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In-Situ Strain Localization Measurements of Shape Memory Alloy Actuators during a Research Experience for Undergraduates Program

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Abstract

The research experience for undergraduates (REU) program was completed by the author during the summer of 2012. This paper describes the research conducted and the preliminary results achieved during the development of a new measurement method to study the strain localization in shape memory alloy (SMA) actuators. With access to a diverse population of graduate students and professors from different specializations and institutions, the student was empowered with much knowledge and ideas to develop a virtual instrument for in-situ measurements. Development and implementation of this method shows a promising potential in understanding SMA actuator fatigue failure mechanisms. Valuable time was comprised of working on a challenging problem through integration of software, hardware, and algorithms to produce in-situ data. The program enriched the student's educational experience through development in research, problem solving, technical writing, and software knowledge required of a solid engineering education.

Guidance from mentors prior to the REU program provided the student with the ideas to independently develop the method during the summer. The research objective was to develop a method to measure visual deformation and to acquire the real-time strain in regions of a specimen during high-cycle fatigue tests. The extent and location of the deformation helps to evaluate if localized strains contribute to early failure. A unique in-situ, non-contact extensometry method controlled by LabVIEW Vision Acquisition virtual instruments (VIs) was developed to measure strain in multiple regions during fatigue testing. A custom LabVIEW code and a webcam tracked and correlated markings on the specimen surface. The method was used in conjunction with a time controlled LabVIEW scheme. As a result, VIs performed image acquisition and distance measurements in real-time based on phase transformation timing. To test the image processing VI, images were acquired between cycles 0 to 1440 with specimen failure at 1683 cycles. The largest strain occurred during the martensitic, or cooling, phase when the specimen elongated under constant loading. The last image processed at 1440 cycles showed a concentration of strains higher than 40% in the central regions of the specimen, indicating the highest localized strains evolved near specimen failure. Strains during the austenitic, or heating, phase were lower as the specimen underwent shape recovery. The actuation strain during all cycles and for all regions measured remained nearly constant at 5% strain, indicating overall shape recovery. Average strains over the entire gauge length of a specimen were also compared between the data produced by the VI and a linear variable differential transducer (LVDT). Results were comparable, which concludes that LabVIEW VIs are effective in measuring deformation in multiple regions.

Introduction

The research experiences for undergraduates (REU) project took place in the summer of 2012 in the Department of Aerospace Engineering at Texas A&M University (TAMU) with funding provided by the National Science Foundation. The first author, who is the undergraduate student researcher, applied to the REU program after being inspired by the material science and engineering course completed the previous fall semester. Seeking an increase in knowledge about materials and research, the student gained much appreciation for all the activities experienced during the REU program. The student was selected to work with the Shape Memory Alloy Research Team (SMART), consisting of faculty, research staff, and all levels of students, whose interest includes developing the design capabilities of “smart” structures for actuation control applications. The student researcher worked in the Active Materials Lab which is one of the facilities where thermo-mechanical testing is performed at multiple test frame stations. Developments of new testing protocols for evaluation of SMA actuator fatigue life are undertaken in this lab.

The student was advised and mentored by a faculty in addition to other faculty and graduate students in the SMART team involved with SMA fatigue research. The student engaged in various REU assignments, including the completion of a research plan, progress report, abstract, research paper, and poster session. A one hour research credit was earned by the student upon completion of the program. The progressive assignments distributed throughout the summer allowed the student to improve her technical communication, reinforced by Summer Scholar Series sessions, program meetings, and one-on-one meetings with the faculty mentor. In addition to these research skills, the student learned how to develop and implement hardware and software to create a new experimental setup for real-time measurements acquisition. Significant working knowledge of National Instruments (NI) LabVIEW was gained to design an algorithm to measure two dimensional strain of SMA specimens when loaded in tension and undergoing high-cycle fatigue tests.

REU Program objective

The 10-week research experience objective was to engage the student in a research project that would make a significant contribution to the ongoing SMA fatigue research, specifically in understanding the actuation fatigue mechanisms and failure modes of SMAs. The project involved the development and implementation of a non-contact method to measure in-situ strain during SMA actuations. Integration of hardware, software, and new algorithms was undertaken to identify regions of localized strain during thermal cycling. In addition, the programs mission was to help the student gain an appreciation for and interest in graduate studies and a future research career.

Technical background

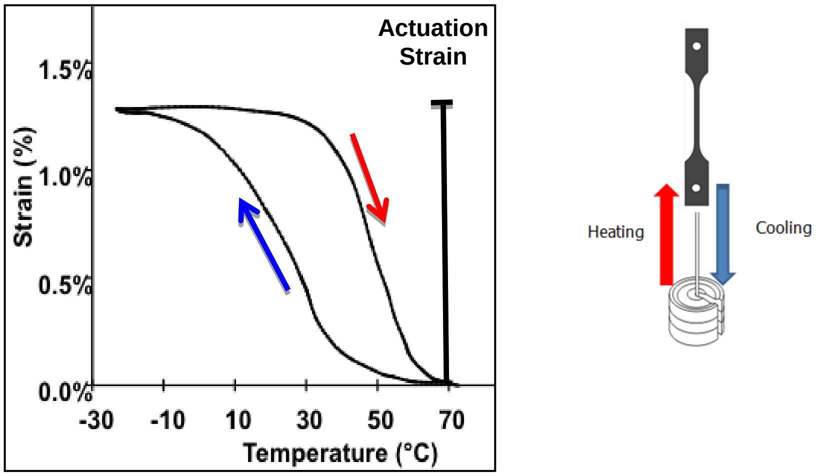
Shape memory alloys are very promising materials for compact actuators, distributed within aircraft wings, horizontal stabilizers, and elevators where space and weight are critical.[1] The multifunctionality of SMAs enables for the installation of one piece components versus an assembly. Performance gains realized from the SMAs will enable the design of morphing or adaptive aircraft structures for optimal fuel efficiency, reduced emissions, and reduced aircraft noise.[5] A major challenge for using these alloys as actuators is understanding their fatigue failure mechanism so as to design actuators with longer fatigue lives.

