
# SMAnalytics – Shape Memory Alloy Test Data Analysis and Reporting Software

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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**

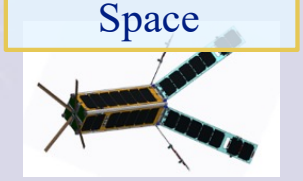
FAA – US Code of Federal Regulations Title 14 Part 25

"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"*

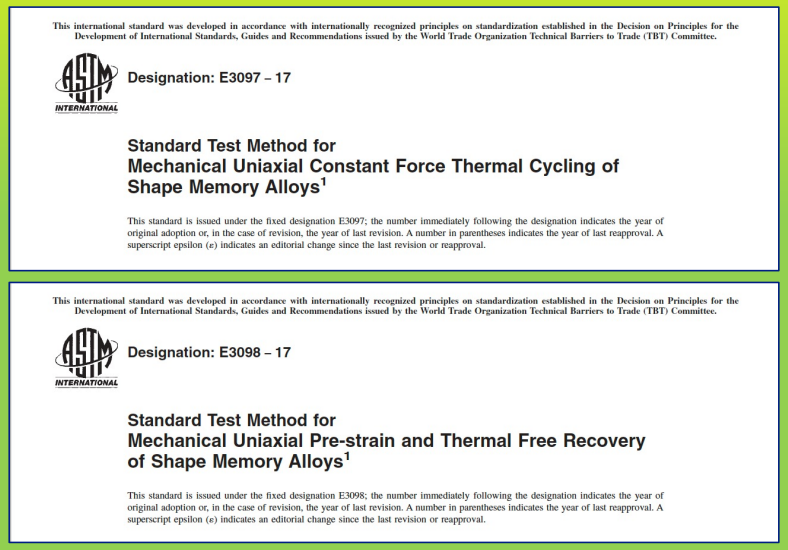
- What standards are there for actuator SMAs?

# 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



This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

Designation: E3097 – 17

Standard Test Method for
Mechanical Uniaxial Constant Force Thermal Cycling of
Shape Memory Alloys[1]

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.



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Mechanical Uniaxial Pre-strain and Thermal Free Recovery
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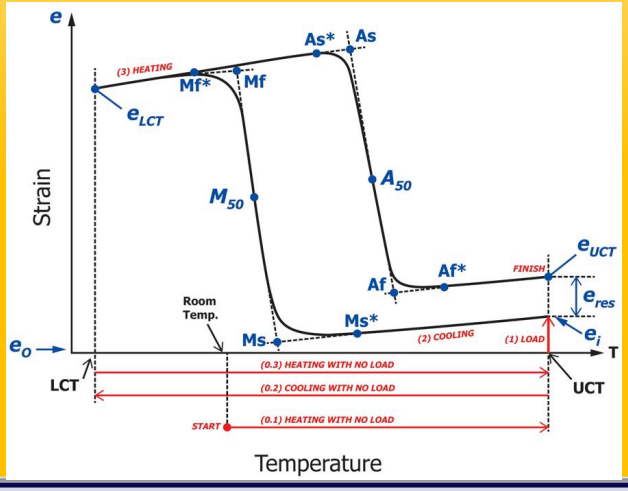
**Analysis methodology is still loosely defined**

*ASTM E3097: "12.2 Graphically determine As, Af, Ms and Mf by the intersection of tangent lines drawn from the steepest portion of the strain verses temperature curves on heating and cooling and lines tangent to the strain verses temperature slopes near the LCT and the UCT as shown in Fig. 1."*





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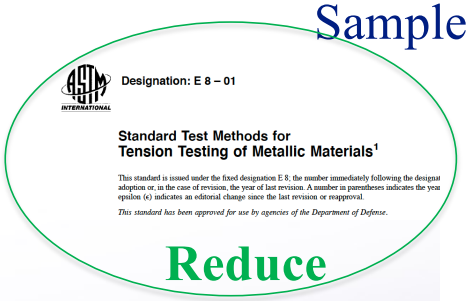
# Reduce Uncertainty in Data

**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

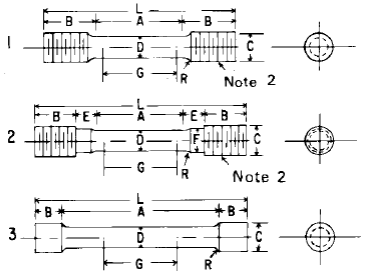

Designation: E 8 – 01

Standard Test Methods for
Tension Testing of Metallic Materials[1]

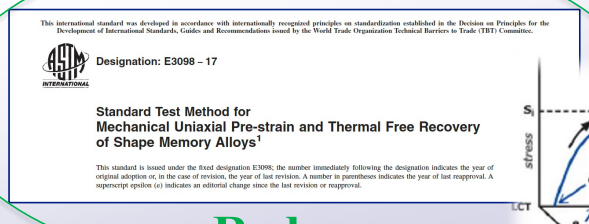
This standard is issued under the fixed designation E 8; the number immediately following the designat adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year epsilon (ε) indicates an editorial change since the last revision or reapproval.

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

**Reduce**




## Testing Methodology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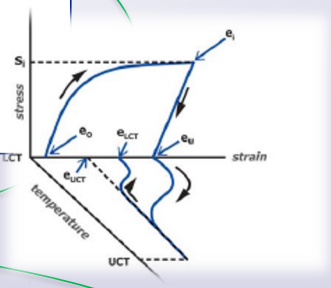
**Reduce**



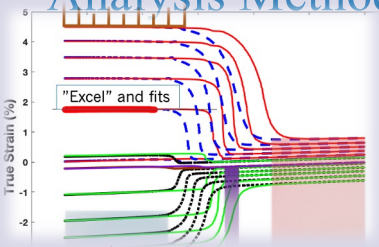

## Test Setup/Equipment

Ruggedness, ILS Testing

| | A | B | 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 Alloys**[1]

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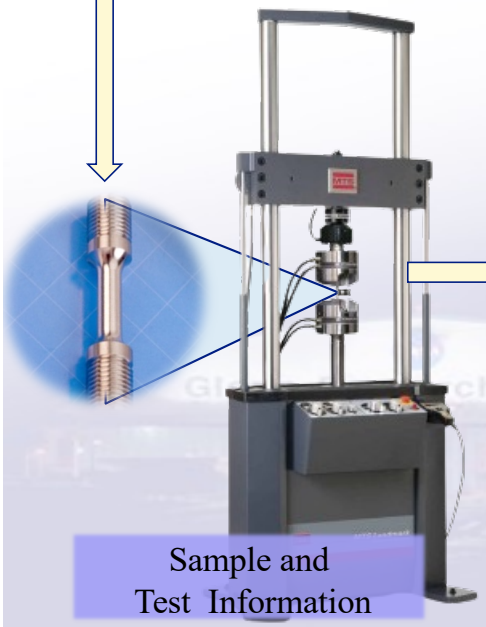
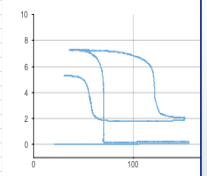


Sample and Test Information

?

ASTM Material Certification Report

| | |
|---|---|
| Test Date | 12/5/17 |
| Lab | NASA-GRC-SH38B |
| Operator | O. Benafan |
| Material | NiTi |
| Sample Indentification | |
| 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) | 67.642 |
| 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

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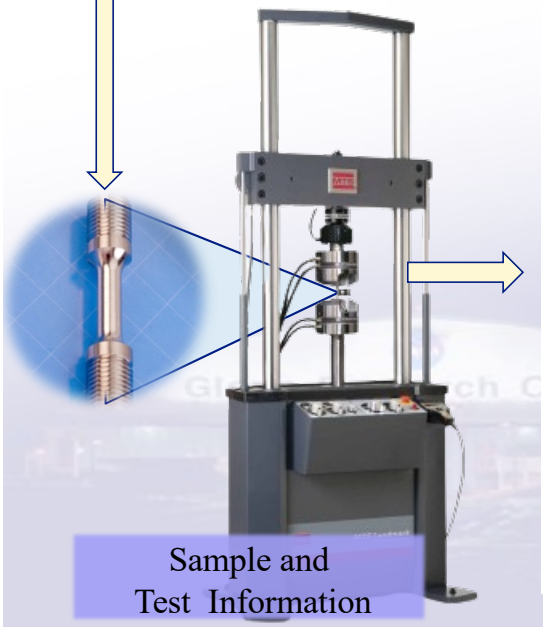
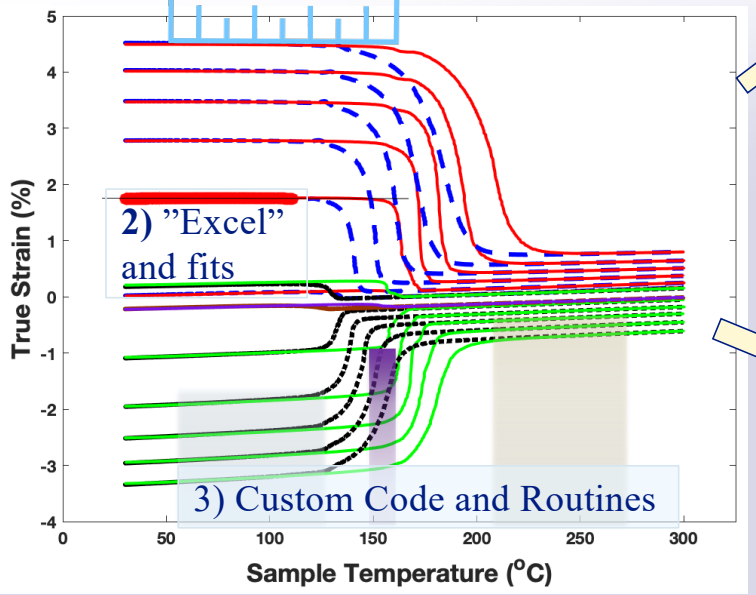


Sample and Test Information

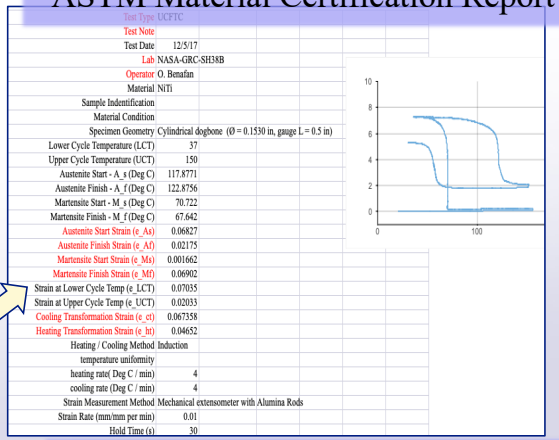
**1)** Plot and Straight Edge




**2)** "Excel" and fits

3) Custom Code and Routines

ASTM Material Certification Report



| | |
|---|---|
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| Test Note | |
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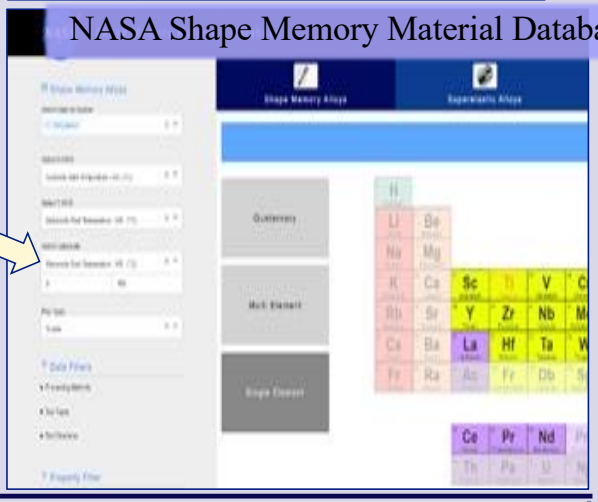
NASA Shape Memory Material Database



# SMAnalytics was designed to fill this gap

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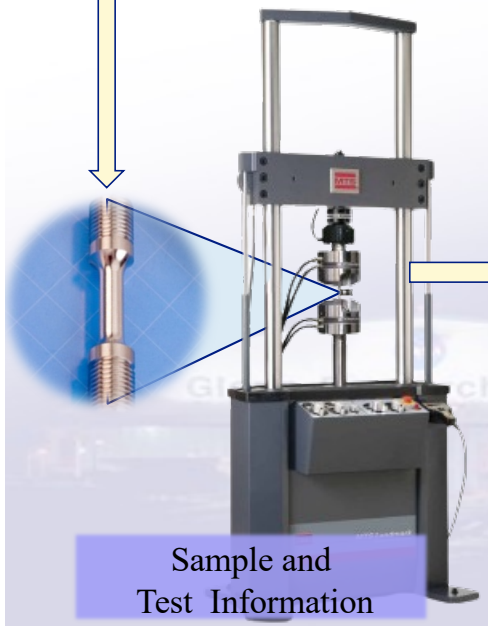
SMAnalytics



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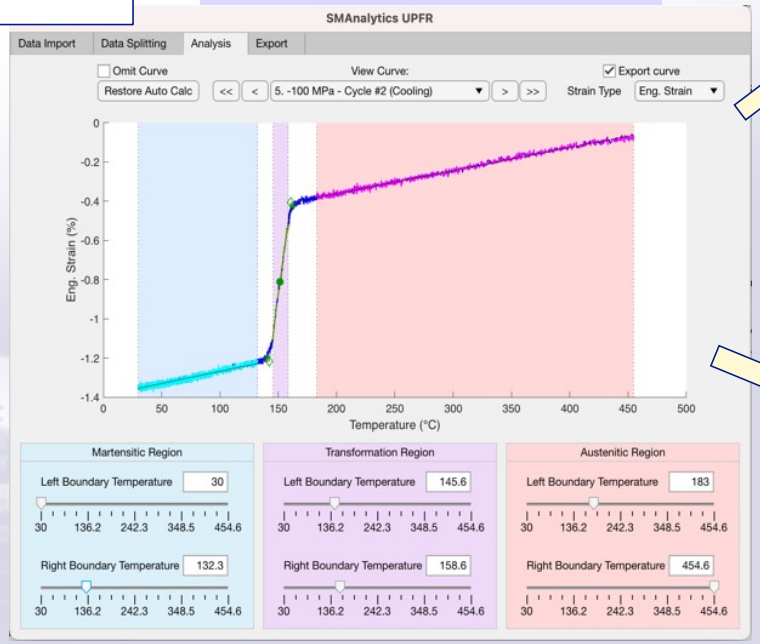


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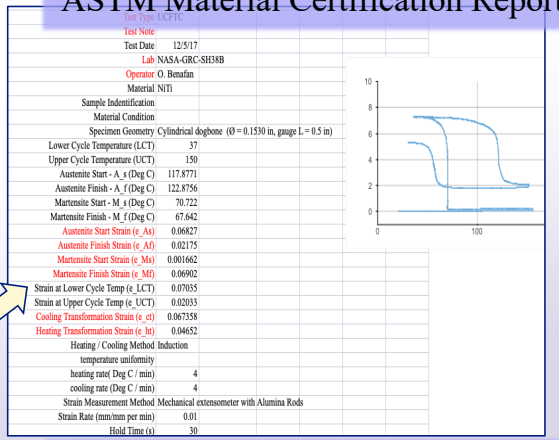
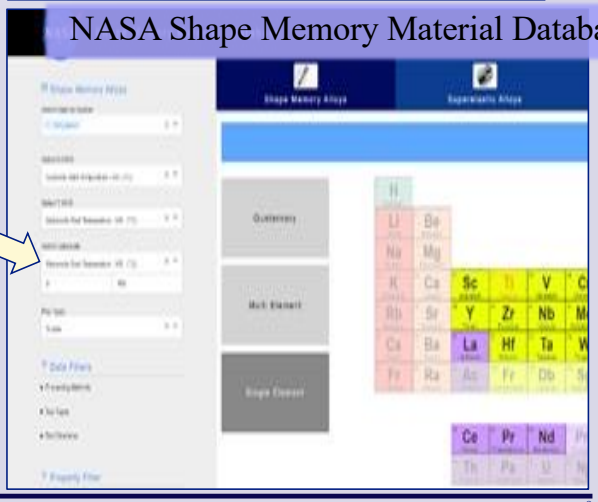



