



SMAnalytics Automated Shape Memory Test Analysis Software User's Manual: UCFTC, UPFR, and DSC Test Methods, Version 1.0.2

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This software builds upon legacy MATLAB® shape memory alloy analysis code originally developed in about 2004. The legacy code was developed and has been enhanced over the years to allow analysis of several types of tests, including uniaxial constant-force thermal cycling (UCFTC), load-biased tests, UPFR, DSC, torsion, and uniaxial tension/compression, among others. However, the code always required user input for fitting the various regions of the test curves for analysis. Automated software that could perform the same analysis with less user input was desired, which led to the development of SMAnalytics.

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Summary

Over the course of 60 years of shape memory alloy research and development, the properties of these alloys have been measured using various testing methods, which are often customized by the organization performing the test. However, commercial adoption of shape memory alloys in aeronautic actuator applications requires reducing property uncertainty through standardizing test methods. Historically, differential scanning calorimetry (DSC) has been used to measure transformation temperatures under stress-free conditions. This testing method is well established, and tests are run under the applicable standard, ASTM F2004-17: Standard Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis. Two other test methods for measuring strains and transformation temperatures under constant load or free recovery after prestraining have only recently been standardized—ASTM E3097: Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of SMAs (UCFTC) and ASTM E3098: Standard Test Method for Mechanical Uniaxial Pre-Strain and Thermal Free Recovery of SMAs (UPFR).

These standards represent a critical step forward in producing reliable material property data for the use of these alloys in aeronautics and other commercial areas. However, no standard programs or software packages were previously available for postprocessing UCFTC- and UPFR-type test data to

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extract property data. Each organization that performed the testing analyzed data using its own custom manual methods, such as using a plot and a straight edge, spreadsheet plotting methods, or custom code routines, to extract the required values for strains, stresses, and transformation temperatures. SMAAnalytics represents the first publicly available uniform software package for processing data generated using the DSC, UCFTC, and UPFR test methods, as well as many modifications of these methods, including loading in martensite versus austenite and performing multiple thermal cycles at stress. In doing so, it provides a tool for reducing potential error or variability in the measured values due to the precision of the technique used and person-to-person variability. It is also expected that this automated data-parsing tool can accelerate the data analysis phase of the test campaign, especially for large data files. This User's Manual describes how the SMAAnalytics software works and the method for its use.

1.0 Introduction

SMAAnalytics was designed as a graphical user interface (GUI) based software suite for automated analysis of Shape Memory Alloy (SMA) test data incorporating the latest ASTM standards. Three ASTM test methods—Uniaxial Constant Force Thermal Cycling (UCFTC) (Ref. 1), Uniaxial Pre-Strain and Thermal Free Recovery (UPFR) (Ref. 2), and Differential Scanning Calorimetry (DSC) (Ref. 3)—form the basis for the three software apps. Each app is designed to allow a user to import test data, define the desired processing parameters, automatically split up the data into the constituent heating/cooling and loading/unloading cycles as needed, automatically analyze the data, and export that data to ASTM-style reports, plots, or a summarized database table of all the parameters measured by the software. In addition to processing ASTM-specific tests, the software allows for analysis of test data produced using modifications of the ASTM methods, such as multicycle and multistress tests, and loading in the martensite as opposed to loading in the austenite.

1.1 Installing SMAAnalytics

SMAAnalytics was written and compiled using MATLAB[®] software, and as such, requires the MATLAB[®] Runtime. The MATLAB[®] Runtime is available packaged with SMAAnalytics through the NASA Software Catalog, <https://software.nasa.gov/software/LEW-20278-1>, or can be downloaded from the MATLAB[®] website at <https://www.mathworks.com/products/compiler/matlab-runtime.html>. However, the MATLAB[®] Runtime used must be the same version as the MATLAB[®] release used to compile the software. To check the MATLAB[®] release used to compile the current SMAAnalytics version, check the readme text file packaged with SMAAnalytics. For help with installing or troubleshooting the MATLAB[®] Runtime, please see <https://www.mathworks.com/help/compiler/install-the-matlab-runtime.html>, especially the later sections of the webpage.

1.2 Special Considerations for Installing and Running SMAAnalytics on macOS[®]

For macOS[®], follow these steps to run SMAAnalytics with temporary changes to the environment variable DYLD_LIBRARY_PATH:

1. Open Terminal in the Mac[®]
2. Change directory to the SMAAnalytics application folder
For example, type: `cd /`
type: `cd Applications/SMAAnalytics/application`
3. Then start the SMAAnalytics software by typing
`./run_SMAAnalytics.sh <mcr_directory>`
where `<mcr_directory>` is the directory where the MATLAB Runtime is installed

For example. If MATLAB[®] Runtime (R2022b) is installed in
/Applications/MATLAB/MATLAB_Runtime/R2022b
just type:
./run_SMAalytics.sh/Applications/MATLAB/MATLAB_Runtime/R2022b

For more information, see <https://www.mathworks.com/help/compiler/mcr-path-settings-for-run-time-deployment.html>.

2.0 Data File Requirements and Preparation

Data files processed using SMAalytics must include at a minimum:

UCFTC: Delimited text file containing (in any order)

1. Strain signal—One of the following: (a) strain, (b) displacement with sample dimensions, or (c) voltage representing displacement or strain signal with gain, offset, and sample dimensions
2. Temperature signal

UPFR: Delimited text file containing (in any order)

1. Stress signal—One of the following: (a) stress, (b) force with sample dimensions, or (c) voltage representing force signal with gain, offset, and sample dimensions
2. Strain signal—One of the following: (a) strain, (b) displacement with sample dimensions, or (c) voltage representing displacement or strain signal with gain, offset, and sample dimensions
3. Temperature signal

DSC: Microsoft Excel[®] file containing columns of (in exact order)

1. Time
2. Temperature
3. Heat flow

Some preprocessing of test data files may be necessary before analysis with SMAalytics. Test data files must conform to certain standards to allow the software to read the entire file and process the data.

- Initial headers defining the test style, process parameters, etc. are permitted, but after the start of the data to be processed, there cannot be additional headers, empty lines, or non-numerical lines that break up the data. Certain testing software apps and controllers provide the option to insert additional headers whenever tests are stopped and restarted or before certain events during testing. It may be beneficial to disable this feature in order to reduce data preprocessing requirements.
- No empty lines at the end of the file.

3.0 Startup

To begin using SMAalytics, double-click on the SMAalytics program icon, which will bring up the Launch Window (Figure 1) with the available test options.

- Select the New Analysis button for the desired test method. This will bring up the analysis window for that method.
- The Load Analysis button under each app heading is grayed out for now. The ability to load a previous UCFTC, UPFR, or DSC Analysis for refining or adjusting will be included in a future release of SMAalytics.

4.0 Overview of Test Methods

4.1 Uniaxial Constant Force Thermal Cycling (UCFTC)

The UCFTC test can be used to measure the transformation temperatures, strains, and hysteresis of a shape memory alloy sample (Figure 2). This is accomplished by heating a sample to an upper cycle temperature (UCT), loading to a specified force (stress), holding at that force, and thermally cycling (cooling and heating) under that constant force while recording the temperature and strain as defined in ASTM E3097: Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys (Ref. 1). The SMAAnalytics UCFTC app analyzes tests performed using the standard method, but it also allows analysis of modifications of the method, such as heating then cooling thermal cycles, multiple thermal cycles at a stress level, and multiple cycles at different stress levels.

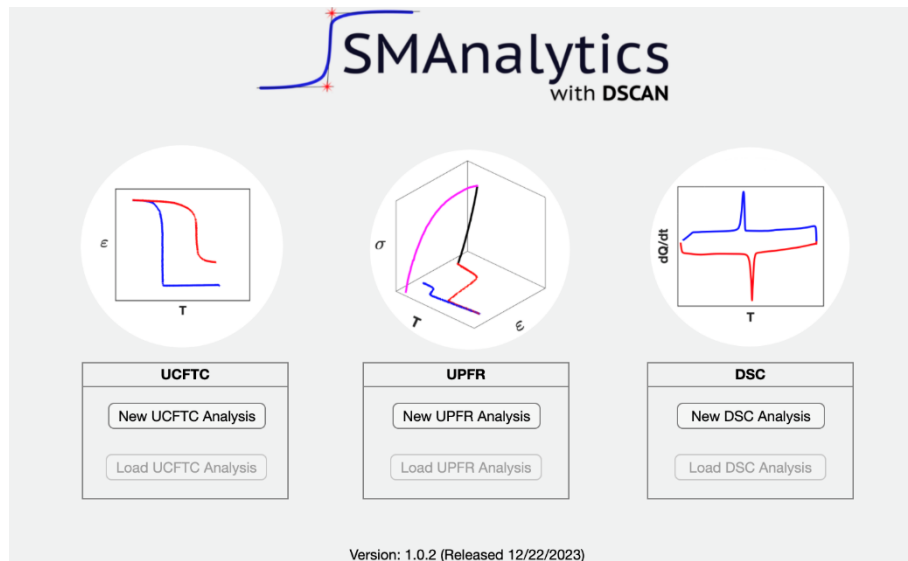


Figure 1.—SMAAnalytics launch window showing available test analysis options.

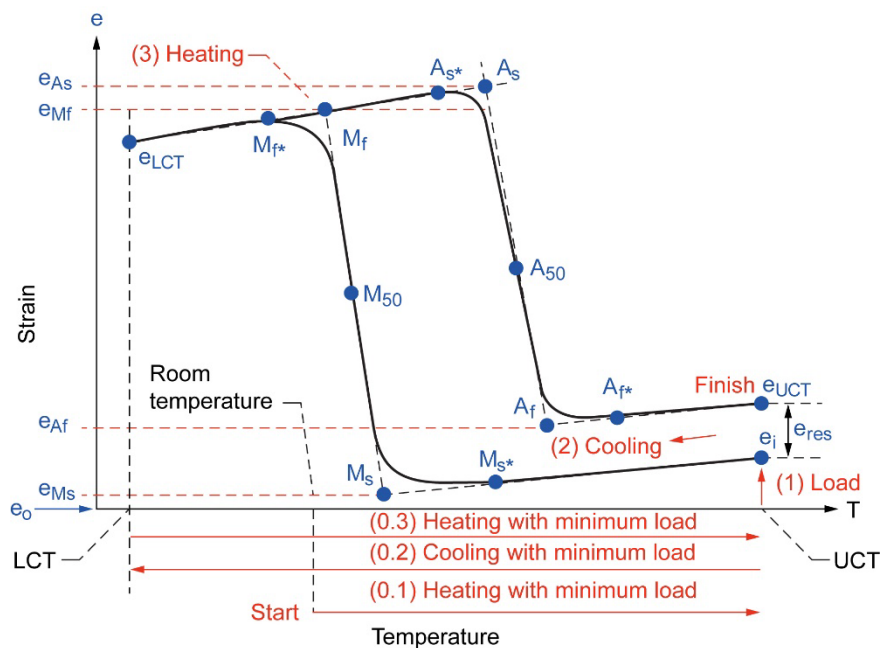


Figure 2.—Uniaxial Constant Force Thermal Cycling test with measured test parameters. Refer to ASTM test method for definitions and additional details (Ref. 1).

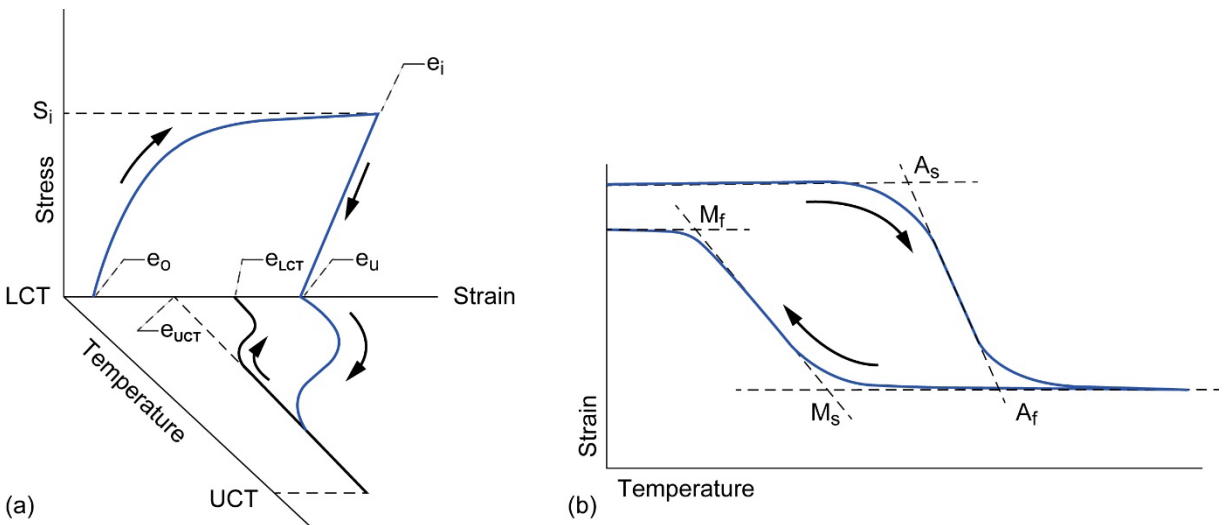


Figure 3.—Uniaxial Pre-Strain and Thermal Free Recovery (UPFR) Test with measured test parameters. Refer to ASTM test method (Ref. 2) for definitions and additional details. (a) UPFR test overview. (b) Closeup of thermal cycle with associated measured transformation temperatures.

4.2 Uniaxial Pre-Strain and Thermal Free Recovery (UPFR)

The UPFR test can be used to measure the recovery strain, transformation temperatures, strains, and hysteresis of a shape memory alloy sample (Figure 3). This is accomplished through prestraining a sample to a specified strain level, unloading, and thermally cycling the sample under a minimal load as defined in ASTM E3098: Standard Test Method for Mechanical Uniaxial Pre-Strain and Thermal Free Recovery of Shape Memory Alloys (Ref. 2). The SMAnalytics UPFR app analyzes tests performed using the standard method, but it also allows analysis of modifications of the method, such as prior normalization thermal cycles, additional post-UPFR thermal cycles, and multiple UPFR sets.

4.3 Differential Scanning Calorimetry (DSC)

The DSC test (Figure 4) can be used to determine transformation temperatures and enthalpies of shape memory materials as defined in ASTM F2004-17: Standard Test Method for Transformation Temperature of Nickel-Titanium Alloys by Thermal Analysis (Ref. 3). During heating, the sample will undergo an endothermic reaction during transformation, producing a measurable peak (or peaks) in the heat flow, and undergo an exothermic reaction during transformation on cooling, also producing a measurable peak (or peaks) in the heat flow. The SMAnalytics DSCAN DSC app provides automated analysis of this data while allowing manual adjustment to the fitting parameters as well as the capability to analyze multiple peaks.

5.0 Figure Toolbars

Throughout the different SMAnalytics apps, wherever there is a figure, mousing over the figure axes will cause the axes toolbar to appear in the upper right (Figure 5). Depending on the specific figure, the axes options may differ, but they will contain one or more of the following: Export, Data Brushing, Data Tip, Pan, Zoom In, Zoom Out, and Restore View. The Export toolbar option has three suboptions: Save As (to save the current figure as an image or MATLAB® figure), Copy As Image (to copy the current image to the clipboard for pasting into a document or graphics editing program), and Copy As Vector Graphics (to copy the current image to the clipboard for pasting into a document or graphics editing program).

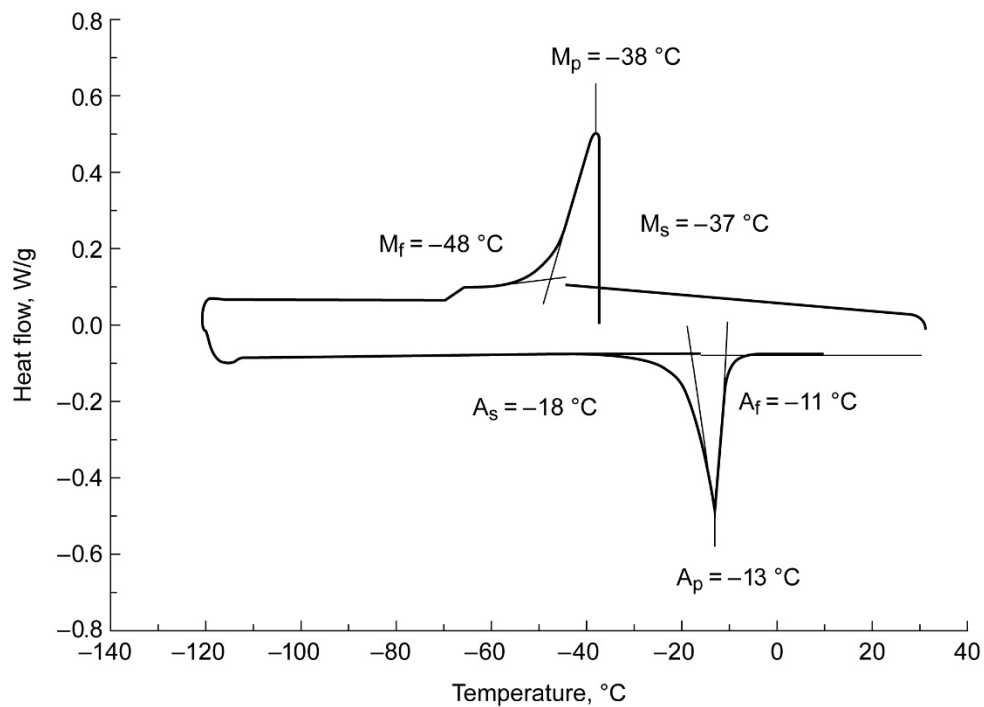


Figure 4.—Example DSC curve from Reference 3.