The fatigue of shape memory actuator literature was first reviewed to understand SMA strain and measurement with cameras to prepare for the implementation of the new method for in-situ strain measurements. This provided the student her first in-depth exposure to the process of assessing the scientific body of knowledge about the widely studied fatigue in superelastic SMA components. Surface damage characterization of SMA dogbone actuators revealed that failure is partially due to strain incompatibilities, but there is lack of understanding of the location and dimension of these incompatibilities.[2] Development of an experimental set-up and testing methodology for fatigue studies allowed for the measurement of the average strain by a linear variable displacement transducer (LVDT), giving a large accumulation of irrecoverable strain during the first 1,000 cycles and stability thereafter.[9] However, further understanding of the location and cause for this strain at 1,000 cycles is unknown. Further experiments with the same methodology and LVDT measurements indicated that specimens with the largest irrecoverable strain due to transformation induced plasticity reached a high lifecycle. Additional flat sheet specimen testing confirmed the large accumulation of strain during the first 1,000 cycles.[3]

While strain measurements in undergraduate laboratory experiments are commonly restricted to mechanical extensometry methods, the student had the opportunity to learn about optical methods used for strain measurements. A non-contact video extensometry method was employed to measure strain in polymers using LabVIEW. Algorithms performed pattern learning, pattern searching, and displacement measurement between two markers. This method proved to be a cost effective method compared to laser extensometers. The error using the video extensometry method was less than 5% compared to a laser extensometer. The challenges on marking recognition were due to inconsistent marking shape and orientation changes during testing.[7] Laser extensometry has also been employed for the evaluation of the local strain of welds in polymers to determine their damage tolerance.[3] Finally, Digital Image Correlation (DIC), an in-situ optical technique, was applied to measure strain near crack tips in thin sheets of nitinol, resulting in a strain accuracy of about 0.1% .[6]

Inspired by evolving fatigue testing methods and various non-contact techniques to measure strain, the research project for acquiring in-situ strain localization measurements was initiated with the creation of various standalone LabVIEW virtual instruments (VIs). The VIs were employed to measure the austenitic, martensitic, and actuation strains undergone by an SMA specimen per the actuation fatigue behavior of SMAs shown in Fig. 1.

The following sections present the various activities and the research work undertaken by the undergraduate student. The research work includes the specimen preparation, experimental setup, in-situ method development, results and discussion, and work in progress. Finally, the summer research program is assessed and its implications on future academic and career plans.



(A) (B)

Fig. 1. SMA Actuation (A) Representative strain vs. temperature plot for an SMA corresponding to a complete transformation cycle (blue = cooling, red=heating) (B) Temperature-induced phase transformation with applied load

Student activities

To accomplish the REU Program objective, technical skills were developed via considerable technical reading of literature and learning of the technical language in the studies of SMAs. This included reading of dissertations, thesis documents, software manuals, and technical papers. The student learned the vocabulary and presentation of research work in these formats. In addition, reading about the field enabled the student to design experiments, including mastering the LabVIEW software. Furthermore, the student completed a research plan, weekly progress reports, weekly progress presentations to her peers during program meetings, an abstract, a final report, and one poster presentation at the end of the program. The presentation was given to peers, graduate students, and faculty from diverse engineering disciplines. Feedback gained during each of these assignments strengthened the student's oral and written technical communication. During the SMART meetings, the student also learned about the expectations and method of delivery of scholarly work.

In addition to the focused technical development and guidance, the REU Program offered a wealth of complementary activities for the research experience. The student attended a tour to the Southwest Research Institute (SWRI) in San Antonio, TX. SWRI performs various full-scale testing of structures. The student witnessed how LabVIEW is used at SWRI as a primary data acquisition tool, similar to her research initiatives. The visit increased her awareness on how nondestructive technologies can be applied for monitoring crack growth in fatigue studies of materials. The perspective about a future research career broadened when realizing that large scale labs, such as SWRI, perform tests for industries across the world.

The weekly progress presentations to her peers enabled the student to communicate to a broader audience unfamiliar with her work. To better improve communication, each student was evaluated by fellow graduate and undergraduate researchers throughout the summer. Evaluation feedback was provided to each presenter to improve on clarity of presentation content, delivery, slides, and graphics. In addition, each student was recorded during his or her presentation to self-evaluate their presentation skills. Reflecting on her presentation style, the student became aware of her weaknesses in delivery and made immediate improvements in subsequent program meetings based on the feedback from the scholarly community.

