12-2014

Fabrication, Testing and Analysis of a Fatigue Sensor for Structural Health Monitoring

Subash Gokanakonda

Western Michigan University, subash24584@gmail.com

Follow this and additional works at: http://scholarworks.wmich.edu/dissertations

Part of the Biomedical Engineering and Bioengineering Commons

Recommended Citation


http://scholarworks.wmich.edu/dissertations/375

This Dissertation-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Dissertations by an authorized administrator of ScholarWorks at WMU. For more information, please contact maira.bundza@wmich.edu.
FABRICATION, TESTING AND ANALYSIS OF A FATIGUE SENSOR FOR STRUCTURAL HEALTH MONITORING

by

Subash Gokanakonda

A Dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Mechanical and Aerospace Engineering
Western Michigan University
December 2014

Doctoral Committee:
Muralidhar K. Ghantasala, Ph.D., Chair
Daniel Kujawski, Ph.D.
Peter A. Gustafson, Ph.D.
John Patten, Ph.D.
A novel fatigue monitoring sensor (FMS) is designed, fabricated and tested for detecting and monitoring the fatigue damage and estimating the remaining life of structures and components subjected to cyclic loads. The concept is based on the characteristics of stress / strain life cycle relationship of engineering materials. Sensor consists of alternate slots and strips having different strain magnification factor with respect to the nominal strain. The sensor is designed in such a way that the strips will experience the strain which closely resemble the actual strain distribution in the notch or critical area of the component. The sensor can be placed outside the notch but still would experience the same fatigue damage as the notch tip. The sensor is attached to the surface of structural member which is being monitored. The strips fail in a sequential manner from the strip experiencing the highest stress/strain magnification to the lowest. Each strip failure corresponds to the particular fatigue damage accumulated by the critical location of the structure being diagnosed. The fatigue sensor monitors the actual fatigue damage of the structural component and can be used for both diagnosis and prognosis of the remaining useful life.

This research mainly involves the design and simulation of the fatigue sensor with respect to different geometrical parameters and materials. Numerical and analytical modeling was carried out to determine the optimal design. The finite element analysis
is carried out using COMSOL and ANSYS softwares. Fabrication of the fatigue sensor constitutes a major part too. The prototype fatigue sensors were fabricated using Wire EDM (-Electro Discharge Machining) and microfabrication technologies. Relative advantages of these processes are established and discussed. The commissioning of the sensor with a suitable data acquisition system and testing it under different conditions is also an important part of the work. Analysis of the obtained experimental data constitute the final part.
Acknowledgments

First and foremost I would like to use this opportunity to express my sincere gratitude to my advisors Dr. Muralidhar K. Ghantasala and Dr. Daniel Kujawski, who have encouraged and guided me with their valuable suggestions and been source of inspiration to me in my work. I am thankful for their aspiring guidance, invaluably constructive criticism and friendly advice during the course of time. I am sincerely grateful to them for sharing their truthful and illuminating views on a number of issues related to the work. It has been an honor to work with you for the past 7 years. I express my warm thanks to the members of my committee, Dr. John Patten and Dr. Peter Gustafson for their valuable time and effort to review my work. I would like to thank Dr. Ajay Gupta and his team at WiSE Lab, College of Engr. and Applied Sciences, Western Michigan University for the help provided with the data acquisition system. Special thanks are due to Mr. Glenn Hall, machinist at CEAS WMU and Mr. Pete Tannhauser and other technicians with the Department of Mechanical and Aerospace Engineering, for guiding and helping me out with the "Know-how" of the machining and other aspects of my work. My sincere thanks also goes to Dr. Sandrine Martin and Dr. Pilar Herrerra-Fierro at Lurie Nanofabrication Facility, University of Michigan, Ann Arbor for their help and support in the micro-fabrication at their facility. I also wish to thank the Director and staff of Central
Acknowledgments—Continued

Manufacturing Technology Institute, Bangalore, India for their help in the fabrication of the prototypes.

I am very much grateful to my loving parents and well wishers for the continuous moral support they have been giving me all my life especially during the past 5 years when I needed the most. Last but not the least, I would like to thank all my friends who have been very supportive and encouraging all through my stay here.

I would like to acknowledge and thank for the Graduate Assistantship provided by the Department of Mechanical and Aeronautical Engineering at Western Michigan University. This work was partly funded by the U.S. Army TACOM Life Cycle Command under Contract No. W56HZV-08-C-0236, through a subcontract with Mississippi State University and was performed for the Simulation Based Reliability and Safety (SimBRS) research program.

Subash Gokanakonda
# Table of Contents

ACKNOWLEDGMENTS ................................................................. ii

LIST OF TABLES ................................................................. vii

LIST OF FIGURES ............................................................... viii

1 Introduction ................................................................. 1
   1.1 Introduction to Fatigue .................................................. 1
   1.2 Fatigue Challenges ...................................................... 5
   1.3 Organization of the Thesis ............................................ 7

2 Background ................................................................. 9
   2.1 Monotonic and Cyclic Behavior of Materials ...................... 9
      2.1.1 Transient cyclic response ..................................... 13
      2.1.2 Steady state cyclic behavior ................................ 14
   2.2 Concepts of Fatigue .................................................... 15
      2.2.1 Stress based fatigue approach ................................ 16
      2.2.2 Strain based fatigue approach ................................ 30
      2.2.3 Critical plane approach ........................................ 36
      2.2.4 Variable amplitude loading .................................... 39
   2.3 Fatigue Sensors - Literature Review ............................... 43
      2.3.1 Fatigue fuses ..................................................... 44
      2.3.2 Piezo-electric based fatigue sensors ......................... 56
3 Design of the Sensor

3.1 Concept of the Design

3.2 Analytical (Elastic) Modeling

3.3 Numerical Simulations

3.3.1 Elastic finite element simulations

3.3.2 Elastic-plastic FEA simulations

3.4 Effect of Ligament Dimensions on Strain Ratio

3.5 Summary

4 Fabrication of the Sensor

4.1 Fabrication using Micro Wire-EDM

4.2 Fabrication using Photo-Lithography

4.2.1 Surface preparation of the substrate

4.2.2 Sputtering of thin film adhesive and conductive layers

4.2.3 Lithography process

4.2.4 Electroplating

4.2.5 Resist removal and release of sensors

4.3 Summary

5 Experimental Testing and Validation

5.1 Design Requirements

5.1.1 Adhesive selection
Table of Contents—Continued

5.1.2 Gluing area determination .............................. 126
5.2 Experimental Testing ...................................... 128
   5.2.1 Single ligament testing ............................... 130
   5.2.2 Full sensor testing .................................. 136
5.3 Analysis of Test Results ................................. 142
5.4 Summary .................................................. 155

6 Testing and Data Acquisition ................................. 156
   6.1 Circuit Design .......................................... 156
   6.2 Testing of the DAQ System .............................. 157

7 Conclusions and Future Recommendations ................... 163
   7.1 Conclusions ............................................. 163
   7.2 Future Recommendations ................................. 169

REFERENCES .................................................. 170

APPENDICES .................................................. 177

A Matlab Codes ............................................... 178
   A.1 Matlab code for calculating strain ratios ............... 178
   A.2 Matlab code for calculating length of the ligaments ........ 180
   A.3 Matlab code for calculating average force from the stress distributions on
       the top edge of the specimen where the displacements were applied. ........ 181

