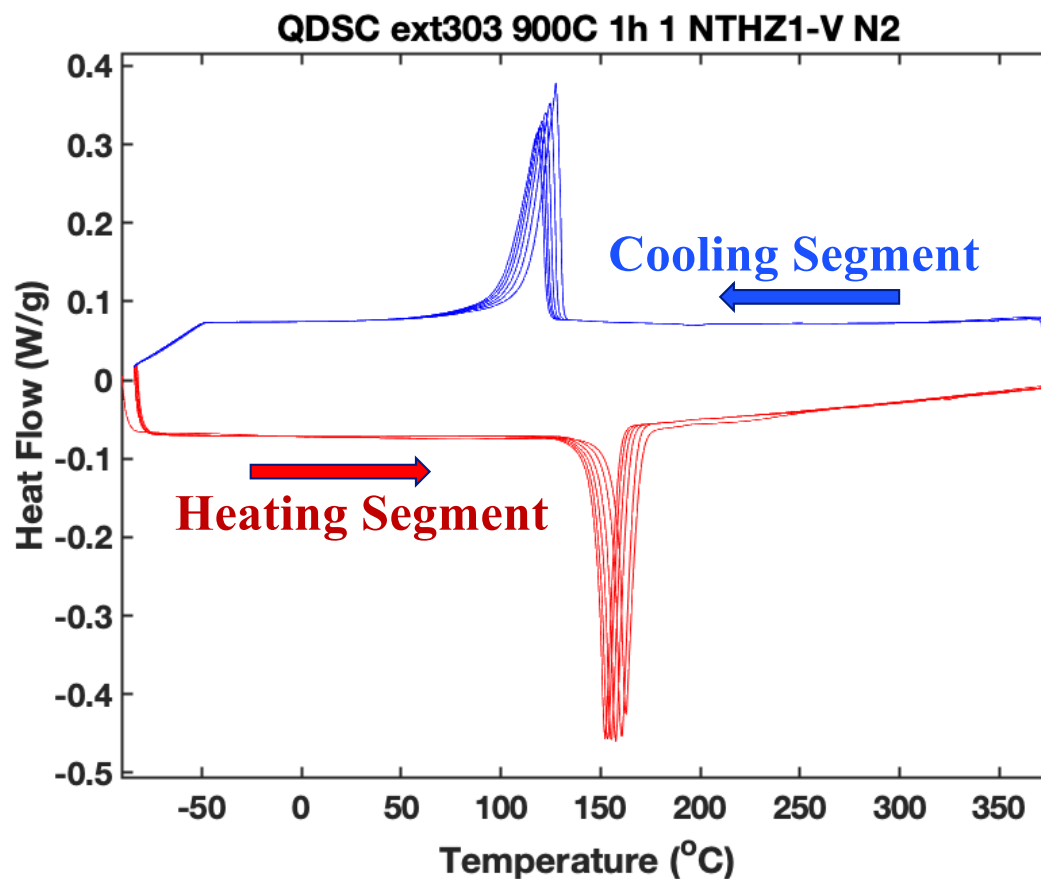
ASTM F2004

Version: 1.0.2 (Released 12/22/2023)



DSCAN Methodology – Split Cycles

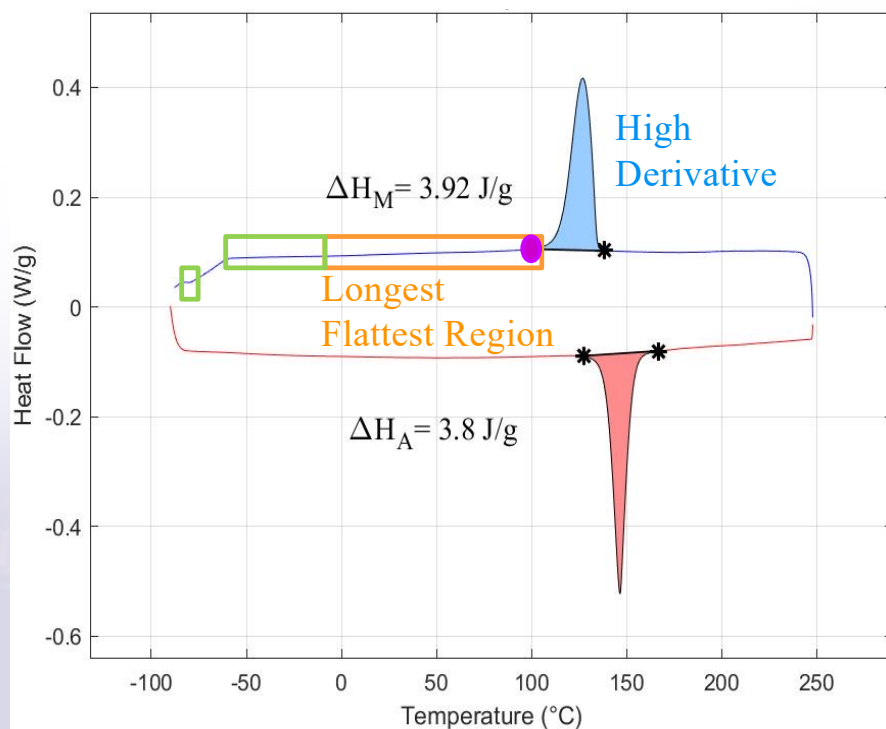
Split each file into cycles
Split cycles into **Heat** and **Cool**



