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Designing and Building of a Micro-Fatigue Testing Device for Scanning Electron Microscope (SEM) In-Situ Testing for Naval Applications

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Abstract

An improvement in capability to better manage and reduce degradation of materials in U.S. Navy's assets requires a workforce educated and trained in the application of the tools, principles, and practices of fatigue and fracture mechanics. However, the current level of effectiveness of failure engineering curricula in universities is not sufficient to address the Navy's need to improve safety and reliability and reduce costs due to premature fatigue and fracture failure. Many of the Navy assets experience cyclic mechanical loads during their lifetimes which result in fatigue crack initiation and growth and eventually premature failure. The understanding of fatigue crack initiation and growth mechanisms at microscales, where material's microstructure plays a significant role in fatigue mechanism, is of paramount importance. The senior design (capstone) program in the mechanical engineering (ME) program at George Mason university with the support of the Department of Navy has implemented the fatigue test design challenges into the senior design course. In this paper, we present the design and development of micro-fatigue testing device for conducting in-situ fatigue testing in a Scanning Electron Microscope (SEM). The device is capable of conducting user defined fatigue loading scenarios in and ex-situ of an SEM. The device was prototyped by a senior design team of four ME students and is relatively small, lightweight, and fully programable. It provides capabilities to observe the deformation and crack growth in real-time under SEM.

Introduction

Fatigue failure is the degradation of a material due to repeated loading or repeated deformation [1]. Fatigue is one of the most predominant modes of failure in a diverse array of man-made components and natural systems [1]. According to the National Bureau of Standards, the costs associated with material fractures for a single year (1978) in the United States was $119 billion dollars per year (1982 dollars) of 4% of the Gross National Product [2]. Fatigue damage poses a major safety risk to military and civilian aircraft structures [3]. A study by Bhaumik et al. [4] concluded that about 60% of failures of aircraft components in service are due to fatigue. A historic example of aircraft fatigue failure is the Aloha Airline aircraft accident that occurred on April 28, 1988. According to the report of the National Transportation Safety Board (NTSB Number: AAR-89-03), fatigue was the main cause of failure since the plane had experienced an unusual high number of fatigue cycles due to frequent takeoff-landing cycles among islands in Hawaii. As a result, while the plane was in flight, approximately 18 ft of the fuselage was ripped away at the altitude of 24,000 ft. Another example was the Southwest Flight 1380 that made an emergency landing in Philadelphia on Tuesday, April 17, 2018, after an engine ripped apart mid-air, shattering a window on the 737 and nearly sucking out a passenger and one of 144 passengers died. An early review of the accident revealed preliminary evidence of metal fatigue where a fan blade had broken off. Later the investigation confirmed evidence of metal fatigue.

Fatigue critical components must be designed based on rigorous laboratory and/or full-scale component testing before they are placed in service. Fatigue failures typically start from high stress concentration areas such as notches, holes or scratches. Fatigue behavior is known to be a weak-link process significantly influenced by local microstructural configurations [5]. The origin of failure can be traced back to the microstructure and materials behavior at microscale under repeated loading. However, it is often impossible to identify the mechanism of fatigue damage initiation and accumulation by post-mortem investigations, as many different microstructural configurations can lead to damage accumulation and subsequent crack initiation [5-7]. For this reason, design and utilization of an in-situ (i.e., in scanning electron microscope) fatigue testing machines that shed light on microscale behavior of materials is crucial in understanding the underlying mechanisms of fatigue failure.