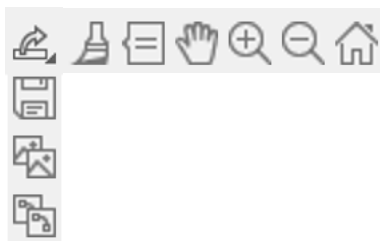


Figure 5.—Figure axes toolbar options, from left to right: Export, Data Brushing, Data Tip, Pan, Zoom in, Zoom out, Restore View. The drop-down options for Export are Save As, Copy As Image, and Copy As Vector Graphics.

6.0 UCFTC and UPFR Apps

The overall operations of the UCFTC and UPFR apps are very similar, given that a UPFR test is essentially an isothermal load–unload operation followed by a UCFTC thermal cycle at some minimum load (<7 MPa). Here are the major differences between the two apps: (1) the Data Splitting algorithm for UPFR relies on the strain behavior to determine whether there is a loading or unloading segment occurring, and (2) UPFR contains isothermal load and isothermal unload segments that are handled in a separate figure in the Analysis tab. Therefore, this section of the user’s manual will guide the user through the common operations of the UCFTC and UPFR apps, inserting additional information relevant to the specific test type when needed.

Upon opening the UPFR and UCFTC apps, the default profile window (Figure 6) will appear, which allows selecting a default user profile. This user profile contains the parameters for importing and splitting sample data. An example profile is included with the program, but custom profiles can be created for specific test types, material types, and test setups to streamline analysis of groups of test data. The user profile window shows the profile name, creator, and test machine from which the profile is intended to process data. Additionally, it shows the import and splitting settings saved in that profile (right-hand box).

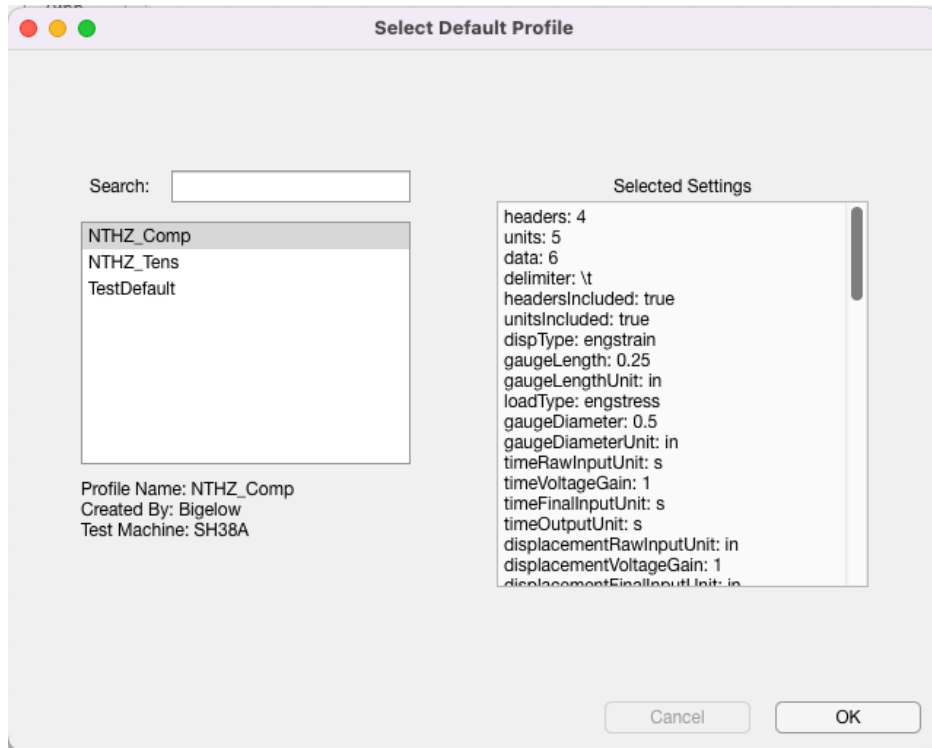


Figure 6.—Default profile window showing available default profiles and settings contained within selected profile.

6.1 Data Import Tab

6.1.1 Selecting a Data File

Once a default user profile has been selected, the main app window for UPFR or UCFTC will become active (Figure 7). The order of steps for processing data follows the order of the tabs at the top of the window: Data Import > Data Splitting > Analysis > Export. Within the Data Import tab, a user begins by clicking the Select Data File button to choose the test data to be imported and processed. A separate File Explorer (PC) or Finder (macOS[®]) window will open to allow browsing to and selecting a test data file. The name of the file selected will show up in the main app window in the text box above the Select Data File button, indicating a file has been selected.

Once a test data file is selected, the Sample and Test Information window will open (Figure 8). The sample and test pedigree information entered in this window will later be exported with the processed data into the ASTM-style report and the database file to help with sample tracking. The Sample Name input into this window will also be appended to the main app figure title at the top of the window.

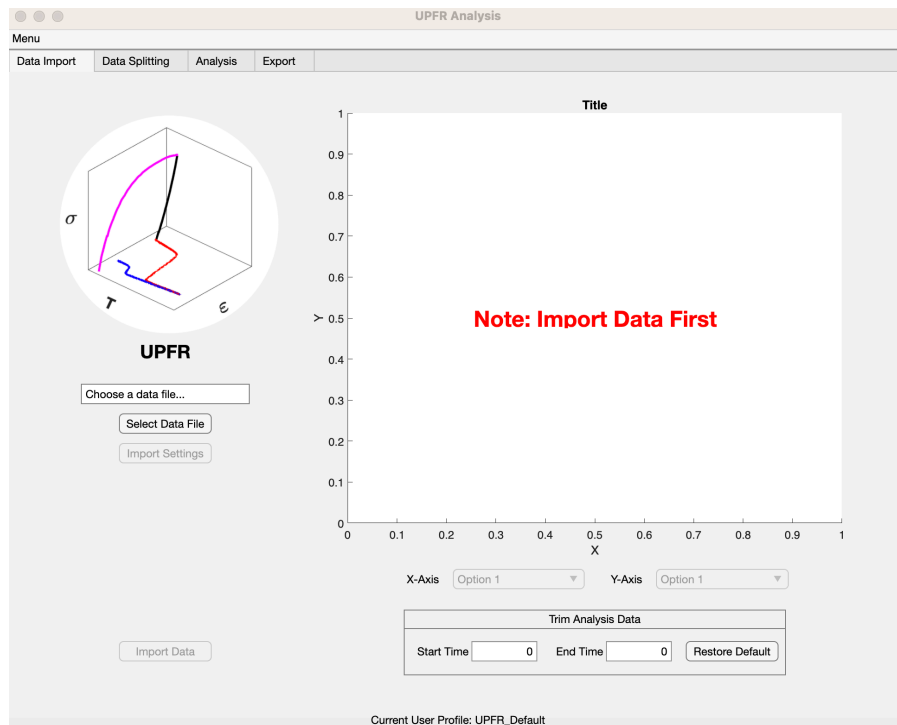


Figure 7.—Initialization of UPFR analysis window, starting on the Data Import tab.

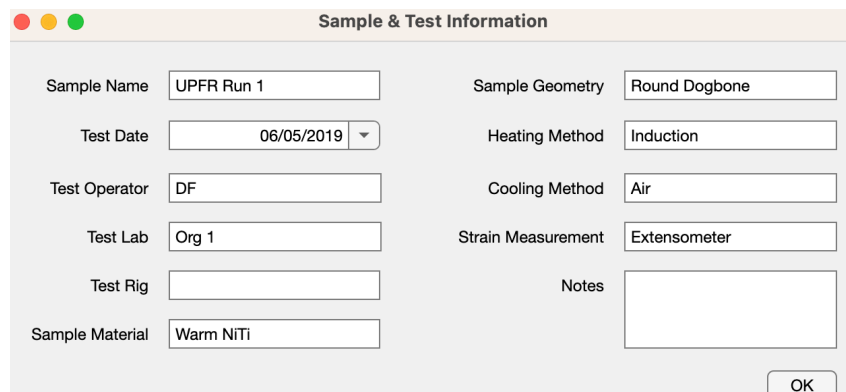


Figure 8.—Sample and test information window.

6.1.2 Import Settings for Test Data

After a test data file is selected and the desired sample and test information are input, clicking the Import Settings button will open the Import Settings window, starting on the Test File Settings tab (Figure 9). Here, the user can see the first ~50 lines of the selected test data file. The Raw Data File tab on the left shows the data as it appears in the test data file (Figure 9(a)); the Import Results tab on the right displays the data as it is parsed using the selected delimiter (Figure 9(b)). If the delimiter selected matches what is used in the text-delimited file, the data displayed in the Import Results tab will be split up into separate columns for each signal (Figure 9(c)). On either the Raw Data tab or the Import Results tab, the user will need to select the appropriate File Delimiter for the test data file, and the rows for the Column Headers, Units, and First Data Line. If the test data file does not include Column Headers or Units, the user can click the checkbox, indicating that these are Not Included.

Once the appropriate selections for the File Delimiter, Column Headers, Units, and First Data Line have been made, the user will need to select the Data Settings tab in the Data File window (Figure 9(d)). Here, the user can select the Displacement Data Type (type of data being used for the Strain signal) and Load Data Type (type of data being used for the Stress signal), and the Data Columns and units to be used for the Time, Strain, Stress, and Temperature signals from the data file to be imported. If Displacement or Load are selected for inputs, the user will need to provide specimen dimensions (gage length and diameter or equivalent diameter for a noncylindrical cross section) so the software can calculate the corresponding Strain or Stress. This window also allows selecting different output units for converting the input data units. In the lower left of the Data Settings tab, a table will show all available Data Column signals that can be imported. The selected data signals used for Time, Strain, Stress, and Temperature are required, but any additional available Data Column signals can be selected for import and will be available for viewing on overview plots or for export later.

6.1.3 Importing Data

After selecting the desired import settings, click the Import Data button to import the data. This will bring up a dialog box (Figure 10) asking if the user wishes to use the default settings (the initial settings from the Default Profile window) or the session settings, which include any changes made in the Import Settings window. When a selection is made, the software will bring up another dialog box and a file browser window instructing the user to select the output directory where the results from the SMAAnalytics UPFR or UCFTC apps will be saved.

When the data has been imported, it will be displayed in the Data Import figure on the Data Import tab. Here, the user can preview the test data and can plot any of the available imported signals with respect to another by selecting the desired signal in the x-axis and y-axis drop-down menus.

Finally, if there is unwanted data before or after the test data, it can be trimmed by entering the desired Start Time and End Time in the Trim Analysis Data box. If these times are not known, the user can use the Zoom-in tool in the toolbar at the upper right of the Data Import figure, and then use the Data Tips tool to click on the desired start or end of the data. The Data Tip will then display the time value at that point, which can be entered in the appropriate edit box (Figure 11). The data that will be used for the analysis will remain blue, while the unwanted data will appear gray.

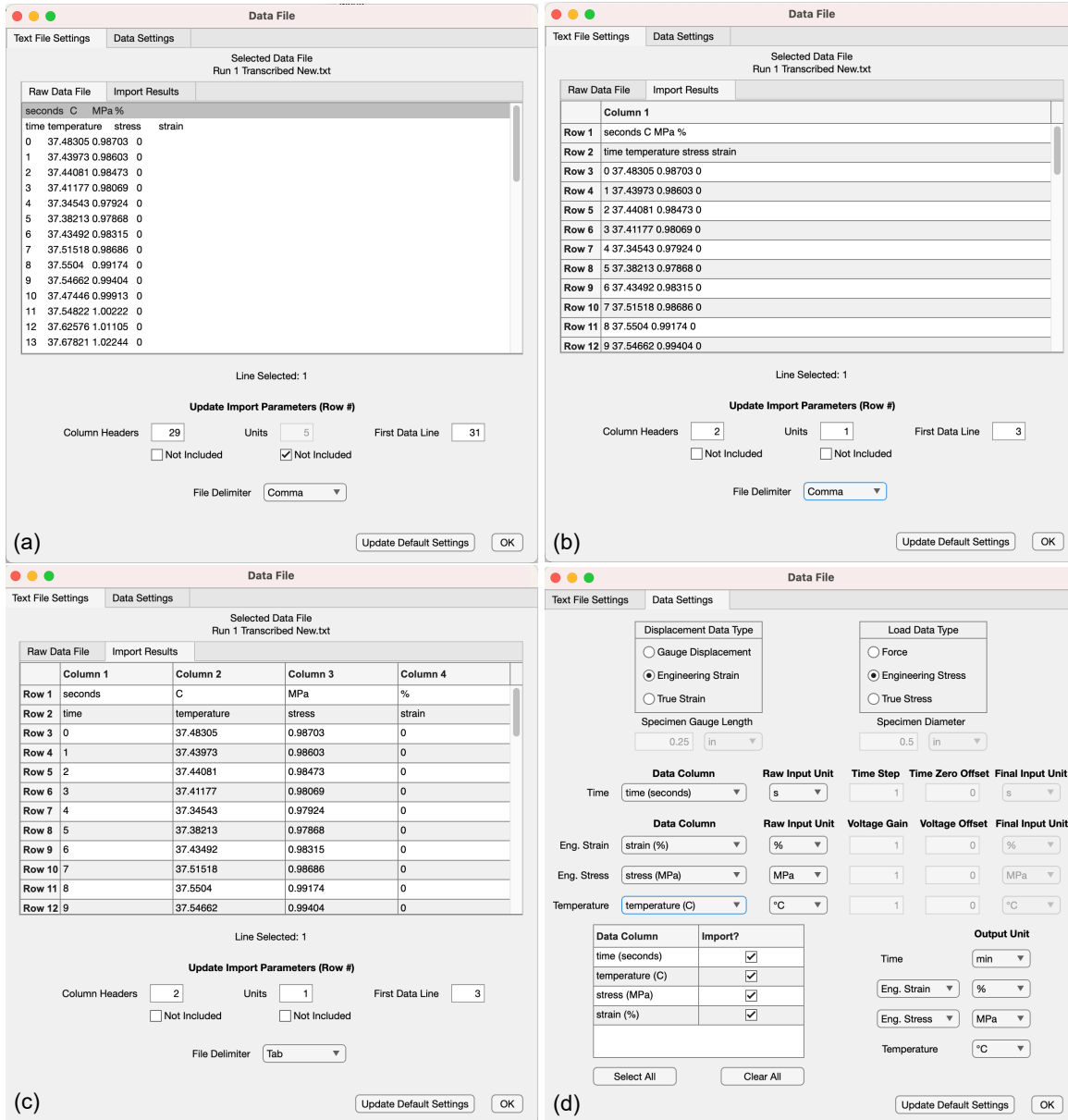




Figure 9.—Import settings windows. (a) Raw Data file before selecting Column Headers, Units, and First Data Line. (b) Import Results before selecting appropriate File Delimiter. (c) Import Results tab after selecting correct File Delimiter. (d) Data Settings tab showing selection options for Displacement Data Type, Load Data Type, Input signal Data Columns, and Output Units.

 **Tool Tip:** If the test data being imported does not have a Time signal or the Time signal restarts or is broken, a new Time signal can be generated by selecting the Raw Input Unit drop-down menu for the Time signal and choosing “Time Step.” Then the desired Time Step and initial Time Zero Offset can be entered.

 **Tool Tip:** **UCFTC:** If the data is for a modified UCFTC test at a constant stress for the entire test, but there is no Stress or Force signal, a dummy stress can be created by selecting the Raw Input Unit drop-down menu for the Stress signal and choosing “V.” Then, an appropriate Voltage Gain (greater than 0) and Offset can be entered.