B Results from FEA Simulations ................................. 196

C DAQ Wireless Network ...................................... 205
# List of Tables

2.1 Extracted cycles using Rainflow cycle counting method ........................................ 43
2.2 A summary of some of the fatigue sensors developed in the past ......................... 70

3.1 The length of the ligaments as input and the resulting strain ratios .................. 77
3.2 The length of the middle portion of the active ligaments as output .................... 80
3.3 The length of the outer portion of the active ligaments as output ....................... 80
3.4 The total length of the active ligaments calculated ............................................. 80
3.5 Elastic material properties of Al 1100 alloy ......................................................... 82

5.1 The calculated length of gluing region ................................................................. 128
5.2 Table showing the elastic modulus and yield strength of materials used in testing ..................................................................................................................... 140
5.3 The results from FEA simulation of electroplated Al 1100 on Al 1100 specimen ................................................................. 152

6.1 The results from the manual cutting of the ligaments ........................................... 159
6.2 The results of the voltage change per each ligament cut obtained using wireless ..................................................................................................................... 161
List of Figures

1.1 A schematic of the fatigue process in a specimen under cyclic loading . . 2
1.2 A schematic showing the markings and striation on the fracture surface . 4

2.1 Schematic of elastic-plastic stress versus strain plot . . . . . . . . . . 10
2.2 Bauschinger effect . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 12
2.3 Stress response under constant strain amplitude cycling. . . . . . . . . 13
2.4 Hysteresis loop . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15
2.5 A schematic of the cyclic loading pattern and all the symbols used . . 18
2.6 A plot of the S-N curve . . . . . . . . . . . . . . . . . . . . . . . . . . . 18
2.7 Method of S-N testing with 14 specimen size . . . . . . . . . . . . . . . 21
2.8 Interpretation of fatigue limit as the average stress over finite distance $\delta$
   ahead of notch . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
2.9 Effect of mean stress on the fatigue data . . . . . . . . . . . . . . . . . 24
2.10 Construction of constant life diagrams in $\sigma_a$ and $\sigma_m$ coordinates . . 26
2.11 Stress gradient in smaller and larger diameter specimen . . . . . . . . . 29
2.12 A schematic of the strain based fatigue testing . . . . . . . . . . . . . . 30
2.13 A schematic of strain-life curve . . . . . . . . . . . . . . . . . . . . . . 33
2.14 Mean stress relaxation under strain controlled cycling with a mean strain
   . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
2.15 Morrow’s mean stress correction model . . . . . . . . . . . . . . . . . . 34
2.16 Schematic showing Case A and Case B cracks . . . . . . . . . . . . . . 37
2.17 Schematic representation of crack in Fatemi and Socie model . . . . . . 38
2.18 Tensile crack growth . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39
List of Figures—Continued

2.19 A schematic showing two stress points in S-N curve .......................... 40
2.20 A schematic of the rules for three point cycle counting ......................... 41
2.21 A schematic of Rainflow cycle extraction ........................................... 42
2.22 The side view and plan view of the remote and powerless miniature fatigue
    monitoring device ................................................................................. 45
2.23 The fatigue indicator with slots ......................................................... 47
2.24 The top and side view of fatigue sensor with slots .................................. 47
2.25 The longitudinal rib load counter with notches attached on to the structure 48
2.26 The fatigue monitoring coupon with mild stress raisers ......................... 50
2.27 The fatigue monitoring coupon with severe stress raisers ..................... 50
2.28 The fuse containing coupons with notches .......................................... 51
2.29 A schematic of the fatigue damage indicator with a slit ....................... 52
2.30 The front and the side view of the fatigue sensor with variable slots ...... 54
2.31 Fatigue sensor with ligaments and slots ............................................. 55
2.32 The built-in piezo-electric sensor/actuator network ............................. 57
2.33 The piezo-electric strain sensor array ................................................. 59
2.34 A schematic of the PZT-driven dynamic structural sensor .................... 60
2.35 Schematic of the piezo-electric paint sensor ....................................... 62
2.36 Schematic of crack detection technique using piezoelectric paint sensor . 63
2.37 A schematic of the electrochemical fatigue sensor .............................. 64
2.38 Typical MWM sensor and MWM sensor arrays ................................... 66
2.39 A schematic of transducers set-up on a plate with center hole ............... 67
2.40 Schematic of apparatus for leakage magnetic flux measurement ........... 68

3.1 Fatigue gage and its mounting configuration ......................................... 73
3.2 Design of the coupon with symmetry in the active ligaments ................. 75
3.3 A schematic depicting the loading direction of the gage ....................... 76
List of Figures—Continued

3.4 Strain distribution in reference ligament ‘R’ . . . . . . . . . . . . . . . . 83
3.5 The coupon with two reference ligaments . . . . . . . . . . . . . . . . . . 84
3.6 Strain distribution in the reference ligaments ‘R 1’ and ‘R 2’ . . . . . . . 84
3.7 The strain distribution in the smallest ligament of the coupon without
symmetry . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 86
3.8 Fatigue sensor with a double symmetry design . . . . . . . . . . . . . . . . 86
3.9 Strain distribution in the ligament # 4 of the coupon with double symmetry 87
3.10 Bilinear and multi-linear stress vs. strain curves . . . . . . . . . . . . . . 89
3.11 The 2-D view of the coupon representing the boundary conditions . . . . 90
3.12 Nodes created after meshing the 2D model in Ansys . . . . . . . . . . . . 91
3.13 Plot of stress vs. total strain . . . . . . . . . . . . . . . . . . . . . . . . . 92
3.14 Multilinear hysteresis curve from the fatigue sensor simulation for aluminum 92
3.15 Dimensional nomenclature of 2D model for sensitivity of strain ratio analysis 93
3.16 Plot of strain ratios of active ligaments for different 'L' ratio . . . . . . . 94
3.17 Plot of strain ratios with varying 'L' ratio and widths of the outer region
of the active ligament . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 96

4.1 A schematic depicting the wire EDM process . . . . . . . . . . . . . . . . . 99
4.2 A schematic depicting the wire EDM process . . . . . . . . . . . . . . . . . 100
4.3 Prototype full sensor fabricated using Wire EDM process . . . . . . . . . 100
4.4 Dimensional details of the prototype single ligament . . . . . . . . . . . . 101
4.5 A schematic of the PVD process . . . . . . . . . . . . . . . . . . . . . . . . 104
4.6 Cross-sectional layout of the silicon substrate with Ti and Cu layers . . . 105
4.7 A picture of the PVD sputtering machine . . . . . . . . . . . . . . . . . . . 106
4.8 Photo-resist spinning . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 107
4.9 A schematic of the soft bake process . . . . . . . . . . . . . . . . . . . . . 108
4.10 Pattern layout on the primary mask (transparency) . . . . . . . . . . . . 109
List of Figures—Continued

4.11 Mask fabrication ........................................... 111
4.12 A picture of the MA 6 mask aligner ......................... 112
4.13 A schematic of the PEB procedure .......................... 113
4.14 Exposure and development process ........................ 114
4.15 A schematic of electrolytic cell setup ....................... 115
4.16 Electroplating setup ...................................... 117
4.17 A schematic of the 2D and 3D views of the Ni plated Si wafer ... 118
4.18 A schematic of the 2D and 3D views of the silicon wafer after resist removal step .................................. 119
4.19 Picture of one of the released Ni structures ................. 120
4.20 Optical microscope image of the released sensor .......... 120