Description of the technical aspects of the project

Specimen preparation

Sheets of equiatomic NiTi were pre-cut and electro-discharge machined (EDM) along the rolled direction with area remaining to allow for clamping in the EDM fixture. The sheets were 25% cold worked with as-received thicknesses of 0.50 and 0.25 mm. After pre-cutting the sheets, each piece underwent heat treatment per each of the temperature and time combinations in the test matrix (Table 1) followed by water quenching. A thermocouple was attached to the sheet to monitor the temperature in the specimen during heat treatment. An assembly was constructed by placing the SMA sheet in between two steel plates secured with bolts and nuts at each corner to eliminate warping during heat treatment and quenching. The furnace was set 10°C above the desired heat treatment temperature with no special environment. The nitinol and steel assembly was loaded with the attached thermocouple. When the thermocouple reading reached 20°C below the desired heat treatment temperature, the time for aging was started and the furnace environment was reduced to the heat treatment temperature. At the end of the aging time, the assembly was water quenched.

Table 1: Test matrix for actuation fatigue testing (not all specimens tested during this research)

Treatment Time

Treatment Temperature

	1 hour	2 hours	3 hours
350 °C		X	X
365 °C		X	
375 °C	X	X *	X
385 °C		X	
400 °C	X	X	

X: 2 tests at 200 MPa
*: 1 test at 150 MPa and 1 test at 250 MPa

The dog-bone specimens were then EDM cut from the pre-cut heat treated sheets into the final dimensions shown in Fig 2. Next, the gauge length edges were polished to remove the recast layer, consisting of metal bits, created by the EDM process. The polishing technique for the edges is the same employed by Schick and Calhoun.[2, 9] The specimens prepared per the test matrix were not all tested during the summer research time period. Finally, equidistant horizontal marks were applied along the gauge length of the specimen with a black Sharpie® extra fine point permanent marker. The specimen preparation process provided the student with the hands-on experience necessary to complement the full experimental process. The student’s material science course did not include a laboratory component, and this experience exposed the student to some techniques used in controlling material properties.

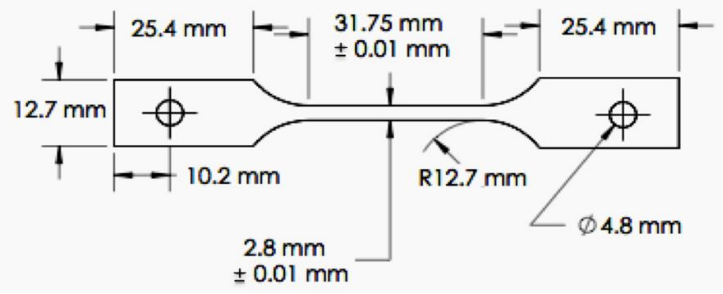


Fig 2. Dogbone specimen dimensions

Experimental set-up for in-situ measurements

An existing experimental setup previously used by Calhoun[4] was modified to include a Microsoft® Lifecam Studio™ high definition webcam. The webcam features a high-precision glass element lens and manual focus adjustment. A stable position for the camera was established through trial and error to control the precision and accuracy of the measurements. A platform was selected to reduce the distance between the tripod and the testing chamber. Calibration of the camera supports was completed with a level on the tripod and platform end to sustain a horizontal position during testing. The platform was clamped to the tripod at their interface. The camera was attached to the platform sideways to allow the widescreen sensor to capture high definition images of the specimen gauge region as shown in Fig. 4.

A distance of 10 mm separates the camera lens from the chamber window to ensure the specimen image area occupies most of the image resolution of 1920 x 1080 pixels. The lens axis was oriented perpendicular to the specimen gauge area to minimize lens distortion.[8] A halogen lamp with a magnetic base was also fixed at an angle away from the camera to improve specimen illumination for marking detection. The modification of the in-house developed fatigue test set-up provided the student with an opportunity to design experiments and control variables. Most standard engineering courses lack the opportunity to set up an experiment due to the limited time to complete laboratory exercises.

In-situ measurement method development

The time-controlled LabVIEW scheme developed by other fatigue researchers[4, 9] contains a series of case and sequence structures to control the data acquisition and cycle times recorded for average displacement and strain measurements by an LVDT. There is a while loop that encloses these primary functions of the program. The code generated for the real-time in-situ measurements was created for insertion to this top level program. The LabVIEW software to generate the code is capable of machine vision to detect markings and perform measurements as in conventional inspection procedures. The challenges in the method development, including camera selection, new algorithm generation, and measurement methods comparison provided the student an opportunity to integrate all components of the experiment and gain an appreciation for the graduate student experience and the stages of scholarly work.