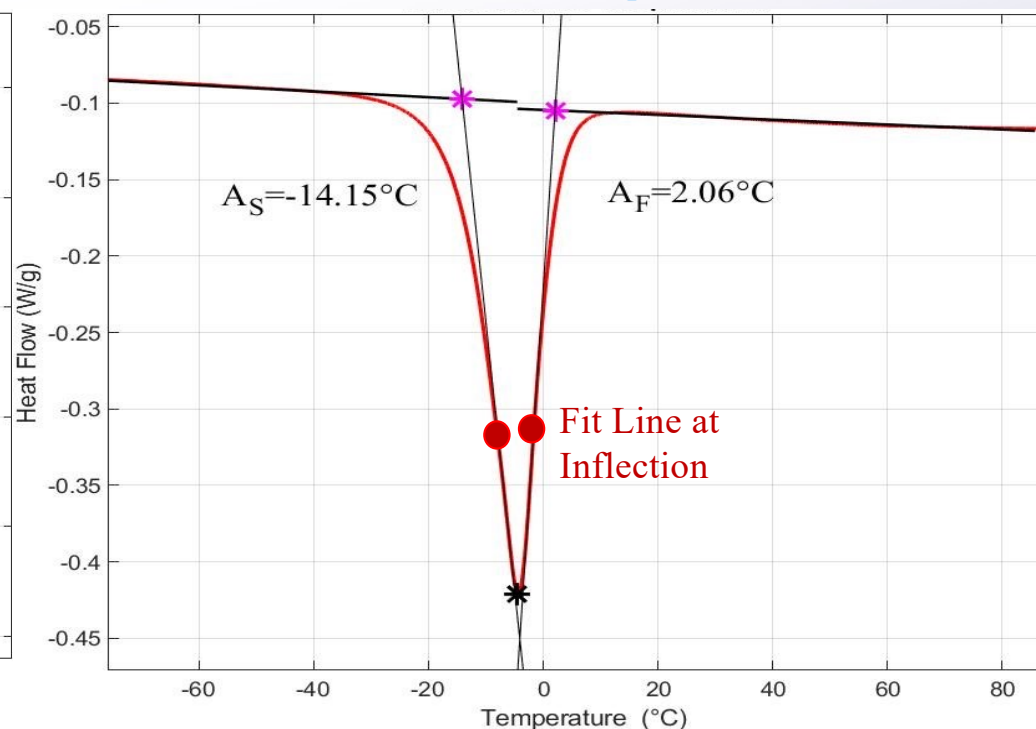


DSCAN Methodology – Automatic detection of:

Enthalpies



Transformation Temperatures





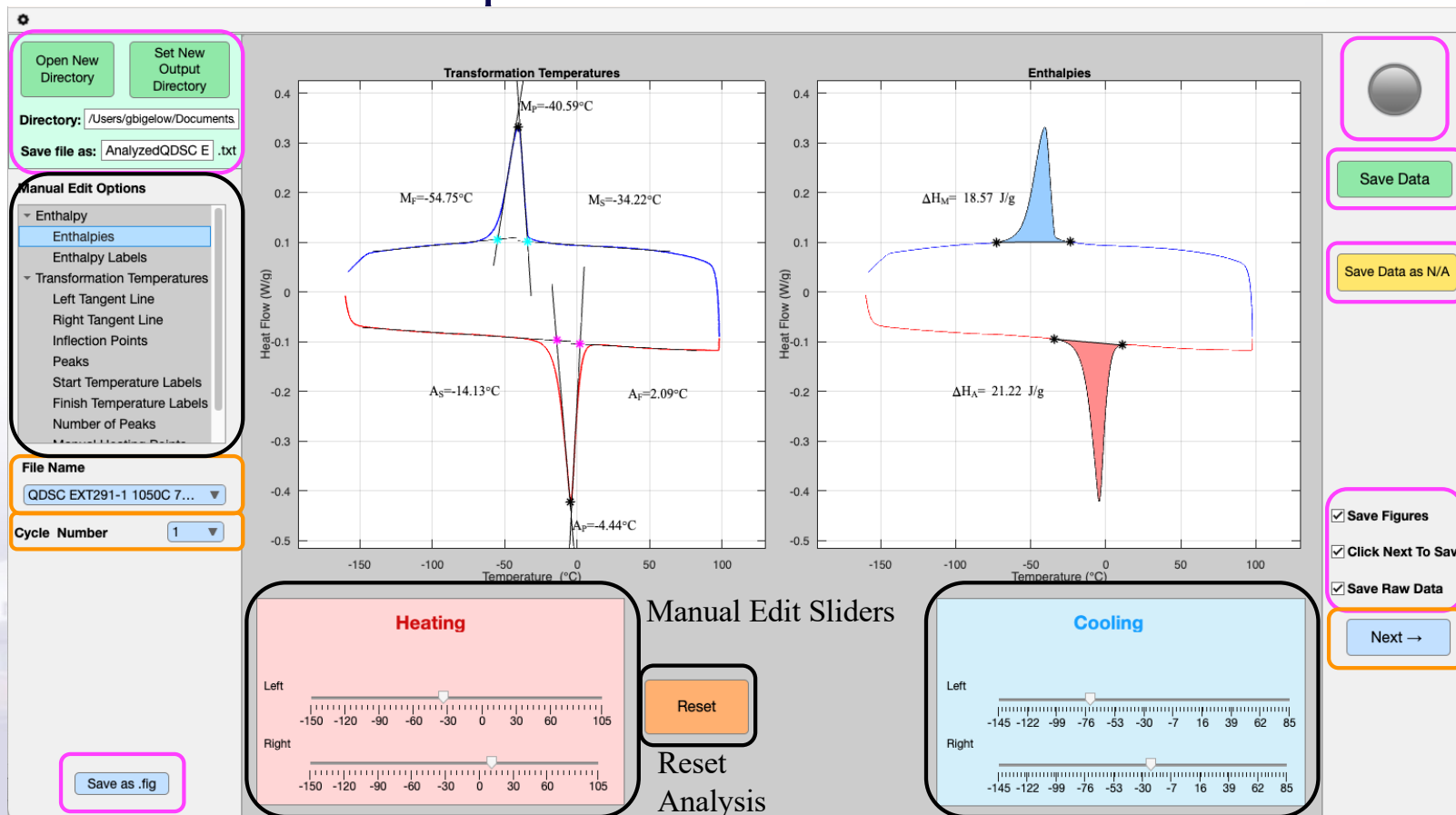
DSCAN: Customizable menu to handle routine DSC and complex DSC cases