NASA Shape Memory Material Database



# SMAnalytics addresses 3 common SMA tests
# (1) Differential Scanning Calorimetry - DSC

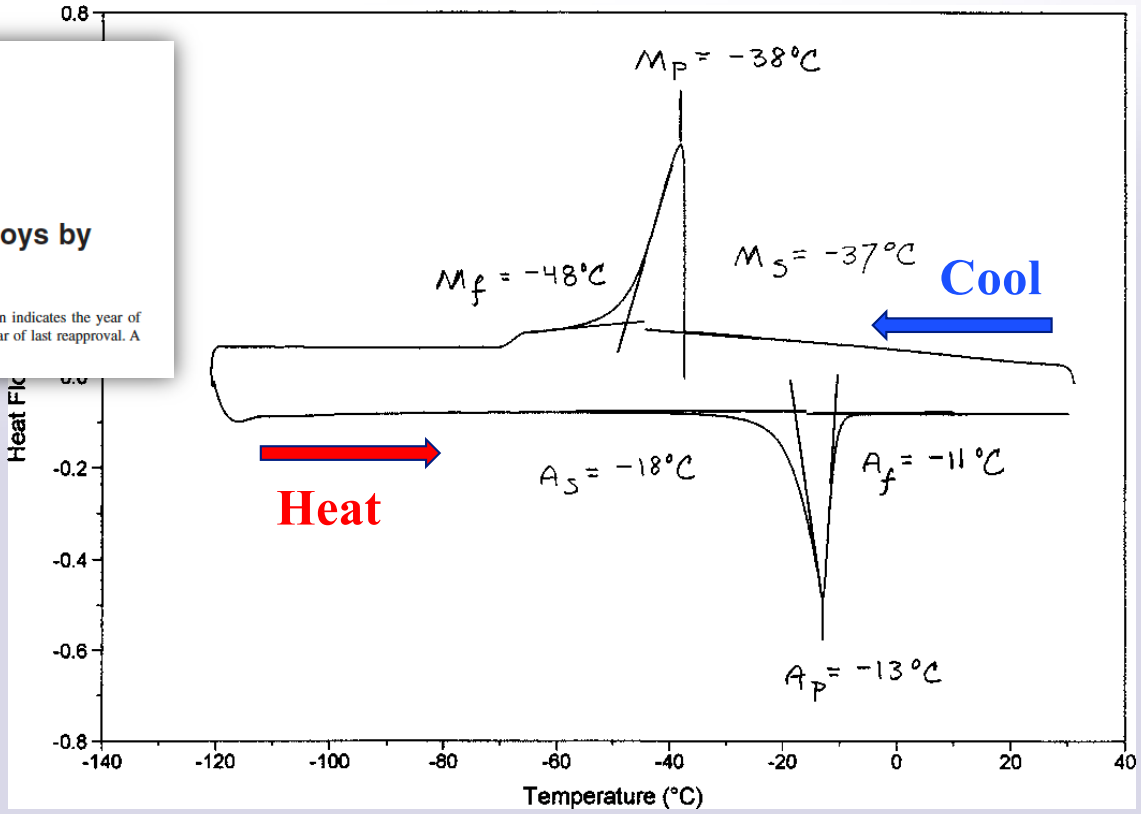
**Designation: F 2004 – 05**

**Standard Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis[1]**

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



# SMAnalytics 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 Alloys[1]**

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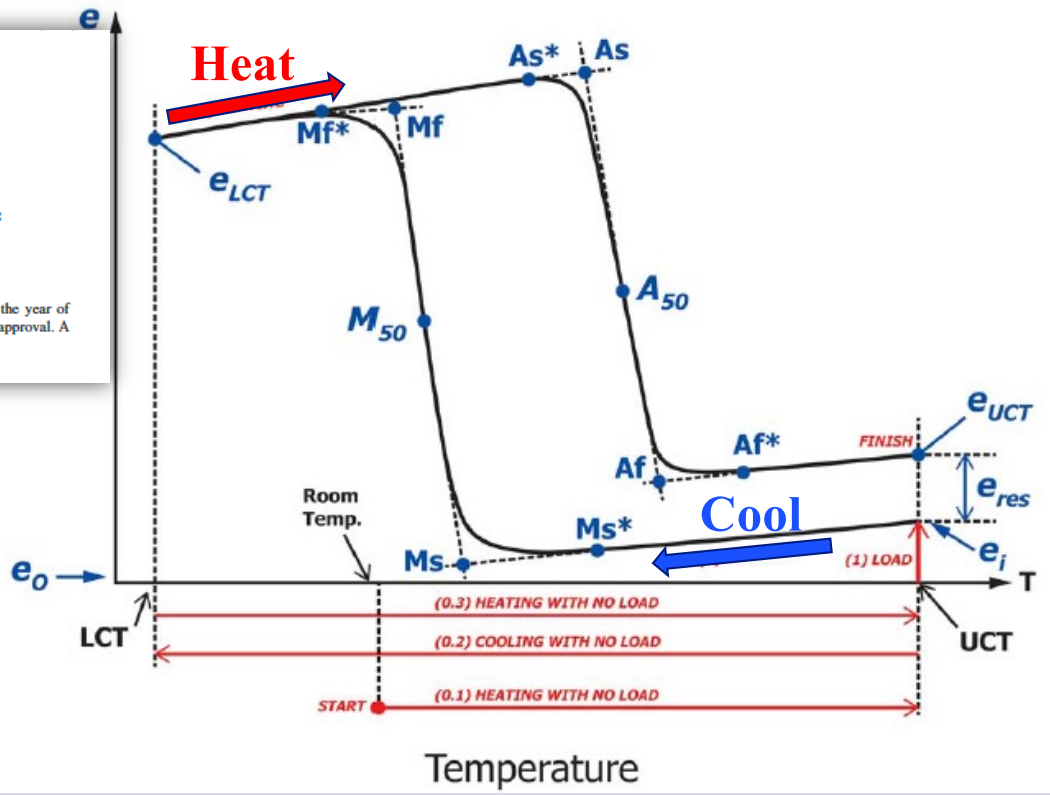
**Transformation Temperatures**

**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**
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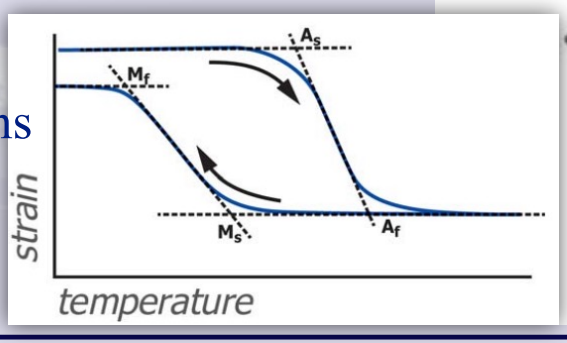
**Transformation Temperatures**

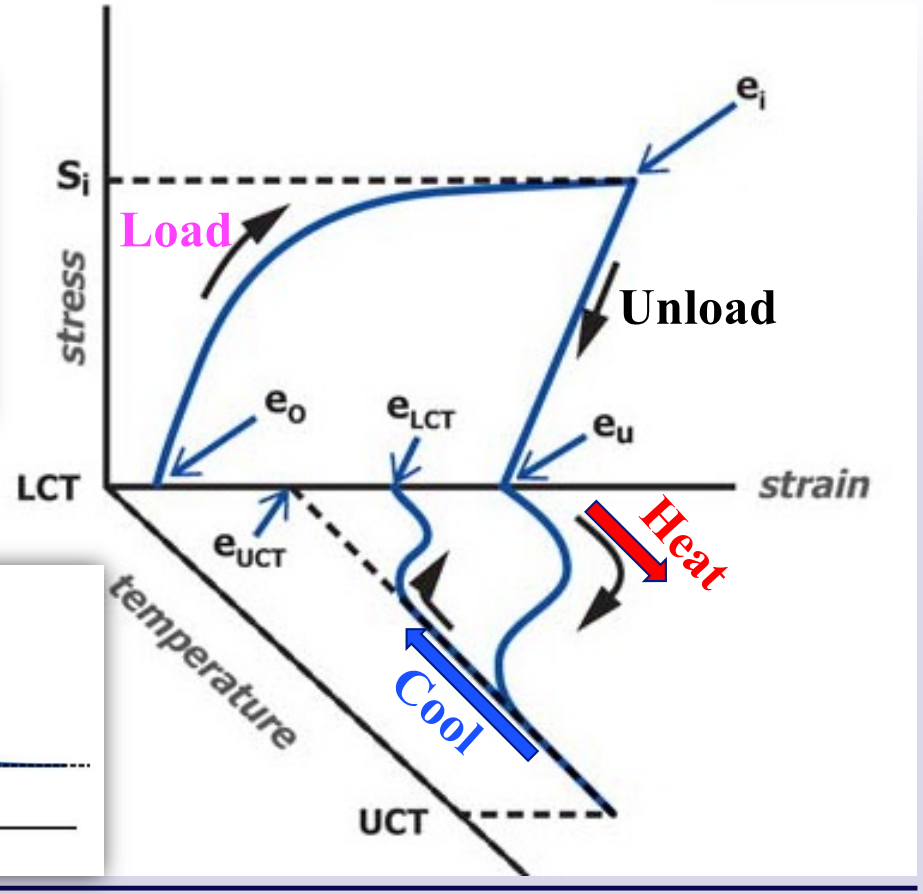
**Transformation Strains**

**Strain Recovery**

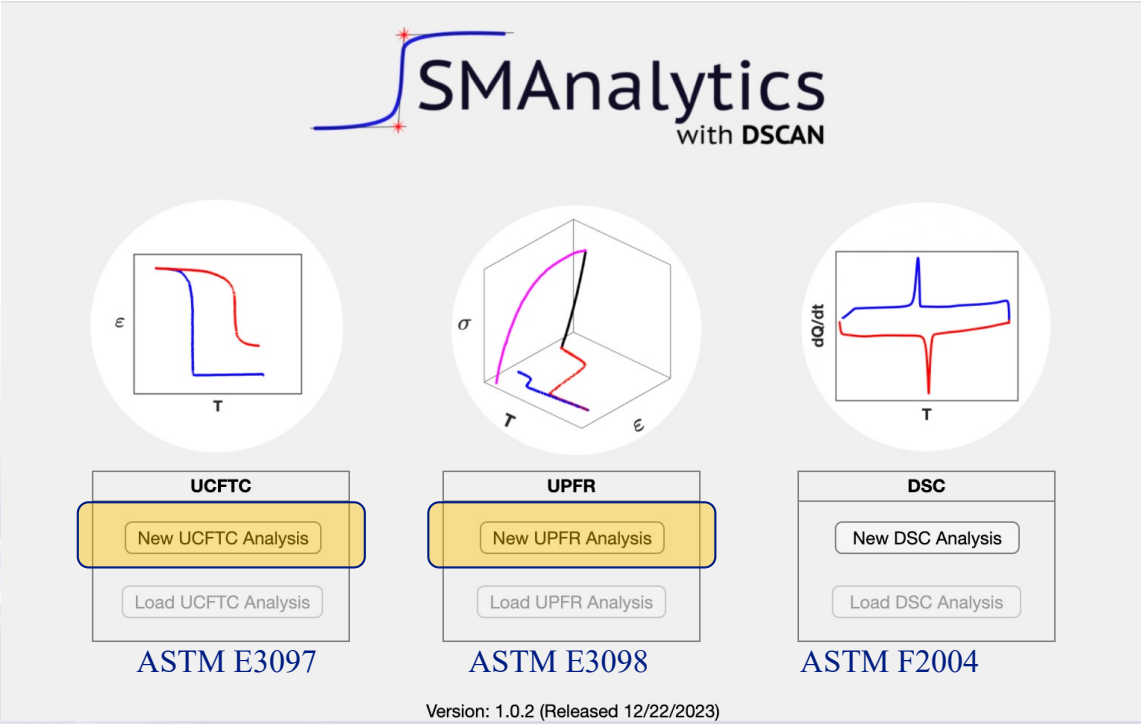
+ Representative conditions

+ Stress Free or Stressed



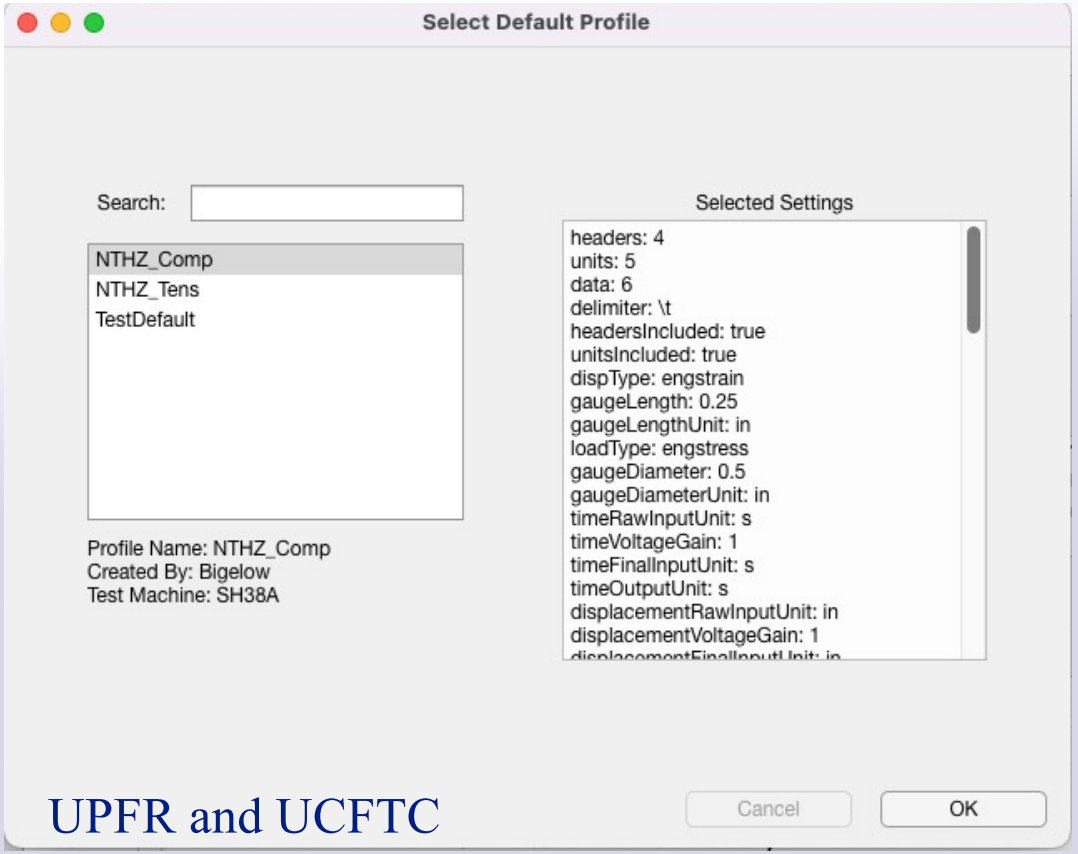



# A User-Friendly Graphical Interface Launch Window



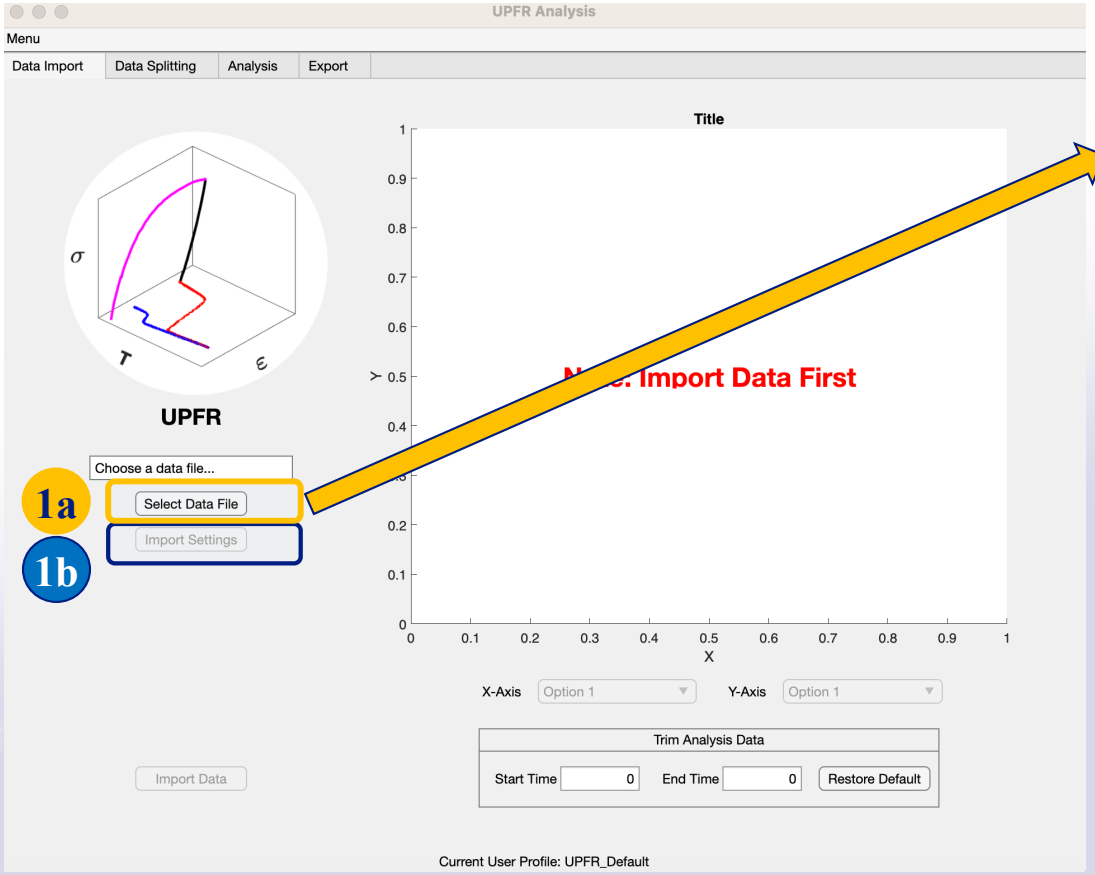
# Create, save, and reuse Profiles: Streamline Analysis

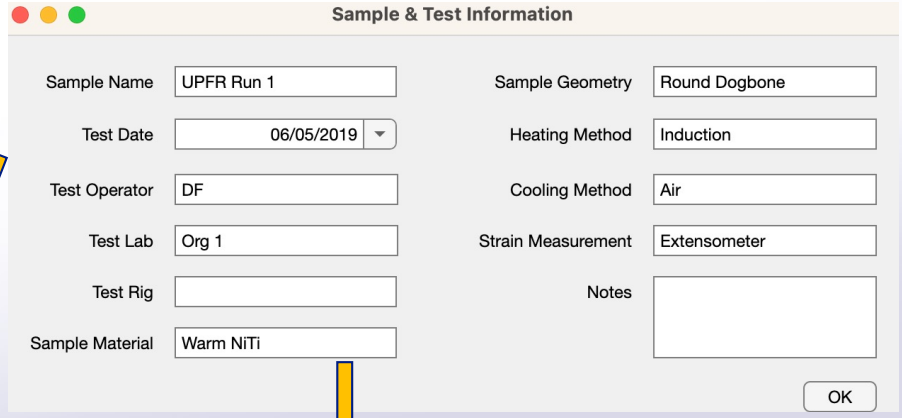
- **Test type profiles**
  - **Compression**
  - **Tension**
  - **Cyclic**
- **Lab based profiles**
  - **My lab**
  - **Your lab**
- **Data characteristic profiles**
  - **Noisy load**
  - **Fast vs slow heat/cool**