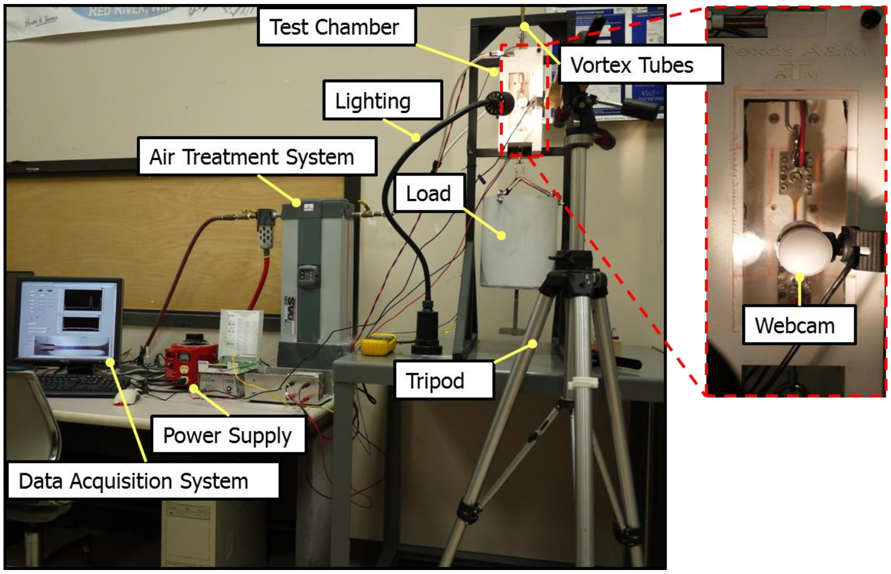


Fig.4. Modified existing in-house developed shape memory alloy fatigue test set-up and program. Installed camera for real-time image acquisition ≈ 10 mm from the chamber

Webcam

The webcam software advance settings allows for manual focus, resulting in the best image to capture the thin marks on the specimen surface. The photo resolution of 1920 x 1080 pixels was selected for compatibility with the NI Measurement and Automation Explorer (MAX). The settings and capabilities in the webcam software interface with MAX to establish the camera attributes, including focus. The camera was selected by the student to contain the features required for compatibility with LabVIEW and the capability to acquire high definition images for real-time measurement.

LabVIEW Vision Development Module

The LabVIEW Vision Development Module was used to interface with the webcam and the remainder of the hardware in the fatigue experimental setup. LabVIEW controls the webcam and acquires and processes images, detects markings, and performs distance measurements between markings. The code was developed in the LabVIEW block diagram. Virtual instruments in the code perform the functions of traditional measurement instruments. Throughout the progression of the REU Program, the student created multiple VI codes, combining the VIs that were later integrated into the time controlled LabVIEW scheme developed by past fatigue researchers.[2, 4] The final version of the scheme with Vision VIs allowed for the visual deformation measurements realized at the end of the program. Codes were designed in an organized, simple, and commented fashion for other end users to understand the function of each VI. The final code is easily adaptable to various measurement applications in engineering, creating an invaluable tool for research and industrial settings.

A preliminary code was developed to open and configure the camera for continuous image acquisition to accommodate the phase transformation cycle time of the equiatomic NiTi. The time-controlled LabVIEW scheme displays a waveform chart plotting LVDT displacement vs. time as shown in Fig. 5. Two images were acquired over each cycle, one at the end of heating (austenite position) and one at the end of cooling (martensite position).[9] The time to reach the displacement plateau is an indicator that the prepared specimen requires about 4 seconds of heating to transform the specimen above the A_f temperature. For cooling, 56 seconds are allowed to cool the environment inside the chamber to transform the specimen to below the M_f temperature. The total cycle time amounts to 60 seconds.

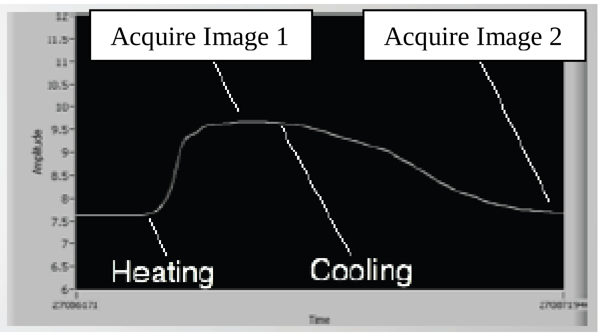
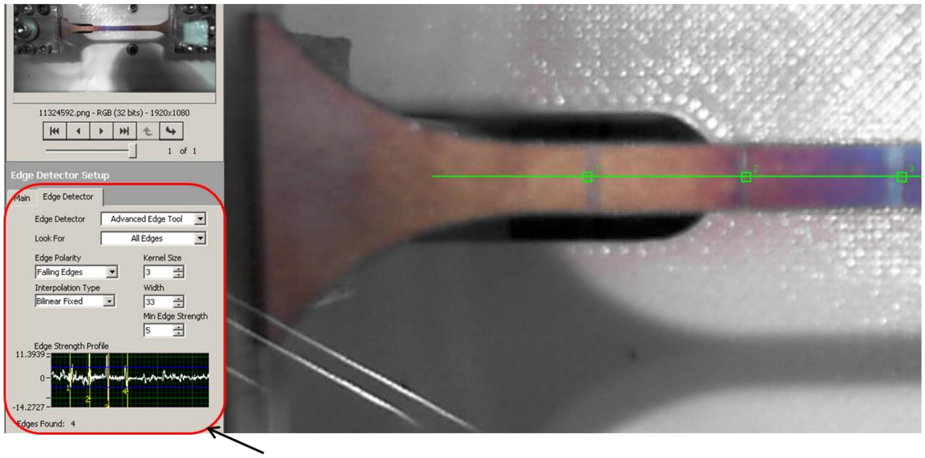


Fig.5. LabVIEW waveform chart for LVDT displacement vs. time during fatigue testing

Sub-VIs were created and embedded into the time-controlled LabVIEW scheme to collect the image processing, saving, and strain computation functions in a clearly coded manner (see Appendix, Fig. A1). Each sub-VI consists of a Vision Assistant Express VI for image processing. The Vision Assistant script created includes the following steps: original image, edge detector, set coordinate system, calibration from image, and calipers for each region measured, sequentially.