Set Output Dir

Output File

Manual Edit
Option MenuCurrent File
Current Cycle

Save Figure



Save

Indicator

Save Data

Save N/A

Save

Options

Next Cycle



DSCAN: Detect and flag questionable data

Set Output Dir

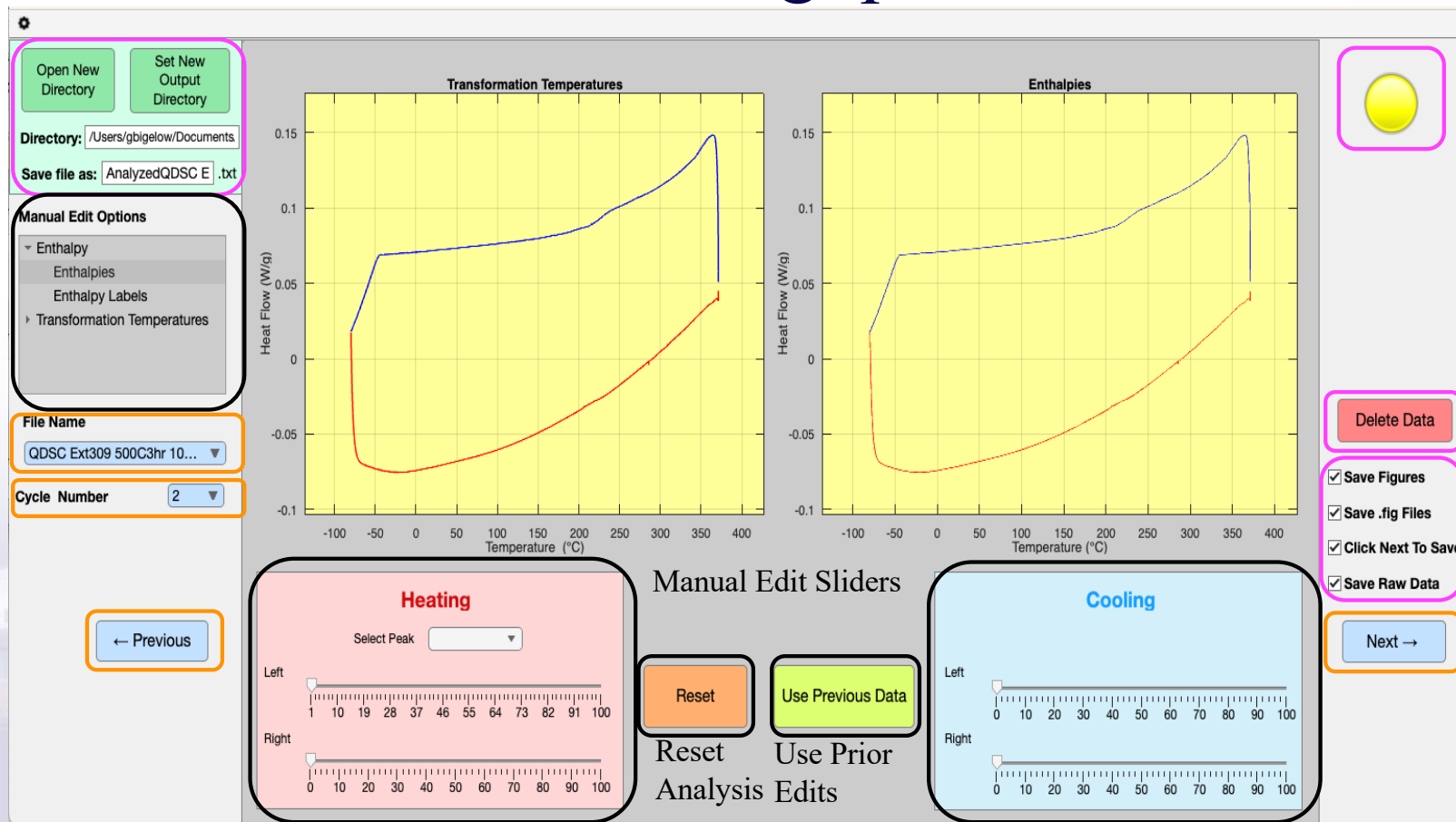
Output File

Manual Edit
Option Menu

Current File

Current Cycle

Prior Cycle

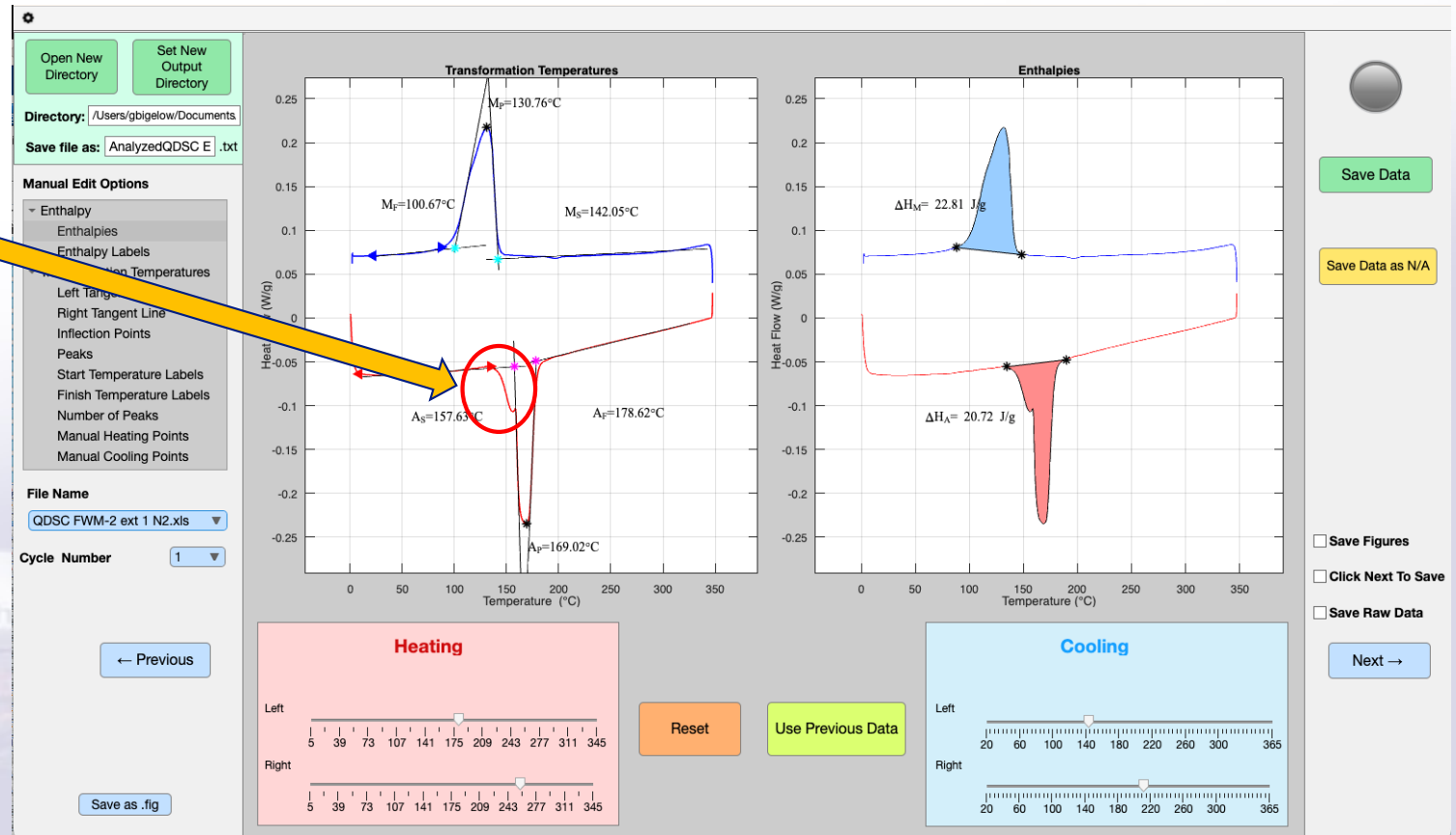
Saved
IndicatorDelete
Saved
Cycle Data
Save
Options