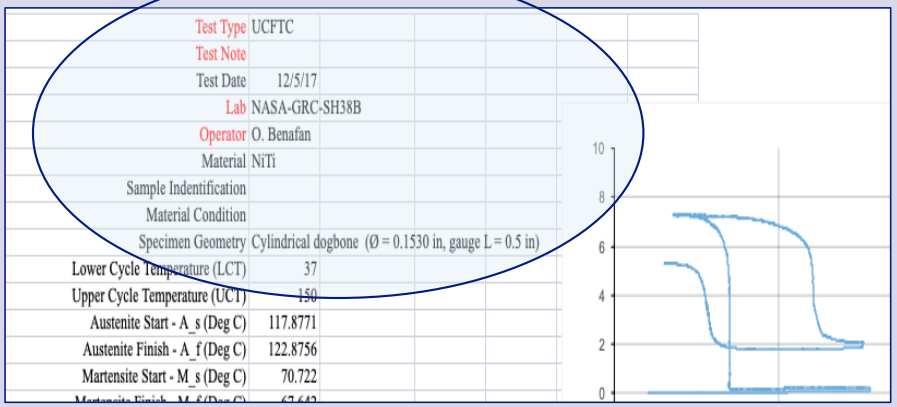



UPFR and UCFTC

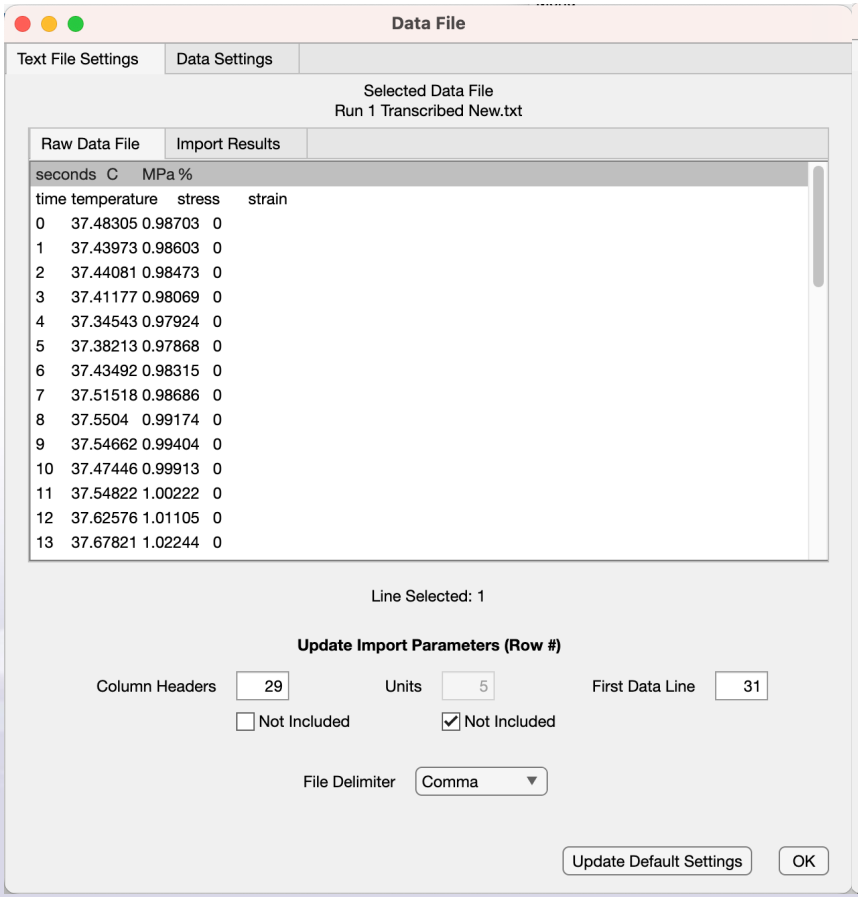
# Pedigree – Traceability, ASTM Report

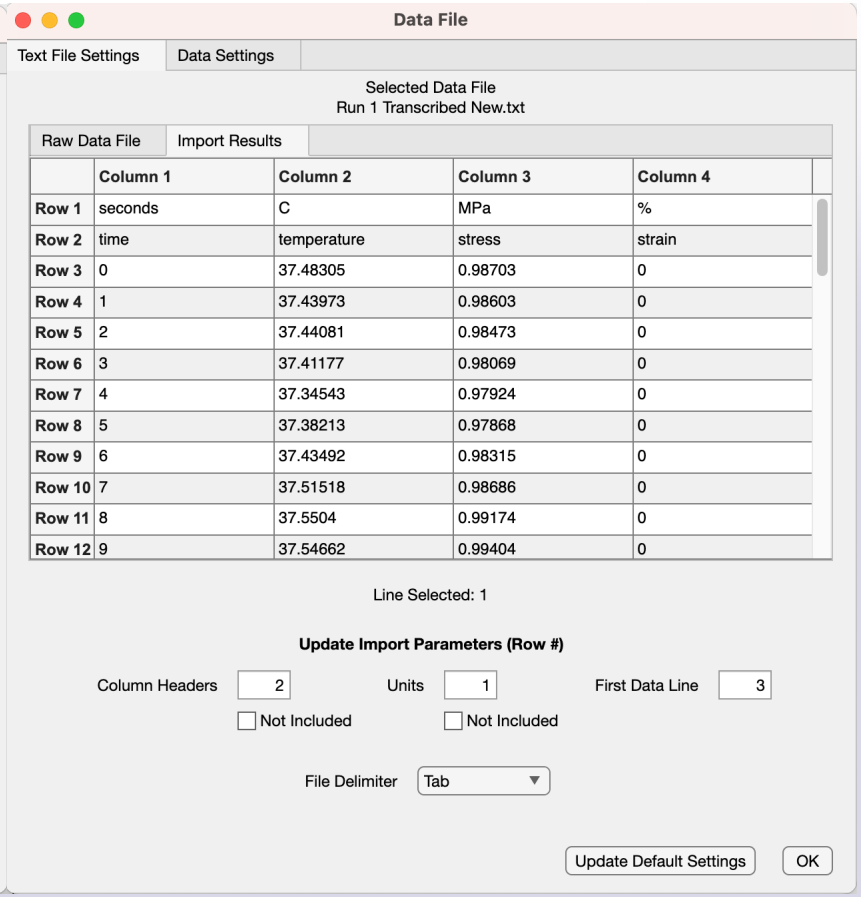


# 1b Accepts many file formats and allows easy parsing

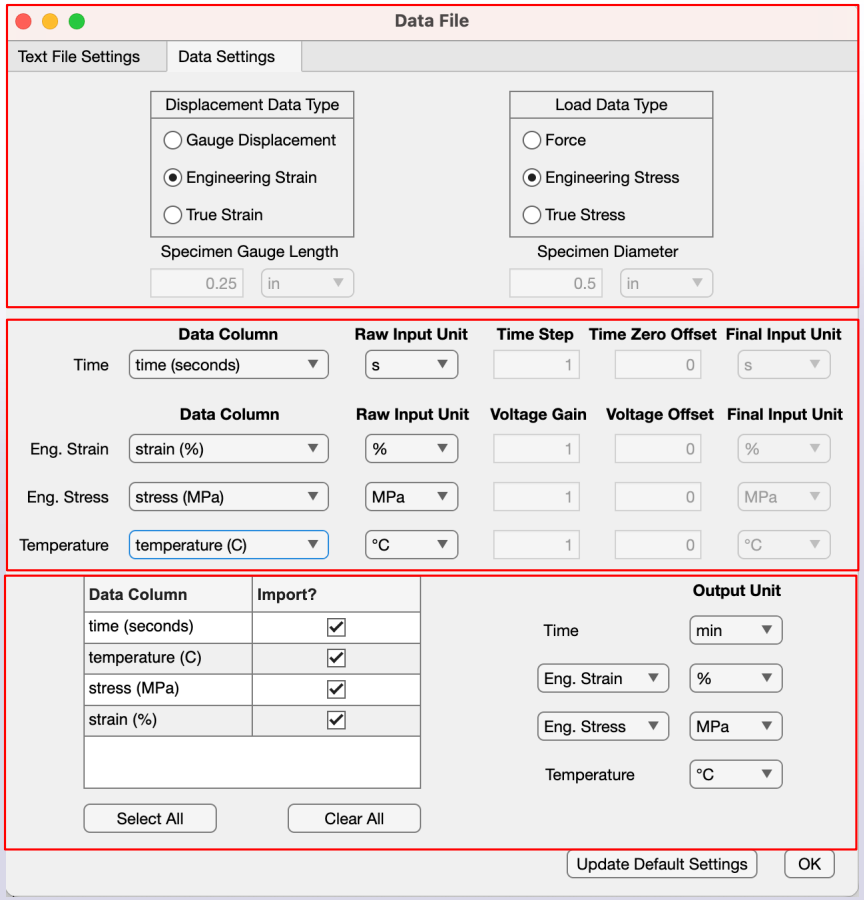


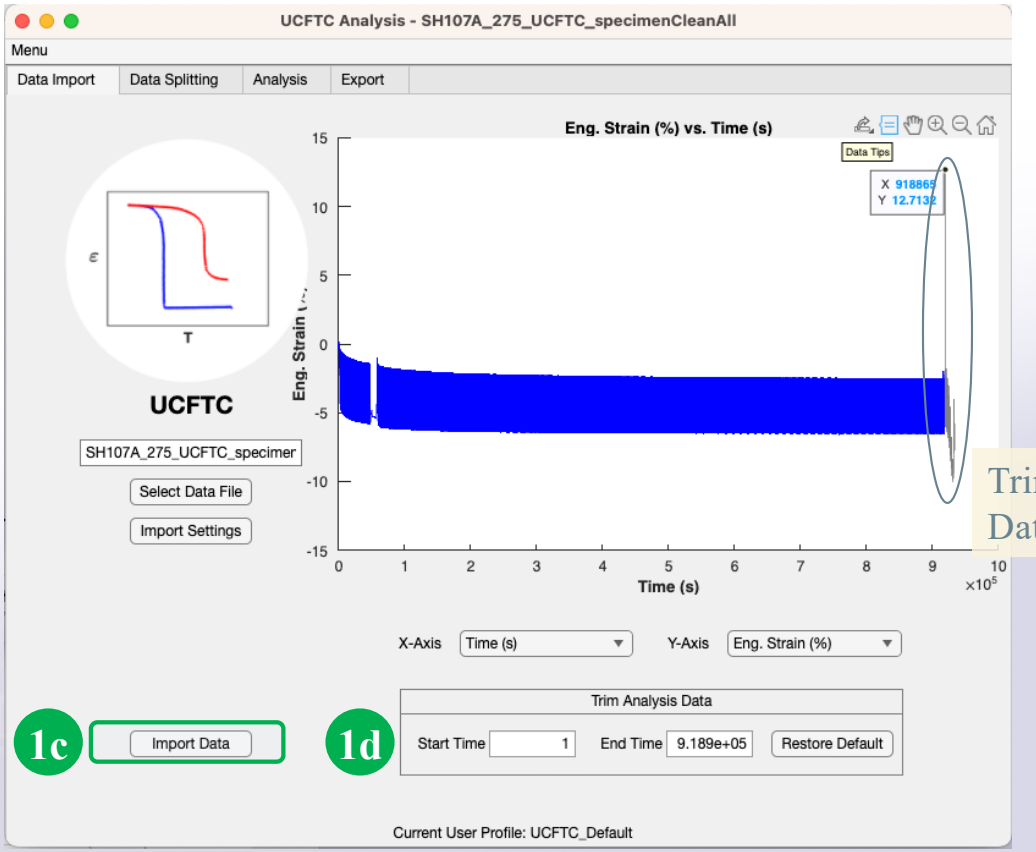
1b

# 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



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



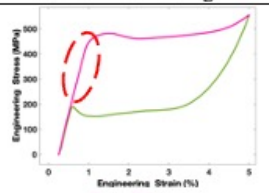
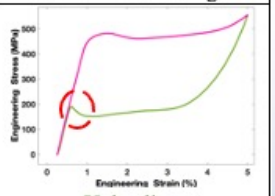
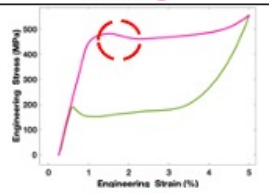
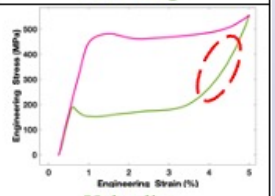
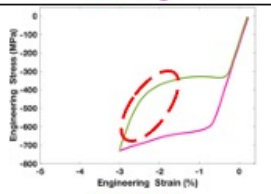
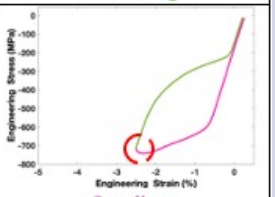
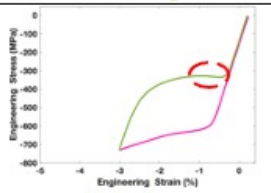
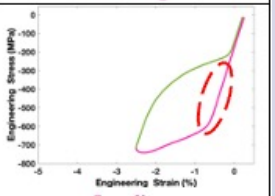

Trimmed Data

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 ↑
- Cooling:
  - Stress Constant
  - Temperature ↓
- Loading, Unloading

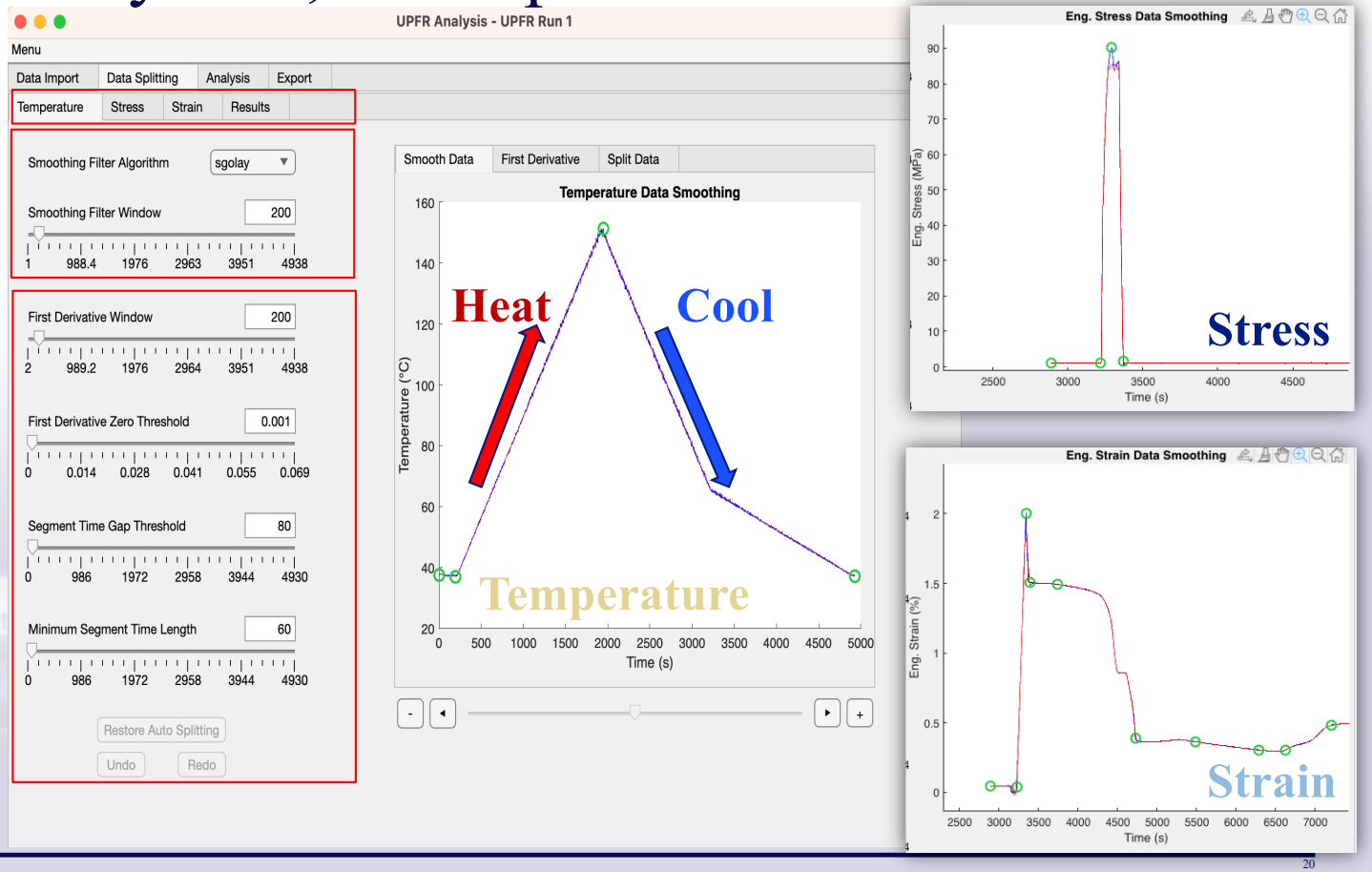
| | | Strain Increasing | Strain Decreasing |
|---|---|---|---|
| Stress Positive | Stress Increasing |  Loading |  Unloading |
| Stress Positive | Stress Decreasing |  Loading |  Unloading |
| Stress Negative | Stress Increasing |  Unloading |  Loading |
| Stress Negative | Stress Decreasing |  Unloading |  Loading |