The edge detector is the principal instrument used to locate all the horizontal markings on the gauge area as shown in Fig.6. Parameters can be customized for each specimen tested and allow for marking movement during specimen actuation.



Edge Detector: Advanced Edge Tool

Look For: All Edges

Edge Polarity: Falling Edges

Kernel Size: 3

Interpolation Type: Bilinear Fixed

Width: 33

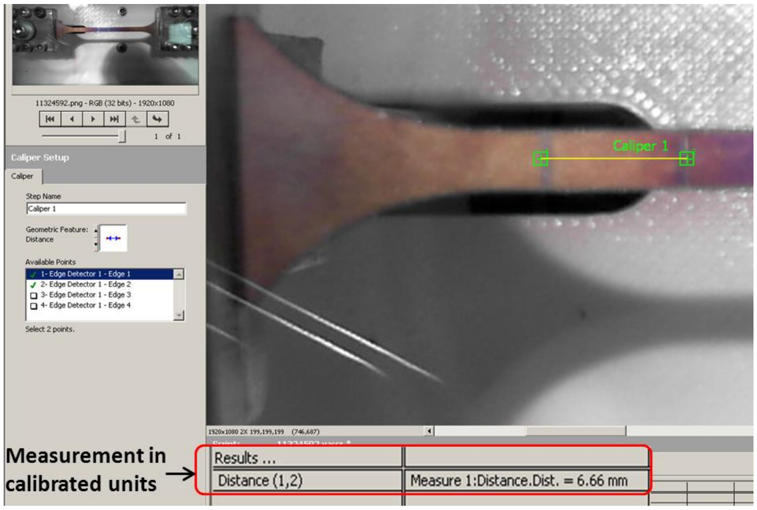
Min Edge Strength: 5

Edges Found: 4

Parameters customized for each specimen tested

Fig.6. Edge Detector step in Vision Assistant algorithm to locate markings

Another important step in the Vision Assistant script includes the virtual caliper. This tool performs distance measurements between the markings detected as shown in Fig.7. The number of calipers used corresponds to the number of regions created in the gauge area during marking.



Step Name: Caliper 1

Geometric Feature: Distance

Available Points
- ✓ 1- Edge Detector 1 - Edge 1
- ✓ 2- Edge Detector 1 - Edge 2
- ☐ 3- Edge Detector 1 - Edge 3
- ☐ 4- Edge Detector 1 - Edge 4

Select 2 points.

Results ...	
Distance (1,2)	Measure 1:Distance.Dist. = 6.66 mm

Fig.7. Caliper step in Vision Assistant algorithm to perform distance measurements between markings

Strain was calculated by the code for both the austenite and martensite locations according to equation 1

$$\epsilon = \frac{Displacement - Initial\ Distance}{Initial\ Distance} \qquad (1)$$

where displacement is the difference between the acquired image and the initial image taken during specimen heating. The initial distances correspond to the distance measurements on the first austenite image. The actuation strain is calculated by taking the difference between the strain in the martensite and the austenite phases for a cycle. A flowchart of the vision code developed for in-situ measurement is presented in Fig.8.

Experimental set-up for measurement methods comparison

The in-house SMA fatigue test set-up previously used by Calhoun[4] was used to fatigue test specimens to compare the LVDT and the LabVIEW VI measurements. The testing apparatus with the addition of a Canon Powershot S3 IS digital camera mounted onto a tripod was used to acquire digital photos at random number of cycles. The camera setup was placed about 28 mm in front of the testing chamber. Similar to the in-situ measurement set-up in Fig. 4, the lens axis orientation was maintained perpendicular to the specimen center. A similar lamp was used for specimen illumination. The same Vision Assistant script was used to post process each photo.