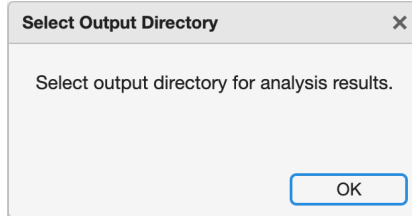
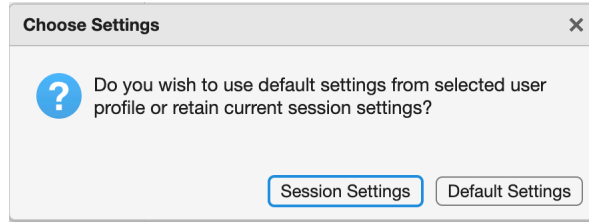


Figure 10.—Import Data button dialog boxes.

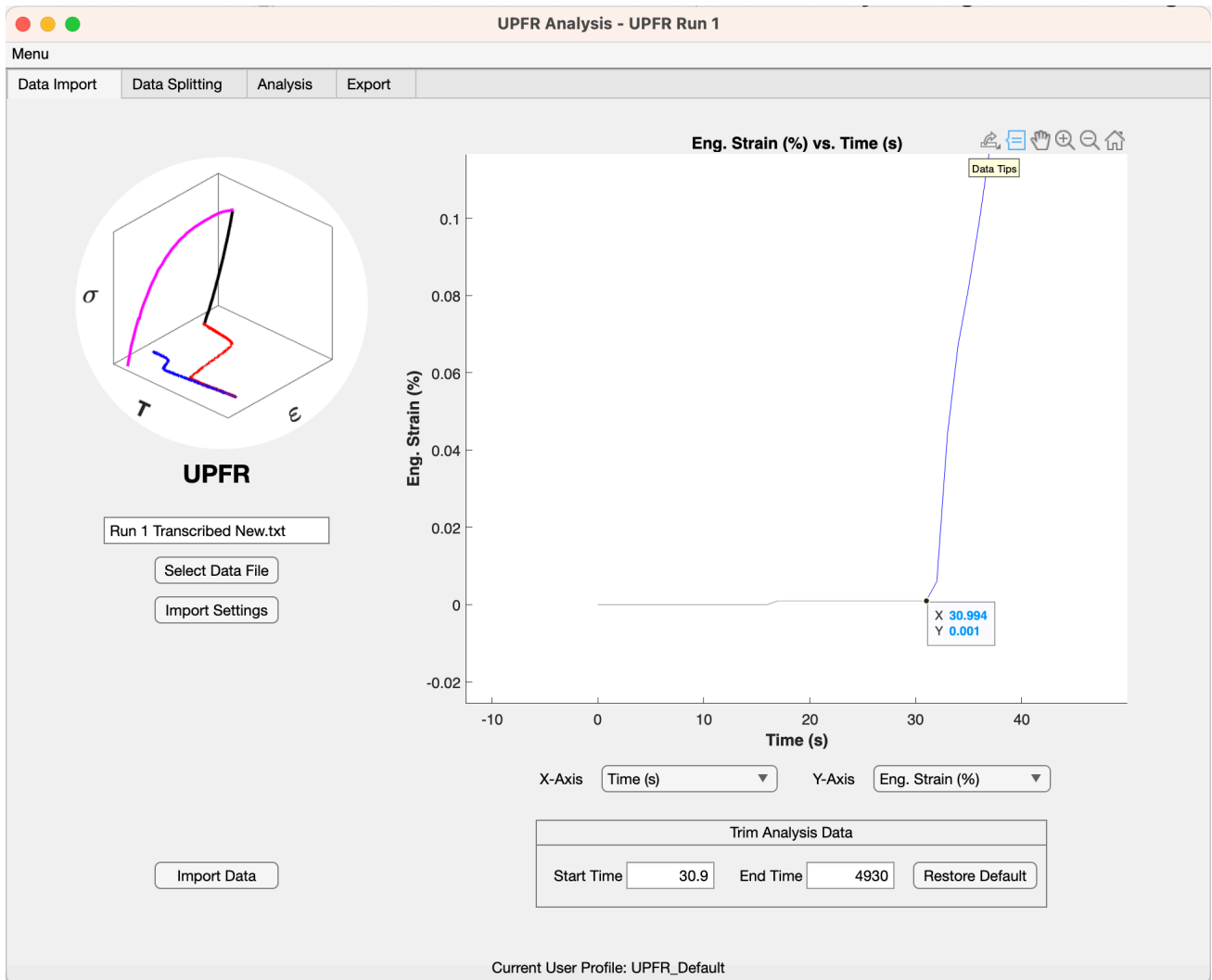


Figure 11.—Data Import tab after test data has been imported. Data Tip tool has been used to select beginning of desired test data region, and “X” value displayed is entered in Start Time edit box in Trim Analysis Data box to trim beginning of data region to that point.

6.2 Data Splitting Tab

The Data Splitting tab allows viewing and adjusting the way the SMAAnalytics UPFR or UCFTC app splits the test data into individual Loading, Unloading, Heating, and Cooling segments. SMAAnalytics accomplishes this by examining the Temperature, Stress, and Strain signals, determining the locations of maxima, minima, and dwell segments within each signal, and then combining the split points from the individual signals to separate the test data into segments in the following manner:

- Heating: Stress dwell, Temperature increasing
- Cooling: Stress dwell, Temperature decreasing
- Loading and Unloading are defined as Temperature dwell, with Stress and Strain behavior as depicted in Table 1.

TABLE 1.—DETERMINATION OF LOADING/UNLOADING SEGMENTS

		Strain Increasing	Strain Decreasing
Stress Positive	Stress Increasing	<p style="text-align: center;">Loading</p>	<p style="text-align: center;">Unloading</p>
Stress Positive	Stress Decreasing	<p style="text-align: center;">Loading</p>	<p style="text-align: center;">Unloading</p>
Stress Negative	Stress Increasing	<p style="text-align: center;">Unloading</p>	<p style="text-align: center;">Loading</p>
Stress Negative	Stress Decreasing	<p style="text-align: center;">Unloading</p>	<p style="text-align: center;">Loading</p>

The Data Splitting tab for UPFR is shown in Figure 12. This tab has subtabs for the Temperature, Stress, Strain (UPFR) data channel signals, and Results. Each data channel signal subtab has figures for the Smooth Data, First Derivative, and Split Data. The user profile selected when opening UCFTC or UPFR provides the initial settings for the Smoothing Filter Algorithm, Window lengths, Thresholds, and Minimum lengths. Using these settings, SMAalytics will calculate where the minima, maxima, and dwell regions are for each data channel signal and mark these split points with green circles, as shown in Figure 12(a). When all the settings are correctly adjusted, the plot in the Data Splitting—Results subtab, will appear similar to the ones in Figure 12(b) to Figure 12(d), in which the loading and unloading segments appear as black dotted (Increasing Stress) or black dashed (Decreasing Stress) lines, with triangle symbols to indicate loading (upward pointing) or unloading (downward pointing), and red and blue to indicate heating and cooling segments, respectively.

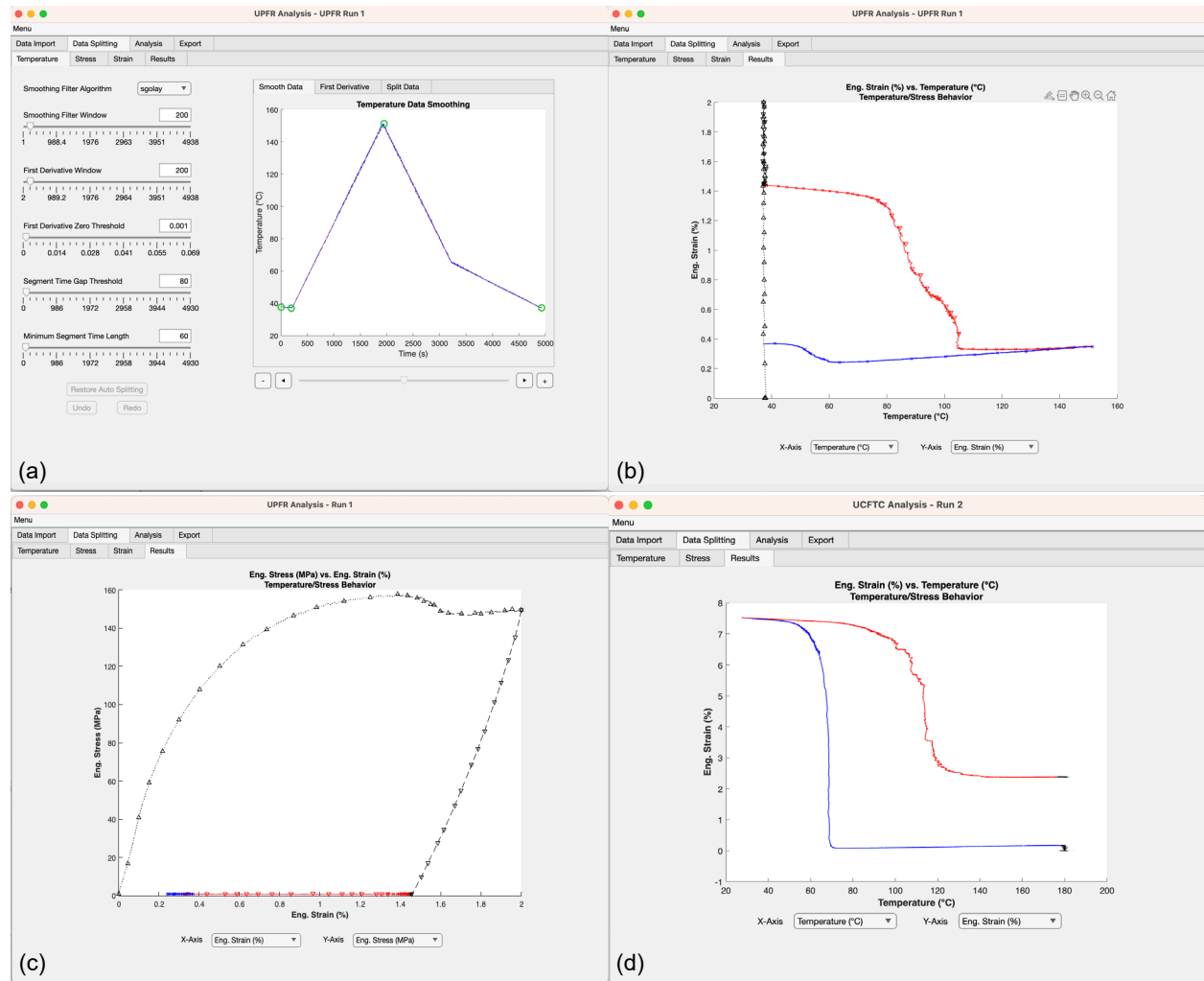


Figure 12.—SMAalytics Data Splitting tab. (a) Three data channel signals and results subtabs with expected split points in Smooth Data subtab, and expected results. (b) UPFR Temperature-Strain space results. (c) UPFR Strain-Stress space results. (d) UCFTC Temperature-Strain space results.

6.2.1 Manually Adjusting Splitting Settings

In each of the Temperature, Stress, and Strain subtabs, there should be split points at the minima and maxima of each segment (i.e., heating and cooling segments for the Temperature subtab, and loading and unloading segments for the Stress and Strain subtabs), and a split point at the beginning and end of each isothermal dwell (e.g., in the Temperature subtab during an isothermal loading and/or unloading segment for UPFR). If these split points are not determined automatically or are in the wrong positions, the following parameters can be adjusted.

- *Smoothing Filter Algorithm*—SMAalytics provides eight different filters with which to smooth data for help with splitting. The Smoothing Filter Algorithm is used to smooth the selected data channel (Temperature, Strain, or Stress) using the Smoothing Filter Window width (time) as described in Table 2.
- *Smoothing filter window*—Time window that the smoothing filter smooths over
- *First derivative window*—Time window that the first derivative is calculated over
- *First derivative zero threshold*—Threshold bounds to be considered as zero or dwell
- *Segment time gap threshold*—If two segments are separated (in time) by less than the segment time gap threshold, the program will consider them to be continuous. If two segments are separated by more than the threshold, the program considers them to be separate.
- *Minimum segment time length*—Minimum time for a segment to be considered a separate segment (dwell, increasing, decreasing). If the time length of a segment (load, unload, heating, or cooling) is less than the overall minimum value of the minimum segment time length selected for any of the Temperature, Stress, or Strain, it will be automatically omitted (but can be un-omitted in the Analysis tab).

TABLE 2.—FILTER OPTIONS FOR SMOOTHING DATA*

Filter	Description	Strengths (when to use)
movmean	Average over each window width	This method is useful for reducing periodic trends in data.
movmedian	Median over each window width	This method is useful for reducing periodic trends in data when outliers are present.
gaussian	Gaussian-weighted average over each window width	-----
lowess	Linear regression over each window width	This method can be slower but results in fewer discontinuities.
loess	Quadratic regression over each window width	This method is slightly slower than “lowess”.
rloess	Robust linear regression over each window width	This method is a slower version of the method “lowess”, but it is more robust to outliers.
rloess	Robust quadratic regression over each window width	This method is a slower version of the method “loess”, but it is more robust to outliers. The method assigns zero weight to data outside six mean absolute deviations.
sgolay	Savitzky-Golay filter, which smooths according to a quadratic polynomial that is fitted over each window width	This method can be more effective than other methods when the data varies rapidly. The method assigns zero weight to data outside six mean absolute deviations.

*From <https://www.mathworks.com/help/matlab/ref/smoothdata.html>



Tool Tip: When reviewing data in the Data Splitting tab, the scroll slider beneath the figure allows zooming in and out using the plus and minus buttons or panning left and right using the arrow buttons.

If the figure is zoomed in using the Zoom In option in the Figure Toolbar, the zoom level of the y-axis will remain constant. This feature is useful when reviewing Zero Threshold limits.

However, if the figure is zoomed in using only the plus button on the scroll slider, the data y-axis in the figure window will be auto-scaled when panning left or right using the arrow buttons and will follow the data if the y-value changes. This feature is useful when reviewing split points on a test with many cycles.

Data Splitting Case 1: UPFR Test—Isothermal dwell not detected automatically.

Figure 13 depicts a UPFR test where the heating and cooling segments are being detected, but the loading and unloading segments are not because they are not completely isothermal (i.e., there is a small temperature change during the loading and unloading), and they occur over a short time period compared to the heating and cooling segments. Figure 13(a) shows the Temperature—Results subtab where what should be the isothermal dwell section is being tagged as a cooling segment. Figure 13(b) depicts the Temperature—First Derivative subtab, which reveals that this is because the First Derivative Zero Threshold is too small, which does not encompass the initial isothermal segment. In Figure 13(c), the First Derivative Zero Threshold is increased to capture the initial segment, which allows SMAAnalytics to tag it as an isothermal dwell (black color) in Figure 13(d).

Data Splitting Case 2: UPFR Test—Unloading segment not properly detected.

Figure 14 depicts a UPFR test where the unloading segment is not properly defined. In Figure 14(a), the Data Splitting—Stress subtab shows the expected split points at the beginning and end of the loading and unloading segments. However, in Figure 14(b), there is no split point at the end of the unloading segment in the Data Splitting—Strain subtab. Figure 14(c) reveals that although there is a First Derivative Zero Threshold crossing at the end of the loading segment, the threshold is too low to capture the crossing at the end of the unloading segment. In Figure 14(d), the First Derivative Zero Threshold has been increased to capture the end of the unloading segment. Also, the First Derivative window was decreased to reduce the smoothing of the data, and the Segment Time Gap Threshold and Minimum Segment Time Length were decreased to ensure that the unloading segment would not be omitted despite its short time length.

Data Splitting Case 3: UCFTC Test—Too many split points show up in stress dwell.

Figure 15 depicts the Data Splitting—Stress subtab of a UCFTC test in which the automated analysis detected several extraneous split points due to noisy stress data. It is possible to adjust this by simply increasing the First Derivative Zero Threshold, but that can also cause the correct split points to be pushed away from the true points where the stress changes. Here, the Smoothing Filter Algorithm is changed from *movmedian* to *movmean* to reduce the effect of the noisy data on the first derivative data (Figure 15(b)). Then the Segment Time Gap Threshold (the minimum time between segments) is increased to include the segment at 8.9×10^4 s (Figure 15(c)).

