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Shape-Memory Alloy Investigation

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HIGH CYCLE FATIGUE BEHAVIOR OF SUPERELASTIC NITINOL WIRE

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Total Funding Request: $944.75

2 Project Summary

Since its discovery in the 1950s by the Naval Ordinance Laboratory, the nickel-titanium alloy known as Nitinol has been utilized for its shape memory properties for the design of components such as thermal actuators but has found more widespread use in the biomedical industry in its superelastic form[11]. Owing to its ability to fully recover strains in excess of those that would permanently deform other contemporary alloys, implant devices such as endovascular stents are commonly fabricated from Nitinol[6]. Unfortunately, the stress-induced transformation that creates superelastic behavior also results in complex fatigue behavior which to this day is still not fully understood[8]. Currently, there is a deficit of experimental fatigue data for “small” crack propagation (usually preexisting results of manufacturing history) and thus damage tolerant based design of small medical devices utilizes data for “large” crack propagation (usually resulting from component damage during its service life) [10]. This method has been identified as a severe limitation to biomedical component design in that it can result in non-conservative fatigue behavior predictions. This research effort aims to contribute to the fatigue data available to biomedical engineers for the design of medical components using improved fatigue life prediction methods. A thorough study of the high cycle fatigue behavior of 0.0235 inch diameter superelastic Nitinol wires will be conducted through the development and implementation of a closed-loop fatigue testing machine. A scanning electron microscope will be used for surface analysis to identify and monitor flaws present in the wires resulting from manufacturing and processing history.

3 Project Description

a. Background

Undergraduate research focusing on the testing of Nitinol under the supervision of Dr. Lanning began in the fall of 2014 as an Honors Program Directed Study for ES320/ES321. This research focused on the shape memory properties of this alloy, particularly the effects of heat treatment duration and temperature on the work output of helical spring thermal actuators. This project succeeded in producing and analyzing over forty Nitinol thermally activated actuators and a poster detailing this research endeavor is currently on display in AXFAB.

The research project discussed in this proposal is effectively a continuation of this previous work. Following the completion of the Fall 2014 work, a substantial amount of superelastic Nitinol wire remained unused in the Materials Testing Lab. The original intent of this research was to expand the investigation of shape memory alloy actuators from work output characteristics to fatigue behavior. However, due to the limited use of small shape memory alloy actuators in industry and the complex interaction of thermal and mechanical fatigue occurring in said actuators, it was decided that a study of the fatigue behavior of superelastic Nitinol would not only yield more conclusive results but would also take less time to complete at a lower cost. A literature survey performed in fulfillment of an AE399 Directed Study this semester revealed the widespread use of small devices fabricated from superelastic Nitinol wire in the biomedical industry[3]. Furthermore, it was also found that there is an ongoing need for further studies regarding the high cycle fatigue behavior of these small medical devices[11].

It is the collective opinion of this student researcher and the faculty advisor to this project that by utilizing the resources of the AXFAB Materials Testing Laboratory, an experimental study of superelastic Nitinol fatigue damage characteristics in the high cycle regime would be beneficial to society. Not only will it enable a more comprehensive understanding of this relatively new material but will also allow biomedical engineers to design safer and more effective implant devices and thus will allow more widespread implementation of said devices.

b. Project Thesis

This project will analyze the growth of preexisting flaws in superelastic Nitinol wires tested into a fatigue cycle range exceeding 10^7 cycles[7]. Experimental results will be compared with the fatigue life estimates provided by the damage tolerant analysis models currently used to predict the fatigue behavior of Nitinol devices[12]. The growth of pre-existing flaws resulting from the processing history of the wire specimens will be monitored to gain an understanding of critical flaw sizes and their effect on the useful life of superelastic Nitinol medical components[10]. If the damage tolerant modeling approaches currently used to design these devices is found to be consistent with experimentally obtained data, the contemporary design methodology will be verified. However, the appearance of major discrepancies between theoretical and experimental results will indicate a significant flaw in contemporary methods of predicting fatigue lives of Nitinol components and will provide a basis for the continuation of this research with the goal of improving fatigue modeling of Nitinol components.

c. Project Objectives

The primary objectives of the proposed research project can be summarized as follows:

- To develop a high cycle fatigue testing method that can be utilized and improved for future undergraduate research studies.
- To analyze the behavior of superelastic Nitinol wires subjected to high cycle fatigue regimes in order to provide an understanding of the mechanisms by which pre-existing flaws can reduce the useful life of biomedical devices.
- To expand the experimental fatigue database for superelastic Nitinol to allow biomedical engineers and future studies to utilize the results of this research for improved device fatigue life prediction and to provide a basis for the future expansion of this research.

d. Project Approach (Methods)

This research will take place in the AXFAB Materials Testing Laboratory and will also make use of software available on computers throughout the facility. An ANSYS modal analysis on a beam of identical dimensions to the test specimens used for this research will be used to determine the resonant frequencies of the material. This computer simulation will be supplemented with a separate calculation of the resonant frequencies of the beam specimens as a means of verification before proceeding with testing. Specimens will be fabricated and processed with MicroClean MV etchant obtained for use in the research performed during the Fall 2014 semester to remove the oxide layer that is present on the wires as-shipped and can significantly influence the fatigue behavior of the material. The individual specimens will be subjected to a thorough scanning electron microscope analysis to assess their condition prior to testing to allow the identification of areas of concern where surface flaws are present.