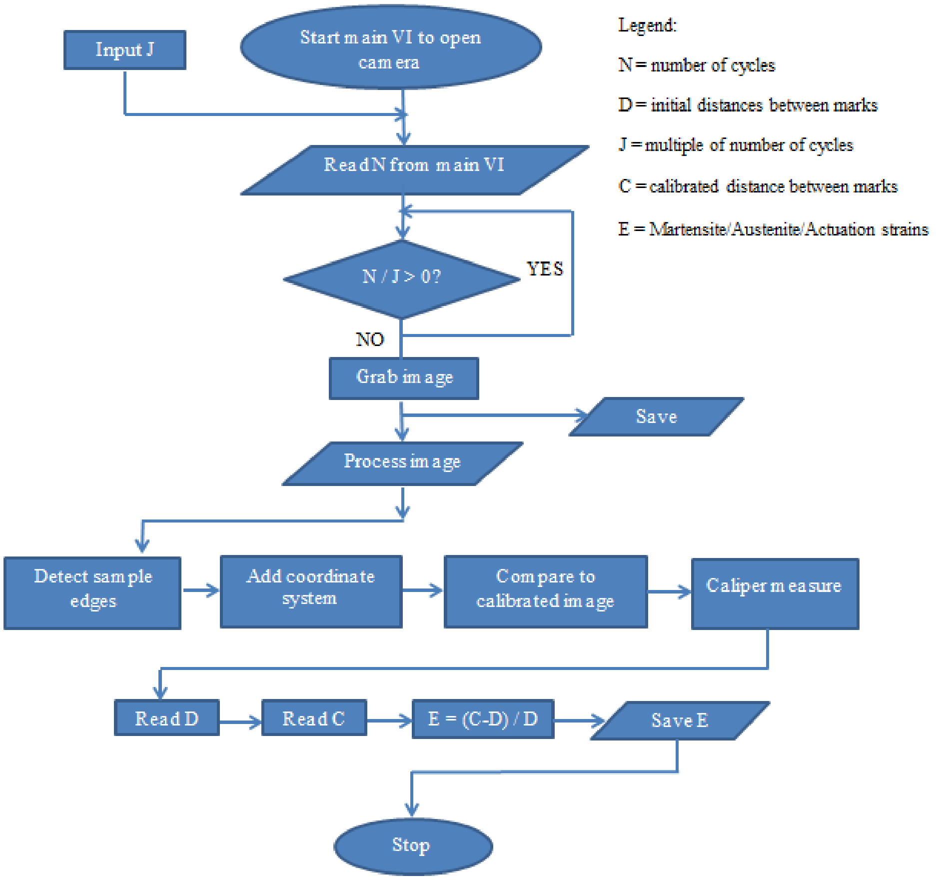


Fig.8. Flowchart of image acquisition and processing for in-situ measurement

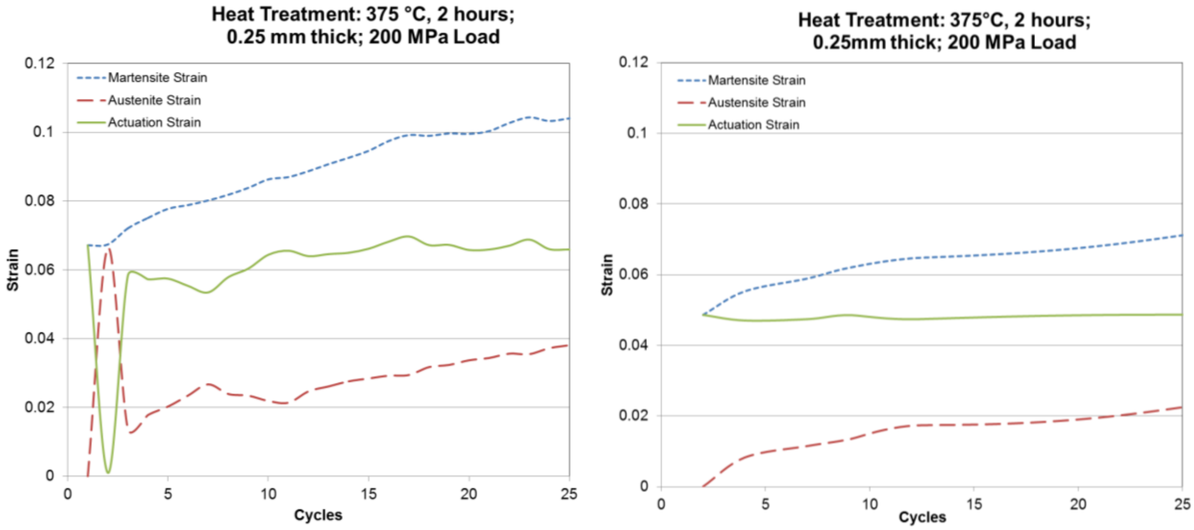
Results

Measurement methods comparison

An equiatomic NiTi specimen heat treated at 375°C for two hours with a thickness of 0.25mm was fatigue tested under 200 MPa constant stress with the established experimental set-up, producing the strain results given in Fig. 9. The specimen was prepared as described in the section 'Specimen preparation.' LVDT data is presented for the first 23 cycles for comparison with the graphical measurements obtained via image post processing with the LabVIEW VI.

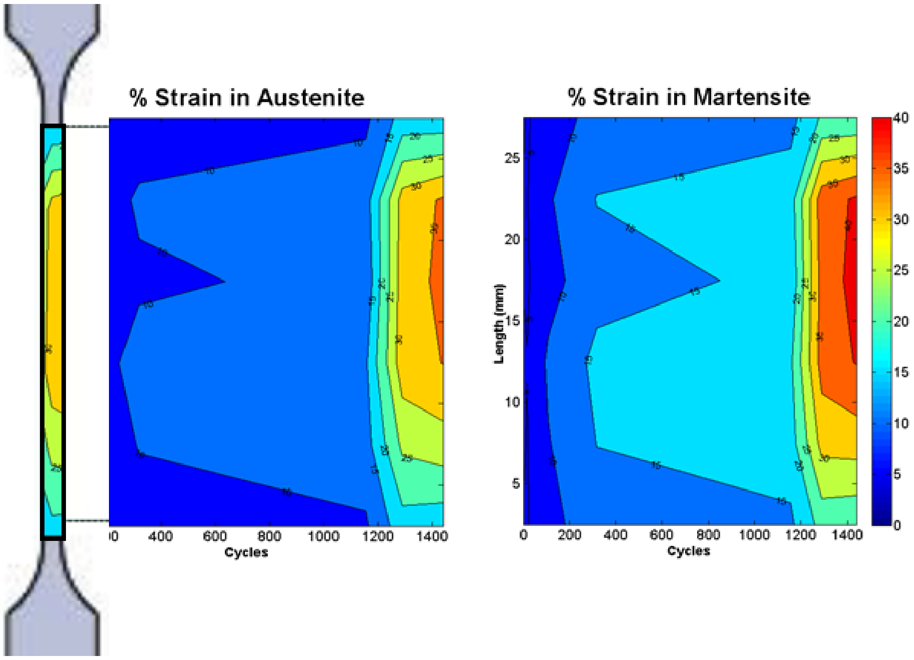
Strain localization measurements with LabVIEW VI