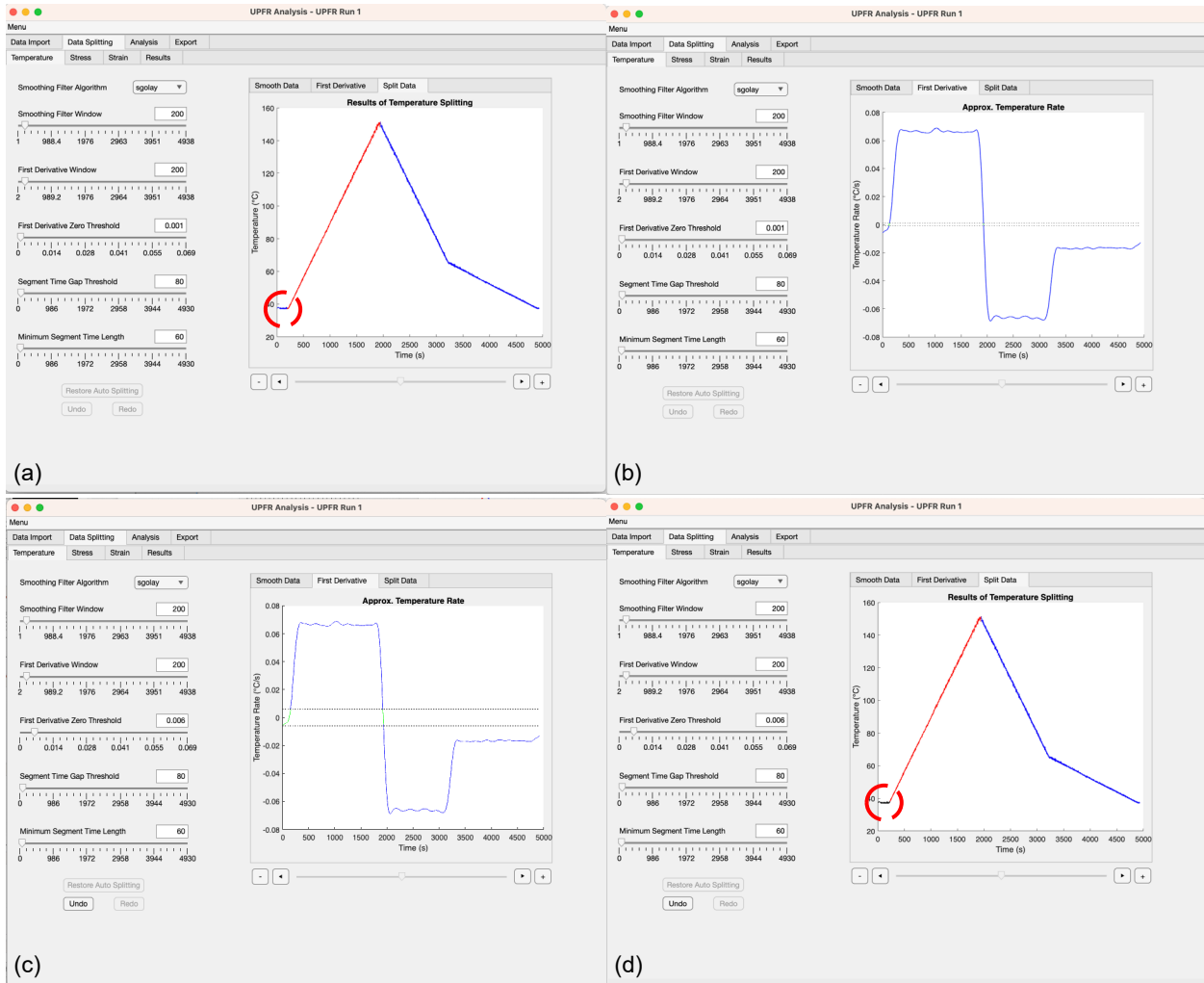


Figure 13.—Data Splitting—Temperature subtab. (a) Initial Split Data results. (b) Initial First Derivative settings. (c) Adjusted First Derivative Zero Threshold. (d) Corrected Split Data results after adjusting First Derivative Zero Threshold setting.

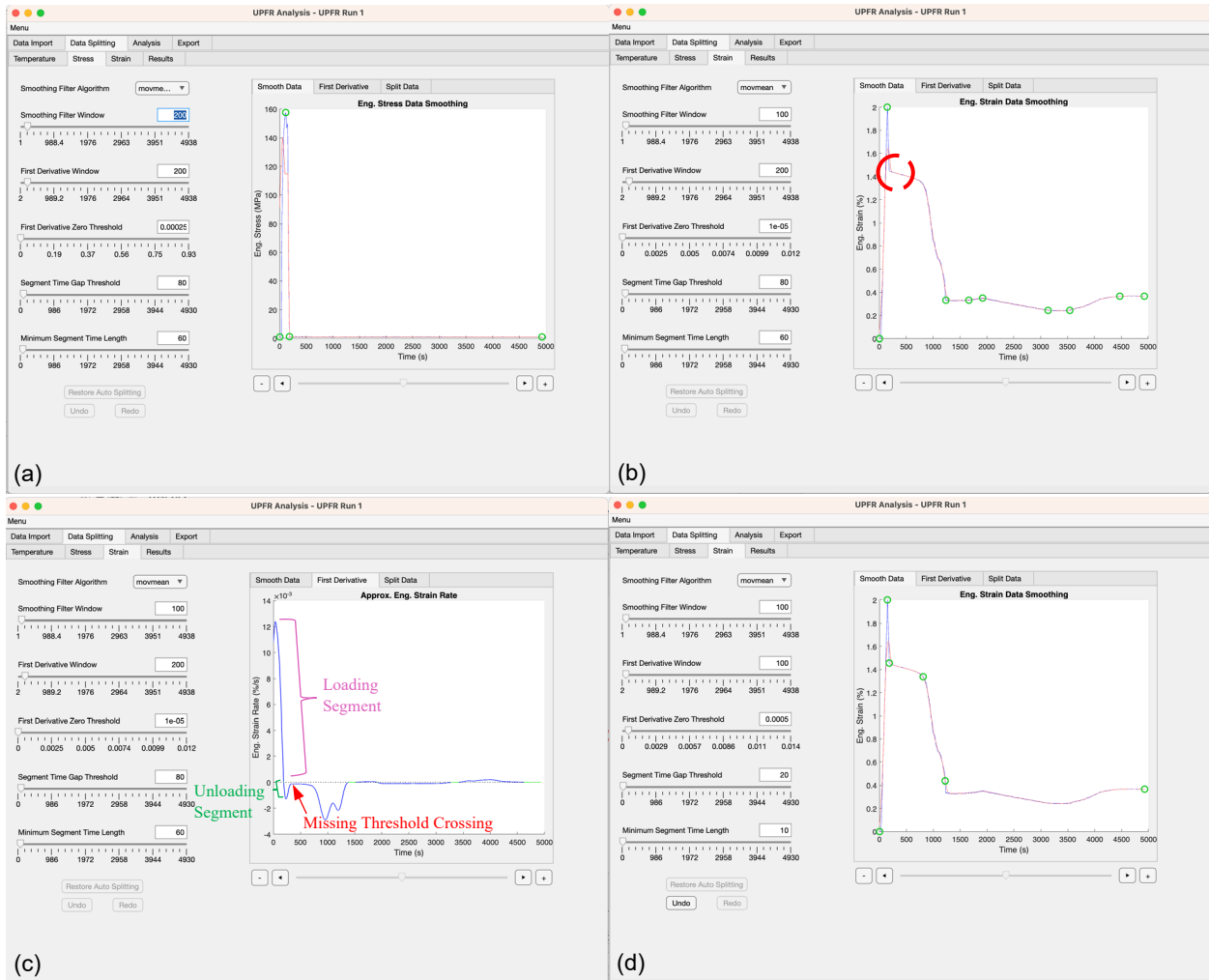


Figure 14.—Data Splitting tab showing manual adjustment of split points. (a) Data Splitting—Stress subtab showing split points at beginning of lading segment, maximum stress, and end of unloading segment. (b) Initial Strain-Smooth Data subtab showing missing minimum split point at end of unloading segment. (c) Strain-First Derivative subtab showing initial settings and First Derivative Zero Threshold are too small to fully capture regions where strain is not changing. (d) Final Strain-Smooth Data subtab showing necessary split points at beginning and end of loading and unloading segments.

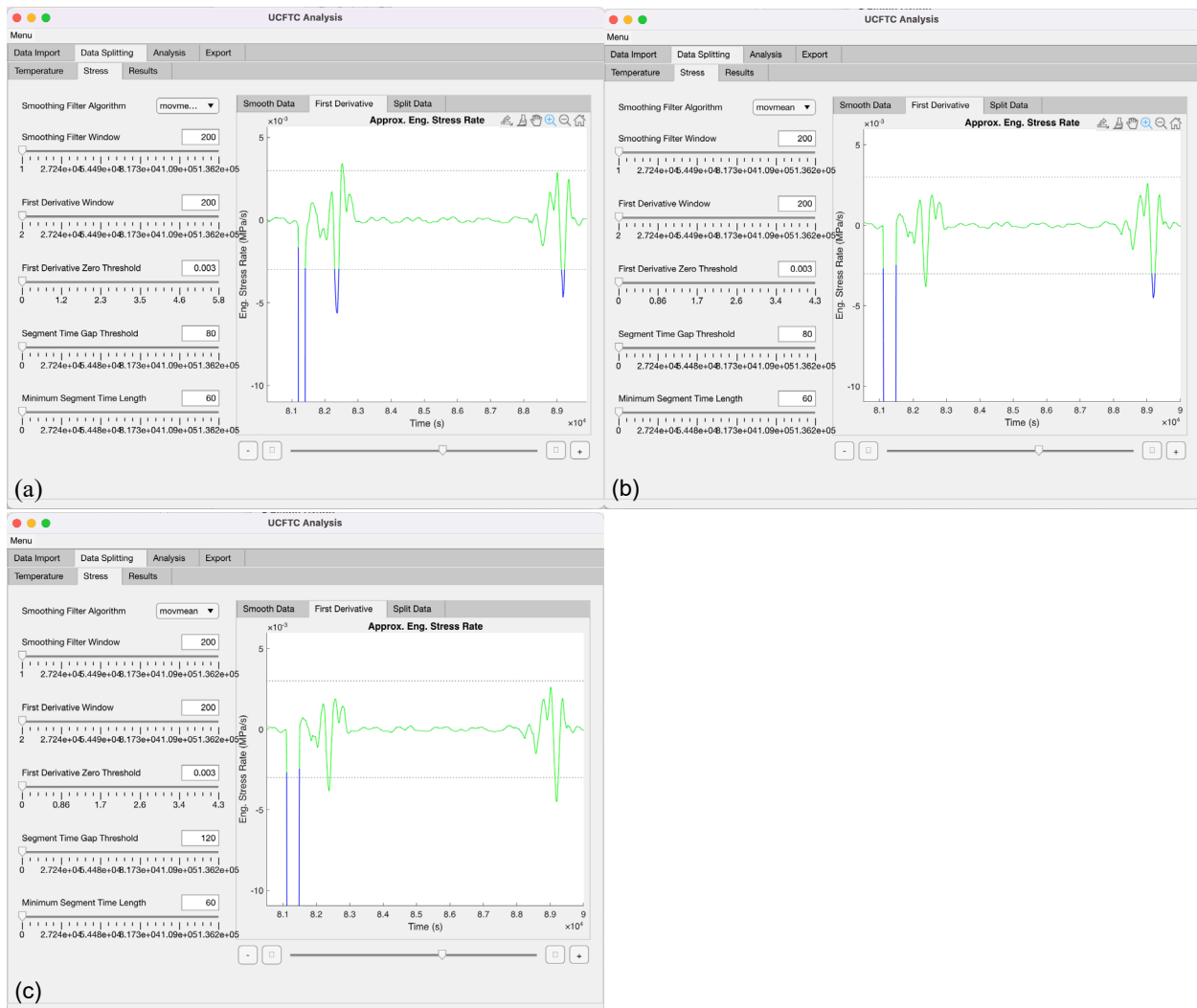


Figure 15.—Data Splitting tab showing manual adjustment of split parameters to handle noisy stress data. (a) Initial automated parameters. (b) Effect of changing Smoothing Filter Window on First Derivative stress data. (c) Inclusion of spike at 8.9×10^4 s by increasing Segment Time Gap Threshold.



Troubleshooting Tip: If the load and unload segment for UPFR is not showing up, check the Minimum Segment Time Length to make sure it is shorter than the load or unload segment. This also means that the Minimum Segment Time Length may need to be shorter than the segment of data within the Segment Time Gap Threshold that represents the crossing point for the temperature dwell in the Data Splitting > Temperature > First Derivative tab.



Tool Tip: If the sliders are not producing the desired split points, use the Data Brushing tool to manually create the desired split points.

See the [Adding and Deleting Split Points with Data Brushing](#) section.

6.2.2 Adding and Deleting Split Points with Data Brushing

When fine-tuning of the split points is needed and/or the split points are not working properly with the slider settings, split points can be added and deleted manually by editing the split points using the Data Brushing tool in the Figure Toolbar of the desired data signal (Figure 16). To edit split points manually using the Data Brushing tool, click and drag to make a box around the desired data or split point, then right-click on the brushed data, and select one of the following options (Figure 17):

- Delete Highlighted Split Point—When there are unneeded split points or it is necessary to adjust where the split points are; make sure to delete the old ones first.
- Create Minimum Split Point—When the app has not properly detected the transition between cooling–heating segments or unloading–loading segments.
- Create Maximum Split Point—When the app has not properly detected the transition between heating–cooling segments or loading–unloading segments.
- Create Dwell Split Points—When there should be a dwell in a specific signal, such as a dwell in temperature during the loading and unloading segments of UPFR or a dwell in stress during thermal cycling for UPFR and UCFTC.



Figure 16.—Edit Split Points option with the Data Brushing tool.

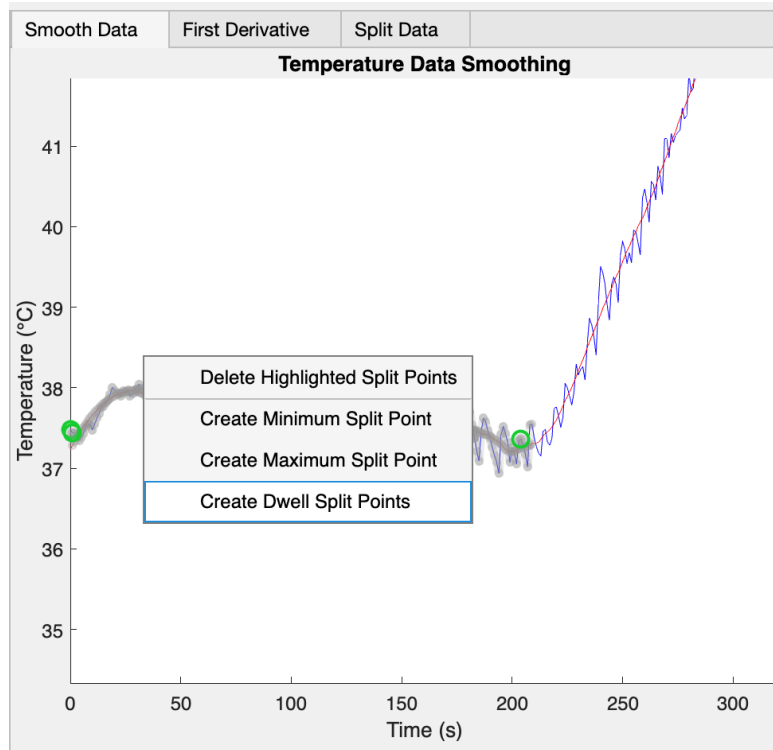


Figure 17.—Available Edit Split Point options after selecting data with Data Brushing tool and right-clicking on brushed data.

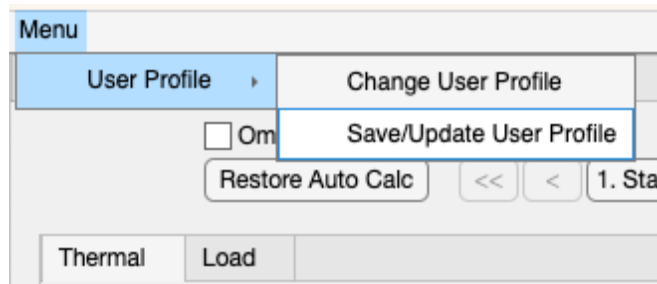


Figure 18.—Accessing Save/Update User Profile option through Menu.