# 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



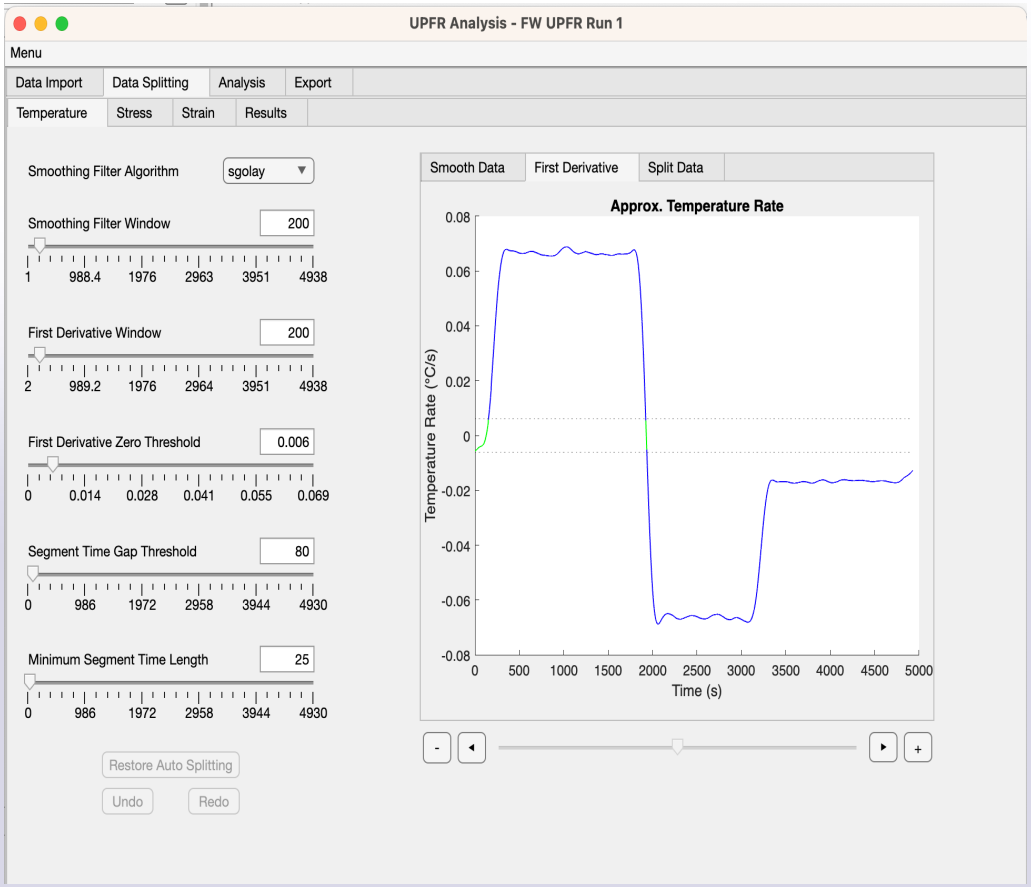
# Processing Algorithms – Mathematically based

**Derivatives**

- Splitting
- Transformation Temperatures

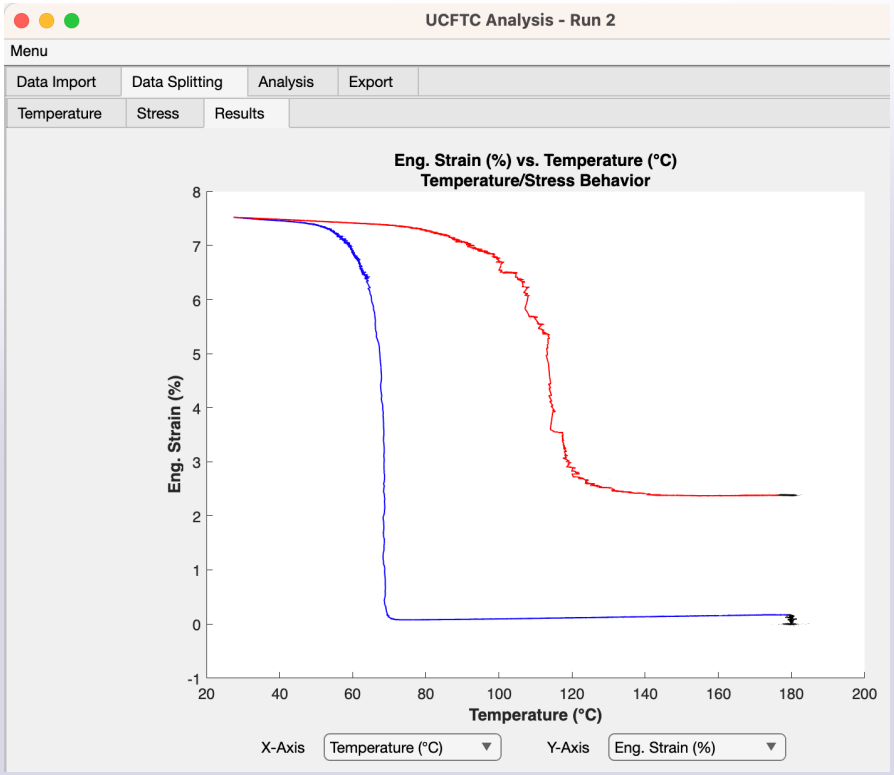
**2nd Derivatives**

- Transformation Region
- Star Temperatures



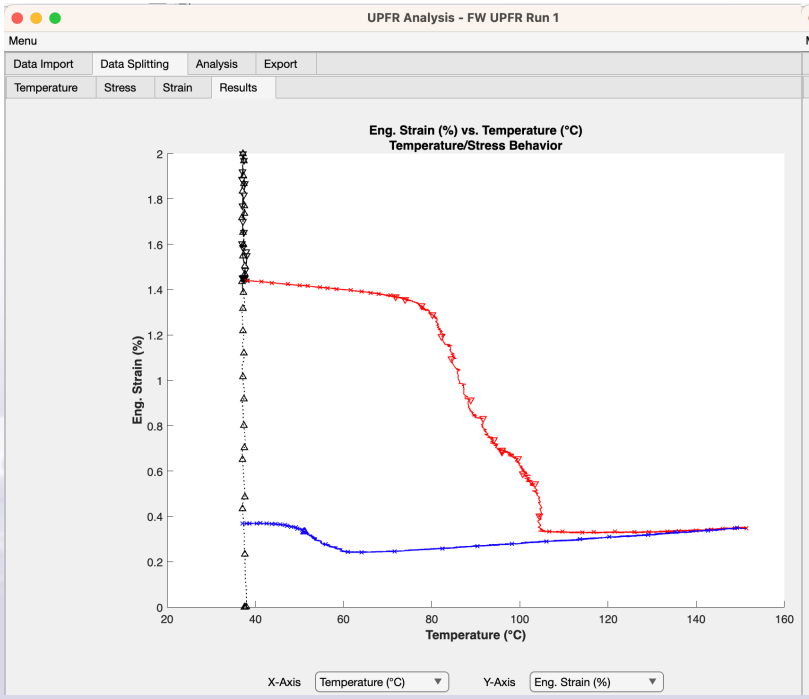
# UCFTC Results: Software can identify key data segments during splitting

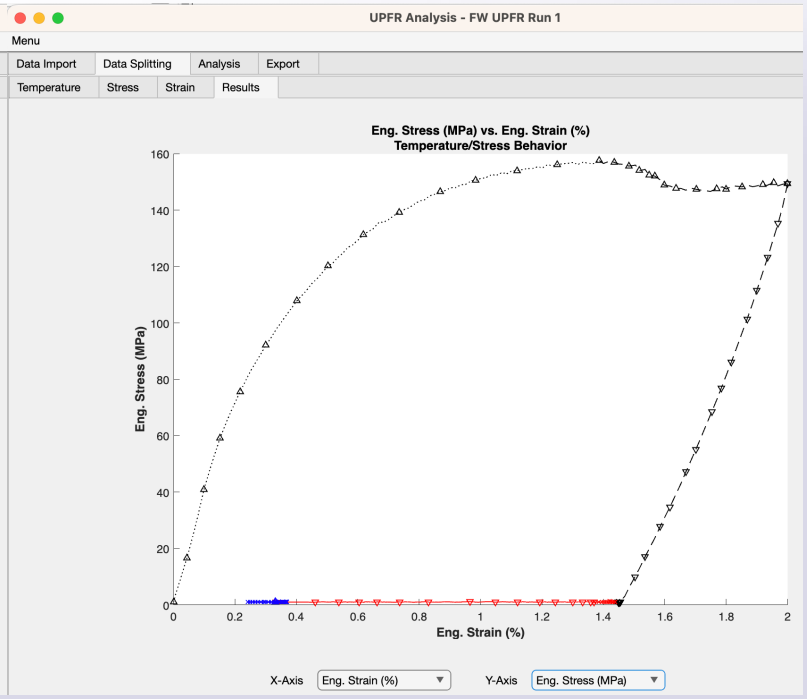
- Heating
- Cooling
- Loading ∆
- Unloading ∇



# UPFR Results: Software can identify key data segments

Heating Cooling Loading Δ Unloading ∇

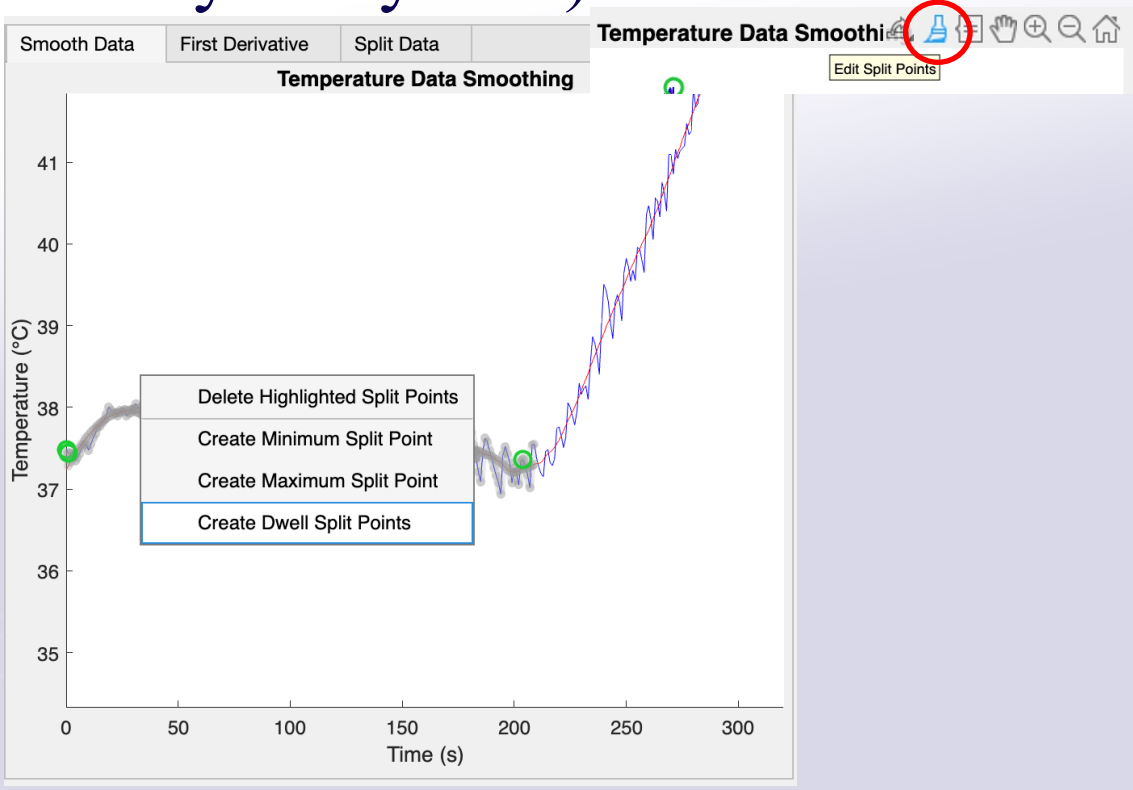


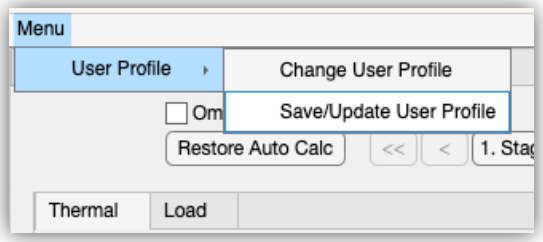
# Manual editing available

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

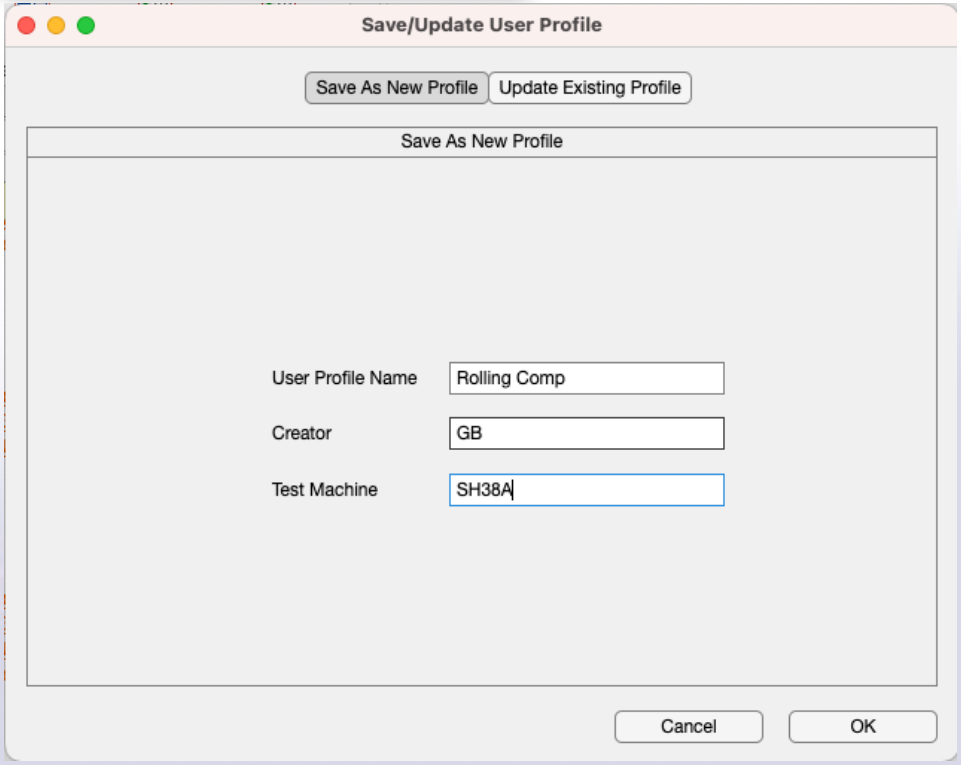
- Use Brush Tool in Toolbar
  - "Edit Split Points"
- Select (Box) data of interest
  - Few points for Max/Min
  - Range of points for Dwell
- Select Desired Action

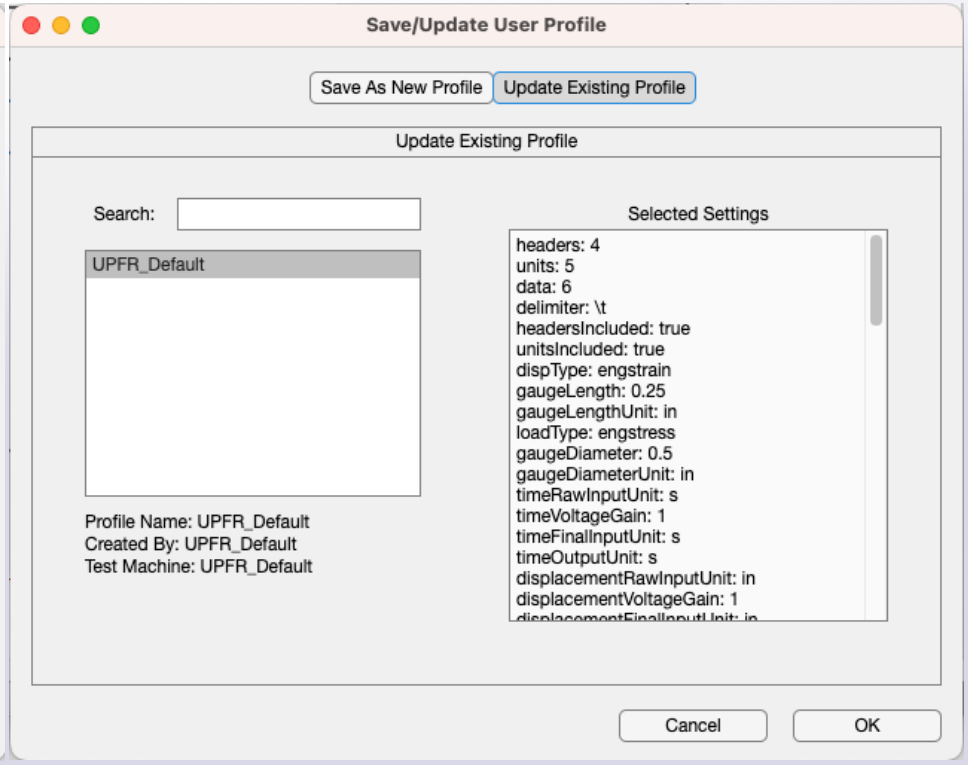


# Creating/Updating Profiles



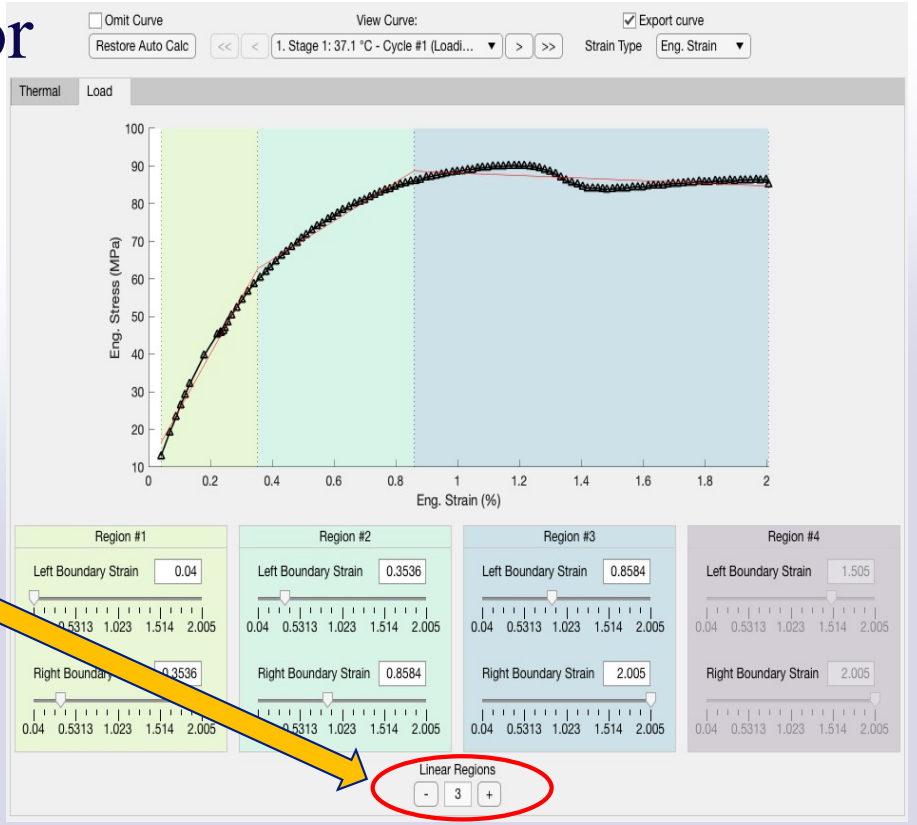

- Profiles save settings from import and splitting
- Reduces need for user input during import and splitting