Next Cycle



Complex case: Can analyze multiple or overlapping peaks

Example:
DSCAN not
catching A_S from
secondary peak

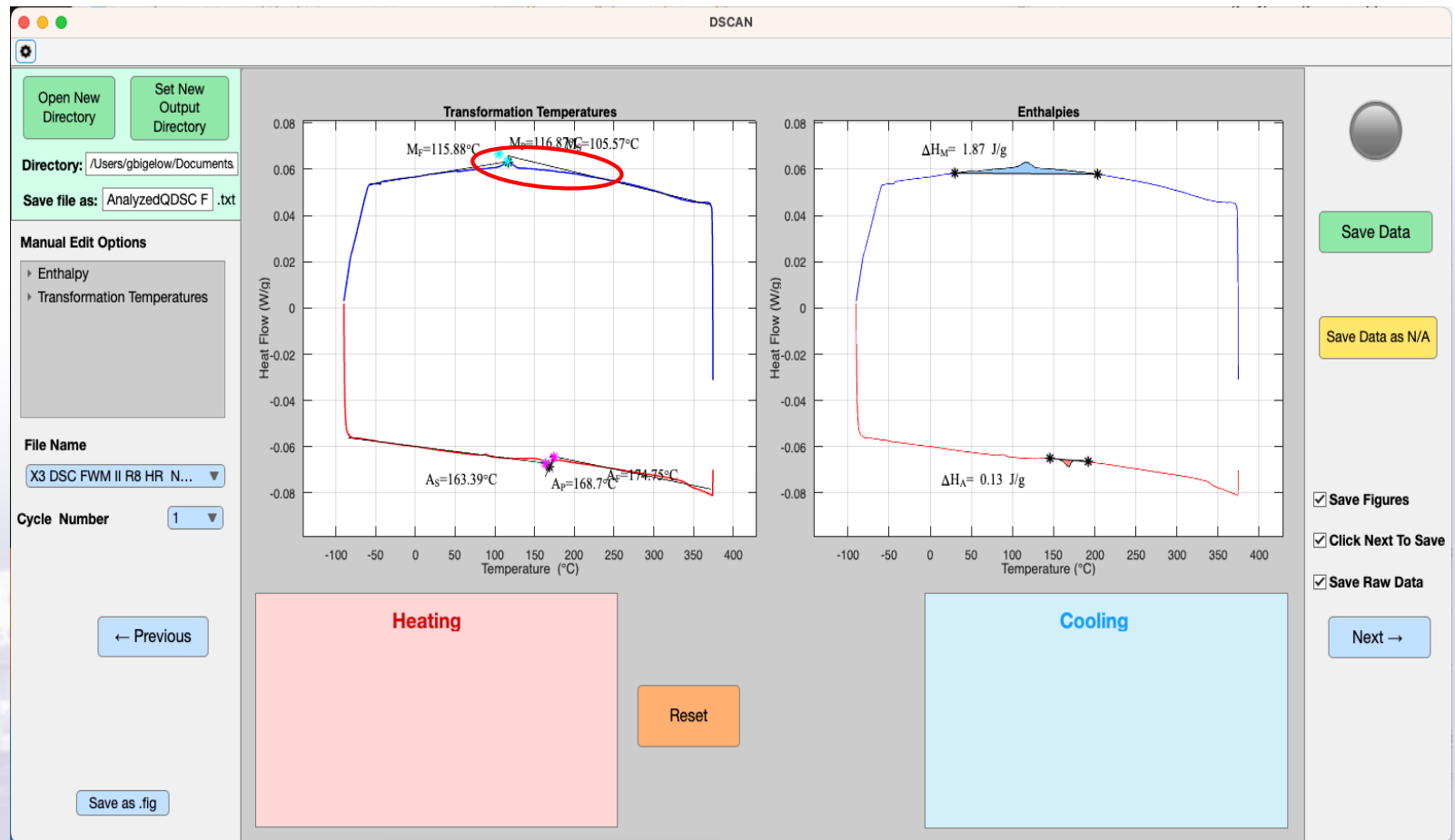


Complex case: Can analyze small peaks, curved baseline



DSC has
small peaks
and a curved
baseline

DSCAN not
catching peak
edges



Complex case: Can analyze small peaks, curved baseline

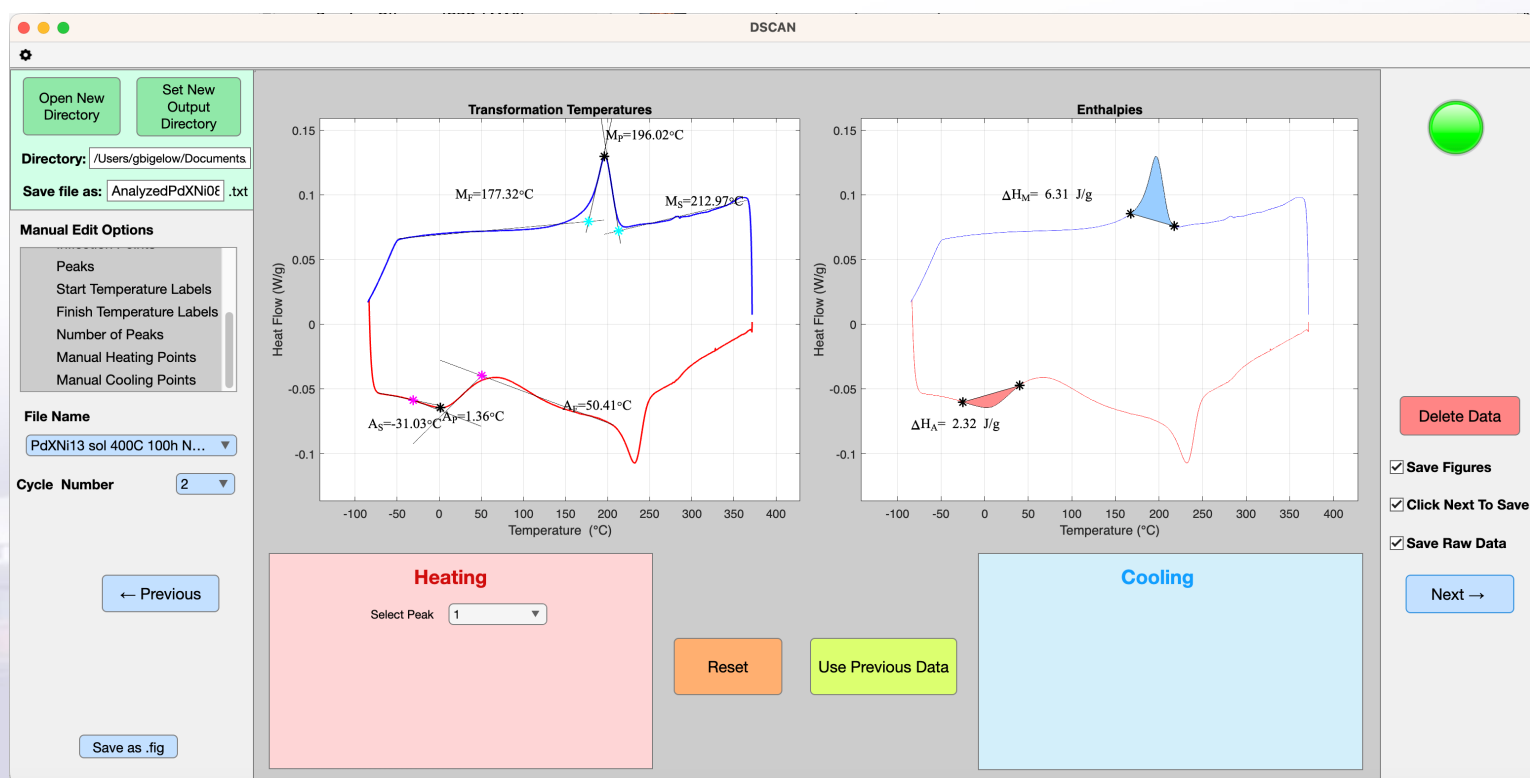
Adjusting
cutoff values
produces
tighter fit





Oddly shaped DSC: Manual Edit to account for “Wrong” Peak

Wrong peak is Automatically detected





Refocusing on the Present ...

Shape Memory Alloy Analytics Software— For the Benefits of All

- Was built for NASA projects
- Made available to all Researchers, Engineers, Designers, Explorers in the SMM field