In a subsequent fatigue test, photos were acquired with the digital camera over a range of 0-1440 cycles for a specimen that was tested until failure at 1683 cycles. The image processing sub-VI was used to assess the percent strain undergone for each region. Two images for each transformation cycle, each containing six regions to be measured, were processed to produce the results given in Fig. 10.



(A) (B)

Fig.9. Strain evolution vs. cycles obtained from (A) LVDT measurement and (B) LabVIEW VI over the entire gauge length



Example Cycle:
1290

Fig.10. Strain evolution for 0-1440 cycles: Strain localization increases significantly in the central regions of the specimen above 1,000 fatigue cycles during both the austenite and martensite phases. Results are consistent with the specimen failure in the center.

Discussion

Average strains over the entire gauge length of a specimen were compared between the data produced by the VI and the LVDT. The LVDT data shows the austenitic strain increases about 2% while the martensitic strain increases by about 3% during the first 23 cycles. The measurements performed by LabVIEW show that the same sample underwent about 2% increase for both phases. The recoverable strain is close to 6% for the LVDT results and 5% for the LabVIEW results. It is noteworthy to mention that the image measurement results are more consistent over the first 23 cycles compared to the LVDT. LVDT data shows more variation in the austenitic and martensitic strain, resulting in varying actuation strains. There is a consistent increase in strain for both phases when the images were processed with the Vision Assistant script.

For the subsequent fatigue test, results in Fig. 10 show the largest strain occurred during the martensite phase when the specimen elongated under constant loading. The last image processed at 1440 cycles shows a concentration of martensitic strains higher than 40% in the central regions of the specimen. Results are in agreement with specimen failure near the center. The actuation strain during all cycles and for all six regions measured remained nearly constant at 5% strain, indicating length recovery. Data beyond 1440 cycles is required to confirm how further concentrations of strains identify exact specimen failure location.

Work in progress

Work in progress for implementation of the in-situ strain localization measurement method includes the identification of an alternative marking material besides permanent ink to allow the markings to remain on the specimen surface through a full lifecycle. In the specimens tested, it was observed that markings faded after 1,000 cycles and the exact cause is unknown. It is believed that the markings fade due to the large accumulation of strain during the first 1,000 cycles[2]. The gradual fading of markings during testing presents a need to monitor and adjust several Vision Assistant parameters to ensure markings are always detected. As a result, additional steps in the Vision Assistant script may be required, including color plane extraction to increase the contrast between markings and the specimen. The parameters for each step require a customized adjustment for each specimen, as these have a significant effect on the success of the marking recognition. Similar challenges were experienced with Vic-2D software used in DIC.[6] Inadequate lighting, specimen color, and vertical alignment of the specimen can produce unreliable measurements and system errors. The end goal is to retain all parameters constant through a full test, requiring minimal adjustments and sustaining automatic image acquisition and processing of all images.

Before the in-situ strain measurement system is implemented, the processing time of the computer will be reduced by readjusting the rate of webcam image acquisition, and the Vision Assistant and DAQ Assistant processing parameters. The DAQ Assistant contains time settings for the number of samples to read at a specified sampling rate. The readings occur for both the voltage applied to the specimen and the environment temperature measured by the thermocouple inside the chamber. In addition, the Vision Assistant portion of the current code is currently tasked with processing the gauge section and unstrained regions alike. Processing time can be reduced using a masking step to restrict processing to the gauge area only. Finally, the continuous acquisition of the webcam may be contributing to the low processing speed of the computer. Various error messages are displayed when the main SMA Fatigue Test VI is executing, indicating that a combination of the mentioned processes may be stopping the VI from running once image processing begins at the first cycle completed.

Work in progress provided the student the opportunity to mitigate the issues leading to the culmination of the summer 2012 REU project. The student enrolled in a semester research course during the following academic year under the supervision of a faculty mentor. The student has the advantage to gain a total of three credit hours of research to fulfill a technical elective. The continued research experience involves further development and implementation of the hardware and software for real-time image acquisition and processing of visual deformation measurement during high-cycle fatigue tests. Sustained exposure to the research environment and collaborative work with a faculty mentor, graduate students and industry will offer the student an extensive research experience that can be transferred to graduate studies and a future research career.

Student assessment

The knowledge gained during the REU program has added value to the student's well rounded engineering education. The greatest value was in learning LabVIEW, which is a common tool used in laboratory courses. Learning LabVIEW without any prior experience provided her with an opportunity to explore and use various features not commonly introduced during the standard laboratory course activities. The process followed in developing the sub-VIs embedded in the existing LabVIEW scheme helped the student to write MATLAB codes for a Numerical Methods for Engineers course the following semester. Attendance to the REU Summer Scholars luncheon series also benefited her engineering education. She was reminded about establishing research goals, communicating with her research team, articulating her experience on a résumé, and preparing to produce concrete results to take away. All the presenters during the series brought tips and guidance for immediate application to her academic career.