5.1 A schematic showing the specimen for adhesive testing ........ 123
5.2 Plot showing the adhesion strength of the adhesives ........... 126
5.3 Sensor depicting the variables used in sensor design .......... 128
5.4 The MTS machine used for the testing of the prototype sensor .... 129
5.5 The notched specimen fixed in the MTS machine and the tele-microscope set-up used to observe the ligaments ............... 130
5.6 A schematic showing the actual dimensions of the single ligament .... 130
5.7 Layout of the model for single ligament FEA simulations ....... 131
5.8 Strain ratios in each of the active ligaments ................ 132
5.9 The specimen layout for testing the single ligaments ........ 133
5.10 Stress distribution across the width of the backing specimen for single ligament testing .................................. 134
5.11 The specimen with single ligaments attached on to the specimen .... 134
5.12 Results from the single ligament testing .................... 135
5.13 The pictures of broken single ligaments from testing .......... 136
List of Figures—Continued

5.14 Results from the testing of EDM fabricated Al 1100 full sensor on Al 1100 alloy specimen ................................................. 137
5.15 Results from the testing of micro-fabricated Ni full sensor on Al 1100 alloy specimen ....................................................... 139
5.16 Results from the testing of micro-fabricated Ni full sensor on Al 6061 alloy specimen ....................................................... 139
5.17 Results from the testing of micro-fabricated Ni full sensor on SS 304 alloy specimen ....................................................... 140
5.18 Illustration of plastic zone around the notch tip corresponding to a maximum load of 5500 N in the two Al alloy specimen .......... 142
5.19 2D models for FEA with cracks in Al 1100 specimen at 4000 N .... 143
5.20 Typical meshing profile of the simulated specimen .................... 145
5.21 Boundary conditions applied on the specimen for the FEA simulations . 146
5.22 The stress distributions on specimen for each displacement step from the FEA simulations ................................................. 147
5.23 Illustration of Force vs. displacement plot .................................. 148
5.24 The fatigue sensor showing the individual active ligaments considered for the FEA simulations ......................................... 149
5.25 Meshed 2D model of single active ligament ................................. 149
5.26 The schematic depicting the boundary conditions on the ligament .... 150
5.27 The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 3000 N ..................... 151
5.28 The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 4000 N ..................... 153
5.29 The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 5500 N ..................... 153
List of Figures—Continued

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Constant current DAQ circuit</td>
<td>157</td>
</tr>
<tr>
<td>6.2</td>
<td>Fatigue sensor used for DAQ and the schematic of the spot welded wire terminals</td>
<td>158</td>
</tr>
<tr>
<td>6.3</td>
<td>The spot welding machine used for welding the wire terminals on the fatigue sensor</td>
<td>158</td>
</tr>
<tr>
<td>6.4</td>
<td>The schematic showing the numbering of the ligaments</td>
<td>159</td>
</tr>
<tr>
<td>6.5</td>
<td>Screenshot showing the software interface</td>
<td>160</td>
</tr>
<tr>
<td>6.6</td>
<td>The results from the fatigue sensor DAQ testing</td>
<td>161</td>
</tr>
<tr>
<td>6.7</td>
<td>The fatigue sensor DAQ module</td>
<td>162</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Introduction to Fatigue

Mechanical failures due to fatigue have been the subject of engineering efforts for more than 150 years. Fatigue failures continue to be a major concern in engineering design. The economic costs of fracture and its prevention are quite large, and that an estimated 80% of these costs involve situations where cyclic loading and fatigue are at least a contributing factor [1]. These costs arise from the occurrence or prevention of fatigue failure for ground vehicles, rail vehicles, aircraft of all types, bridges, cranes, power plant equipment, offshore oil well structures as well as a wide variety of miscellaneous machinery and equipment including everyday household items, toys and sports equipment. For example, wind turbines used in power generation are subjected to cyclic loads due to rotation and wind turbulence, making fatigue a critical aspect of the design of the blade and other moving parts.

Components of machines, vehicles and structures are frequently subjected to repeated loads and the resulting cyclic stresses can lead to microscopic physical damage to the materials involved. Even at stresses well below the ultimate strength of the material, this microscopic damage can accumulate with continued cycling until it develops into a crack that leads to failure of the component. This process of damage and failure due to cyclic
loading is called fatigue. Fatigue is a damage process of a component produced by cyclic loading. It is the result of the cumulative process with the culmination of three important stages which are, crack initiation, propagation and final fracture of a component. During cyclic loading, localized plastic deformation may occur at the highest stress site. This plastic deformation induces permanent damage to the component and a crack develops. As the component experiences an increasing number of loading cycles, the length of the crack (damage) increases. After a certain number of cycles, this leads to the component failure.

Cracks start on the localized shear plane at or near high stress concentrations such as persistent slip bands (PSB), inclusions, porosity or discontinuities [1]. The localized shear plane usually occurs at the surface or within grain boundaries. Micro crack nucleation is considered as the first step in the fatigue damage process. Once nucleation occurs and cyclic loading continues, the crack tends to grow initially along the plane of maximum shear stress and then perpendicular to the direction of the applied load. Figure 1.1 illustrates fatigue damage process in terms of crack nucleation, which starts at the highest stress concentration site in the persistent slip bands.

![Figure 1.1: A schematic of the fatigue process in a specimen under cyclic loading [1]](image)

The next step in the fatigue process is the crack growth stage. This stage is divided between the growth of Stage I and Stage II cracks. Stage I crack nucleation and growth are usually considered to be the initial short crack propagation across a finite length of
the order of a couple of grains on the local maximum shear stress plane. In this stage, the
crack tip plasticity is greatly affected by the slip characteristics, grain size, orientation
and stress level because the crack size is comparable to the material microstructure.
Stage II crack growth refers to long crack propagation normal to the principal tensile
stress plane globally and in the maximum shear stress direction locally. In this stage, the
characteristics of the long crack are less affected by the properties of the microstructure
than the Stage I crack [2]. This is because the crack front and crack tip plastic zone for
Stage II is usually much larger than the material microstructure.

In engineering applications, the amount of component life spent on crack nucleation
and short crack growth is usually called the crack initiation period, whereas the compo-
nent life spent during long crack growth is called the crack propagation period. Typically,
in the high-cycle fatigue regime (approximately \( > 10^5 \) cycles) the crack initiation period
accounts for most of the fatigue life of a component. On the other hand, in the low cycle
fatigue regime (approximately \( < 10^5 \) cycles) most of the fatigue life is spent on crack
propagation.

Once a crack has formed and/or complete failure has occurred, the surface of a fa-
tigue failure can be inspected. A bending or axial fatigue failure generally leaves behind
clamshell or beach markings. An illustration of these markings is shown in Figure 1.2.
The crack nucleation site is the center of the shell and the crack appears to propagate
away from the nucleation site usually in a radial manner. A semielliptical pattern is left
behind. In some cases, inspection of the size and location of the beach marks left behind
may indicate where a different period of crack growth began or ended. Within the beach
lines are the striations. The striations in Figure 1.2 appear similar to the rings on the
cross-section of a tree. These striations represent the extension of the crack during one
loading cycle. Instead of a ring for each year of growth, there is a ring for each loading
cycle. In the event of a failure, there is a final shear lip, which is the last bit of material
supporting the load before failure. The size of this lip depends on the type of loading,
material and other conditions.