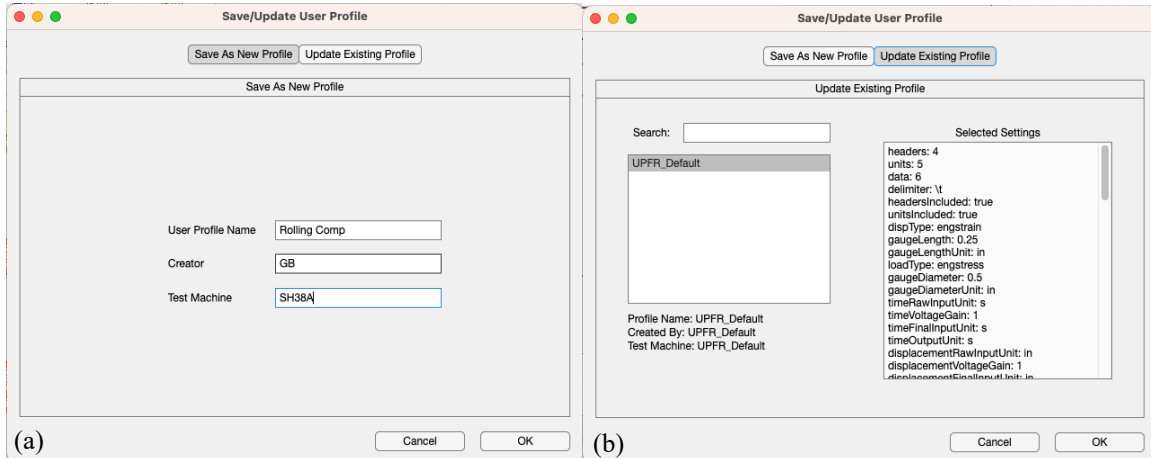


Figure 19.—Pop-up window options for Saving/Updating a user profile. (a) Saving a new profile. (b) Updating an existing profile.

6.2.3 Updating or Saving a Profile

Whenever settings for import or data splitting are changed, the current settings can be saved as a new profile or used to update the active profile. To do this, select the Menu at the top left of the UCFTC or UPFR app and select the desired action (Figure 18). The pop-up window will either allow providing a name and identifying information for the profile to be saved (Figure 19(a)) (to help with categorizing what tests/test machine the profile will be used for) or allow viewing the profiles available for updating and their associated parameters (Figure 19(b)).

6.3 Analysis Tab

The Analysis Tab shows the automatic analysis of the loading–unloading (UPFR) and heating–cooling segments, and allows manual adjustment of the automated fits. Any curve segments that the program determines are orphan curves or only curve segments are automatically tagged as OMITTED and the Omit Curve checkbox will be selected. If the user wishes to analyze the omitted curve, the Omit Curve checkbox can be deselected. To delete a curve from the final database output, it can be omitted by selecting the checkbox for that curve. If any sliders have been manually adjusted, the automated fits can be restored by clicking the Restore Auto Calc button.

For UPFR, SMAnalytics automatically measures the initial strain (ϵ_0), maximum loading strain (ϵ_i), stress at maximum strain (S_i), and unloaded strain (ϵ_u), and attempts to fit the curve with from one to four separate segments based on the number of linear regions detected (Figure 20). The number of linear regions used for the loading or unloading fit can be manually changed by indexing the Linear Regions selection at the bottom of the Analysis tab, which will show the initial automated analysis calculated by

SMAAnalytics for the number of regions. The initial automated fit region boundaries are tied to the boundary for the adjacent region, but they can be manually adjusted to fit only a desired region selected using the sliders or edit boxes provided. The behavior is the same for the unloading curves (Figure 21).

The heating and cooling curves are automatically fit with a three-region fit for the low-temperature martensite region, the transformation region, and the high-temperature austenite region (Figure 22). The transformation region is fit by a line tangent to the region of the highest slope. The martensite and austenite regions are fit by calculating the slope of the region between the data at the lower cycle temperature (LCT) for the martensite or the upper cycle temperature (UCT) for the austenite and the data at the transformation region. The slope is calculated multiple times while moving the boundary from the transformation out toward the data extents and determining when the slope of the fit data stops changing by a threshold value. Just as with the loading and unloading curves, these automated fits can be manually adjusted by moving the sliders associated with the region to be adjusted (Figure 22(b) and Figure 22(d)). A Datatip can be used to visualize the value of a parameter of interest as shown in Figure 23 and can show the effect of changing the fitting region on the parameter.

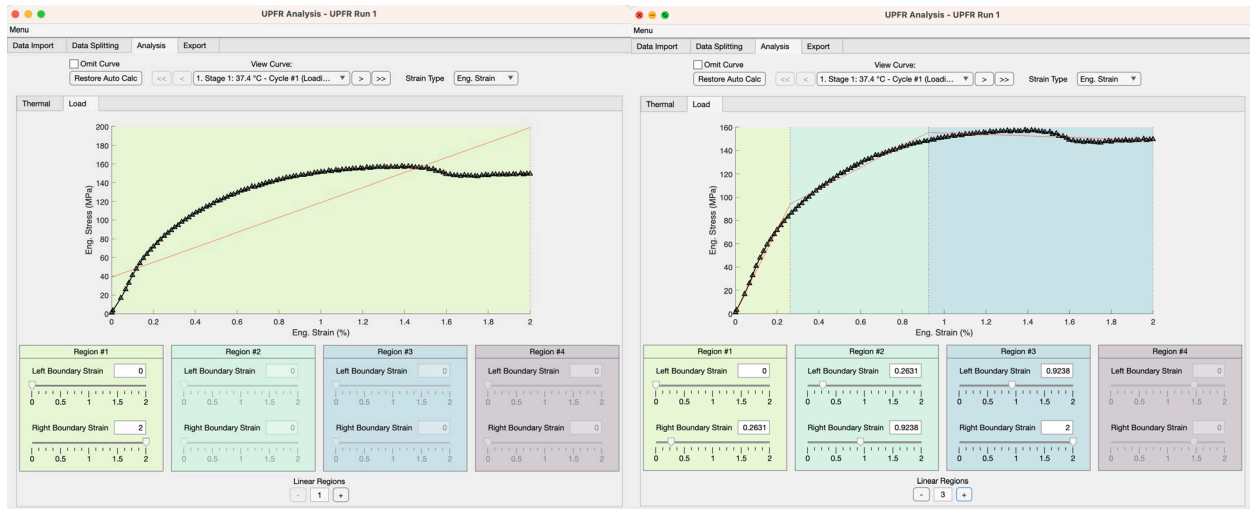




Figure 20.—Loading segment of UPFR shown in Analysis tab with varying numbers of linear region fits.



Figure 21.—Unloading segment of UPFR showing initial fit using a single region.

 Tool Tip: The slider position can be fine-tuned by mousing over the desired slider and using the mouse scroll wheel to scroll up or down.

* To use this capability, deselect the figure axes zoom and pan tools.

 Tool Tip: To review long, multicycle tests, use the keyboard's left and right arrow keys to move from curve to curve.

* To use this capability, deselect the figure axes zoom and pan tools.

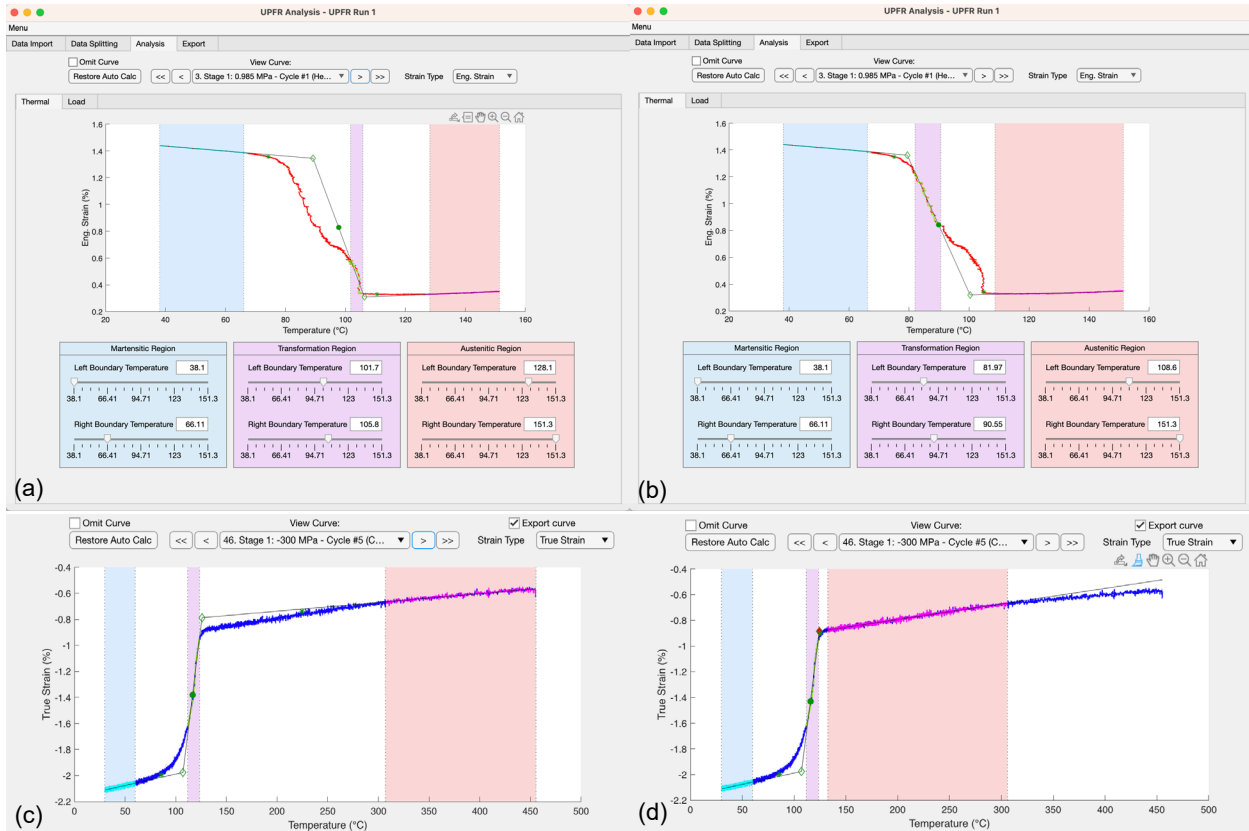


Figure 22.—Analysis of thermal segments. (a) Automated analysis of a dual stage transformation. (b) Manually adjusted analysis to measure first stage of dual-stage transformation. (c) Automated analysis with fit to upper section of long austenite region. (d) Manually adjusted fit to capture austenite region immediately adjacent to transformation.

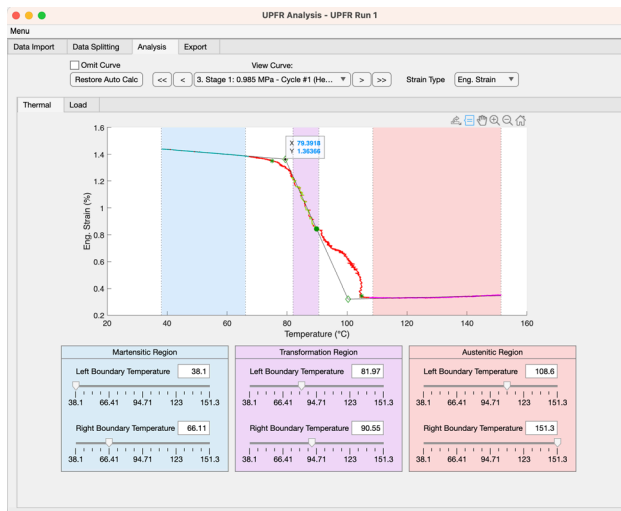


Figure 23.—Analysis of a thermal heating segment. Datatip used to show value of A_s .

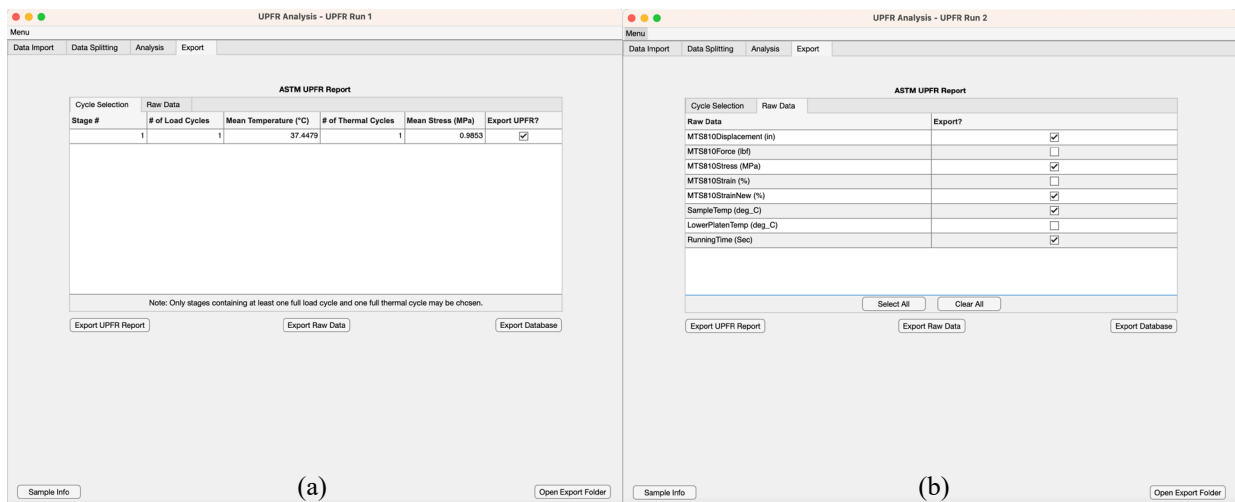


Figure 24.—Export tab for UPFR. (a) Stages available for exporting to ASTM-style UPFR Report. (b) Additional Data Channel signals to be exported to Raw Data file.

6.4 Export Tab

The Export Tab for UPFR is shown in Figure 24. The data used for the analysis can be exported to the Raw Data file. Analyzed test data can be exported to an ASTM-style report or a summarized Microsoft Excel® database.

The Raw Data subtab shows any additional available Data Channel signals that can be exported to the Raw Data text file. If no signals are selected, the Raw Data text file will only include the processed Time, Temperature, Stress, and Strain data that was imported, converted (if needed), and used for the data analysis.

The ASTM-style report can only be exported if a complete test has been performed—a pair of cooling and heating (or heating and cooling) segments run sequentially at the same stress level for UCFTC or a sequence of loading, unloading, heating, and cooling segments for UPFR. If these conditions are met, a checkbox will be available for that cycle or stage and can be selected to output the ASTM-style report. This report is generated in Excel® format and includes the information described in References 1 and 2, along with the tabulated Time, Temperature, Stress, and Strain for the selected stage or cycle. For UCFTC, if the test is a modification of the standard, where the cycle is a heating–cooling cycle instead of a

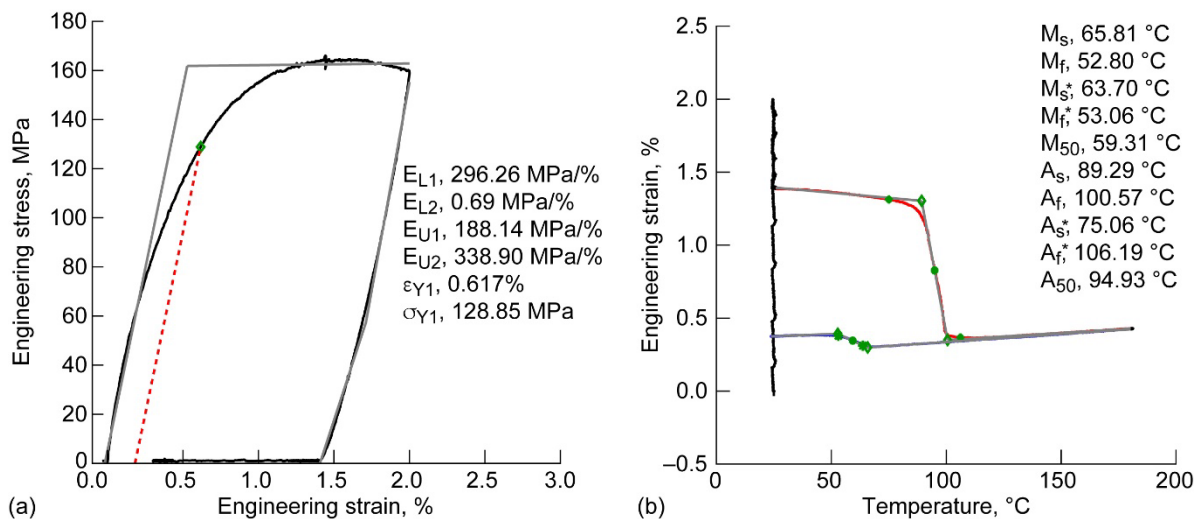


Figure 25.—Figures exported with ASTM-style UPFR report. (a) Isothermal loading and unloading segments. (b) Free recovery heating and cooling segments.

cooling–heating cycle, the following note will be added to the report: “Note: This data does not adhere to ASTM E3097 specification to begin UCFTC cycle in austenitic region.” Along with the Excel[®] report, one or more figures will be generated to show the results of the analysis for the segment or cycle selected (Figure 25).