 - ESTABLISH Uniform Analysis Methodology
 - PRODUCE Certification Data
 - ACCELERATE Data Throughput
 - CLARIFY Property-Processing-Microstructure Interactions
 - PROVIDE Reliable, Traceable data for Database and Design
 - Path towards MACHINE LEARNING



Acknowledgements

OVERVIEW

This software was developed at NASA Glenn Research Center with funding from the Aeronautics Research Mission Directorate (ARMD), Transformational Tools and Technologies (T³) project.



DEVELOPERS

The software was developed by:

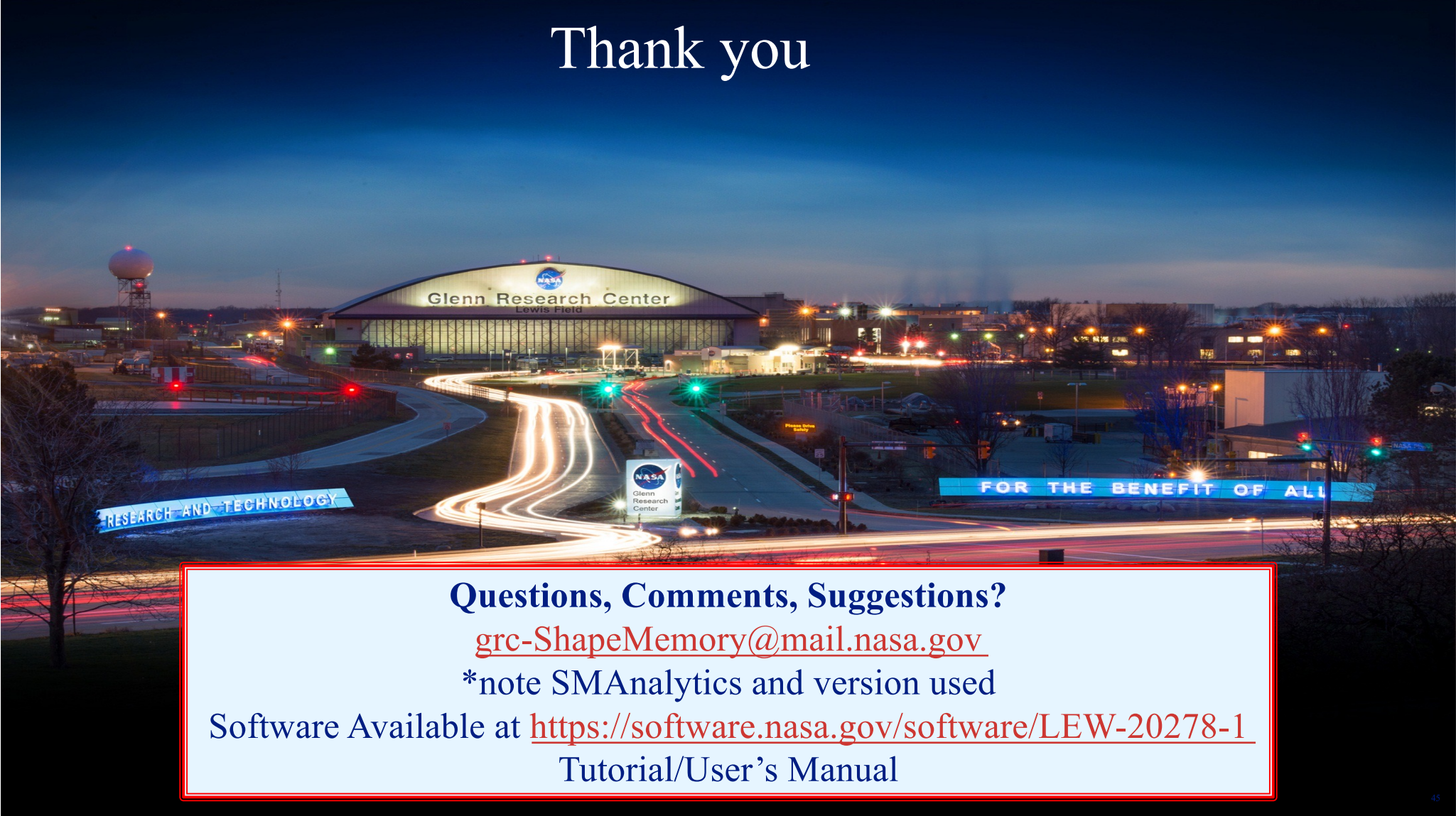
- Glen Bigelow (SMAanalytics Lead), Dr. Othmane Benafan (DSCAN Lead)
- Zachary Toom, Julie Foroosh, Peter Caltagirone