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

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



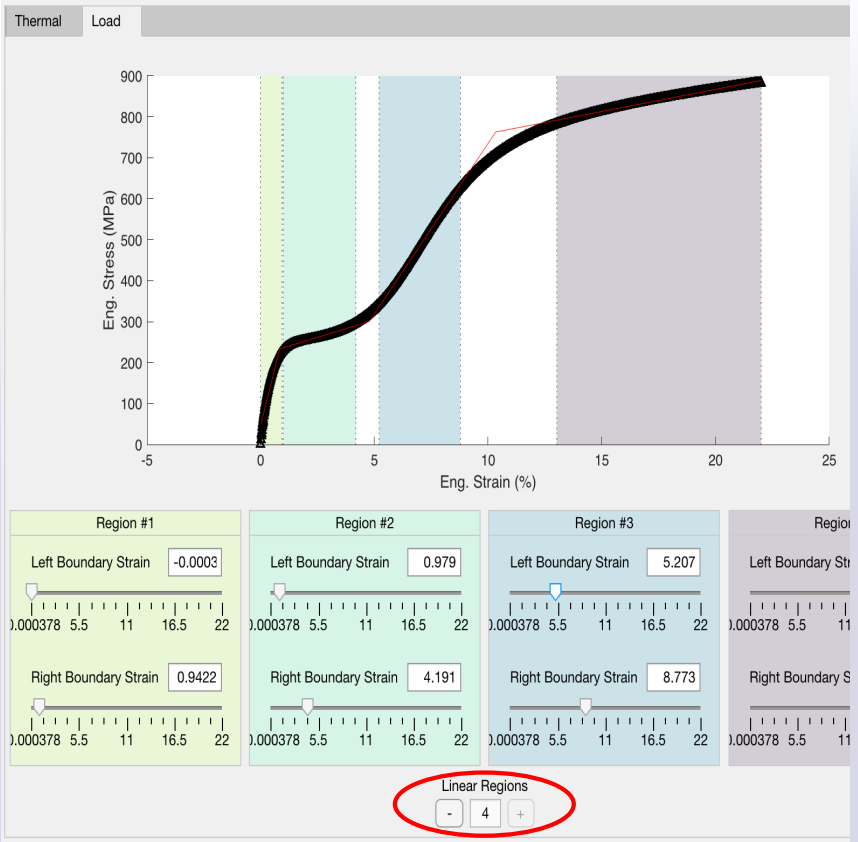

Manually adjust with up to 4 Linear Regions + Adjust Boundary Sliders

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

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

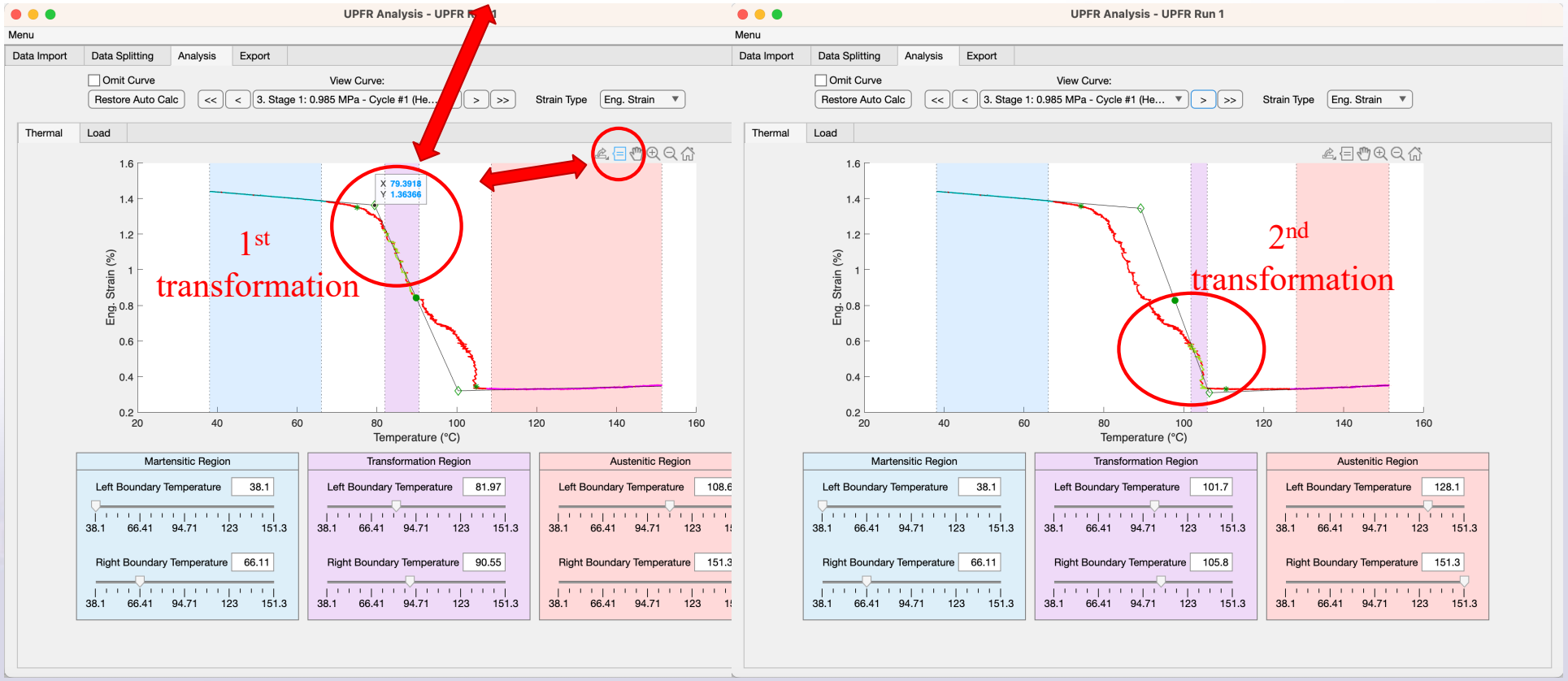
To Capture:

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



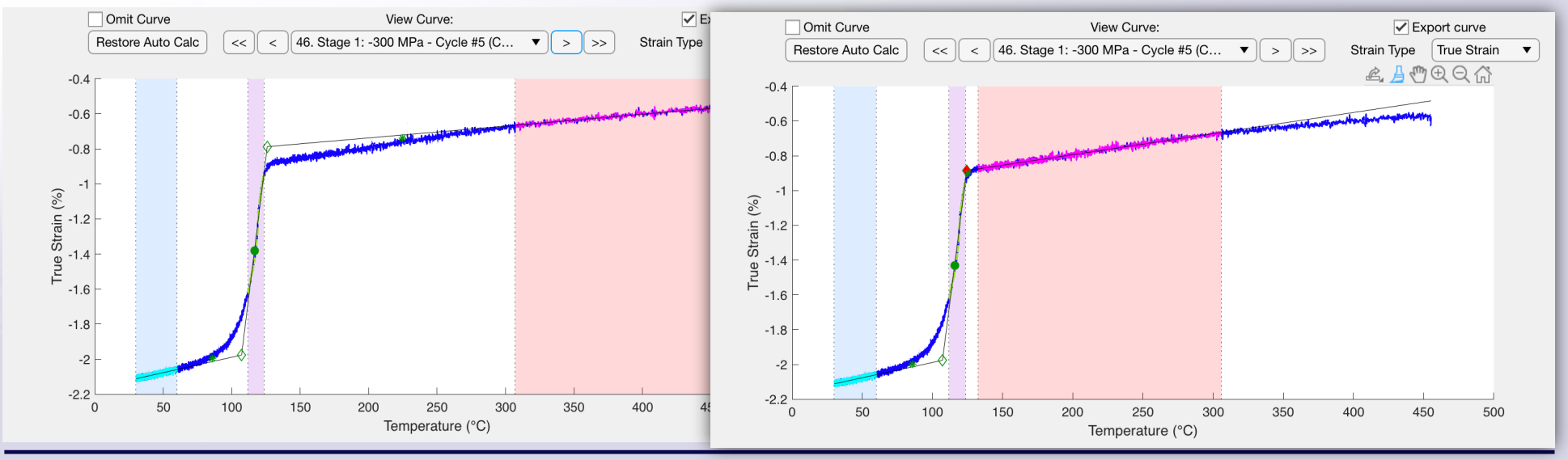
# Accounting for multiple phase transformations

## Can use Data Tips to view measured values



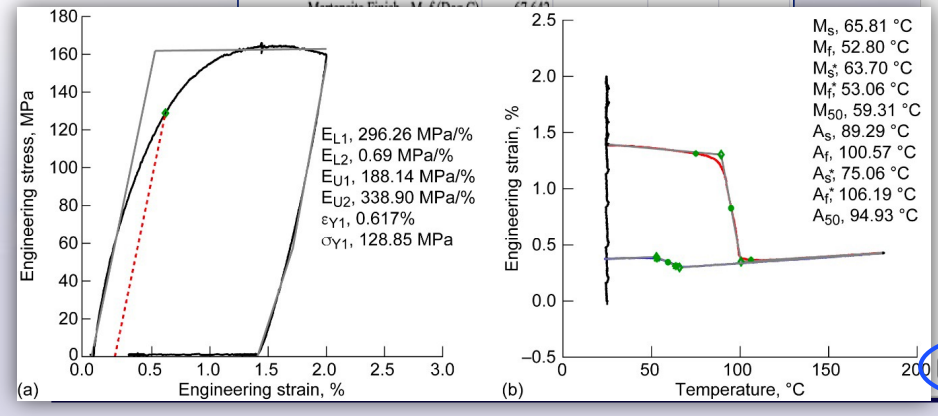
# Editing Heat/Cool Segments

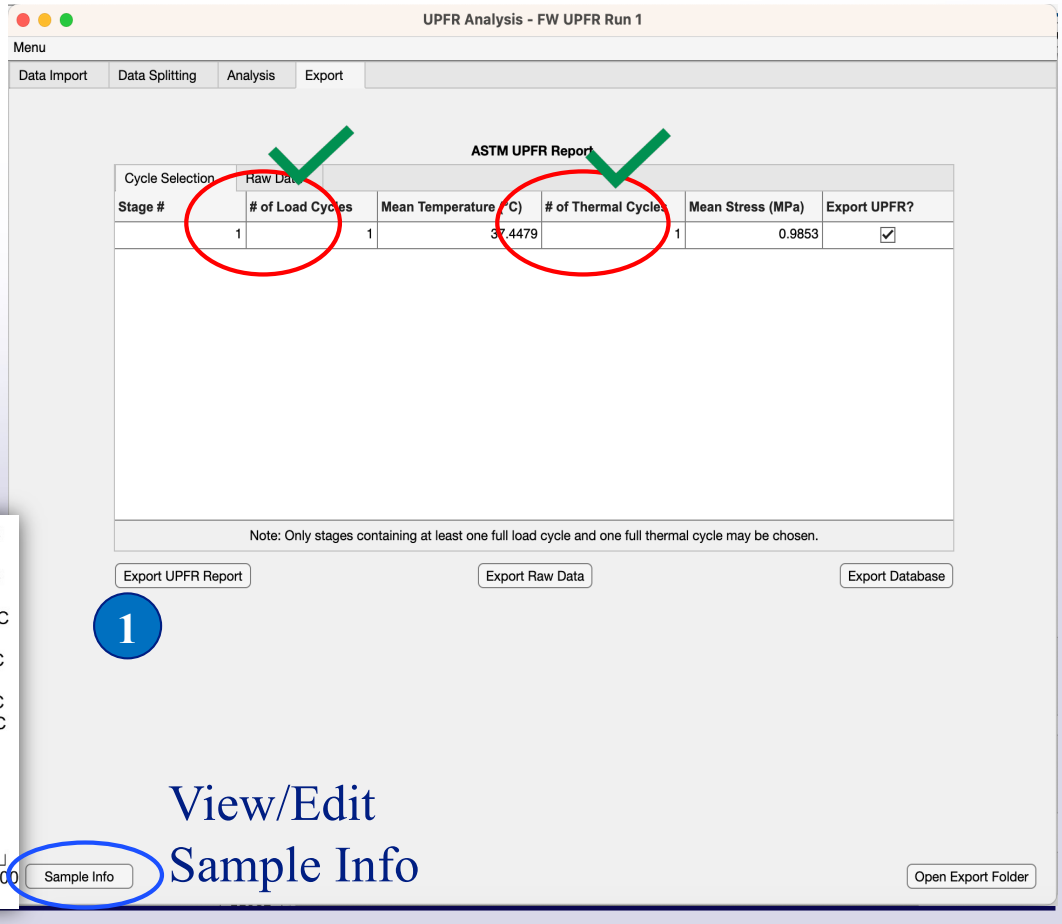
- Can manually adjust any region/fit
- Adjust Boundary Sliders as desired
  - ** Mouse over slider and use scroll wheel to fine tune
- Use Data-Tip to view values if desired



# Exporting – ASTM Report

| | |
|---|---|
| Test Type | UCFTC |
| Test Note | |
| Test Date | 12/5/17 |
| Lab | NASA-GRC-SH38B |
| Operator | O. Benafan |
| Material | NiTi |
| Sample Indentification | |
| 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 |