UNCLASSIFIED: Distribution Statement A. Approved for public release
The prime factor governing these inherent microscopic material defects to grow and coalesce is the presence of an intense stress or strain field above a critical stress so called as fatigue or endurance limit. Such intense stress concentrations generally occur in the vicinity of sudden discontinuities or stress raisers such as holes, notches etc. within a structural configuration. Thus, fatigue failure generally originates at such stress concentration zones and is believed to begin whenever a certain critical stress or strain is exceeded. In the past few decades, structural engineers have endeavored to sidestep the problem of fatigue by designing structures in a way as to maintain the stresses developed in the critical areas of a structure at a level well below the known endurance limits of the material employed in the structure. As a result of which, holes and fillets with minimal possible radii are introduced into the design of the structural members along with the deployment of only mild stress raisers and hence decrease the effect of fatigue. This way of designing might result in structures that are safe and relatively free of fatigue failure but on the other hand, it also resulted in unexpected penalties.

Structural engineers must be able to determine the fatigue strength and failure life of any material that is used as a load carrying component subjected to a repetitive or cyclic stress loading condition. This requirement stems from the fact that the repetitive stress on a structure will eventually cause material failure due to fatigue. Extensive studies
on the fatigue life of structural materials have been made to accurately determine the current state of fatigue damage and to predict the remaining service life. These studies showed that the fatigue strength is a function of material properties, processing methods, environment and operating conditions. It has also been a proven fact that the fatigue in the structures result even when the structural members are subjected to the repetitive stresses of magnitudes that are well below the ultimate stress of the material. This is due to the continuous accumulation of the damage in the critical areas of the structures which results due to the induced plastic damage. It was shown that the service life of a given structural material is inversely proportional to the applied stress i.e., the greater the applied stress, the shorter the service life of the structural member.

At present, there are four major approaches to analyzing and designing against fatigue failures. The traditional stress-based approach was developed to essentially its present wherein the analysis is based on the nominal (average) stresses in the affected region of the engineering component. The nominal stress that can be resisted under cyclic loading is determined by considering mean stresses and by adjusting for the effects of stress raisers such as grooves, holes, fillets and keyways. Another approach is the strain-based approach which involves more detailed analysis of the localized yielding that may occur at stress raisers during cyclic loading. Critical plane approach deals with the case when there is multi-axial loading i.e., combination of different kinds of loading such as tensile, shear, bending etc. Finally, there is fracture mechanics approach, which specifically treats growing cracks by the methods of fracture mechanics. Each of these will be discussed in detail in the next chapter.

1.2 Fatigue Challenges

In the previous sections, a brief overview of fundamental aspects related to fatigue damage were discussed. As a result of extensive research and practical experience, much knowledge has been gained about fatigue of structures and the fatigue mechanism in the
material. Mechanical failures have resulted in catastrophic effects and significant financial loss. In actual operation of structures, the mechanical failures involve an extremely complex interaction of load, time and environment (temperature and corrosion). Loads acting on the structural members may be monotonic, steady, variable, uniaxial or multiaxial. The loading duration may vary in time based on the application and the respective structures. Temperatures may vary from few tens of Kelvin in cryogenic rockets to over thousands of Kelvin in turbines, furnaces. Corrosive environments can range from severe attack with automobile engine exhaust and salt water exposure to essentially no attack in vacuum or inert gas. The interaction of load, time and environment along with material selection, geometry, processing and residual stresses creates a wide range of synergistic complexity. A good number of the mechanical failures are a result of fatigue [3]. These include door springs to more complex components and structures like ground vehicles, ships, aircrafts and other heavy structural members such as steel bridges.

Even though the number of mechanical failures relative to the number of successful uses of components and structures is minimal, the cost of such failures is enormous. A comprehensive study of the cost of the fracture in the United States is of the order of around $120 billion in 1978, or about 4% of the gross national product [3].

It has been recognized that the fatigue damage is induced in the structural members due to the repetitive nature of loads imposed, which ultimately determines the useful life of these structures. It is customary to identify the parts of the structure thought to be fatigue critical in the design phase and to apply various design techniques to minimize fatigue damage. Such parts are also tested in the laboratory under simulated operating conditions to determine their actual fatigue life. These testing methods have generally been quite successful not only in preventing fatigue failures in actual service but they are helpful in determining the accumulated fatigue damage or remaining fatigue life of a particular structural component. These methods are based on the assumption that the life history of the structural components can be fairly represented by a statistical approximation of the number of loads of various magnitudes that will be encountered in
service called a fatigue spectrum. The application of a cyclic loading pattern, based on such fatigue spectrum to a laboratory specimen, will result in an amount of fatigue damage equivalent to that which the same part would suffer in actual service when subjected to random loading.

Further, it is a known fact that environment can create a substantial effect on the fatigue, however it is quite difficult to duplicate such environmental conditions in the laboratory to which certain parts are subjected under actual service. Therefore, the practice of designing structures to take into consideration the fatigue is empirical and inefficient to a certain extent, since the actual loading conditions experienced by the structures cannot be predicted accurately. In order to overcome such situations there is a need for the development monitoring methods that can calculate the early stages of fatigue damage in the structures and thereby prevent catastrophic failures. One of the methods could be deployment of an indicator or a gage directly on a structural member in actual service, which would indicate the accumulated fatigue damage suffered by the member. Hence, is the current study of the design of a fatigue damage sensor for detecting and monitoring the fatigue damage and estimating the remaining life of structures and components subjected to cyclic fatigue loading. This sensor attempts to overcome some of the challenges in the functions of the components / structures in service. The designed sensor will be subjected to the same ambient as well as loading conditions as that of the structure. This will enable the sensor to give an indication of overall damage in the structure due to various operational conditions.

1.3 Organization of the Thesis

This thesis mainly presents the details of our investigations in the design, simulations, development and testing of a novel micro fatigue sensor. In the next chapter different approaches of fatigue analysis are discussed in detail along with some of the fatigue monitoring devices that were developed in the past. In Chapter 3, the design concept is
presented, which consists of the analytical modeling followed by elastic and elasto-plastic finite element analysis of the sensor. The simulations have been performed for two and three dimensional models. The Chapter 4 describes details of the fabrication of the prototype sensor. The two methods employed for the fabrication of the prototype sensor discussed in this chapter are µWire-EDM (Micro Wire - Electro Discharge Machining) and the optical lithography process conventionally used for the fabrication MEMS devices. Carrying on the work to the next stage, glue characterization and selection is presented in the Chapter 5. Glue characterization and selection is considered an important aspect in the design process since the final dimensions of the sensor are dependent on the tearing strength of the selected glue. The determination of the gluing area of the sensor was done after the proper glue was determined. Finally, towards the end of the Chapter 5, the experimental details and the results of the prototype testing of the ligaments are presented. The prototype testing was done in three stages. In the first stage, single ligaments of the fatigue sensor were put to testing to validate the working principle. In the second stage, the prototype sensors fabricated using the Wire EDM process were tested, which is followed by the testing of the microfabricated prototype sensors. Chapter 6 deals with the data acquisition system development and testing the fatigue sensor in the laboratory using the designed signal conditioning circuit. Last chapter summarizes the important findings of these investigations and presents the recommendations for future work.