CONTRIBUTORS

It would not have been possible to build this software without many contributions from:

- Dr. Santo A Padula II – Legacy MATLAB software framework
- Dr. Ronald Noebe – Legacy SMA lead
- Darrell Gaydosh – Legacy MATLAB code and methodology
- Felix Adams – MATLAB code and algorithms
- Hector Luna – Validation and Verification
- Noah Pittman – Validation and Verification

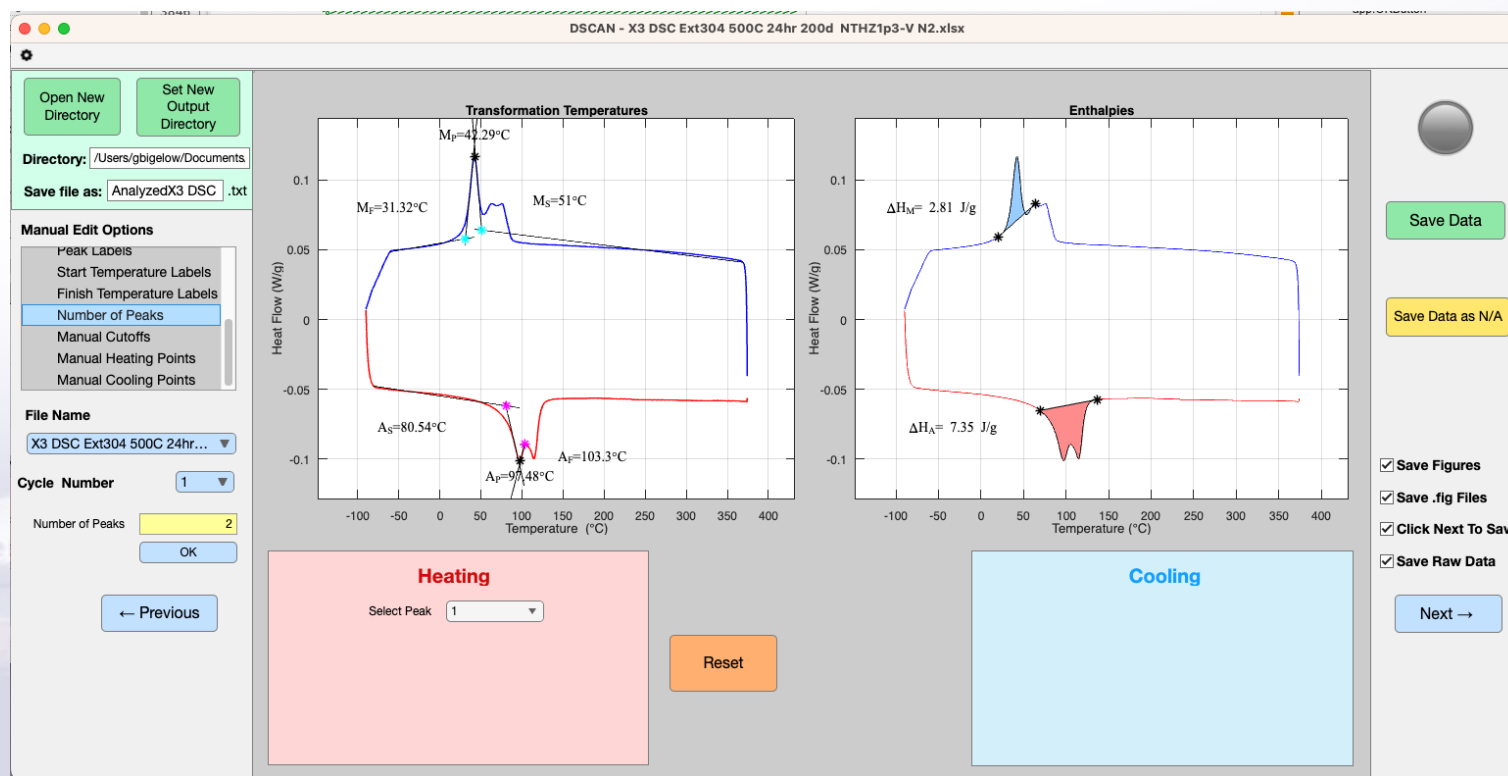
Thank you



Questions, Comments, Suggestions?
grc-ShapeMemory@mail.nasa.gov
*note SMAnalytics and version used
Software Available at <https://software.nasa.gov/software/LEW-20278-1>
Tutorial/User's Manual