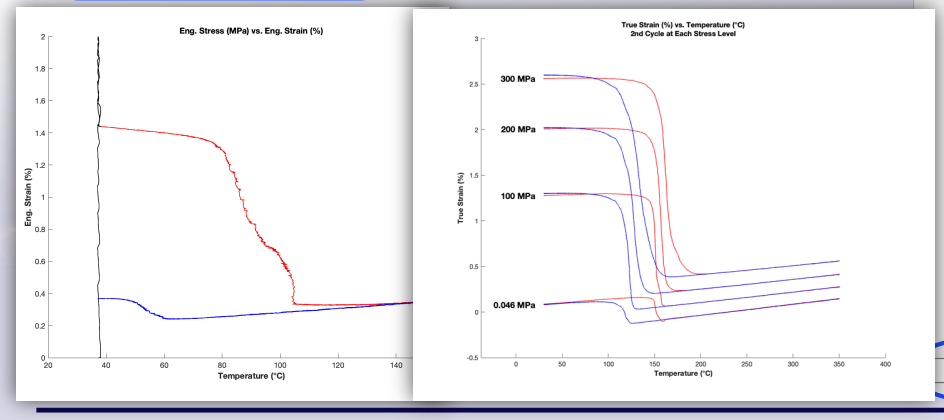


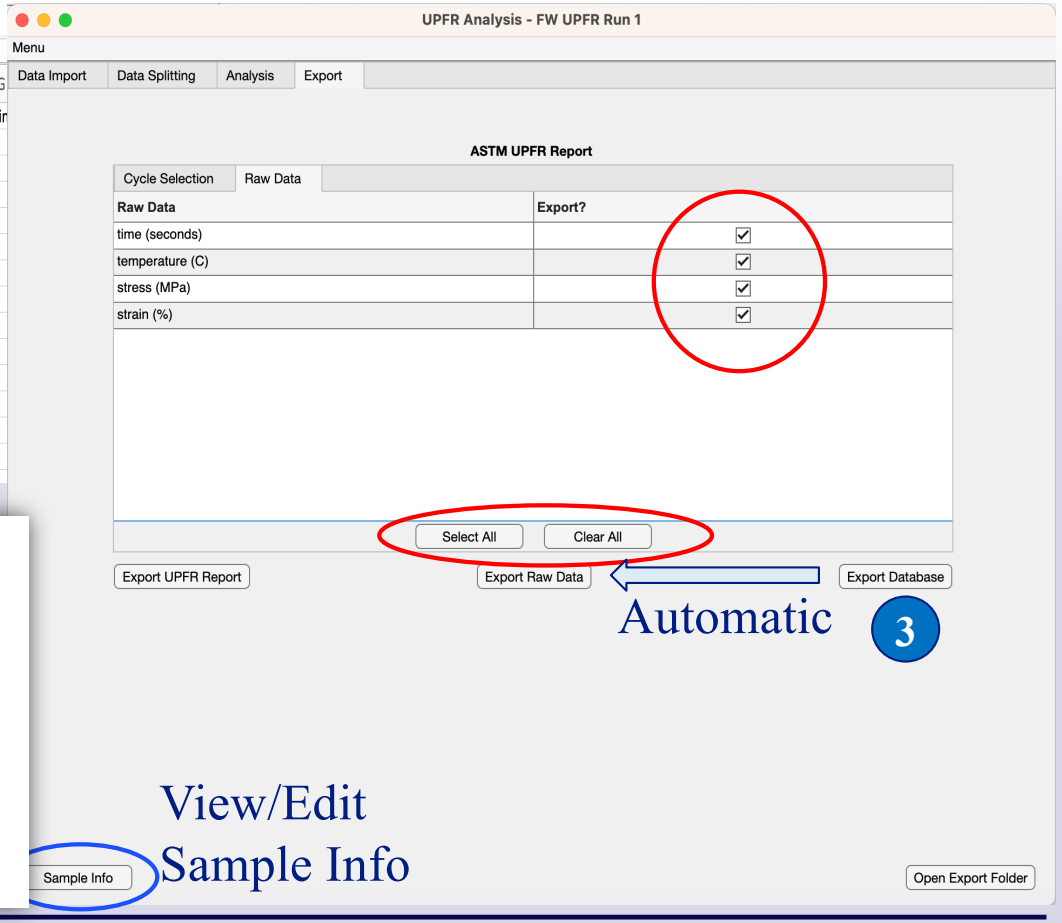




View/Edit Sample Info

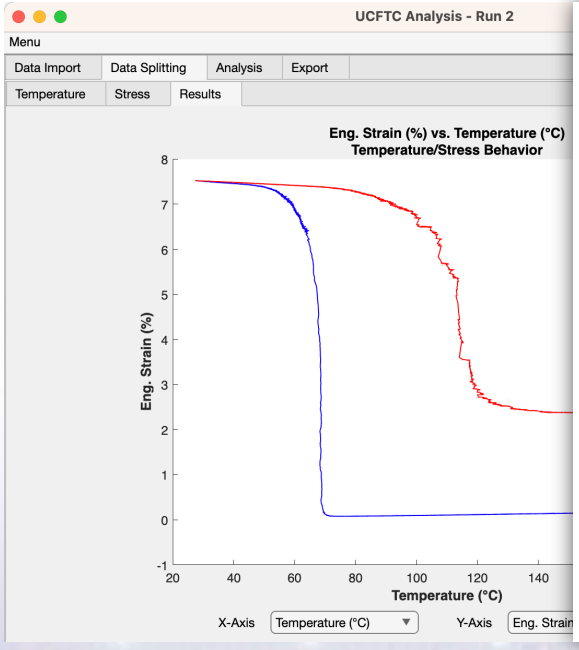
# Exporting – Database format available

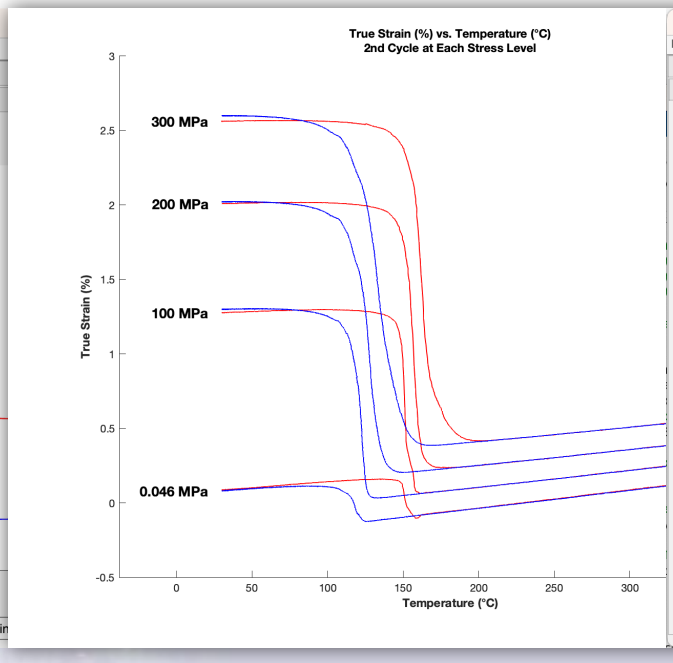
| Test Information | | | Stage # | Load Cycle Type | Load Cycle Temperature | Initial Strain |
|---|---|---|---|---|---|---|
| Test Type | UPFR | | | | °C | % (Eng.) |
| Sample ID | FW UPFR Run 1 | | 1 | Loading-Unloading | 37.43296558 | |
| Test Date | 9/5/23 0:00 | | | | | |
| Operator | | | | | | |
| 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 | | | | | | |

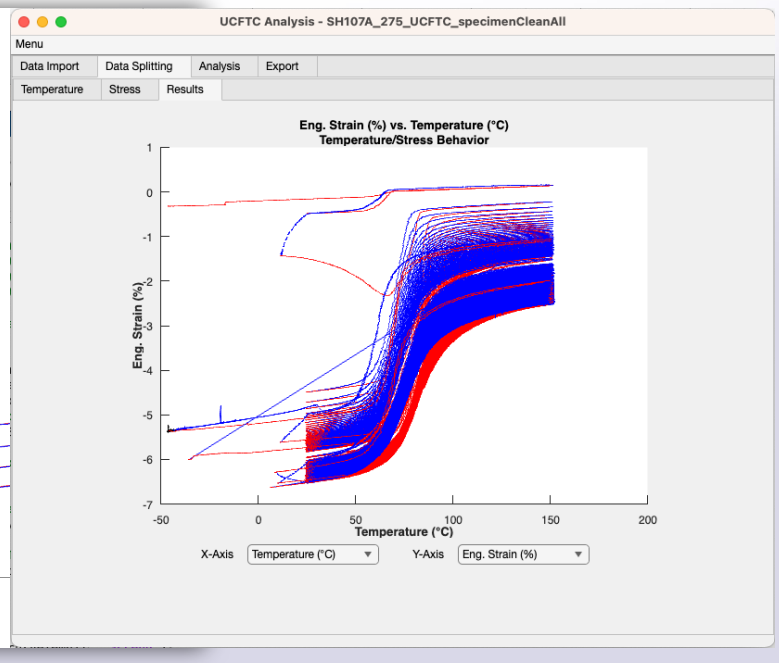


# Powerful, robust algorithm can handle different "flavors" of UCFTC



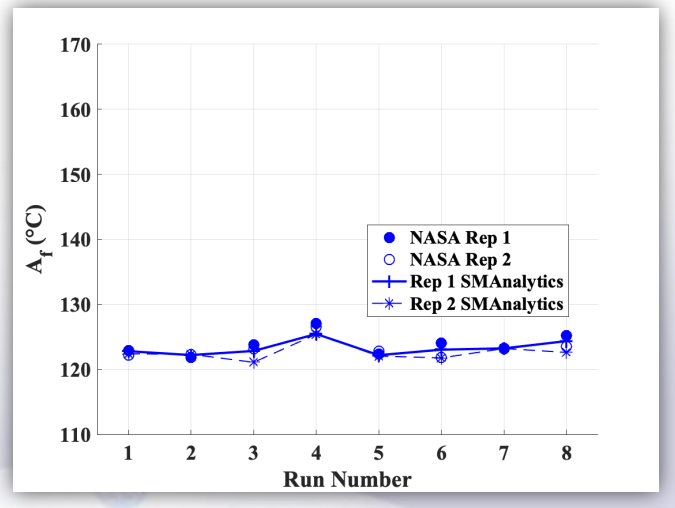




Standard Test Method

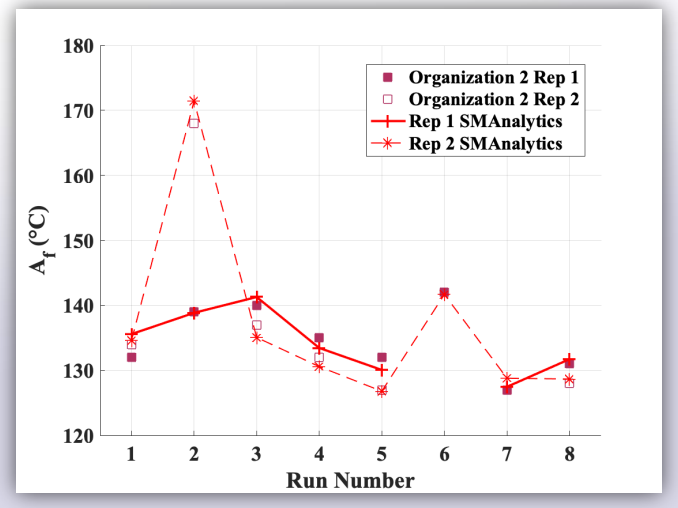
Multiple Stress Levels

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

# SMAnalytics Analysis Matches Human Analysis Automatically



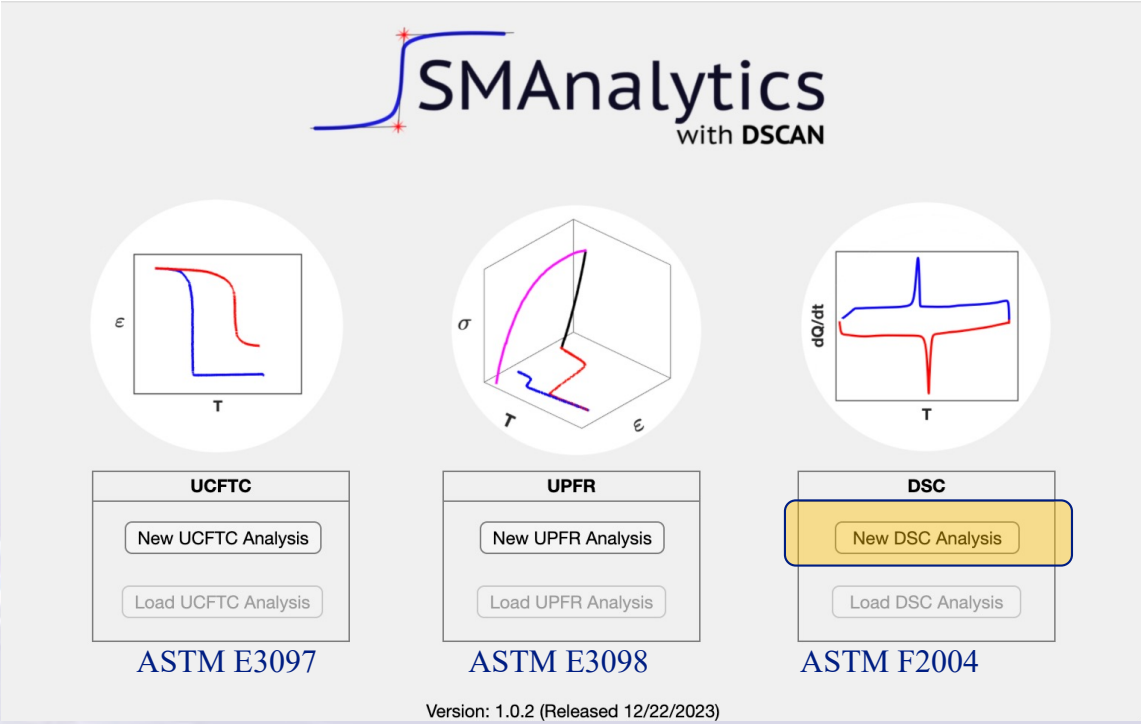

Clean Data




Noisy Data

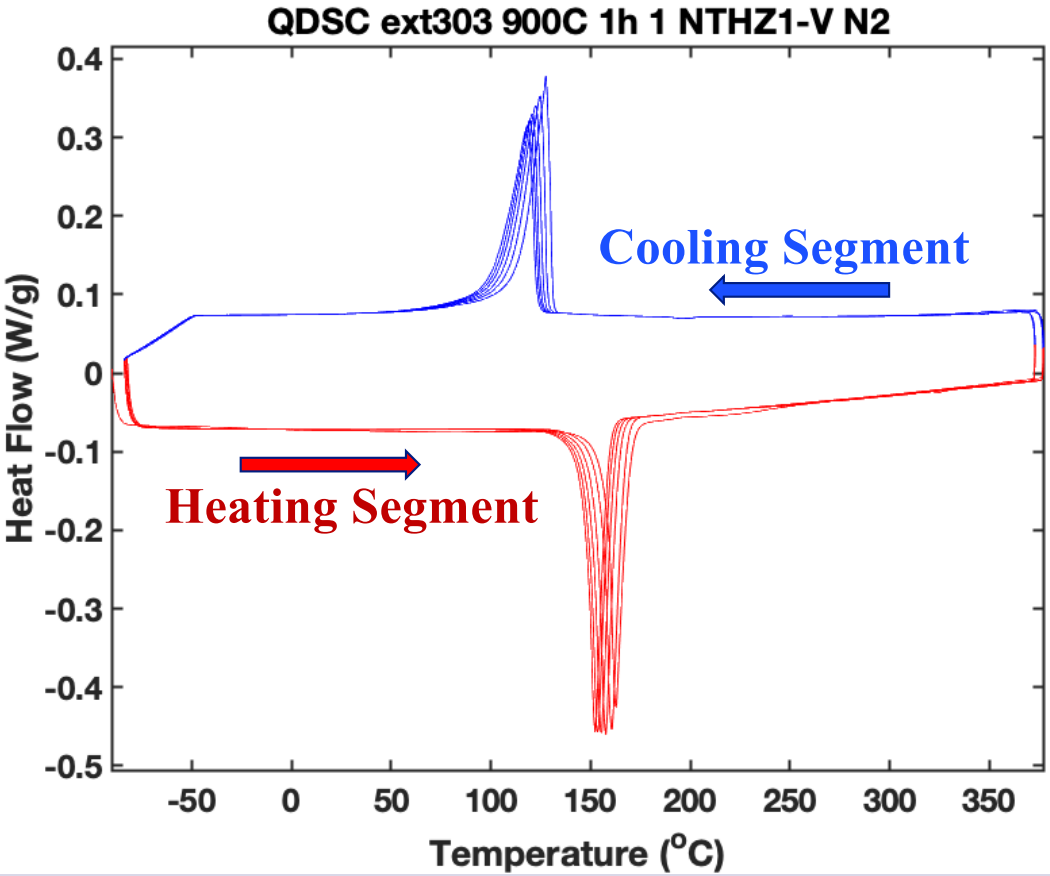
Data from ASTM Ruggedness Software Validation