Problem Definition

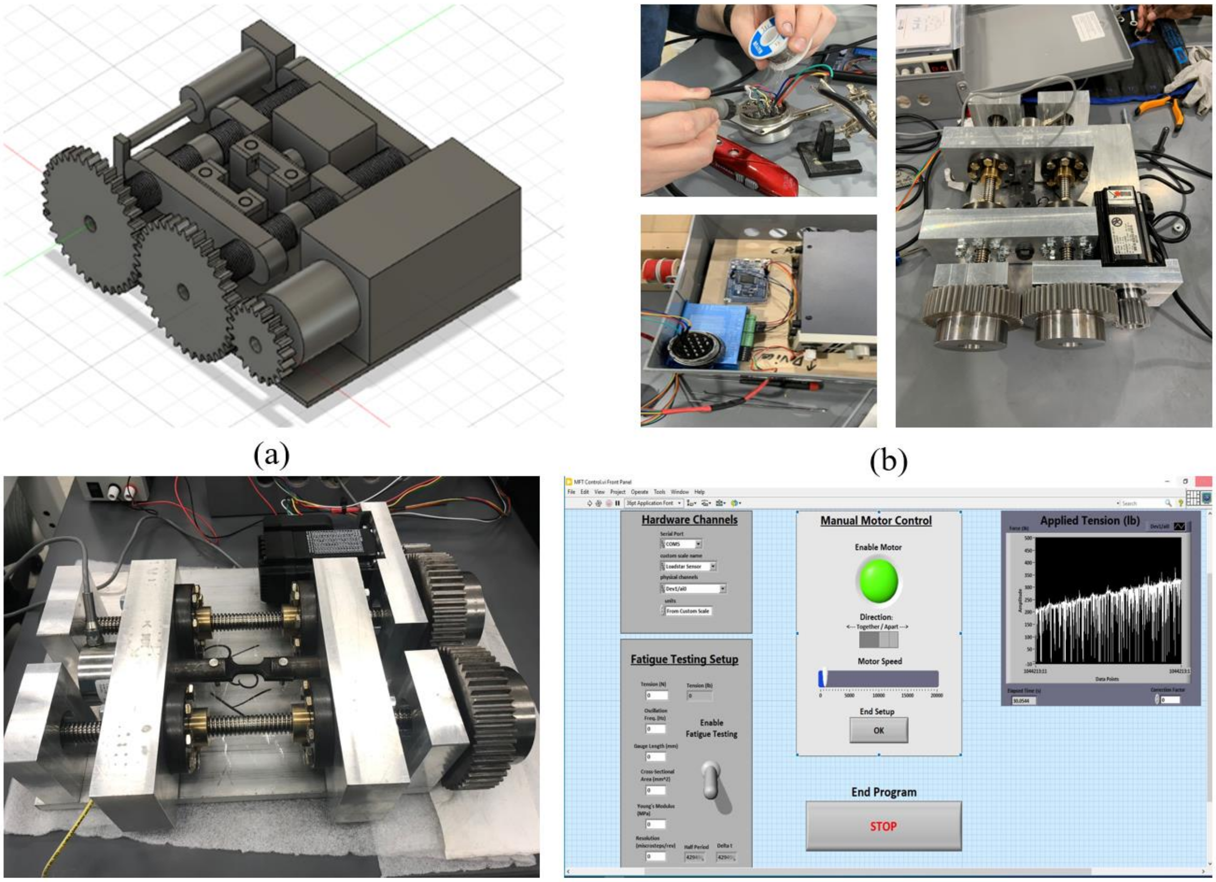
In-situ fatigue testing of materials (e.g., composites and metals) has been difficult to do in real time while being observed by a scanning electron microscope (SEM). There are several points of contention that make fatigue testing difficult while being observed by an SEM: (i) Building a fatigue testing machine small enough to fit within the SEM chamber is a different task; (ii) Building a fatigue tester small enough to fit within the SEM is feasible but most of the ones created for market use are costly; (iii) Building a fatigue tester that can still apply the loads correctly to the sample and at the correct frequency is a difficult task; and (iv) A system that applies cyclic loads to a sample will create vibrations and will obscure the SEM from correctly observing the sample. The goal of this capstone project was to design a micro-fatigue tester for in-situ monitoring of fatigue crack initiation and propagation under a SEM. The team's objective was to build a cost-effective micro fatigue testing device that will conduct fatigue tests on composites and metals in-situ in a SEM or conventional microscope. This required the design of a device that could apply cyclic load to a sample, measuring the amount of force and displacement of the sample and the number of cycles. The design should be able to accommodate the specimen geometry and size requirements by ASTM E466 [8] and ASTM E606/E606M [9].