With this introduction to the concept of fatigue and its importance in structural design, the next chapter would review the motivating factors that led to the development of the proposed fatigue sensor.
Chapter 2

Background

2.1 Monotonic and Cyclic Behavior of Materials

The basic material characteristics are defined by the monotonic tests performed on specimen, which is mostly a 1 D stress state. Monotonic behavior is obtained from a tension test in which, a specimen with a circular or a rectangular cross-section is subjected to a monotonically increasing tensile force until it fractures. The monotonic uniaxial stress-strain behavior can be characterized based on engineering stress-strain or true stress-strain relationships. The engineering stress \( S \) and strain \( e \) are defined by using the original cross-sectional area \( A_0 \) and the original length \( l_0 \) of the test specimen respectively. The engineering stress is calculated as:

\[
S = \frac{P}{A_0} \tag{2.1}
\]

where, ‘\( P \)’ is the applied load. The engineering strain is given by:

\[
e = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \tag{2.2}
\]

where ‘\( l \)’ is the instantaneous length and ‘\( \Delta l \)’ is the change in the original gage length ‘\( l_0 \)’

The true Stress \( (\sigma) \) in the test specimen is given by:
\[ \sigma = \frac{P}{A} \]  \hspace{1cm} (2.3)

where ‘A’ is the instantaneous cross-sectional area. The true or natural strain is given by:

\[ d\varepsilon = \frac{dl}{l} \text{ or } \varepsilon = \int \frac{dl}{l} = \ln \left( \frac{l}{l_0} \right) \]  \hspace{1cm} (2.4)

The true stress in tension is larger than the engineering stress since the cross-sectional area decreases during loading. For small strains (less than 2%), the engineering stress, \( S \) is approximately equal to the true stress \( \sigma \), and the engineering strain \( \varepsilon \), is approximately equal to the true strain \( \varepsilon \). Figure 2.1 shows a schematic of a stress-strain curve obtained from a tension test. The linear portion of the curve represents the elastic region. A material subjected to stresses in this elastic region is supposed to regain its original form when the applied stress is removed. The maximum stress a material can withstand without (or small) permanent deformation is termed as yield stress. In general, yield stress is measured by drawing a line parallel to elastic slope, \( E \), but offset by 0.2% of strain as shown in Figure 2.1. Ultimate stress is the maximum engineering stress that a material can withstand.

---

**Figure 2.1:** Schematic of elastic-plastic stress versus strain plot
Deformation beyond the point of yielding that is not strongly time dependent is called the plastic deformation. During plastic deformation, stresses and strains are no longer proportional as in the elastic region given by the Hooke’s law.

Plastic deformation can impair the usefulness of an engineering component by causing large permanent deflections. Non-uniform plastic deformation commonly causes residual stresses to remain after unloading. They can either decrease or increase the subsequent resistance of a component to fatigue or environmental cracking depending on whether the residual stress is tensile or compressive, respectively. In characterizing the plastic deformation behavior of materials, the obvious starting point is to consider stress-strain curves for monotonic loading. As the yielding is affected by the state of stress, it can be expected that the stress-strain curve beyond yielding is also affected. Inelastic or plastic strain results in permanent deformation, which is not recovered upon unloading. The unloading curve is elastic and parallel to the initial elastic loading line as shown in Figure 2.2. The total strain, $\varepsilon$, is composed of two components i.e., elastic strain ($\varepsilon_e = \sigma/E$) and a plastic component, $\varepsilon_p$.

**Ramberg - Osgood Relationship**

According to this, elastic and plastic strains, $\varepsilon_e$ and $\varepsilon_p$ are considered separately and summed. An exponential relationship is used but it is applied to the plastic strain rather than to the total strain [4]:

$$\sigma = H\varepsilon_p^n$$

(2.5)

where ‘$H$’ is the strength coefficient (stress intercept at $\varepsilon = 1$) and ‘$n$’ is called the strain hardening exponent. The value of $n$ gives a measure of the material’s work hardening behavior and is usually between 0 and 0.5. Elastic strain is proportional to stress according to Hooke’s law, i.e., $\varepsilon_e = \sigma / E$, and plastic strain $\varepsilon_p$ is the deviation from the slope ‘E’.
The total strain is given by [4]

\[ \varepsilon = \varepsilon_e + \varepsilon_p \]

\[ \varepsilon = \frac{\sigma}{E} + \left( \frac{\sigma}{H} \right)^{\frac{1}{n}} \]  

(2.6)

This relationship cannot be solved explicitly for stress. It provides a single smooth curve for all values of \( \sigma \) and does not exhibit a distinct yield point. However a yield strength may be defined as the stress corresponding to a given plastic strain offset of 0.002 (0.2% strain), i.e., \( \sigma_0 = H(0.002)^n \).

The stress-strain behavior obtained from a monotonic tension or compression test can be quite different from that obtained under cyclic loading. This phenomenon was first observed by Bauschinger [1], whose experiments showed that the yield strength in tension or compression was reduced after applying a load of the opposite sign that caused inelastic deformation. The Figure 2.2(c) shows that the yield strength in compression is significantly reduced by prior yielding in tension.

![Figure 2.2: Bauschinger effect. (a) Tensile loading. (b) Compressive loading. (c) Tension followed by compressive loading [1]](image.png)

"UNCLASSIFIED: Distribution Statement A. Approved for public release"
2.1.1 Transient cyclic response

The transient cyclic response of a material describes the process of change in the resistance of a material to deformation due to cyclic loading. If a material is repeatedly cycled fully under reversed cyclic loading, the material may respond in one of the following ways: cyclic hardening, cyclic softening, remaining stable or some combination of these responses. Figure 2.3 indicate the transient cyclic hardening and transient cyclic softening under strain controlled cyclic loading. In transient cyclic hardening the stress developed in each strain reversal increases as the number of cycles increases. In transient cyclic softening the stress decreases as the number of cycles increases. In both the cases, the rate of change of the stress amplitude will gradually reduce and the stress magnitude will reach a stable level and remain stable for the rest of the fatigue life until the detection of the first fatigue crack. This transient phenomenon is due to the stability of the dislocation substructure within the metal crystal lattice of a material.

Figure 2.3: Stress response under constant strain amplitude cycling. (a) Constant strain amplitude of cyclic loading. (b) Cyclic hardening. (c) Cyclic Softening [4]
The extent and rate of cyclic hardening or softening under cyclic testing conditions can be evaluated by recording stress variations as a function of cycles as in Figure 2.3. Cyclic hardening indicates increased resistance to deformation whereas cyclic softening indicates the decrease in resistance to deformation. Changes in cyclic deformation stress are more pronounced at the beginning of the cyclic loading, but the material generally stabilizes gradually as the cyclic loading continues. Such cyclic deformation behavior is therefore called as ‘cyclic transient behavior’. This transient phenomenon is believed to be associated with the stability of the dislocation substructure within the metal crystal lattice of the material. In general, soft materials such as aluminum alloys with low dislocation densities tend to harden and hard materials such as steels tend to soften. Cyclic stabilization is reasonably complete within 10 to 40 percent of the total fatigue life. A hysteresis loop from about half of the fatigue life is often used to represent the stable or steady state cyclic stress-strain behavior of the material.

2.1.2 Steady state cyclic behavior

Fatigue life can be characterized by the steady state behavior because for a test with cyclic loading, the stress-strain relationship becomes stable after rapid hardening or softening in the initial cycles corresponding to the 10 to 40 percent of the total fatigue life. A stable cyclic stress strain response is the hysteresis loop as in Figure 2.4. The total true strain range is denoted by $\Delta \varepsilon$ and the true stress range is denoted by $\Delta \sigma$. The true elastic strain range ($\Delta \varepsilon_e$) can be calculated from $\Delta \sigma/E$ and the total strain range from the Ramberg-Osgood type of relation.