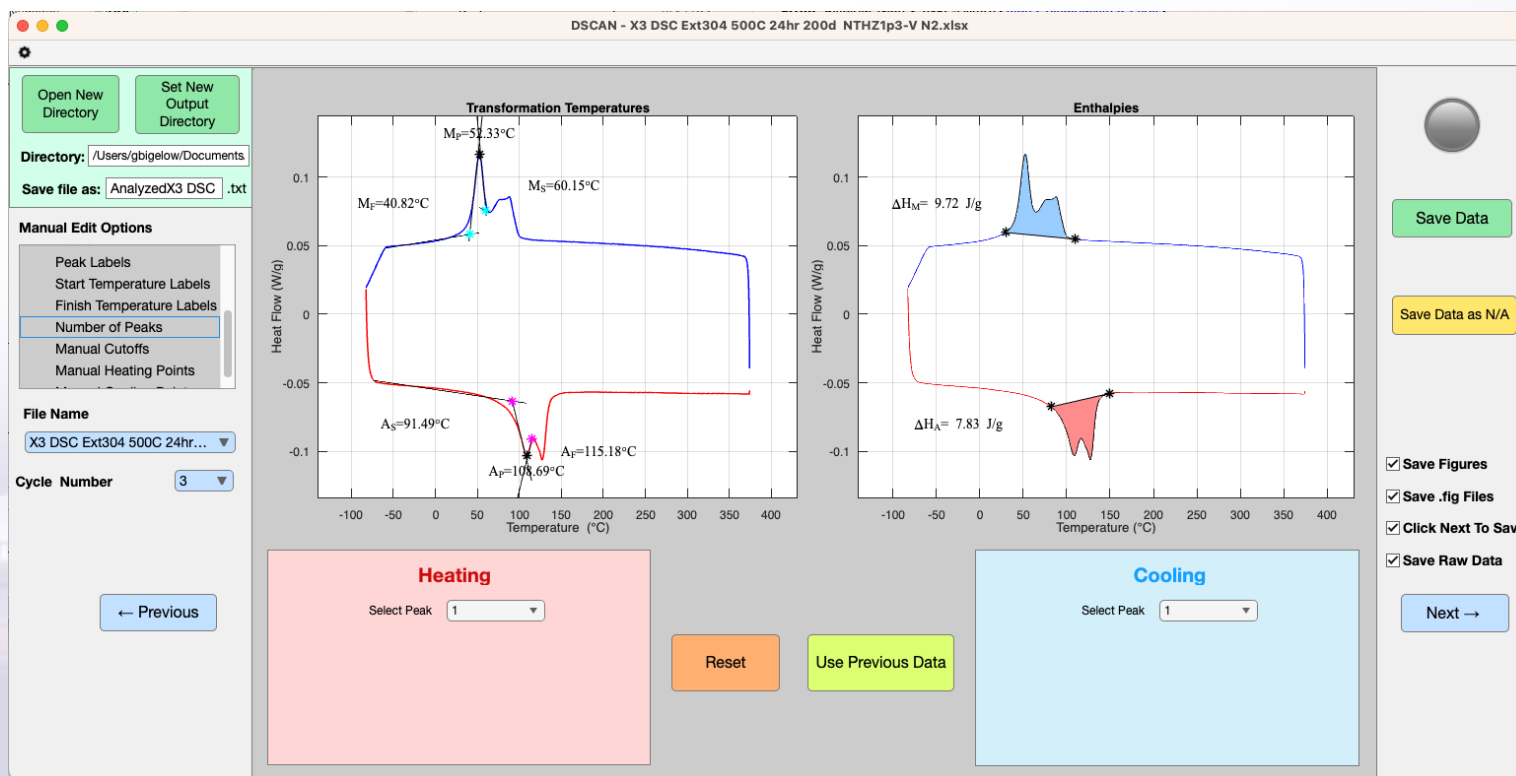


Manual Edit – Missing Peak



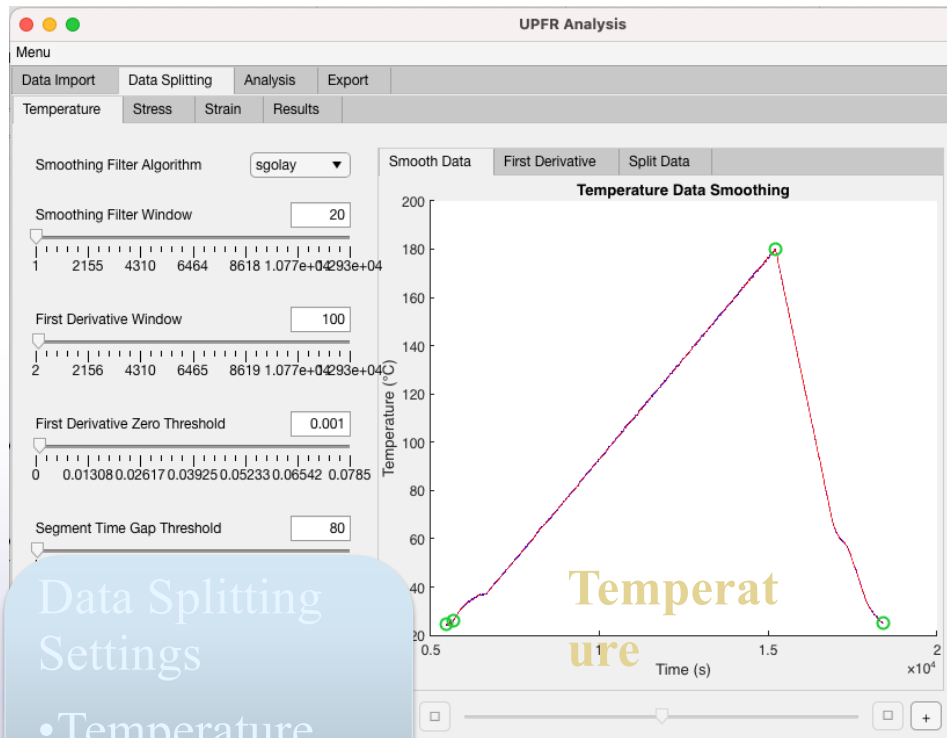


Manual Edit – Missing Peak





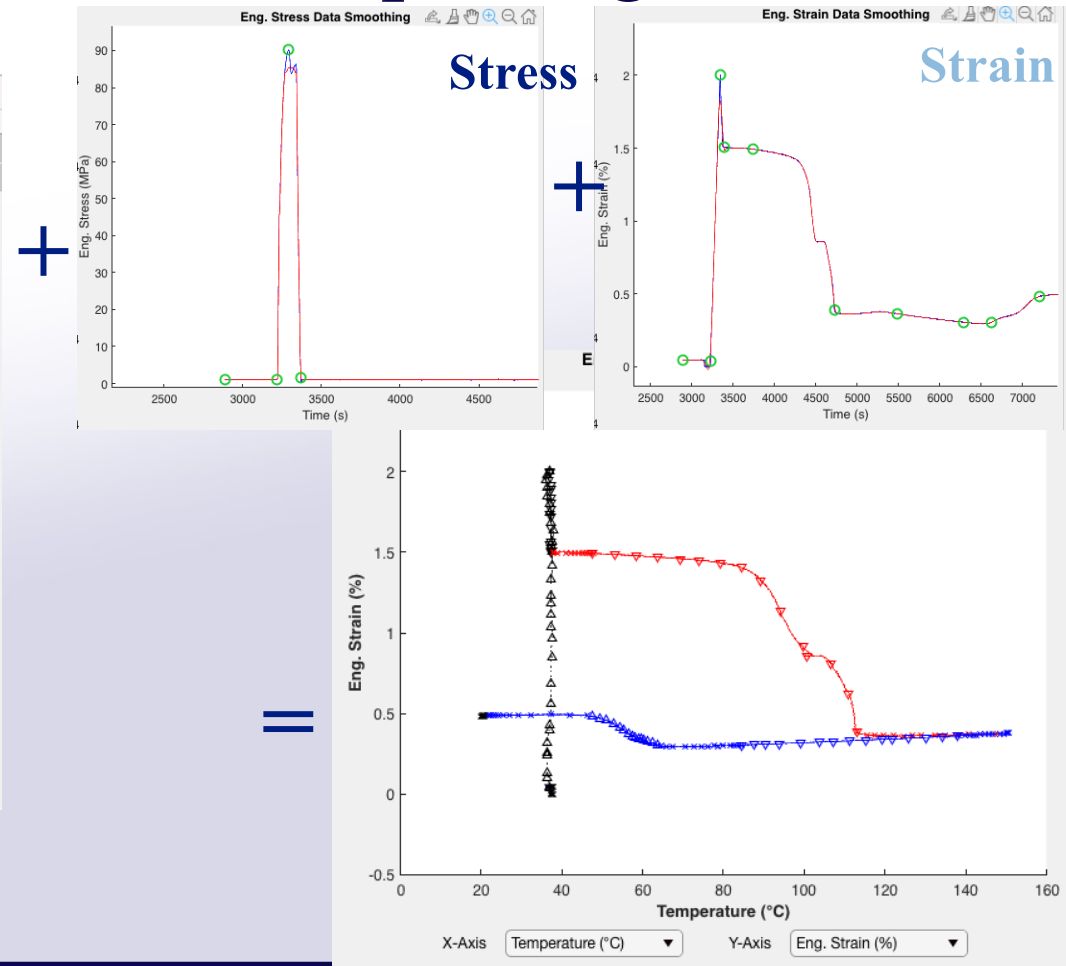
Principle of Operation: Splitting



Data Splitting Settings

- Temperature
- Stress
- Strain

www.nasa.gov

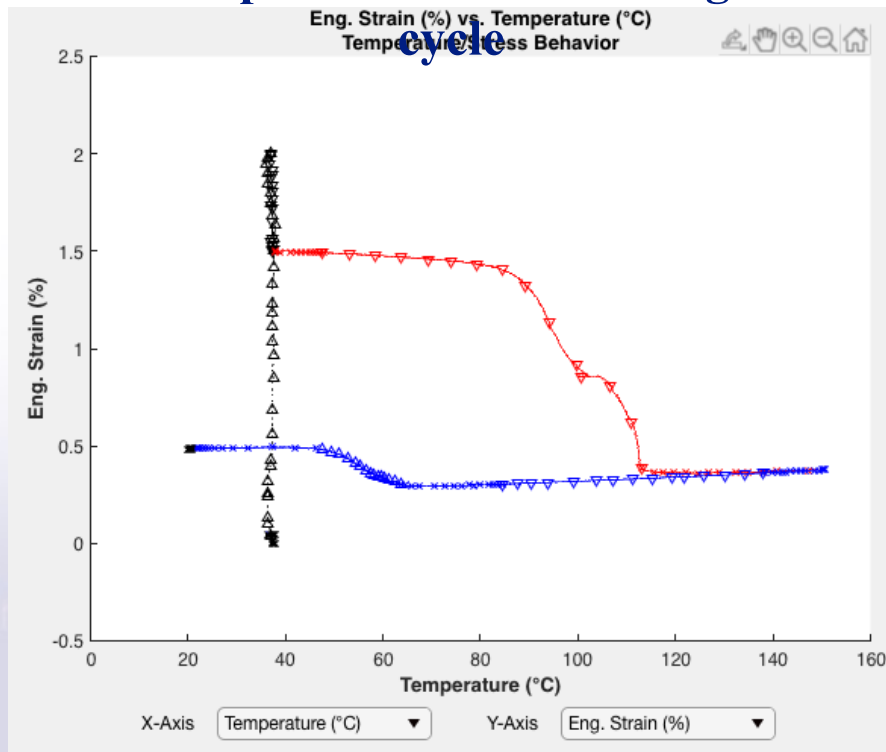




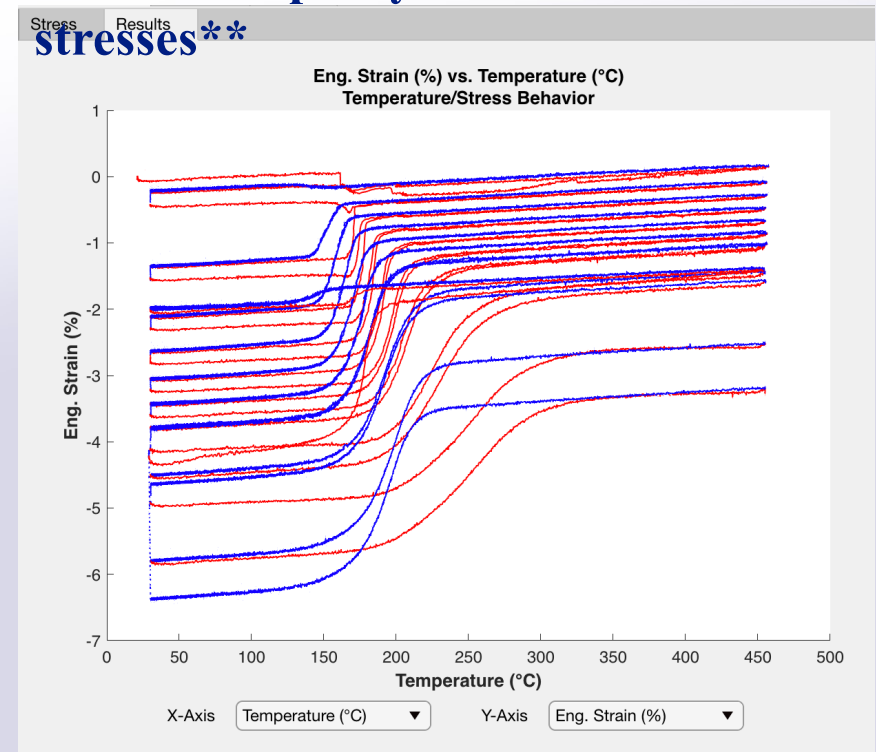
Principle of Operation: Data Splitting

Splitting results in discreet **isothermal** (Loading/Unloading) and **iso-stress** (**Heating**/**Cooling**) segments.

Can perform this for a single
cycle



**** Or multiple cycles at different stresses****



Principle of Use: Fitting - Isothermal



Auto-fit to 1-4 regions

Can be adjusted manually

Regions

Sliders

Outputs:

- Slopes/Modulus
- Beginning, end strain/stress
- Yield stress (0.2% offset, 0.5%)
- Max stress/strain
- Plateau strain/stress