# Launch Window



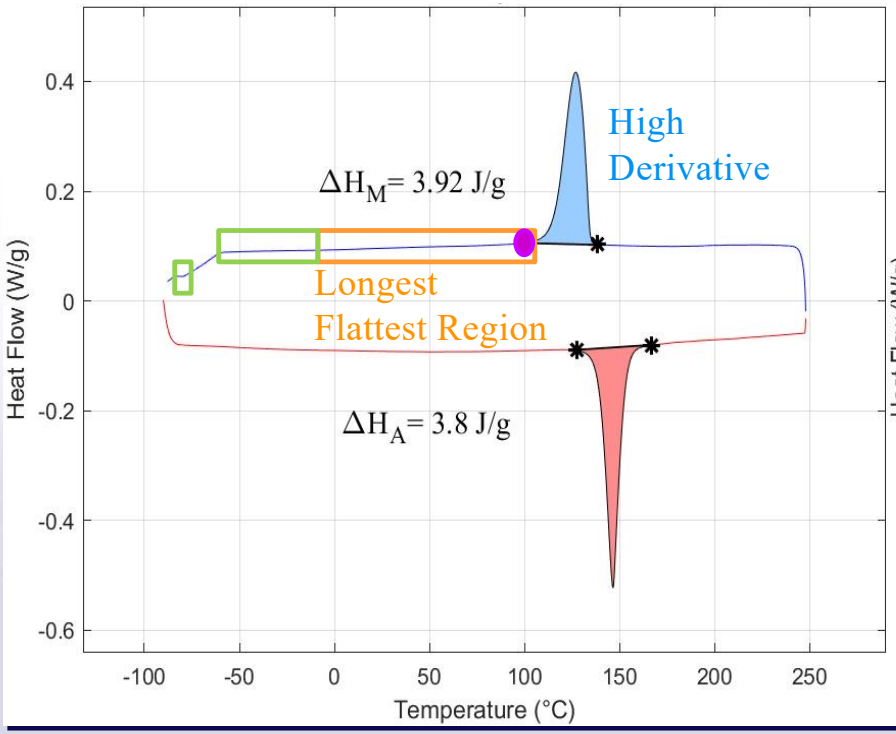
# DSCAN Methodology – Split Cycles

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

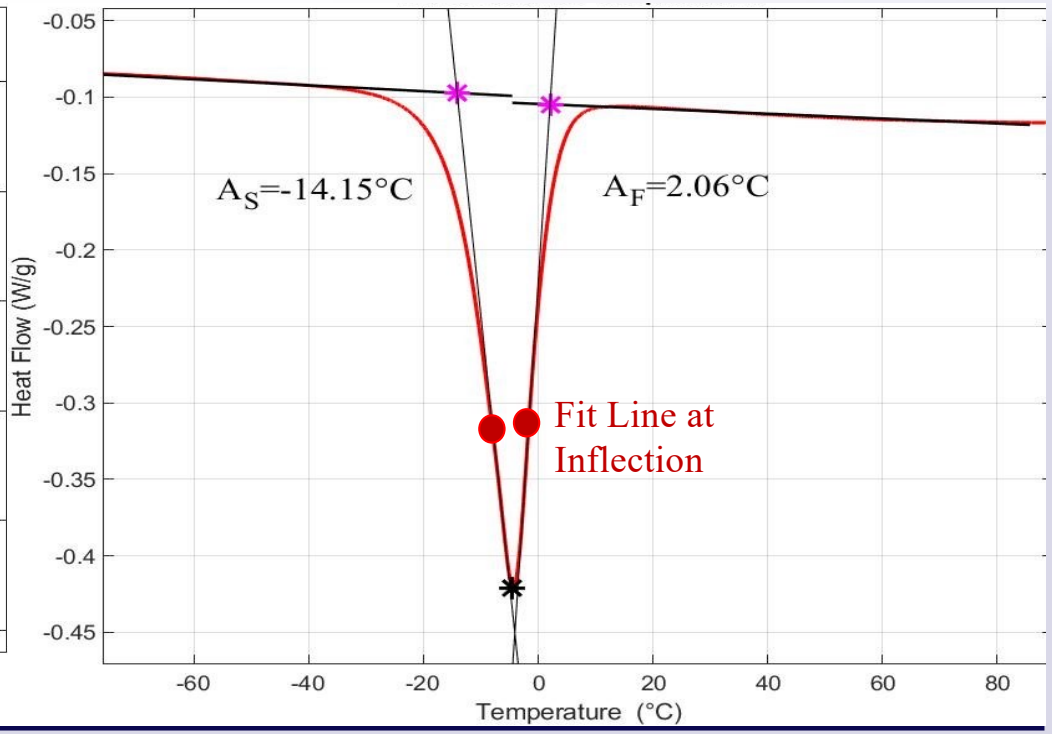


# DSCAN Methodology – Automatic detection of:

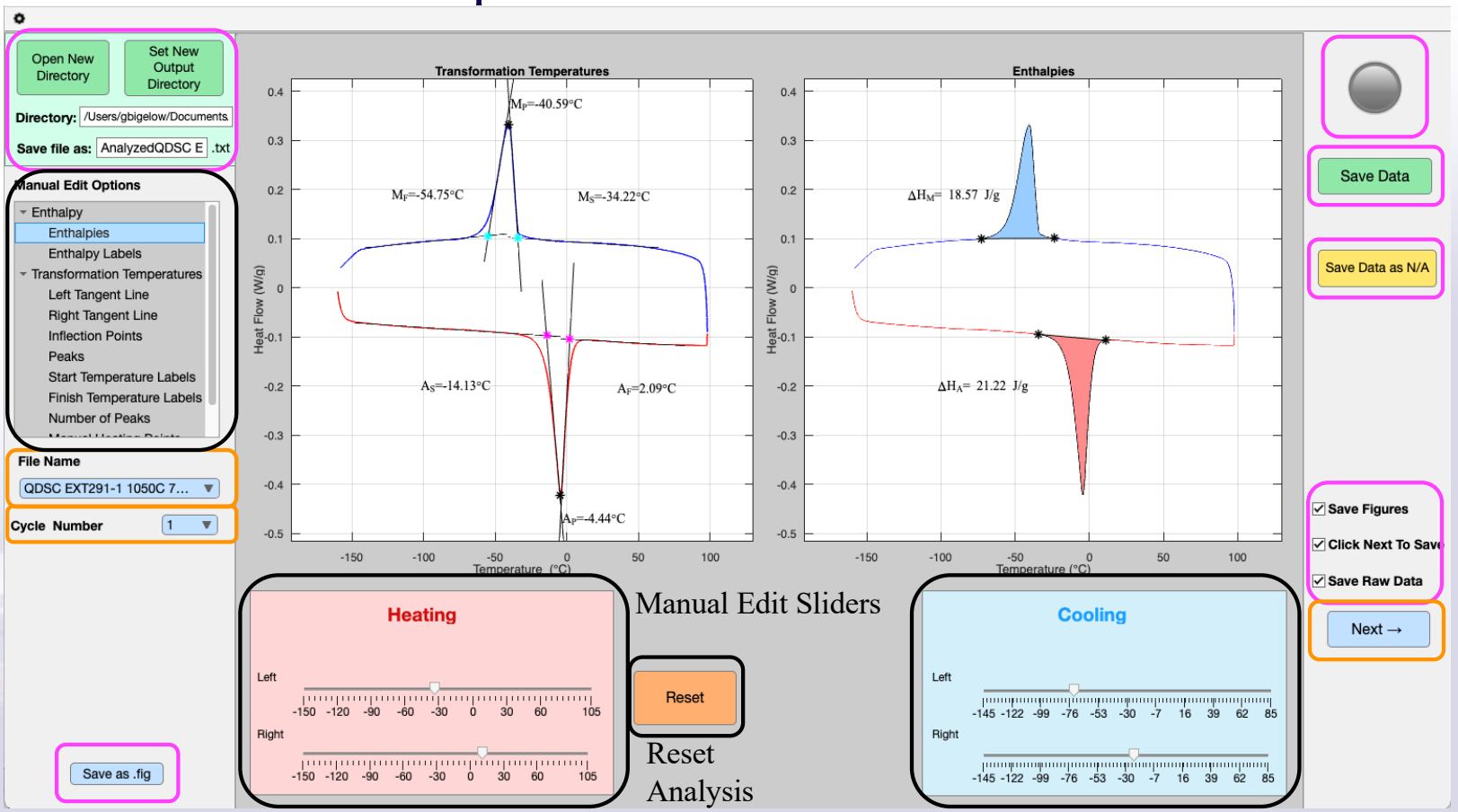
Enthalpies




Transformation Temperatures



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




Set Output Dir

Output File

Manual Edit Option Menu

Current File

Current Cycle

Save Figure

Save Indicator

Save Data

Save N/A

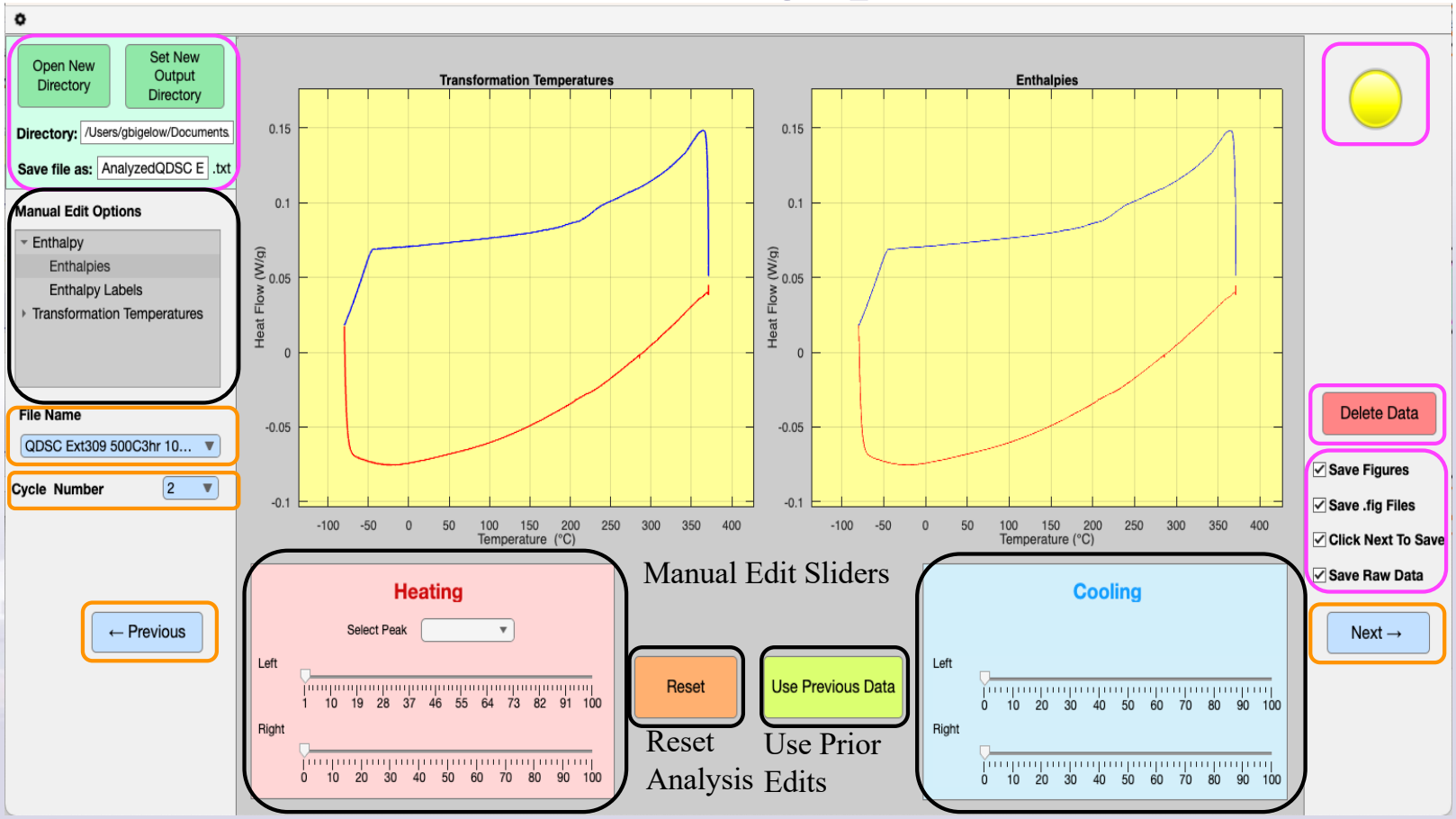
Save Options

Next Cycle

Manual Edit Sliders

Reset Analysis

# DSCAN: Detect and flag questionable data




Set Output Dir

Output File

Manual Edit Option Menu

Current File

Current Cycle

Prior Cycle

Saved Indicator

Delete Saved Cycle Data

Save Options

Next Cycle

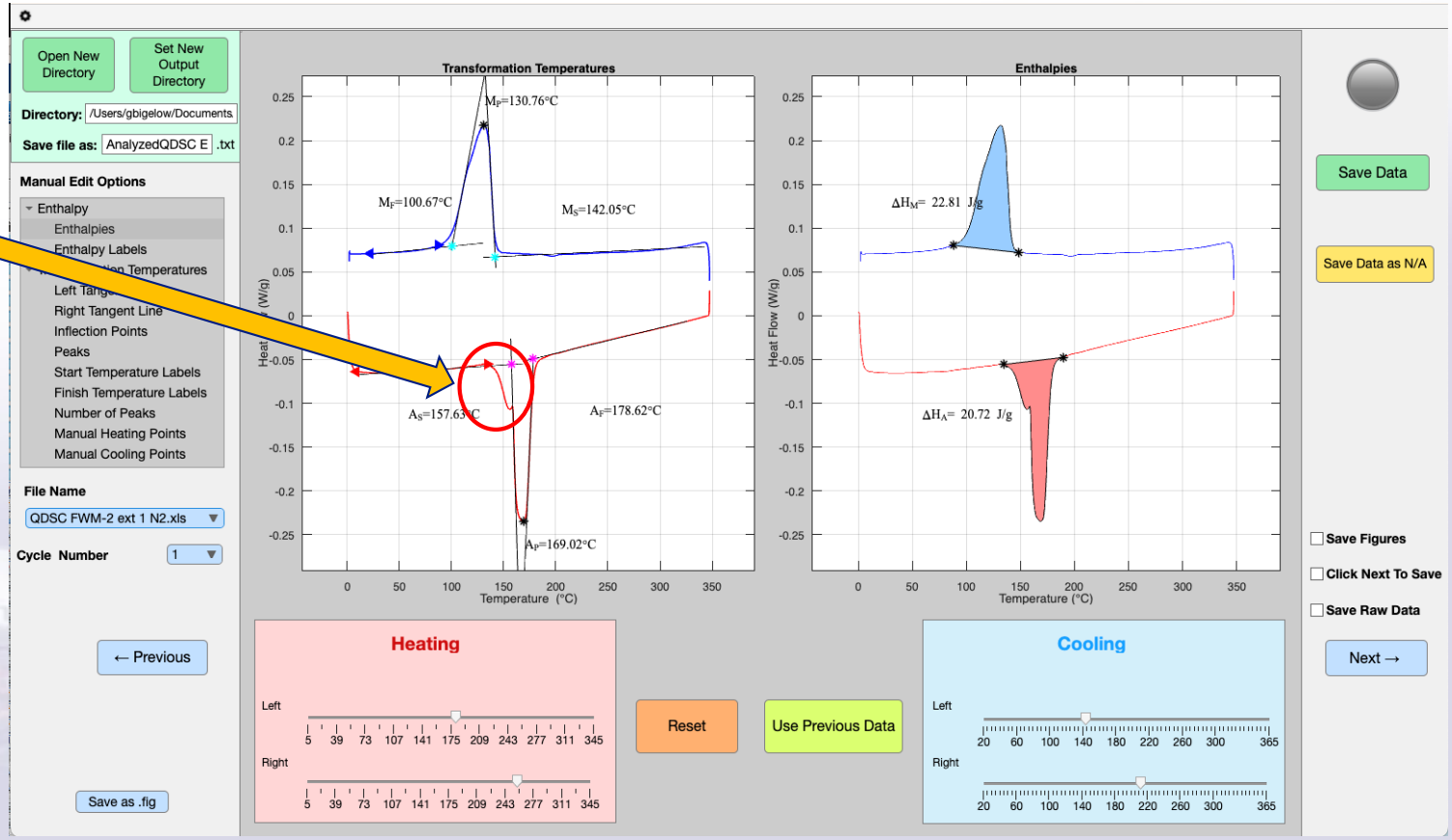
Manual Edit Sliders

Reset Analysis

Use Prior Edits

# Complex case: Can analyze multiple or overlapping peaks

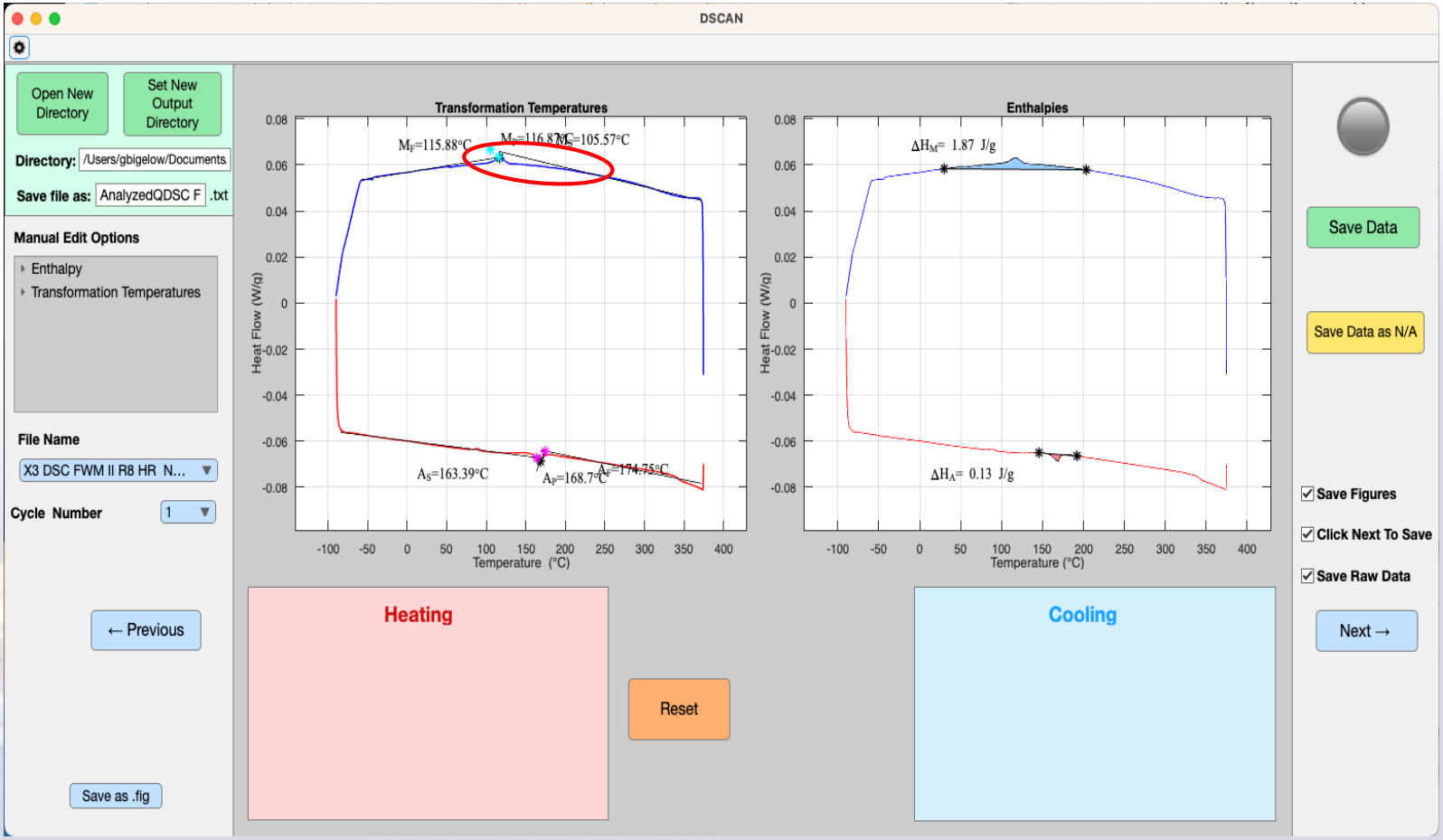
Example: DSCAN not catching $A_S$ from secondary peak



# Complex case: Can analyze small peaks, curved baseline

DSC has small peaks and a curved baseline

DSCAN not catching peak edges

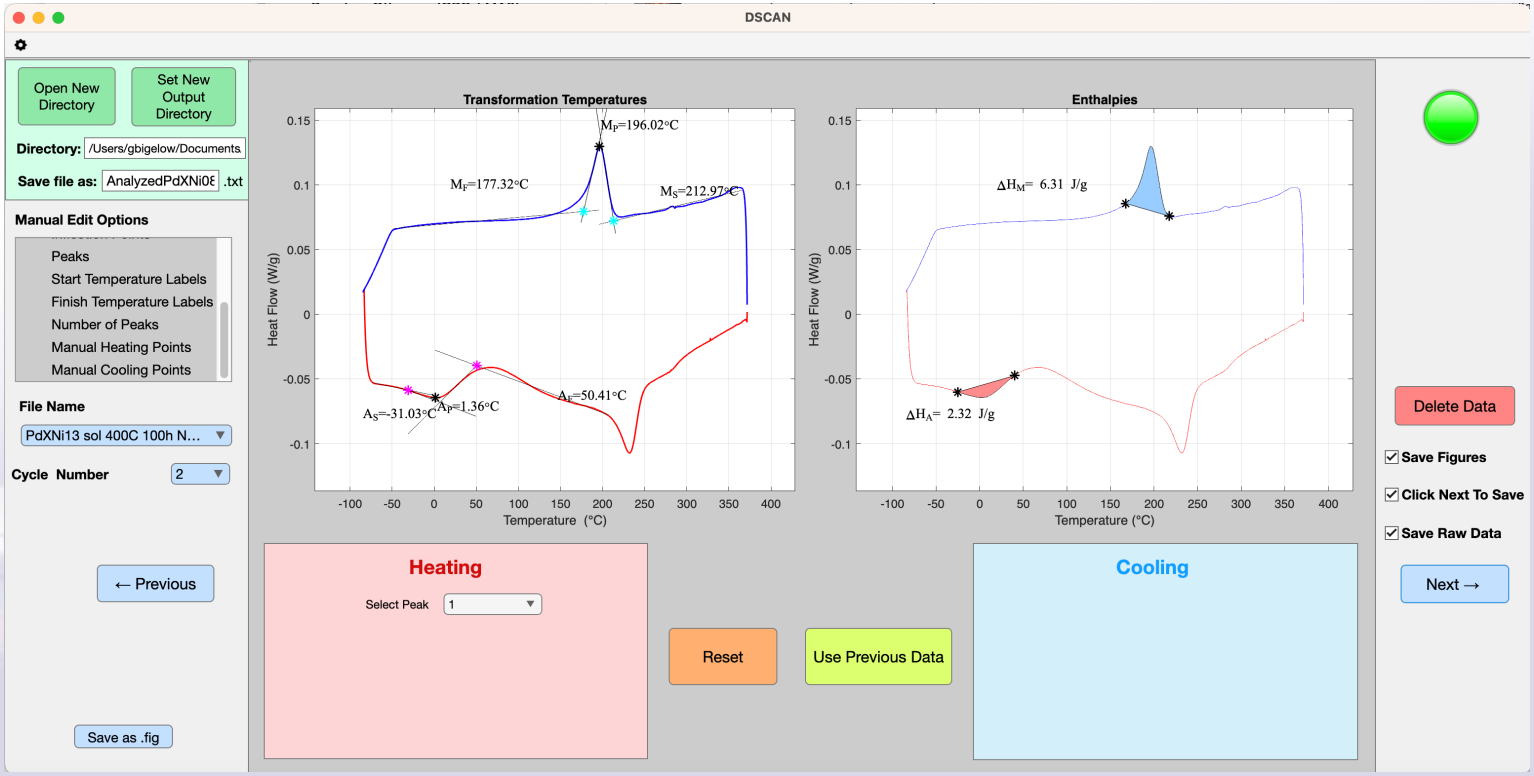


# Complex case: Can analyze small peaks, curved baseline

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 ($T^3$) project.