Proposed Design and Final Design Selection

In order to begin designing to meet the abovementioned requirements, we made a basic list of requirements for our fatigue tester based on the Statement of Work provided to us by the Department of Navy. Any proposed design should be able to meet the following requirements for consideration:

- Must be small size and fit in an SEM chamber.
- Should be able to conduct cyclic loading test and monotonic tensile test up to 5 kN of force.
- Must be able to measure, record, and output the load, displacement, and number of cycles operating at 1to 2Hz frequency.
- Should accommodate reduced size specimens according to ASTM E466 and ASTM E606/E606M.
- Must be programable for running cycle duty fatigue tests.
- Must be able to test a variety of materials such as composites and metals.

The team has investigated various methods to satisfy the requirements of this tester. The main topics of interest were size and weight of the tester suited for an SEM chamber. We also investigated different methods for rearranging the components of the tester so that the minimum overall size be achieved. The micro-fatigue tester can be broken down into four main subsystems: The mechanical system, the electronics system, the SEM port interface, and the digital control system interface. Collectively, these subsystems use the input provided by the user in tandem with the output from the sensors, which measure the stress and strain applied to the sample, in order to continuously adjust the required motor output. Figure 1 shows a) final design CAD model, b) various stages of manufacturing, c) design completion, and d) LabVIEW screen to setup test parameters and view measured data.



(a) (b)

(c) (d)

Figure 1. The micro fatigue tester: a) an isometric view of the tester, showing the mechanical components, b) various stages of manufacturing, c) final micro fatigue tester, and d) LabVIEW screen for monitoring input/output parameters.

Results

The micro-fatigue tester performance was evaluated by testing the functionality of each subsystem as the code for the fatigue tests was conducted. The key components that needed to be monitored were the load, displacement and the number of cycles, which the team kept within the outlined standards. Due to time constraints, evaluation through a long term high-cycle fatigue testing was not possible, but the load reading of the tester was monitored over a long enough period to verify that the mechanical and electrical components maintain the load within the required accuracy. Figure 2 shows the experimental setup for performing fatigue tests on aluminum specimens with middle holes (Fig. 2b). A high-resolution camera attached to a microscope lens is used to observe the crack initiation and propagation as shown in Fig. 2(c). The micro fatigue tester is capable of performing fatigue cycles at predefined load amplitudes over a large number of cycles.