Finally, a database can be exported that contains the sample and test information, the test type and sample ID, and all of the tabulated summarized parameters that were measured and calculated. These parameters include up to 80 different measurements, including the transformation temperatures, strains, and slopes, among others.

7.0 Differential Scanning Calorimetry (DSC) Using DSCAN

7.1 Introduction to DSCAN

The Differential Scanning Calorimetry Analysis (DSCAN) software tool can be used to process DSC data for shape memory alloys to extract transformation temperatures and enthalpies. The DSCAN analysis app is formulated to analyze DSC files automatically by separating the heating and cooling cycles, then analyzing the data to find the transformation temperatures and enthalpies. This analytical process is described in further detail in Section 7.2. The app includes an interactive user interface and manual editing options for cases where a user needs to fine-tune the analysis (e.g., multiple irregular peaks or convergence difficulties).

The flowchart in Figure 26 shows how users can interact with the software tool, and how the automatic analytical process fits together with the interactive components.

Raw experimental data consists of time, temperature, and heat flow values for multiple cycles and multiple files. The experimental data are imported from Microsoft Excel[®] files with the time, temperature, and heat flow data in three columns. The data from each column are stored in separate arrays.

7.2 Principle of Analysis Method

The flowchart in Figure 27 illustrates the automated analysis process performed on one cycle of one file of data. Within the software code, this process occurs after the experimental data has been loaded, and after the cycles have been separated for the file to be analyzed.

This process is described in detail in the following subsections.

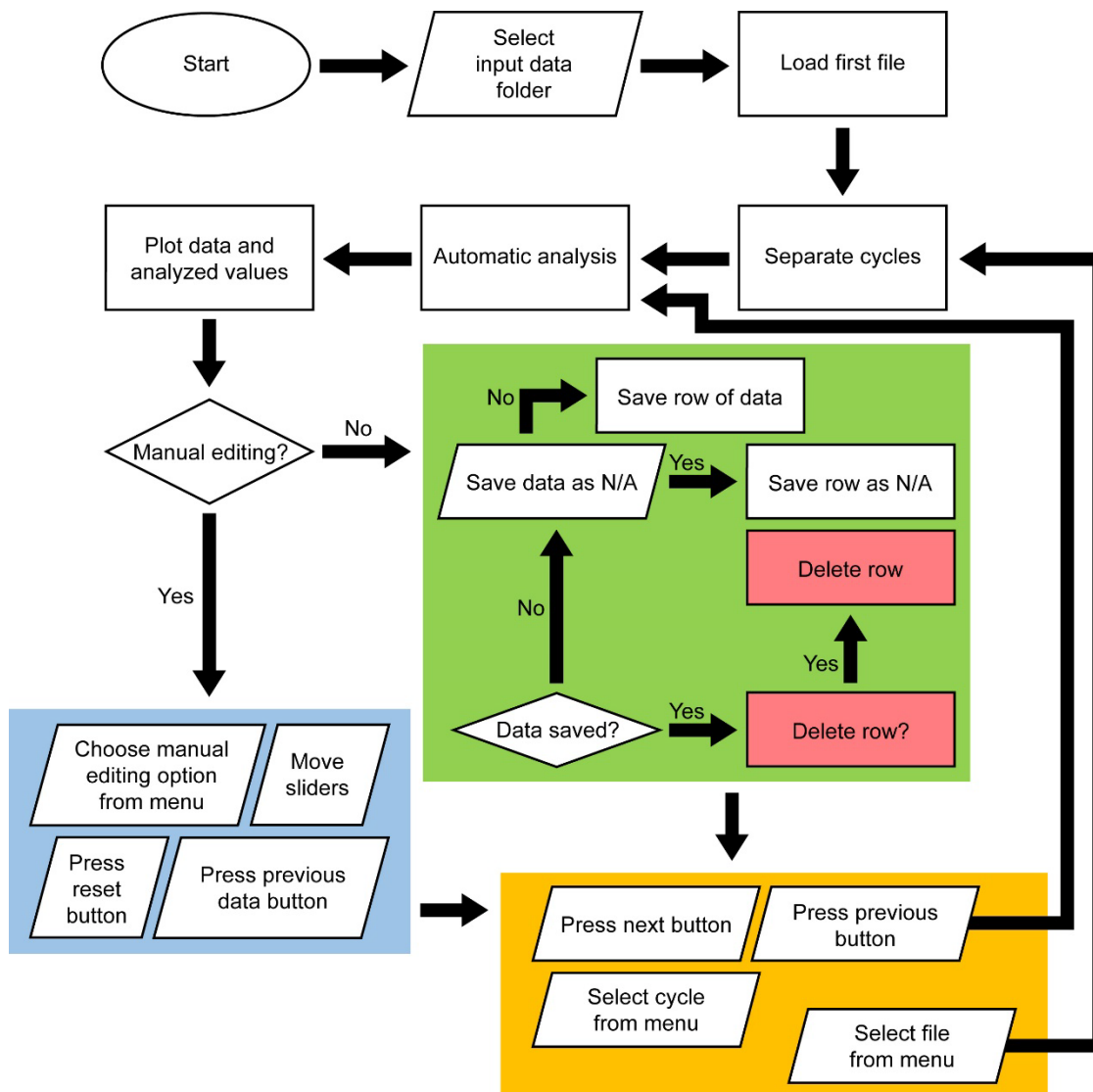


Figure 26.—Procedure employed by DSCAN.

7.2.1 Heating and cooling curves

The first step of the analysis, after separation of cycles, is to separate the heating and cooling curves. The curves can be separated by comparing two consecutive temperature values from the temperature array. If temperature n is less than temperature $n+1$, temperature n and the corresponding heat flow values are placed into temperature and heat flow arrays for heating. Otherwise, if temperature n is greater than temperature $n+1$, the temperature and heat flow values are placed into arrays for cooling. These arrays are then sorted in ascending order by temperature (lowest to highest temperature).

7.2.2 Cutoff end values

As shown in Figure 28, many DSC plots have steep slopes at the ends of the curve (low temperature and high temperature). This near-vertical slope can cause errors in some of the automatic analysis steps, specifically those requiring a derivative. Hence, the ends of the data set are cut off by ignoring a percentage of data from both ends of the heating and cooling heat flow and temperature arrays. For plotting, the full set of data is still displayed. This value, for both the heating and cooling curves, is calculated automatically, and can be adjusted manually if needed.

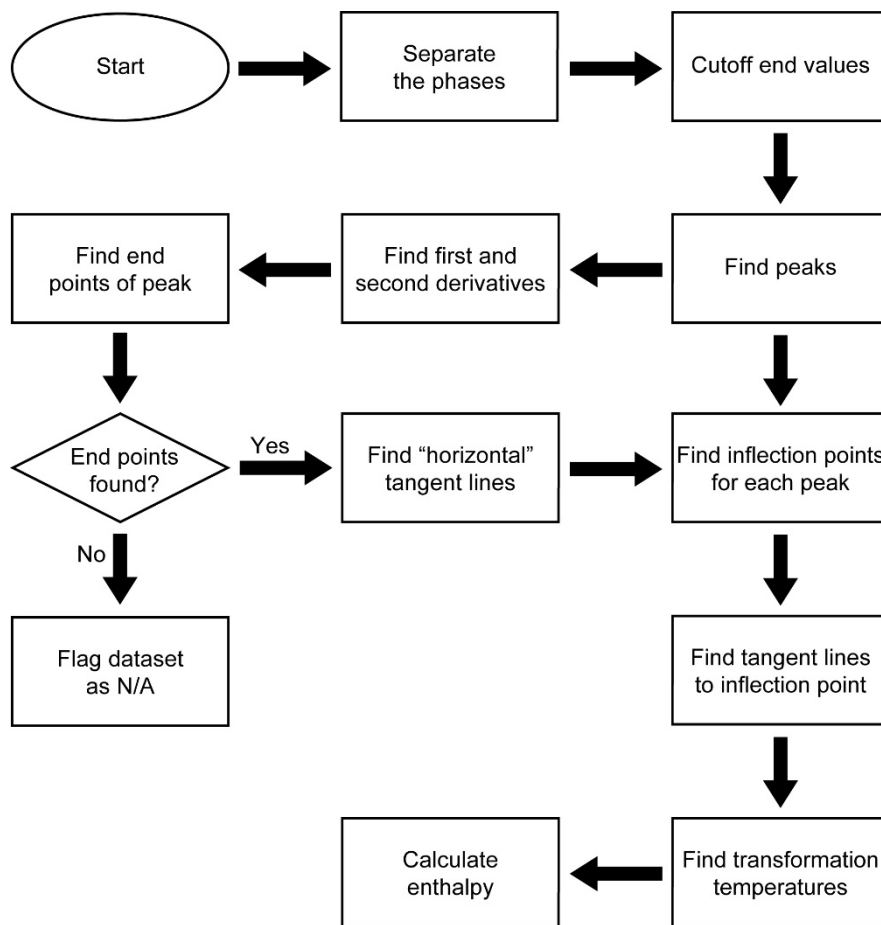


Figure 27.—Automatic analysis process for DSCAN software app.

7.2.3 Peaks

The peaks are found by taking the value of temperature and heat flow at the maximum heat flow point for cooling, and the minimum heat flow point for heating. This is done using the “findpeaks” function provided with the signal processing toolbox in MATLAB®.

7.2.4 First and Second Derivative

The first derivatives are found by producing smoothed cubic spline interpolations of the heating and cooling curves, and then taking the derivative of the interpolated curve. This process is repeated, with the first derivative as input to find the second derivative.

7.2.5 End Points of Peak

The end points of the peaks are found by checking for the longest flat section of the curve to the right and to the left of the peaks. First, a set of flat values from the curve are found by checking for consecutive values of the derivative of the curve that are less than or equal to a specified tolerance. The left-most and right-most indices of each of these sets of consecutive values (start and finish of each flat section) are stored in two separate arrays. The differences between the start and finish values of each flat section are found, giving the length of each of the sections. The longest flat section to the left of the peak is chosen, and the left end point of the peak is given as the last value in that section (right-most value). Similarly, the longest flat section to the right of the peak is chosen, and the right end point of the peak is given as the first value in that section (left-most value).

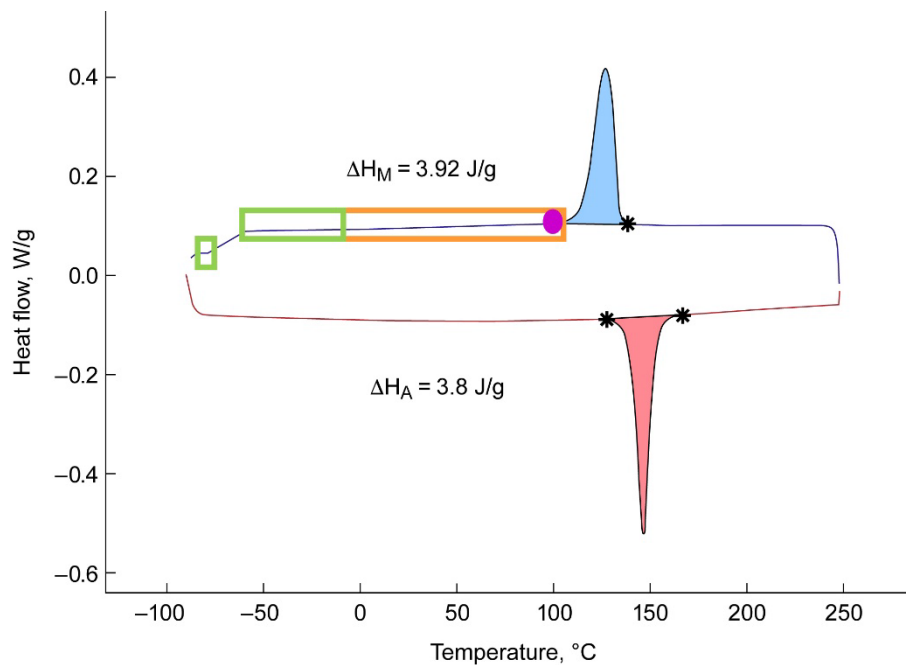


Figure 28.—Procedure for finding enthalpy end points. Green and orange rectangles contain flat sections or sections with a derivative less than or equal to specified tolerance. Orange rectangle contains longest flat section. Purple dot indicates location of end point.

Each DSC data set is different, so multiple tolerance values are used, ranging from 0.0005 to 1. If the initial tolerance value does not return end points, the code loops through the remaining values until peak end points are found. If no end points can be found, the data set is flagged as N/A. Figure 28 shows a schematic of the procedure to find the end points.

7.2.6 Inflection Point Tangent Lines

The inflection points are found by determining where the second derivative is equal to zero (Ref. 4). This corresponds to the peaks (maximum and minimum) of the first derivative. Tangent lines are determined by finding the derivative at the inflection point (slope), and then finding the y-intercept.

7.2.7 Horizontal Tangent Lines

The horizontal tangent lines are found by fitting a line between two points on the curve. These two points are initially chosen as the cutoff point and the end point (i.e., left cutoff point and left end point for the left tangent line).

7.2.8 Transformation Temperatures

As described in ASTM F2004, the transformation temperatures are found by taking the intersection between the inflection point tangent lines and horizontal tangent lines, as shown in Figure 29 (Ref. 3).

7.2.9 Enthalpy Integral

The enthalpy is found through the numerical integration of the area under the peak using Simpson's Method (Ref. 5). The baseline of the integral is taken as the line between the two peak end points. Because the baseline is set above the x-axis, the trapezoidal area between the x-axis and the baseline, which is shown in Figure 30, must be subtracted from the result of the numerical integration.

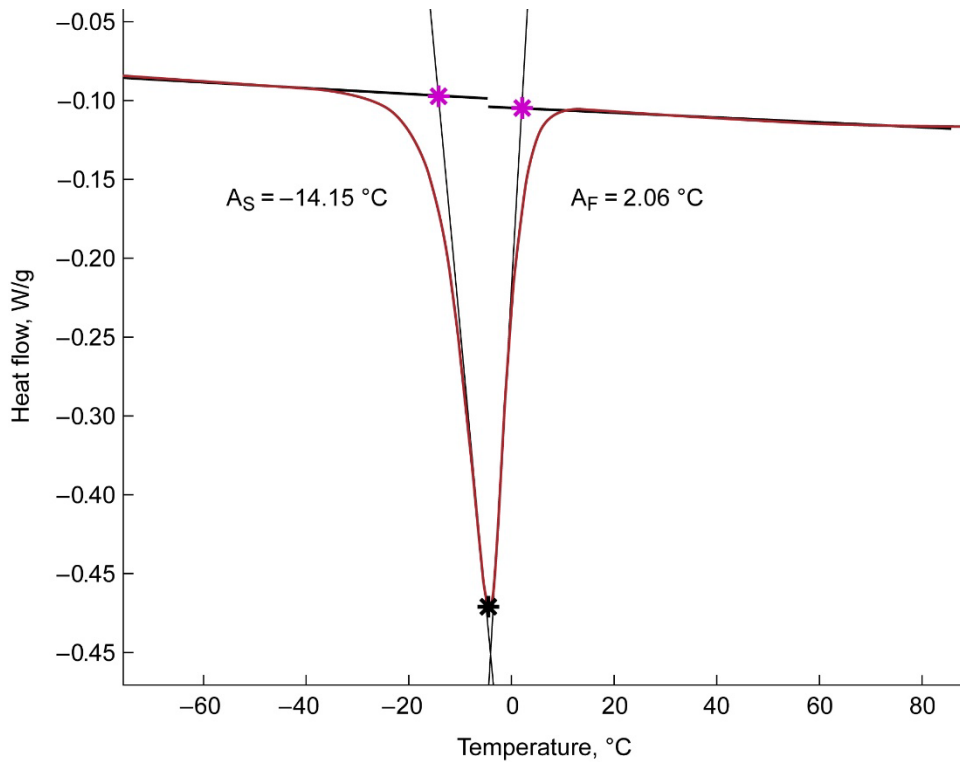


Figure 29.—Plot of heating peak showing transformation temperatures as intersection of horizontal tangent lines and inflection point tangent lines.