When a family of stabilized hysteresis loops with various strain amplitude levels is plotted on the same axes as in Figure 2.4, a cyclic stress-strain curve is defined by the locus of the loop tips and has the following form similar to the monotonic stress strain response.

$$\varepsilon_a = \varepsilon'_e + \varepsilon_p = \frac{\sigma_a}{E} + \left( \frac{\sigma_a}{H'} \right)^\frac{1}{n}\quad (2.7)$$

UNCLASSIFIED: Distribution Statement A. Approved for public release
where, 'represents the parameters associated with cyclic behavior to differentiate them from those associated with monotonic behavior. The cyclic yield stress \( \sigma'_y \) is the stress at 0.2% plastic strain on a cyclic stress-strain curve.

![Hysteresis loop](image)

**Figure 2.4: Hysteresis loop [1]**

### 2.2 Concepts of Fatigue

Potential structural failure due to fatigue constitutes one of the most troublesome areas of structural engineering primarily because fatigue failure occurs suddenly in critical areas of a structure. As mentioned in the previous chapter, the fatigue process is generally initiated with the microscopic imperfections present in the material that makeup the structure. These microscopic imperfections rapidly grow and coalesce to form a macroscopic defect in the form of a crack. The growth and propagation of macroscopic cracks is the immediate cause of a fatigue failure but at high cycle fatigue these cracks appear very late during the fatigue process and thus cannot be relied upon for accessing the impending fatigue life. Traditionally, experimental fatigue data of materials is available in the form of S-N curves which indicate fatigue failure as a function of the cyclic stress level applied vs. number of loading cycles.

*UNCLASSIFIED: Distribution Statement A. Approved for public release*
Different actual structures subjected to repeated loading generally experience varying levels of stress for different number of cycles. Thus the fatigue life of a particular structure greatly depends upon its specific individual stress history. Even for the simplest case wherein just two different stress levels applied to a structure, it has been demonstrated experimentally that structural fatigue life is dependent on the order of application of the stress levels. As outlined in the previous section, the various approaches of fatigue analysis of components are described in detail in the sections to follow.

2.2.1 Stress based fatigue approach

The first fatigue investigations were conducted by Wöhler, a German railway engineer between 1852 and 1870. These tests are the most common type of fatigue testing. From these tests, it is possible to develop S-N curves that represent the fatigue life behavior of a component or of a material test specimen. Regardless of the type of the test sample used, these S-N fatigue tests provide valuable information to an engineer during the design process. When conducting fatigue tests, engineers do not have an unlimited amount of time or an unlimited number of test samples. Thus, it is necessary that the requirements, limitations and approaches to the construction of an S-N curve be understood to effectively plan fatigue life tests. Since the mid-1800s, the standard method of fatigue analysis and design has been the stress-based approach. This method is also referred to as the stress-life or the S-N approach and is distinguished from the other fatigue analysis and design techniques by several features [5]:

- Cyclic stresses are the governing parameter for fatigue analysis
- High-cycle fatigue conditions prevail
  - High number of cycles to failure
  - Little plastic deformation due to the cyclic loading

During fatigue testing, the test specimen is subjected to alternating loads until failure. The loads applied to the specimen are defined by either a constant stress range ($\Delta\sigma$) or a
constant amplitude \((\sigma_a)\). The stress range is defined as the algebraic difference between maximum stress \((\sigma_{\text{max}})\) and minimum stress \((\sigma_{\text{min}})\) in a cycle \(\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}\).

Average of the maximum and minimum values gives the mean stress \((\sigma_m)\).

\[
\sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2}
\]  

(2.8)

Half the range is called the stress amplitude, \(\sigma_a\), which is the variation about the mean.

\[
\sigma_a = \frac{\Delta \sigma}{2} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2}
\]  

(2.9)

Typically, for fatigue analysis, it is convenient to consider tensile stresses positive and compressive stresses negative. The magnitude of the stress range or amplitude is the controlled (independent) variable and the number of cycles to failure is the response (dependant) variable. The number of cycles to failure is the fatigue life \((N_f)\) and each cycle is equal to two reversals \((2N_f)\).

Actual structural components are usually subjected to alternating loads with a mean stress. The parameter, stress ratio \((R)\) is often used as representation of the mean stress applied to an object. The stress ratio is defined as the ratio of minimum stress to maximum stress:

\[
R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}
\]  

(2.10)

To generate data useful for fatigue design using the stress-life approach, stress-life fatigue tests are usually carried out on several specimen at different fully reversed stress amplitudes over a range of fatigue lives for identically prepared specimen. The fatigue test data are often plotted on either semi-log or log-log coordinates. The Figure 2.6(a) shows the bending fatigue data of steel plotted on semi-log coordinates. In this Figure, the single curve that represents the data is called the S-N curve or the Wöhler curve [6].
Figure 2.5: A schematic of the cyclic loading pattern and all the symbols used

Figure 2.6: A plot of the S-N curve [1]. (a) Semi-log plot, (b) log-log plot

When plotted on log-log scale as shown in Figure 2.6(b), the curve becomes linear. The portion of the curve or the line with a negative slope is called the finite life region and the horizontal line is the infinite life region. The point of the S-N curve at which the curve changes from a negative slope to a horizontal line is called the knee of the S-N curve and represents the fatigue limit or the endurance limit. The fatigue limit is associated with the phenomenon that crack nucleation is arrested by the first grain boundary or a dominant micro-structural barrier.

UNCLASSIFIED: Distribution Statement A. Approved for public release
When generating log-log plots of applied stress versus fatigue life from S-N fatigue tests, the y-coordinate is expressed in terms of the stress amplitude or the stress range and the x-coordinate is expressed in terms of the number of reversals to failure or the number of cycles to failure. Here, the fatigue life (cycles or reversals) refers to the life required to nucleate and grow a small crack to visible crack length. The following equation represents a typical S-N curve in log-log coordinates \[1\]:

$$\sigma_a = \sigma'_f (2N_f)^b$$ \hspace{1cm} (2.11)

where ‘b’ is the fatigue strength exponent (the slope of the curve) and $\sigma'_f$ is the fatigue strength coefficient. This expression developed from log-log S-N is the most widely used equation in the stress-based approach to fatigue analysis and design. The above equation is also called a Morrow’s relation.

The stress-life approach generally refers to the use of the cyclic nominal stresses (S) versus fatigue life. Determination of the nominal stress depends on the loading and configuration of the specimen. The most common loading modes are bending (M), axial force (P) or torque (T). These loads can be related to the nominal stresses by using the traditional elastic stress formulae in the following manner \[1\]:

$$S = \frac{Mc}{I} \hspace{1cm} (\text{for bending } M)$$ \hspace{1cm} (2.12)

$$S = \frac{P}{A} \hspace{1cm} (\text{for axial load } P)$$ \hspace{1cm} (2.13)

$$S = \frac{Tr}{J} \hspace{1cm} (\text{for torsion } T)$$ \hspace{1cm} (2.14)

where ‘S’ can be the nominal normal or shear stress depending on the equation used, ‘A’ is the cross-sectional area, ‘I’ is the moment of inertia, ‘J’ is the polar moment of inertia, ‘c’ is the distance from the neutral axis to the point of interest and ‘r’ is the distance from the center of a cross-section to the point of interest.