The summer research experience motivated the student to pursue new endeavors. Understanding that fatigue is a stochastic process encouraged the researcher to seek professors from other disciplines at TAMU to provide ideas on the research project development. A professor from civil engineering explained how experimental data could later be used to develop a stochastic model to simulate deformation and create a probability distribution. Similarly, a professor from industrial engineering introduced the student to the concepts of two types of stochastic models, dynamic and spatial, to further present fatigue data. As a result of the summer REU research completed, the student was selected to participate in the Society of Hispanic Professional Engineers (SHPE) 2012 undergraduate student technical poster competition. Another opportunity for a poster presentation made the researcher aware of improvements to poster delivery thanks to feedback given by a larger pool of professors from universities across the United States and Puerto Rico.

Conclusions

This concludes the work completed during a research experiences for undergraduates (REU) program. The experience motivated the student to enroll in a research credit course to further the project, apply the skills learned during the summer to her academic career, and pursue a future research career. Continuation of the project as a research credit during the academic year provided the student the opportunity to address work in progress issues, prolonging the exposure to the academic research environment. Though further development of the in-situ method is underway, preliminary results achieved during the program demonstrate the capability of the LabVIEW VIs to replace the LVDT in measuring SMA strain. Virtual instruments are adaptable to measuring localized strain while LVDTs are limited to integral strain. LabVIEW measurement results over the first 23 fatigue cycles for a specimen showed more consistent results compared to some variation in the strain given by the LVDT. Edge detector and virtual calipers in LabVIEW enabled for the successful measurement of deformation for a specimen during most of the fatigue life. Significant strain localization was observed after 1,000 cycles, with higher concentrations in areas near the specimen failure. Results prove the VIs are effective tools for an in-situ, non-contact method to evaluate SMA actuation fatigue mechanisms and failure modes. With these results, a basis for this newly developed system to measure deformation localization for a complete set of experiments has been created.

Acknowledgements

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Appendix

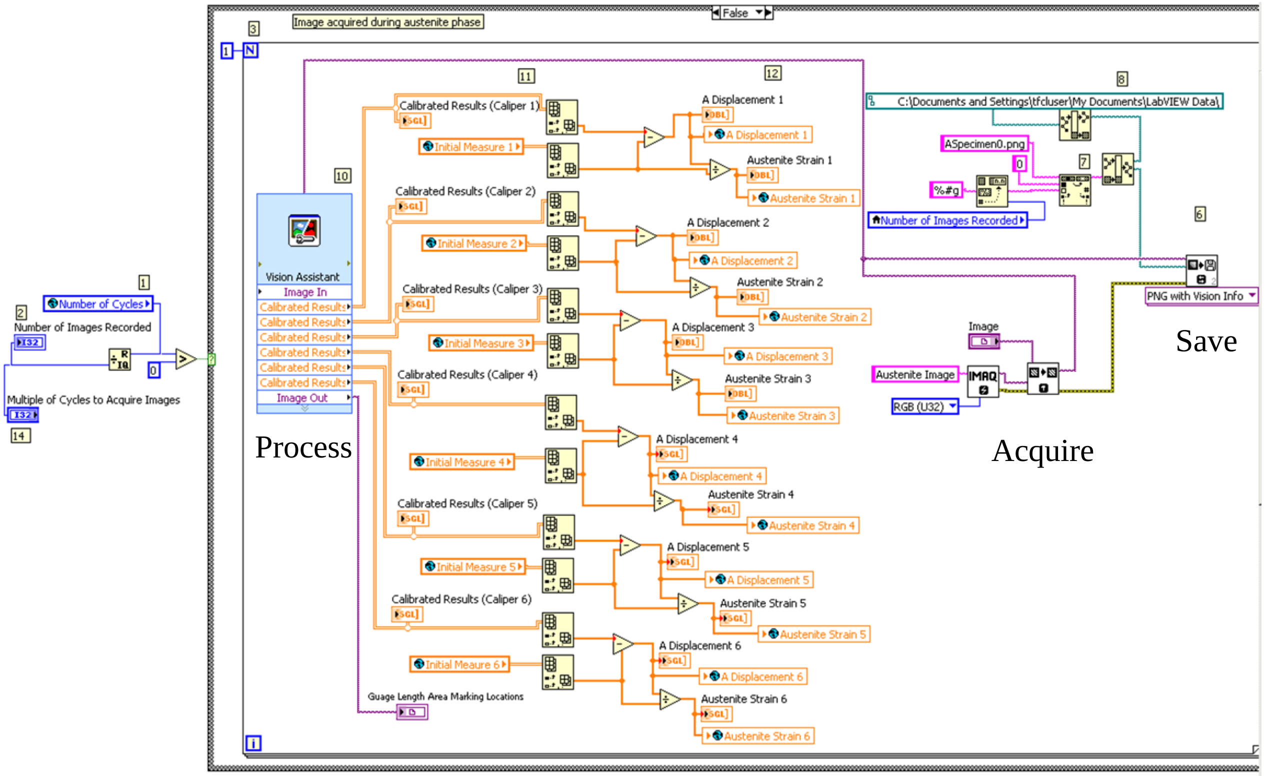

Fig. A1. Sub-VI with Vision Assistant Express VI processing and saving an image during any given cycle time