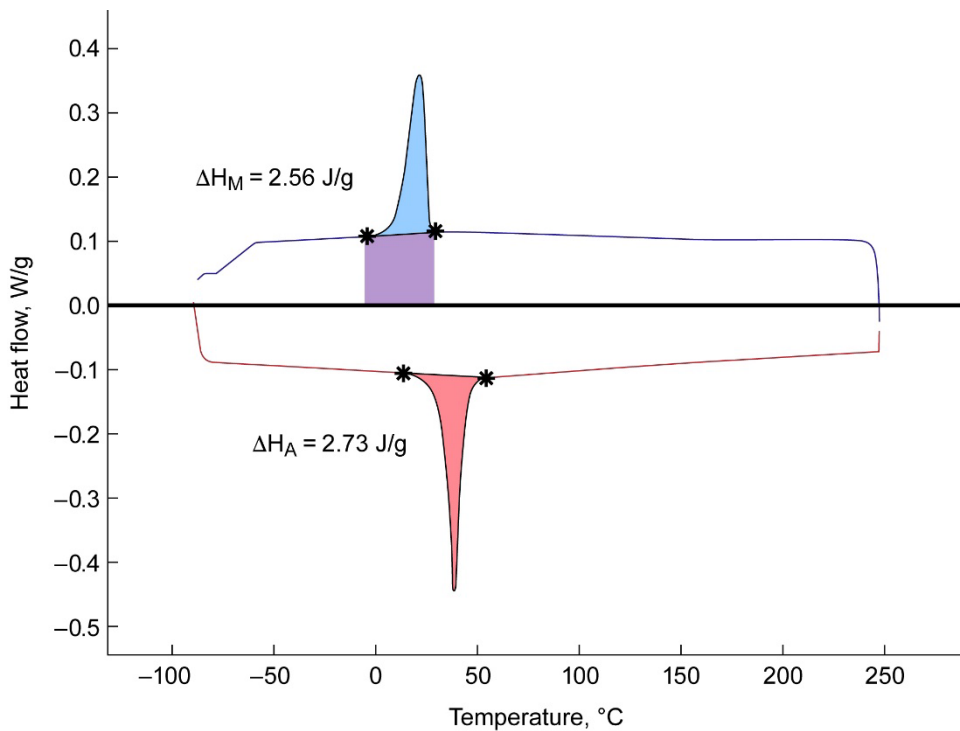


Figure 30.—Schematic of enthalpy calculation for cooling. Area under peak (blue and purple area) is calculated by Simpson's Method. Area of purple trapezoid is then subtracted from that value to obtain enthalpy.

7.3 Using DSCAN

This section describes the components of the user interface and their functionalities. Figure 31 and Figure 32 are images of the user interface of the software tool with the different components labeled and circled. The components are split into three categories: navigation, saving, and editing data.

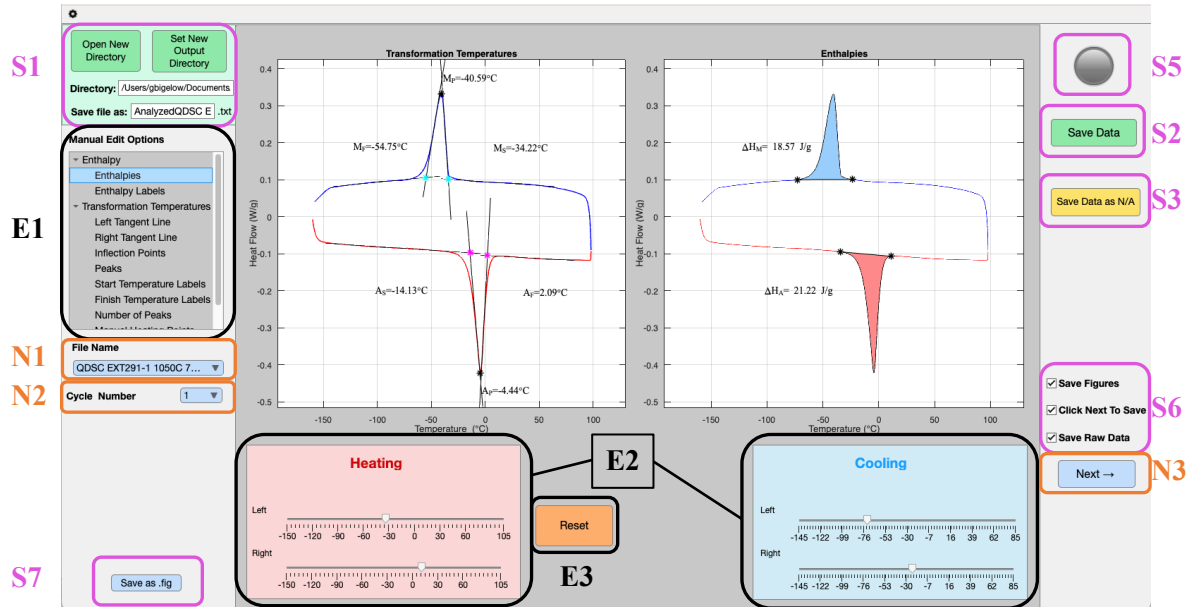


Figure 31.—User interface of software tool.

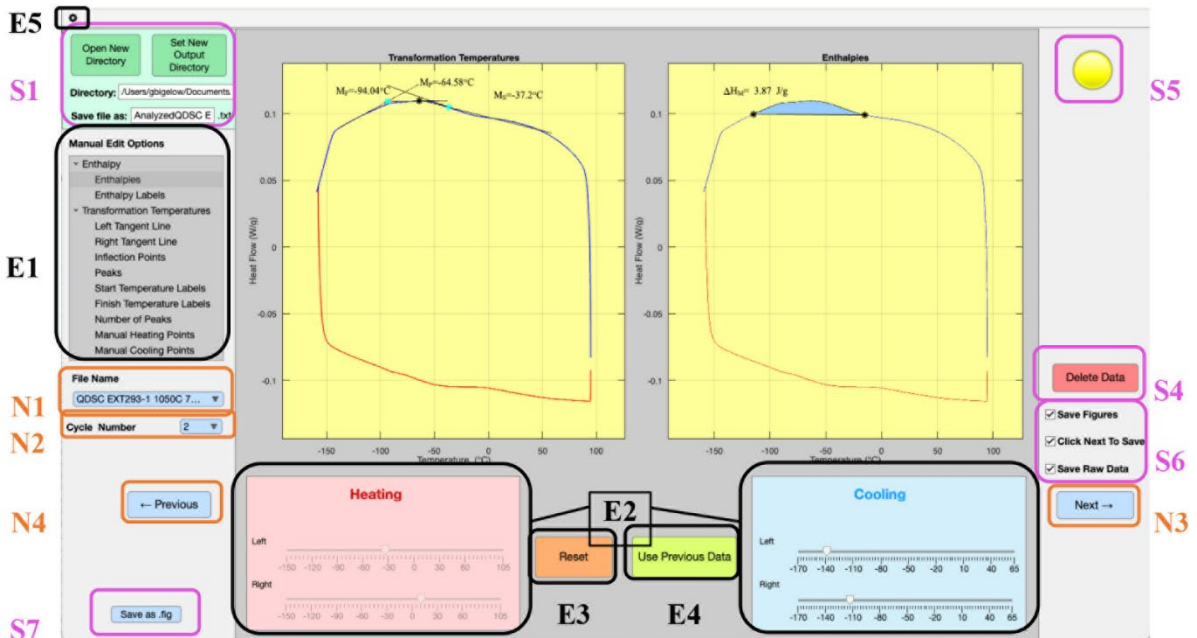


Figure 32.—User interface of software tool showing additional components.

7.3.1 Opening a Data Set

To open a data set (files must be in Excel[®] format), select the Open New Directory button in section S1. A single file or entire folder can be selected for analysis.

7.3.2 Navigation

This category of interactive elements contains buttons and menus that allow the user to navigate between cycles, files, and help menus. Every time a new cycle or file is selected, the automatic analysis process is executed, and the plots are generated. The navigation components are labeled in orange in Figure 31 and Figure 32.

- *N1, File Name Menu*—Allows selecting a file to be analyzed. When a file is selected, the cycles are separated, the first cycle selected, and the data is analyzed and plotted.
- *N2, Cycle Number Menu*—Allows selecting a cycle for the currently selected file.
- *N3, Next Button*—Allows proceeding to the next cycle of the current file, or if the currently selected cycle is the last cycle in the file, to the next file.
- *N4, Previous button*—Allows proceeding to the previous cycle of the current file, or if the currently selected cycle is the first cycle in the file, to the previous file.

7.3.3 Saving

This category of interactive elements contains the buttons and menus used to save the data and figures. The data are saved in a text file as a table, where each row is a set of data for a specific file and cycle. The rows are ordered with the files and cycles in ascending order. The saving components are labeled in purple in Figure 31 and Figure 32.

- *S1, Set Directory Panel*—Clicking the Open New Directory button allows selecting a new file or folder to be analyzed. This also sets the Directory to the directory of the file or folder selected. To save the text file and figures to a different directory, click the Set New Output Directory button. The path for this folder is displayed in the Directory text box below this button. The file name of the output file can be set by changing the text in the Save file as textbox. The default directory is the same as the input folder. The default file name for the output file is Analyzed [name of first file].
- *S2, Save Data Button*—Saves a row of data results in the output text file for the currently selected file and cycle. The data saved, in order from left to right in the table, are: file name, file number, cycle number, austenite start temperature, austenite start heat flow, austenite peak temperature, austenite peak heat flow, austenite finish temperature, austenite finish heat flow, austenite enthalpy, martensite start temperature, martensite start heat flow, martensite peak temperature, martensite peak heat flow, martensite finish temperature, martensite finish heat flow, martensite enthalpy.
- *S3, Save Data as N/A Button*—This button is used to save a row of the output text file when a user wishes to save the transformation temperatures and enthalpies as N/A. This may occur, for example, if the data cannot be analyzed because no peaks are present, as shown in Figure 32. The tool will flag potential candidates for saving the data as N/A, by displaying the plot backgrounds as yellow when the peak end points cannot be located by automatic analysis. However, whether a row is saved as N/A is entirely at the user's discretion and requires clicking the Save Data as N/A button.
- *S4, Delete Data Button*—After a row has been saved (either the Save Data button or Save Data as N/A button has been clicked for a specific file and cycle), the two save buttons are hidden, and

the Delete Data button is displayed for that specific row and cycle. When clicked, the Delete Data button deletes the row in the output text file for that specific file and cycle. The save buttons are then redisplayed. Because save states are stored by the tool for every file and cycle, as the user navigates between files and cycles, the Save Data, Save Data as N/A, and Delete Data buttons will be displayed according to the current save state for the selected file and cycle.

- *S5, Save State Lamp Indicator*—The color of the lamp indicator depends on the current save state of the selected file and cycle. If no action has been taken, the lamp is gray. If the data for the current file and cycle have been saved by clicking the Save Data button, the lamp is green. If the data for the current file and cycle have been saved by clicking the Save Data as N/A button, the lamp is yellow. Immediately after the Delete Data button is clicked, the lamp turns red.
- *S6, Save Options Check Boxes*—When the Click Next to Save checkbox is selected, clicking the Next button acts the same as clicking the Save Data button. Therefore, the user can index through the data files and cycles by clicking the Next button, and the data will be saved automatically, saving an extra step. If the Save Figures checkbox is checked, clicking either the Save Data button or Save Data as N/A button will save a jpeg image of the two plots as currently displayed. The image file is saved in the same directory as the text file is saved. If the Save Raw Data checkbox is selected, files will be saved for each individual heating and cooling segment.
- *S7, Save as .fig Button*—Clicking the Save as .fig button will save a Matlab .fig file of each of the two plots for the current cycle as currently displayed to the output directory.

7.3.4 Editing Data

This category of interactive elements consists of buttons, menus, and sliders related to the manual editing of values. Changing values using the sliders changes the transformation temperatures, enthalpies, and plots dynamically. The editing components are labeled in black in Figure 31 and Figure 32.

- *E1, Manual Edit Options Menu*—The manual edit options menu allows selecting what the sliders can edit. The menu is divided into two subsections: Enthalpy and Transformation Temperatures. Editing options can be selected within each subsection. The menu is as follows:
 - Enthalpy
 - Enthalpies
 - Enthalpy Labels
 - Transformation Temperatures
 - Left Tangent Line
 - Right Tangent Line
 - Inflection Points
 - Peaks
 - Start Temperature Labels
 - Finish Temperature Labels
 - Number of Peaks
 - Manual Heating Points
 - Manual Cooling Points
- *E2, Sliders*—Four sliders are provided for editing the values in the Manual Edit Options menu—two for editing values for the heating curve, and two for editing values for the cooling curve. The sliders labeled Left edit the left editing point, and the sliders labeled Right edit the right editing point. As a slider is moved, the plot changes to display the new value chosen. Any values that have not been edited with a slider continue to be analyzed automatically. The functionality of

each slider for every manual edit option is given in Table 3. Arrows are displayed for tangent lines to show editing points. For all editing options other than the labels, the x-coordinate of the edit point is edited by the slider, while the y-coordinate is given by the corresponding heat flow of the data at the x-coordinate chosen.

- *E3, Reset Button*—Clicking this button resets the plots and deletes the saved manual data, so that the initial automatic analysis is displayed. The menu option chosen resets to the default (Enthalpies).
- *E4, Use Previous Data Button*—This button loads the end points, tangent line coordinates, inflection points, and peaks from the previous cycle or file and applies it to the current cycle or file. A user can click this button to avoid re-editing multiple cycles of the same file if the datasets are similar, or to avoid re-editing if two consecutive files are similar.
- *E5, DSCAN Settings Window*—This window allows manually adjusting the portion of the heating and cooling curve to trim off and exclude from the analysis. These settings can help in cases where there is extraneous data or noise to one or the other side of the true transformation peak, or where the left and right horizontal baseline segments of the curve are not flat. In addition, it is possible to display the derivative of the heating segment or the cooling segment on the plot to see where the program is detecting inflections in the DSC signal.

TABLE 3.—MANUAL EDITING OPTIONS FOR DSCAN SLIDERS

Manual Edit Option	Heating Left Slider	Heating Right Slider	Cooling Left Slider	Cooling Right Slider
Enthalpies	Left peak end point for heating	Right peak end point for heating	Left peak end point for cooling	Right peak end point for cooling
Enthalpy Labels	Heating Enthalpy Label x-coordinate	Heating Enthalpy Label y-coordinate	Cooling Enthalpy Label x-coordinate	Cooling Enthalpy Label y-coordinate
Left Tangent Line	Left-most point of left horizontal tangent line for heating	Right-most point of left horizontal tangent line for heating	Left-most point of left horizontal tangent line for cooling	Right-most point of left horizontal tangent line for cooling
Right Tangent Line	Left-most point of right horizontal tangent line for heating	Right-most point of right horizontal tangent line for heating	Left-most point of right horizontal tangent line for cooling	Right-most point of right horizontal tangent line for cooling
Inflection Points	Left inflection point of heating	Right inflection point of heating	Left inflection point of cooling	Right inflection point of cooling
Peaks	Heating Peak	No functionality	Cooling Peak	No functionality
Start Temperature Labels	Heating Start Temperature Label x-coordinate	Heating Start Temperature Label y-coordinate	Cooling Start Temperature Label x-coordinate	Cooling Start Temperature Label y-coordinate
Finish Temperature Labels	Heating Finish Temperature Label x-coordinate	Heating Finish Temperature Label y-coordinate	Cooling Finish Temperature Label x-coordinate	Cooling Finish Temperature Label y-coordinate

Manual Adjustment Case 1: DSC plot displays a second peak on the heating segment.

Figure 33 shows a DSC plot for a sample having a discernible secondary peak on the heating segment. DSCAN has automatically fit the higher primary peak, but the A_S value does not reflect the start of transformation for the secondary peak Figure 33(a). The Inflection Points Manual Edit option is selected, and the slider for the left heating inflection point is adjusted to move the inflection point to the middle of the secondary peak transformation region Figure 33(b).