An S-N curve can be generated for standard smooth material specimen, for individual manufactured structural components, for subassemblies or for complete structures. Stan-
dard smooth specimen can be flat or cylindrical un-notched precision-machined coupons with polished surfaces so as to minimize surface roughness effects. The material S-N curve provides the baseline fatigue data on a given geometry, loading conditions and material processing for use in subsequent fatigue life and strength analyses. This baseline data can be adjusted to account for realistic component conditions such as notches, size, surface finish, surface treatments, temperature and various types of loading. Other than from testing, there is no rational basis for determining these correction factors. The S-N curve for real components, subassemblies or structures represents the true fatigue behavior of production parts/structures including all the aforementioned variables. However, if a design has changed, it is necessary to regenerate the S-N curve to incorporate the change effect. This adds cost and time to the fatigue design process.

2.2.1.1 Variability of fatigue data

Fatigue life data exhibit widely scattered results because of inherent microstructural in-homogeneity in the material properties, differences in the surface and the test conditions of each specimen and other factors. In general, the variance of log life increases as the stress level decreases. It has been observed that once grains nucleate cracks in a material at high-stress levels, these cracks have a better chance of overcoming the surrounding microstructure [7]. Most of the grains can successfully nucleate cracks at low stress levels but only few of them can overcome the surrounding obstacles like grain boundaries to grow a crack. As a result of the unavoidable variation in fatigue data, media S-N fatigue life curves are not sufficient for fatigue analysis and design. The statistical nature of fatigue must also be considered.

There is a need for statistical S-N testing to predict fatigue life at various stress amplitude and mean stress combinations. The median S-N test with a small sample size can be used as a guideline to determine an S-N curve with a reliability of 50% and a minimum sample size. This method requires 14 specimens. Eight specimens are used to determine the finite fatigue life region and six specimen are used to find the fatigue limit.
The curve for the finite life region is determined by testing two samples at each of four different levels of stress amplitude and the fatigue limit is tested by the staircase method with six specimen. This procedure is shown in Figure 2.7. In the Figure, the number next to the data point represents the order in which the specimen is to be tested. The finite life region data is assumed to be linear in the log-log coordinates and the data is analyzed by least-squares method. The fatigue limit is determined by taking the average of the stress levels in a staircase test.

![Figure 2.7: Method of S-N testing with 14 specimen size [1]](image)

The standards recommend that more than one specimen be tested at each stress level. Tests with more than one test sample at a given stress amplitude level are called tests with replicate data. Replicate tests are required to estimate the variability and the statistical distribution of fatigue life. Depending on the intended purpose of the S-N curve, the recommended number of samples and number of replicated tests vary.

### 2.2.1.2 Notch effects

Geometrical discontinuities that are unavoidable in design such as holes, fillets, grooves and keyways cause the stress to be locally elevated and so are called stress raisers. Stress
raisers here generically termed as notches do require special attention as their presence reduces the resistance of a component to fatigue failure [5]. This is simply a consequence of the locally higher stresses causing fatigue cracks to start at such locations. Fatigue failure of a component typically occurs at a notch on a surface where the stress level increases due to the stress concentration effect. The term notch is defined as a geometric discontinuity that may be introduced either by design such as a hole or by the manufacturing process in the form of material and fabrication defects such as inclusions, weld defects, casting defects or machining marks. For a component with a surface notch, the maximum elastic notch stress (\(\sigma\)) can be determined by the product of a nominal stress (\(S\)) and the elastic stress concentration factor (\(k_t\)) [4]:

\[
\sigma = S \times k_t
\]  

(2.15)

The maximum elastic notch stress can be calculated from an elastic finite element analysis and is sometimes referred to as the pseudo-stress if the material at the notch is actually inelastic. Because the notch stresses and strains are controlled by a net section material behavior, the nominal stress for determination of \(k_t\) is defined by an engineering stress formula based on basic elasticity theory and the net section properties that do not consider the presence of notch [8]. The elastic stress concentration factor is a function of the notch geometry and the type of loading. The stress in a notched member decreases rapidly with increasing distance from the notch as it is depicted in Figure 2.8.

For the same maximum stress inducing a crack in the notched and the un-notched specimen, the nominal strength of an un-notched specimen is higher than that of a notched specimen by a factor of \(k_t\). However, it has been shown that at the fatigue limit, the presence of a notch on a component under cyclic nominal stresses reduced the fatigue strength of the smooth component by a factor of \(k_f\) and not the factor \(k_t\). The actual reduction factor is called the fatigue notch factor \(k_f\) and is denoted by [4]:

\[
k_f = \frac{\sigma_{ar}}{S_{ar}}
\]  

(2.16)

where \(k_f\) is defined only for completely reversed stresses \(\sigma_{ar}\) for the un-notched member.

UNCLASSIFIED: Distribution Statement A. Approved for public release
and $S_{ar}$ for the notched member. The smaller the notch root radius the larger is the
difference between $k_t$ and $k_f$.

![Figure 2.8: Interpretation of fatigue limit as the average stress over finite distance $\delta$ ahead of notch][4]

It is believed that cyclic yielding at notch root in materials reduces the cyclic stress
from the value predicted by $k_t$. Also, based on the high stress gradient, it is assumed
that the fatigue strength of a notched component depends on the average stress in a local
damage zone rather than the maximum notch stress. The average stress is associated
with the stress distribution and the process zone at the notch. The size of the active
process region can be characterized by a dimension $\delta$. Thus, the stress that controls the
initiation of fatigue damage is not the highest stress at $x=0$ but rather somewhat lower
value that is the average out to a distance $x = \delta$. This average stress is then expected to
be the same as the smooth specimen fatigue limit $\sigma_e$, so that $k_f$ is estimated by [4]

$$k_f = \frac{\text{average } \sigma_y \text{ out to } x = \delta}{S_a} = \frac{\sigma_e}{S_a} < k_f$$

(2.17)

The ratio $k_f / k_t$ falls below unity – that is the discrepancy increases if the notch radius
$\rho$ is smaller. This is because the gradient in stress ahead of the notch is more abrupt if

UNCLASSIFIED: Distribution Statement A. Approved for public release
\( \rho \) is smaller. A result of this type might be expected due to discrete microstructure such as crystal grains having the effect of equalizing the stress over a small dimension so that the peak stress is actually lowered.

### 2.2.1.3 Mean stress effects

From the perspective of applied cyclic stresses, fatigue damage of a component correlates strongly with the applied stress amplitude or applied stress range and is substantially influenced by the mean stress. The effect of the mean stress is shown in Figure 2.9 wherein an alternating stress \( S_a \) is plotted against the number of cycles to failure \( N_f \) for different mean stresses [8]. It can be observed that the tensile mean stresses are detrimental and compressive mean stresses are beneficial. This is also shown by the three vertical lines indicating the fatigue life i.e., \( N_{ft} \), \( N_{f0} \) and \( N_{fc} \), which represent the fatigue life for tensile mean stress, zero mean stress and compressive mean stress respectively for a given alternating stress \( S_a \).