## *DEVELOPERS*

The software was developed by:

- Glen Bigelow (SMAnalytics 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?**

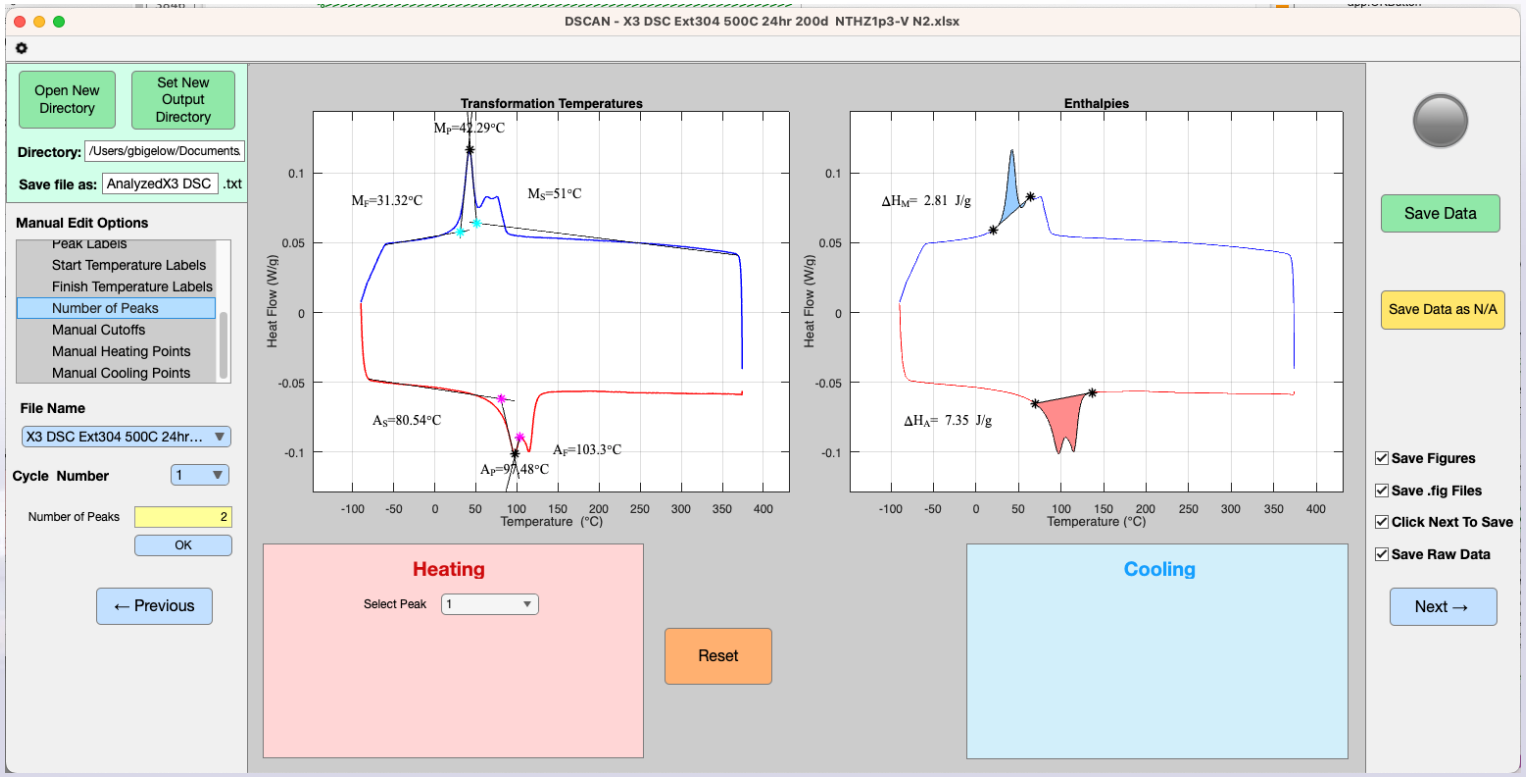
grc-ShapeMemory@mail.nasa.gov

*note SMAnalytics and version used

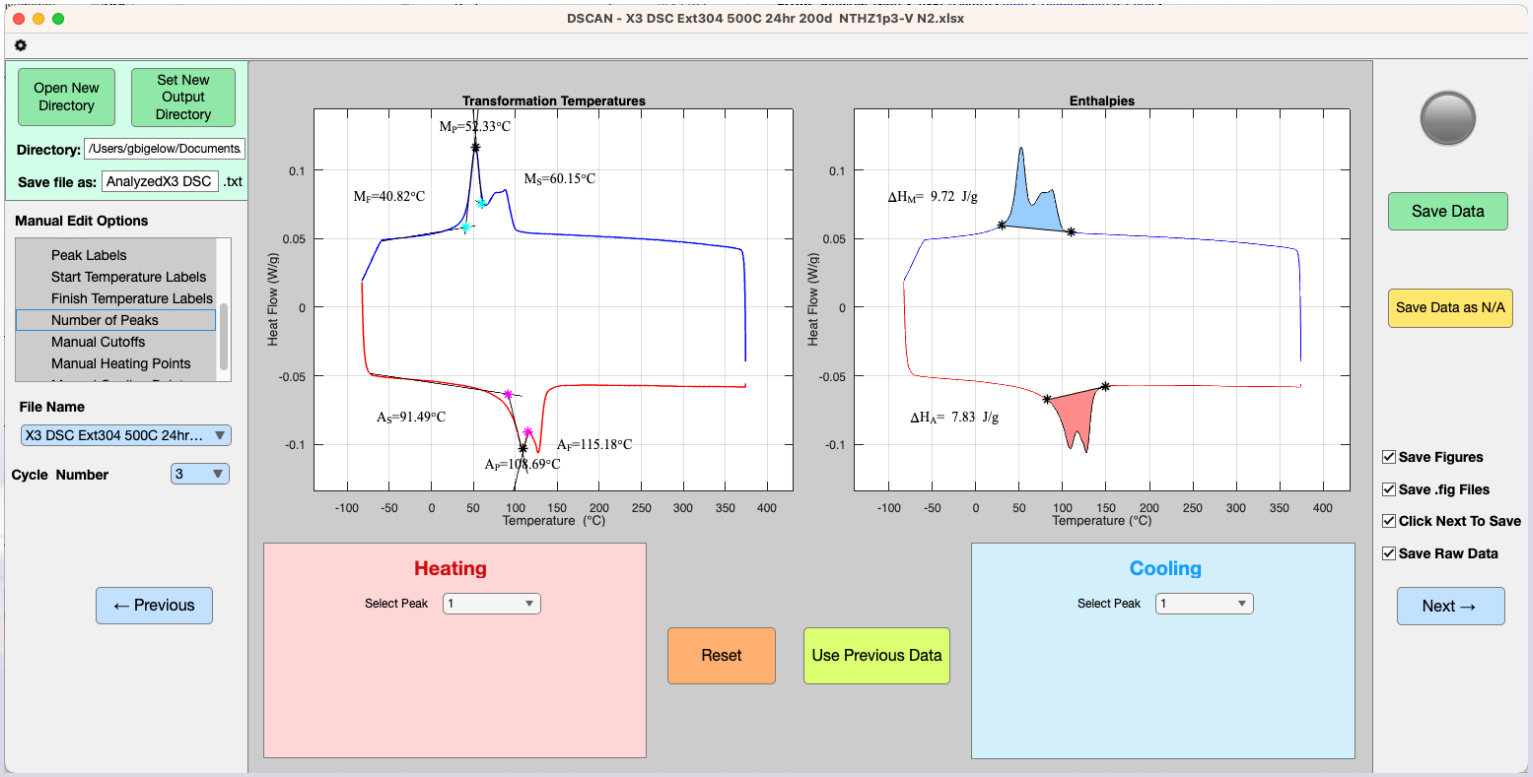
Software Available at https://software.nasa.gov/software/LEW-20278-1

Tutorial/User's Manual

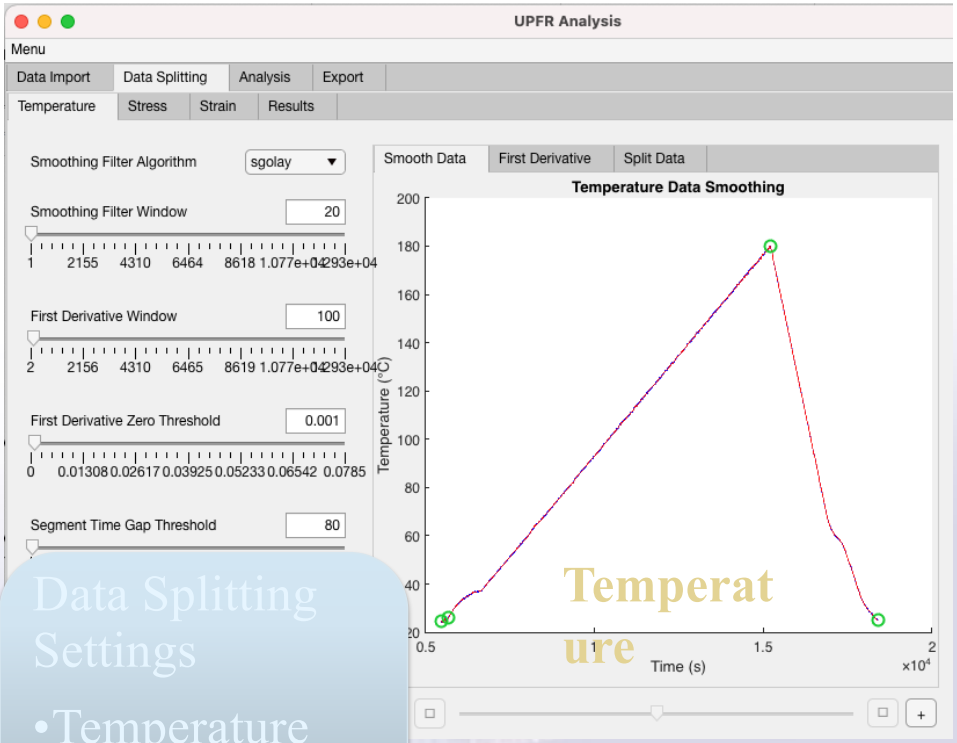
# Manual Edit – Missing Peak



# Manual Edit – Missing Peak



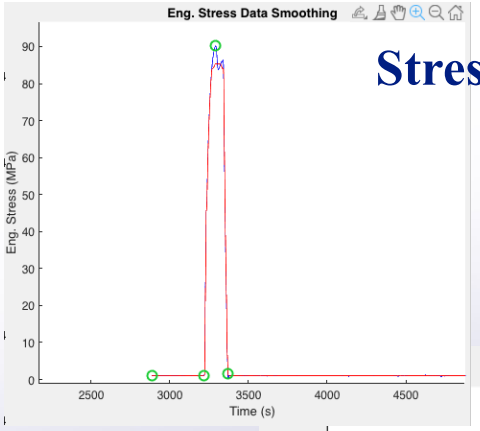
# Principle of Operation: Splitting



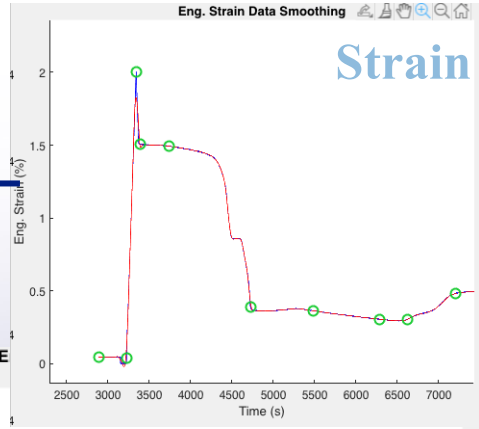

Data Splitting Settings

- Temperature
- Stress
- Strain

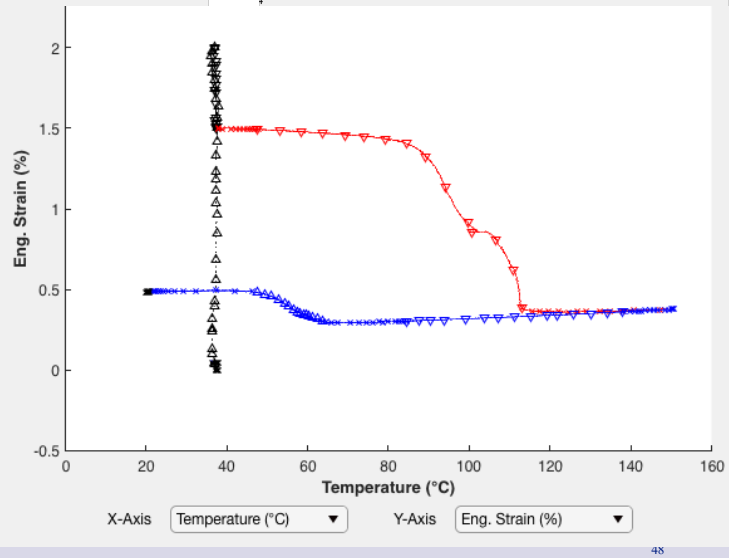
+




+



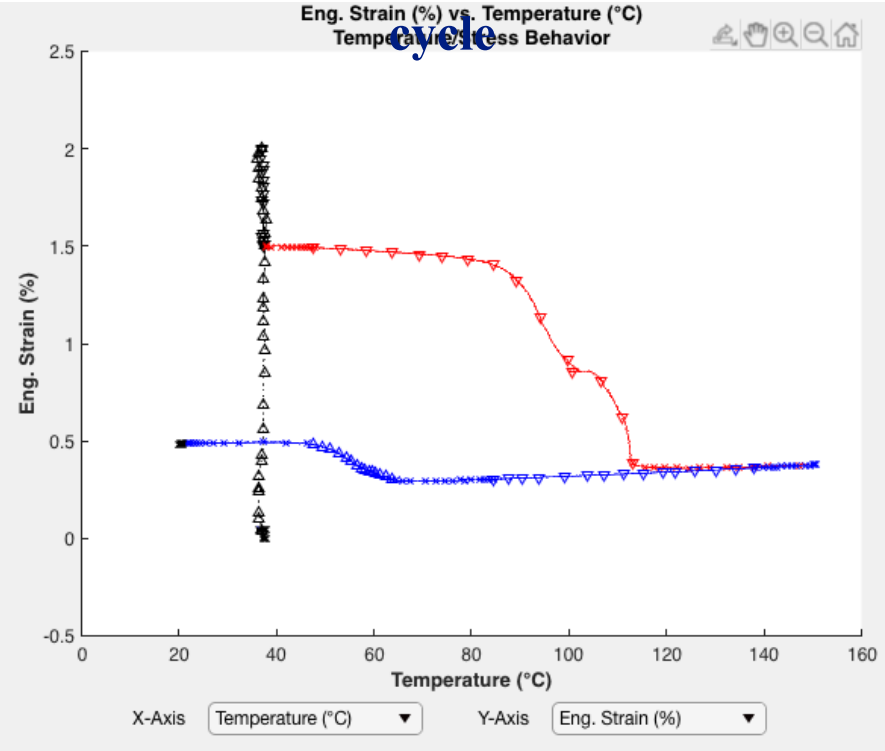

=



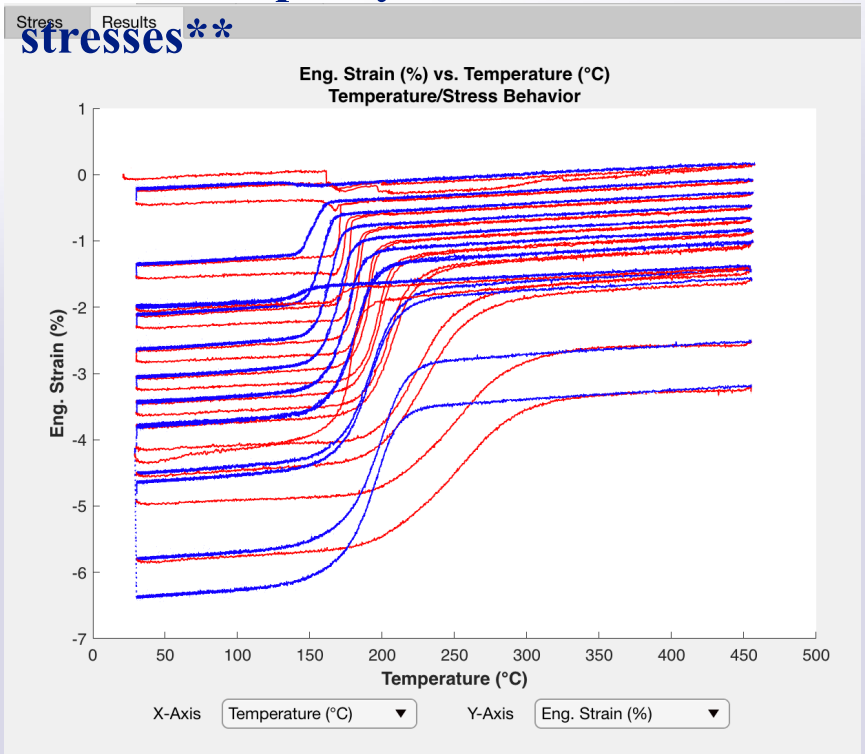
# Principle of Operation: Data Splitting

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