Following the completion of specimen fabrication and processing, the construction of the closed-loop (no sensor feedback) fatigue testing machine will commence[1]. The centerpiece of this device will be a Thorlabs AE0203D08F piezo actuator which is capable of vibrating the specimen at a computer-controlled frequency[13]. This device will be driven by a MiniGen signal generator board driven by an Arduino microcontroller which can be connected to any computer with a USB port[5]. The required software for this system is an open-source based free download. This combined system will output a signal corresponding to the resonant frequency of the Nitinol test specimen which will be connected to the piezo actuator and thus vibrated at resonance. This will enable testing into the high cycle fatigue regime with the closed-loop system being programmed to terminate operation following a desired number of cycles. Following the completion of a test, the specimens will be analyzed with the scanning electron microscope once more to compare the size and shapes of flaws before and after the test regime.

e. Expected Project Outcomes and Significance

As previously mentioned, the expansion of superelastic Nitinol high cycle fatigue data is crucial for the continued evolution of safer and more effective biomedical devices fabricated from this alloy. The results of this testing will provide researchers both internal and external to Embry-Riddle with insight into the fatigue behavior of superelastic Nitinol and will motivate further studies regarding the growth of pre-existing flaws over the operational life of a Nitinol device. It is also possible that this research may observe behavior that has not been previously observed since there have been relatively few studies conducted that have attempted to verify high cycle damage tolerant life prediction models against experimental results[10].

Additionally, there is significant potential for the expansion of this research beyond the end of the summer testing schedule. Due to the interdisciplinary understanding required to conduct this research, the inclusion of advisors and researchers from different engineering disciplines is also a possibility. Future undergraduate researchers at this campus will also benefit from this research since the experimental data obtained will be available on the Scholarly Commons and the hardware procured will be on display in AXFAB following the completion of this project.

f. Description of any IRB, IACUC, or safety related training

This research project will not require any additional training.

4 Researcher Background and Responsibility

Bryce Alexander Milnes

Undergraduate Student

Junior, Aerospace Engineering Major

Expected Graduation: May 2016

Role in Proposed Research Project: Primary Experimenter

Over the course of the Fall 2014 semester, I assisted in the design and analysis of an experiment to assess the work output capabilities of Nitinol shape memory alloy spring actuators in fulfillment of the requirements of an Engineering Materials Science (ES320/321) Directed Study. Upon completion of that project, I chose to continue experimenting with Nitinol under the supervision of Dr. David Lanning who has extensive experience with high cycle fatigue testing of titanium alloys. During the Spring 2015 semester, I performed an extensive literature survey to refine the scope of my continued Nitinol research as required for the fulfillment of the AE399 course requirements culminating in the submission of this proposal. With the combined fatigue testing experience of Dr. Lanning and the extensive knowledge I have gained through months of exploring the contemporary Nitinol fatigue research data and past experience working with this material, I will conduct all specimen preparation, experiment design, and data analysis required for this project.

5 Timeline

The proposed student research project will be conducted in accordance with the following schedule:

- **Literature Survey and Thesis Development (Spring 2015)** was conducted in fulfillment of AE399 course requirements. The scope and feasibility of this research was refined and analyzed in this time period to enable the submission of an IGNITE grant proposal.
- **Preliminary Experimental Design (Spring/Summer 2015)** is presently being conducted and will continue through the first week of May to ensure that a sound, repeatable methodology exists prior to the commencement of specimen preparation and testing.

- **Testing and Analysis (Summer 2015)** will take place through the entirety of the summer research period specified by the terms of the Ignite grant. The preparation and pre-test evaluation of specimens will commence as soon as possible since all materials required for this task are currently stored in the Materials Testing Laboratory. The procurement of the required hardware will be concurrent with specimen preparation to ensure that upon arrival, testing can begin immediately after the assembly of the fatigue testing system. Results will be gathered and analyzed following the completion of tests conducted at a rate of one-per-day until all required data has been obtained. A technical report summarizing the findings of this study will be created and submitted to the Scholarly Commons as the final phase of this project.

6 Itemized Budget

Below is a complete list of items required to proceed with this research project. The unit price, quantity, and extended price is included for each component.

	Price Per Unit (Quantity)	Total
Personnel		
Student Hours	$10.00 (25)	$250
Equipment		
Arduino Starter Kit	$435.00 (1)	$435.00
MiniGen Signal Generator	$29.95(1)	$29.95
AE0203D08F Piezoelectric Actuator	$79.80(1)	$79.80
Miscellaneous Support Hardware/Item Tax & Shipping Costs	$150.00 (1)	$150.00
Publication/Documentation	-	-
Computer Services	-	-
Travel	-	-
Total	-	**$944.75**

Justification

The Arduino Starter Kit includes a simplified Flowcode interface to reduce the time required to program microcontroller routines[5]. Additionally, all required microcontroller hardware required to autonomously run each test is included. An additional signal generator is required to transmit signals between the Arduino board microcontroller and the piezoelectric actuator to produce mechanical vibrations at the resonant frequency of the test specimen. The literature survey performed prior to the onset of this project indicated that for high cycle fatigue testing utilizing resonance, the simplest and least costly approach utilizes a piezoelectric actuator which transforms electrical signals directly into motion[4]. The particular actuator specified in this budget is one of the least expensive of its type available for purchase, for it consists of multiple actuator layers to provide the amplified mechanical response required to oscillate the test specimen[13]. The design of the machine will require both the purchase of fasteners (quantity not yet known) to assemble the components and cables to connect the system to a laboratory computer.

7 Literature Cited

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