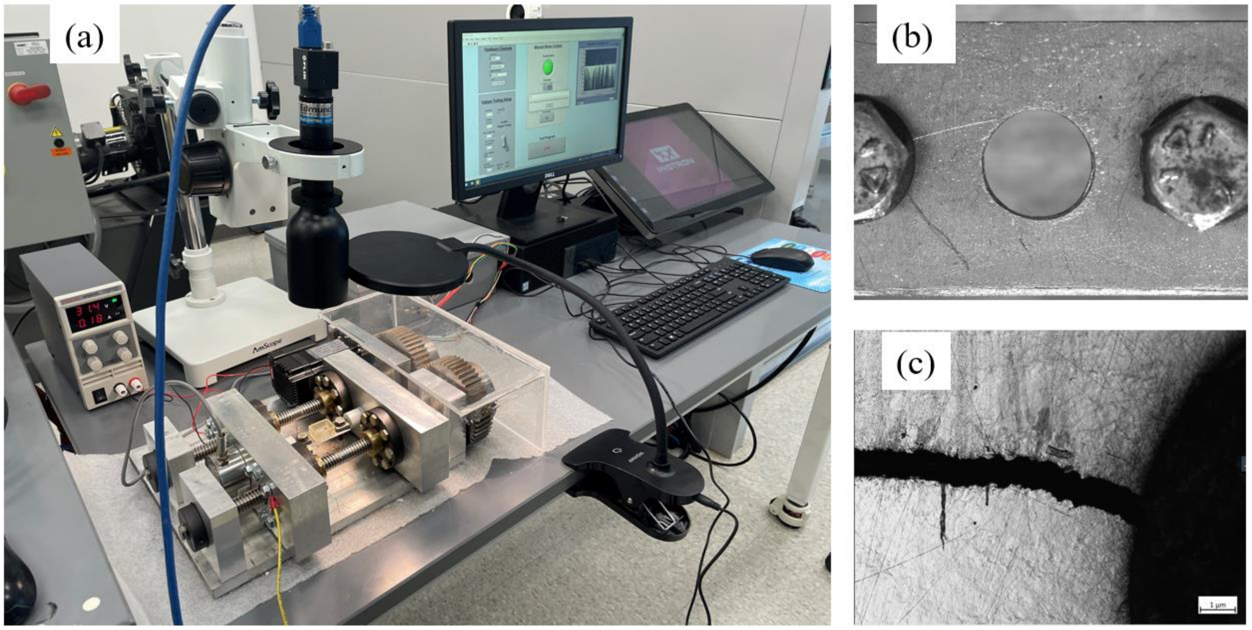


Figure 2. The micro fatigue tester: a) experimental setup with microcopy camera, b) view of an aluminum specimen with middle hole, and c) fatigue crack initiated from the hole edge observed by the microscope.

Impact on Student Learning

There were difficulties which challenged the planned schedule and initial project design. The greatest challenge came from finding a suitable company that could provide a particular displacement sensor, known as a Linear Variable Displacement Transducer (LVDT). Following this, there were subsequent delays in delivery time for the LVDT and other materials which affected the manufacturing timeline. The biggest change made to the design from the initial design document was the addition of more holes and screws on the crosshead bars to improve the pull-out strength of screws and threads. A final challenge that required a design change was the latest decision to incorporate an external camera to our design. As a whole, there were lessons learned regarding making sure to plan out the design further than initially anticipated, allocating more time to finding the necessary parts, and anticipating extended delivery times. This project represented how the team would bring ideas learned over the course of many semesters into a single collection of artifacts. The theoretical skills learned in courses such as ME 313 Materials Science, ME 341 Design of Mechanical Elements and ME 443 – ME 444 Mechanical Design were extremely helpful in the success of this project.

This capstone project helped the team to reinforce these skills and understand methods of preparing good analysis and presenting the findings to the sponsor. Further, the micro fatigue tester is now extensively used in a PhD project by one PhD student and in an undergraduate research project by an undergraduate student. The impact of this capstone project was eminent on the capstone team’s learning and continues to have the same impact on the future undergraduate and graduate students’ learning outcomes.

In capstone projects in our department, students are initially provided with a vaguely defined “Statement of Work” and after preliminary work, they are required to finalize the scope with the sponsor. Subsequently, they plan, design, and prototype their design, and display the final artifact at the capstone day before providing it to the sponsor. Throughout the academic year, they are required to discuss with their faculty advisor and sponsor on a periodic basis to obtain critical feedback. By discovering and designing on their own, students are forced to learn and acquire any new knowledge necessary to complete their project and it forces them to realize the importance of life-long learning.

One of the student members from the capstone team provided the following quote: “This project helped me to cement my understanding of the design process as it provided me a hands-on method of fusing together the skills I had amassed through my studies and allowed me to foster a proposed engineering design from conception to birth." One current graduate student who is using the micro-fatigue testing device stated: “The micro-fatigue tester designed by the senior design team has provided me with a compact and convenient way to conduct new experiments. Now, I have the ability to apply cyclic loading to samples while still being able to run all the corrosion tests that are needed. Ultimately, this enhances the laboratory’s capability and my ability in understanding the effects of corrosion which is vital to performing at a higher level in the industry." We conclude that this project has contributed to the learning of students on the project team and further, it benefits the current students by increasing their understanding of fatigue and corrosion.

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