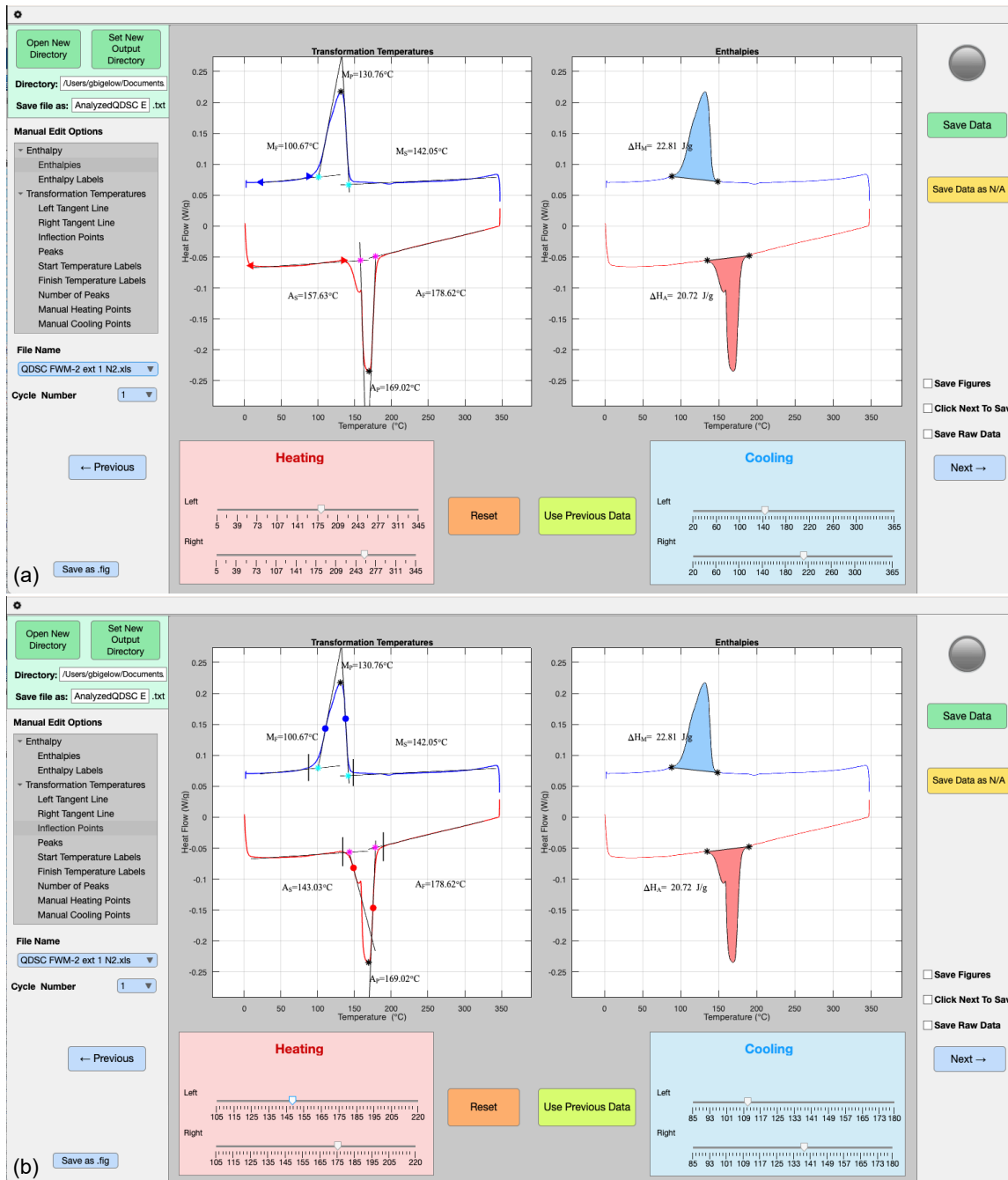


Figure 33.—Manual adjustment of sliders to capture A_S from secondary DSC peak on heating. (a) Initial Automated analysis. (b) Manually adjusted left heating transformation fit.

Manual Adjustment Case 2: DSC plot displays very small peaks, and accentuated curving horizontal regions.

Figure 34 shows a DSC scan for a sample with very small heating and cooling peaks. Because of this, the curvature of the horizontal regions is accentuated, leading to tangent lines that do not intersect the heating and cooling peaks at the base. To account for this, a large portion of the lower and upper heating and cooling data is cut off using the DSCAN Settings window (Figure 34(b)). After manual adjustment of the lower and upper cutoffs, the automated analysis is improved (Figure 34(c)), but it still needs further refining. This is done by selecting the Transformation Temperatures drop-down menu in the Manual Edit Options menu box and manually adjusting the left tangent line and right tangent line sliders for the heating and cooling curves (Figure 34(d) and Figure 34(e)).

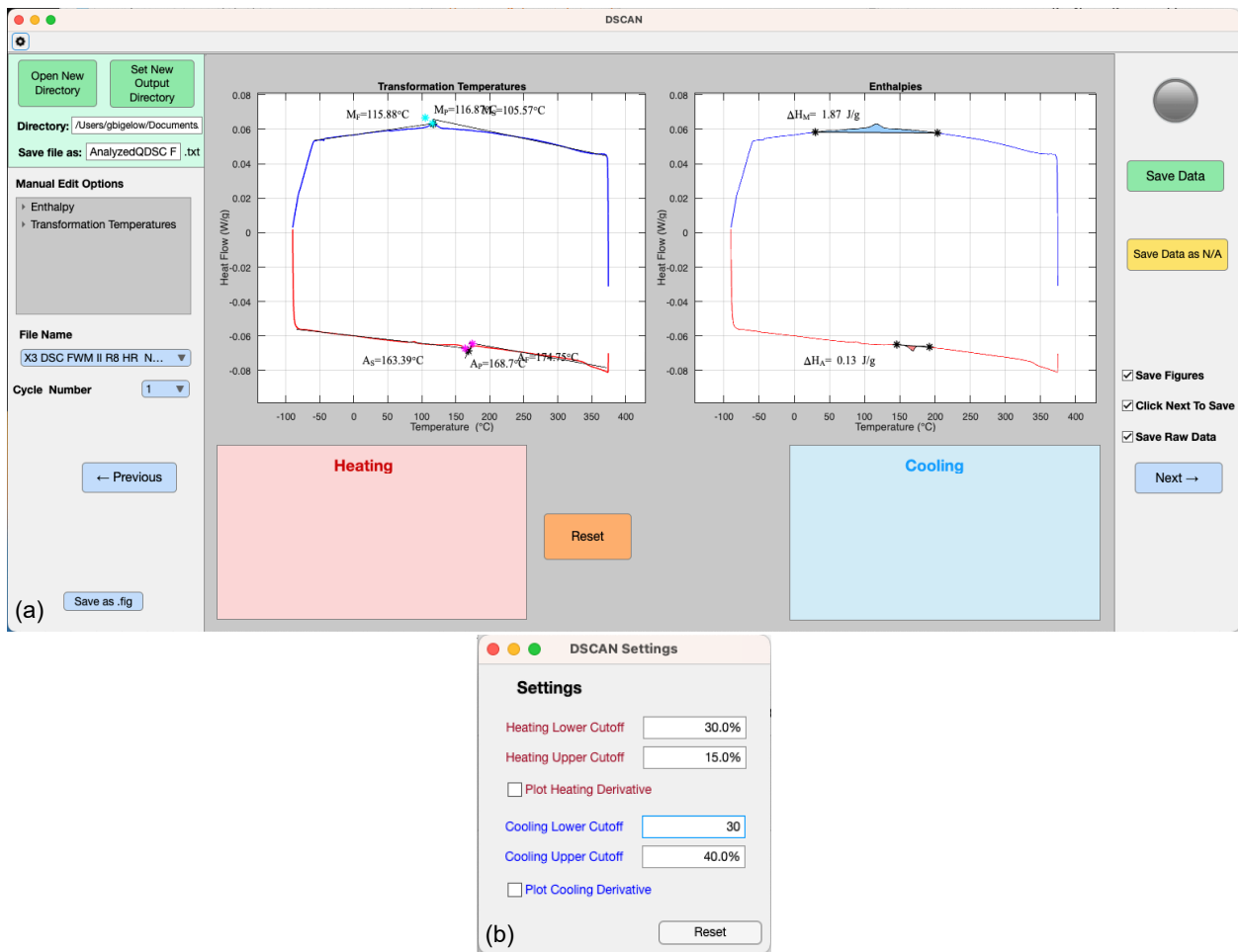


Figure 34.—Manual adjustment of parameters to adjust fit for sample with very small DSC peak. (a) Initial Automated analysis by DSCAN. (b) Manual adjustment of heating and cooling cutoffs. (c) Fit after adjusting cutoffs. (d) Fine-tuning of cooling peak by manual adjustment of left and right tangent lines. (e) Fine-tuning of heating peak fit by manual adjustment of left and right tangent lines.

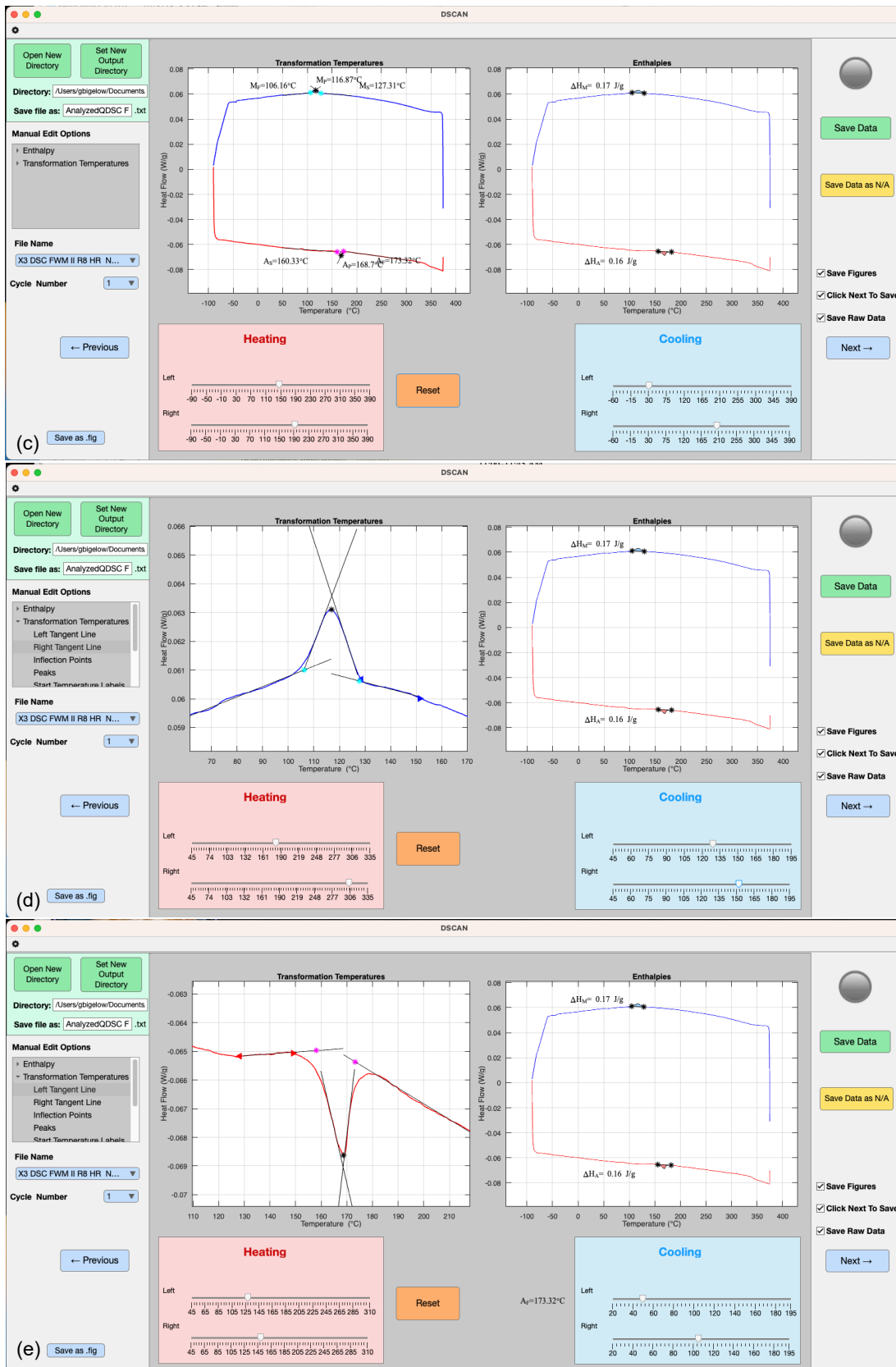


Figure 34.—Concluded.

Manual Adjustment Case 3: DSC plot displays an extraneous curve in the DSC baseline and does not fit the true transformation peak.

Figure 35 shows a DSC scan where the baseline horizontal segment for the heating curve is not flat, and there is extraneous curvature below the transformation peak. DSCAN has identified this as a peak and automatically fit it as the heating transformation peak. The Manual Heating Points option in the Manual Edit Options menu box has been selected, and “1” has been input as the number of peaks for consideration (Figure 35(b)). After the OK button is clicked, DSCAN prompts the user to select three points on the plot that represent the start, peak, and finish of the curve of interest (Figure 35(c)). The order of clicked points does not matter, only that the number of points reflects the number of peaks. Finally, after selecting the three points, DSCAN automatically fits the selected transformation peak, and displays the calculated transformation temperatures (Figure 35(d)). This curve fit will also need further refinement by manually adjusting the left tangent line for the heating curve.



Figure 35.—Manual adjustment of parameters for a curve containing extraneous curvature in baseline horizontal portion of heating curve. (a) Initial automated analysis by DSCAN, which has identified this extraneous curvature as a peak. (b) Selection of Manual Heating Points option in Manual Edit Options menu box and input of “1” in Number of Peaks edit box. (c) Selection of points on Heating Transformation peak. (d) Automated fitting of the new peak.

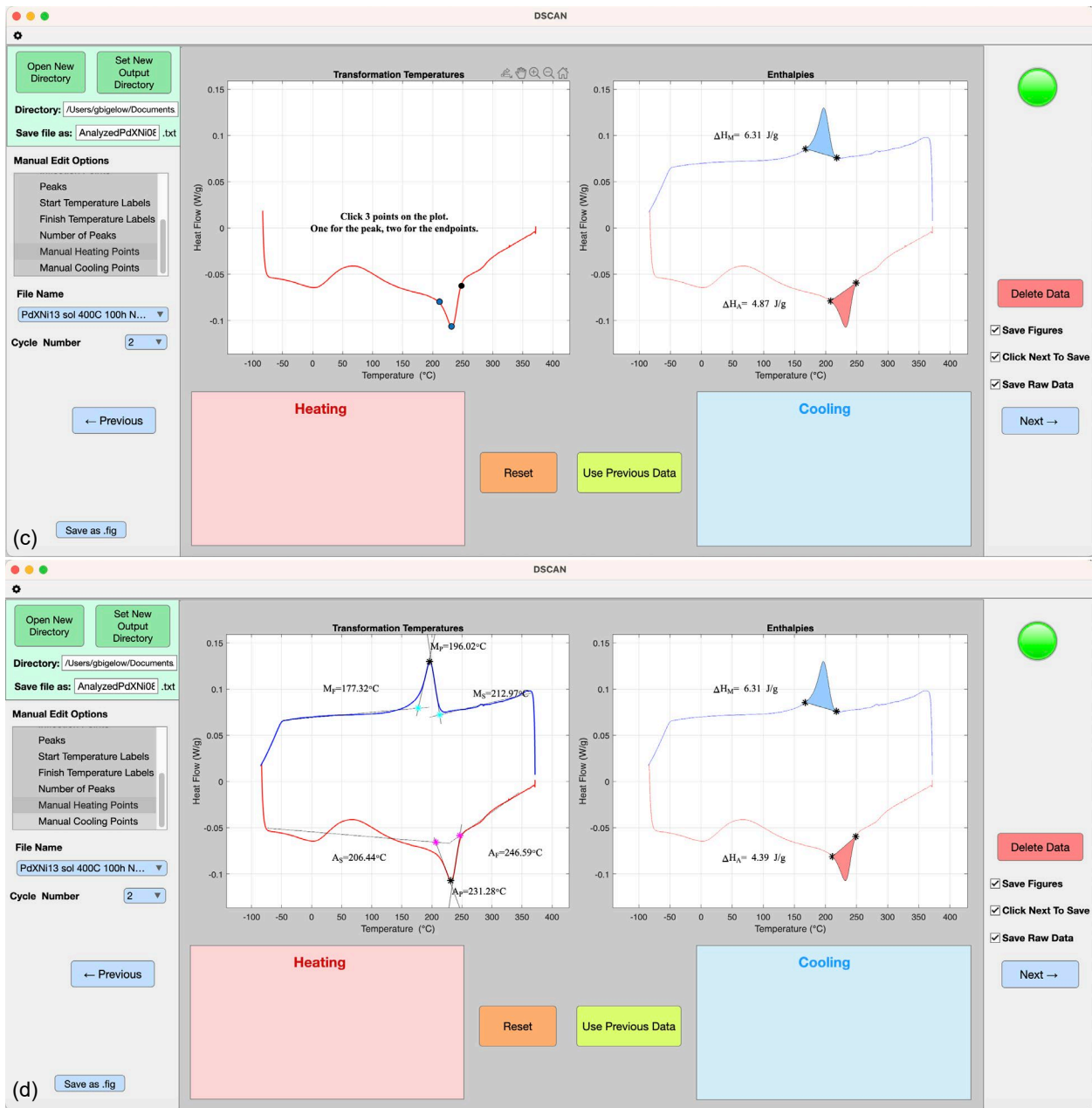


Figure 35.—Concluded.

8.0 Contact Information

Any questions, errors, or suggestions for SMAanalytics can be addressed to grc-ShapeMemory@mail.nasa.gov. In the e-mail, please note “SMAanalytics” and the version being used.

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