![Figure 2.9: Effect of mean stress on the fatigue data](image)

\[ S_m - Compression \]
\[ S_m = 0 \]
\[ S_m = Tension \]
In the high cycle fatigue region, nominal mean stresses have a significant effect on the fatigue behavior of components. Normal mean stresses are responsible for the opening and closing state of micro cracks. Because the opening of the micro cracks accelerates the rate of crack propagation and the closing of the micro cracks retards the growth of cracks, tensile normal mean stresses are detrimental and compressive normal mean stresses are beneficial in terms of fatigue strength. The shear mean stress does not influence the opening and closing state of the micro cracks and has little effect on crack propagation. There is very little or no effect of mean stress on fatigue strength in low-cycle fatigue region in which the large amounts of plastic deformation induces mean stress relaxation which erase any beneficial or detrimental effect of the applied mean stress. Early empirical models by Gerber and Goodman were proposed to compensate for the tensile normal mean stress effects on high-cycle fatigue strength. For example Goodman model can be plotted as constant life diagrams plots of \( S_a \) versus \( S_m \) illustrated in Figure 2.10. These constant life models can be determined experimentally from a family of S-N curves generated with specific values of \( S_a \) and \( S_m \). The mean stress effect proposed by Goodman can be represented as:

\[
\sigma_{ar} = \frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma_u}}
\]  

(2.18)

where \( \sigma_{ar} \) is the fully reversed stress amplitude, \( \sigma_a \) is the stress amplitude, \( \sigma_m \) is the mean stress and \( \sigma_u \) is the ultimate tensile strength of the material. Goodman’s mean stress correction equation works well when the mean stresses are tensile. For ductile materials the compressive mean stress does not benefit fatigue strength. This results in the fully reversed stress amplitude to be same as the stress amplitude in the case when the mean stress is negative.
There are other models for taking into account the effect of mean stresses. According to the fact put forth by Morrow, the sum of stress amplitude and mean stress can never exceed the fatigue strength coefficient [1]. Moreover the monotonic yield strength and the ultimate tensile strength are inappropriate for describing the fatigue strength. The mean stress equation proposed by Morrow replaces the ultimate tensile strength in the Goodman’s equation with the cyclic true fracture strength ($\sigma'_{f}$) of the material and the Morrow’s equation is given by:

$$\sigma_{ar} = \frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma_f}}$$  \hspace{1cm} (2.19)$$

Morrow’s equation can also be written in terms of the stress-life as:

$$\sigma_a = \left(\sigma'_{f} - \sigma_m\right) (2N_f)^b$$  \hspace{1cm} (2.20)$$

Smith, Watson and Topper proposed another method which considers the equivalent fully reversed stress amplitude and is expressed as:

$$\sigma_{ar} = \sqrt{\sigma_{max} \sigma_a} = \sigma'_{f} (2N_f)^b$$  \hspace{1cm} (2.21)$$

This equation assumes that for $\sigma_{max} \leq 0$, the life is infinite and the fatigue cracks does not initiate in such cases.
2.2.1.4 Combined proportional loads

The previously discussed sections deal with the cases where a structural component is subject to cyclic uniaxial loading. However actual components are often subjected to simultaneously to multiple loads in several directions and the components maybe under a multiaxial state of stresses. In many cases, these loads are applied in such a way that the principal stress orientation in the member does not vary with time (proportional loading). Under multiaxial proportional loads a slightly different stress-life approach is taken as follows:

- The baseline S-N curve is established for bending and without correcting the fatigue strength reduction factor ($k_f$)
- For ductile materials, the multiaxial stresses can be combined into an equivalent uniaxial bending stress amplitude. This effective stress can be found by using the von Mises criterion with the stress calculated from the loads and the corresponding fatigue strength reduction factors. For a ductile material in a biaxial stress state (i.e., plane stress state), the local stress amplitudes (for the combination of axial and bending loads) are [1]

\[
\sigma_{x,a} = S_{x,a} * k_{f,N,axial/bending} \tag{2.22}
\]

\[
\sigma_{y,a} = S_{y,a} * k_{f,N,axial/bending} \tag{2.23}
\]

\[
\tau_{xy,a} = S_{xy,a} * k_{f,N,torsion} \tag{2.24}
\]

And the local stresses are

\[
\sigma_{x,m} = S_{x,m} * k_{f,N,axial/bending} \tag{2.25}
\]

\[
\sigma_{y,m} = S_{y,m} * k_{f,N,axial/bending} \tag{2.26}
\]

\[
\sigma_{xy,m} = S_{xy,m} * k_{f,N,torsion} \tag{2.27}
\]

For a smooth specimen/component, $k_f = 1$. The equivalent bending stress amplitude, according to the von Mises theory is

\[
\sigma_{eq,a} = \sqrt{\sigma_{x,a}^2 + \sigma_{y,a}^2 - \sigma_{x,a} * \sigma_{y,a} + 3\tau_{xy,a}^2} \tag{2.28}
\]

UNCLASSIFIED: Distribution Statement A. Approved for public release
• The multiaxial mean stresses can be converted into an equivalent uniaxial mean stress which is derived from von Mises theory:

\[
\sigma_{eq,m} = \sqrt{\sigma_{x,m}^2 + \sigma_{y,m}^2 - \sigma_{x,m} \sigma_{y,m} + 3\tau_{xy,m}^2}
\]  

(2.29)

### 2.2.1.5 Factors influencing S-N behavior

In the section 2.2.1.5 the effects of the mean stresses on the fatigue behavior have been discussed. Besides the mean stress effects, there are other factors that affect the reference fatigue condition (i.e., usually fully reversed \( R = -1 \) bending or axial loading small, unnotched specimen). Such factors that influence the fatigue behavior are notches (section 2.2.1.2), residual stress, surface treatment, variable amplitude loading, multiaxial and torsion loading, corrosion, fretting, low temperature, high temperature, welds, statistical aspects (section 2.2.1.1), microstructure, size effects, surface finish, frequency etc., some of which are discussed in this section.

a. **Microstructure**: In general at the macro level, the metals are modeled as homogenous, isotropic and elastic-plastic but at the microscopic level the metals are non-homogenous and the fatigue damage is influenced by the microstructure. The aspects at the microstructure level that affect the fatigue behavior includes heat treatment, cold working, grain size, anisotropy, inclusions, porosity, delaminations, and other imperfections. Heat treatment and cold working have a great influence on the ultimate tensile strength which in turn effects the fatigue limits. Fine grains generally provide better S-N fatigue resistance than coarse grains except at elevated temperatures (due to the creep-fatigue interactions) [9]. This is because of the reason that the fine grains reduce localized strains along slip bands decreasing the amount of irreversible slip and provide more grain boundaries to aid in transcrystalline crack arrest and deflection thereby reducing the fatigue crack growth rates [5]. Anisotropy caused by cold working gives increased S-N fatigue resistance when loaded in the direction of the working than when loaded in the transverse direction. This is due to the elongated grain structure in the direction of the origi-
nal cold working. Inclusions, porosity and laminations act as stress concentrations and so they are common locations for microcracks to nucleate under cyclic loading. Thus, minimizing inclusions, voids, laminations and other discontinuities through carefully controlled production processes is a key procedure.

b. **Size effects:** It has been observed that for an un-notched specimen subjected to bending fatigue, if the diameter or thickness of the specimen is less than a certain value, then the S-N fatigue behavior is reasonably independent of the diameter or thickness. For larger sizes, S-N fatigue resistance is decreased. For an un-notched specimen subjected to axial loads, S-N fatigue resistance is lower than for most bending conditions. The fatigue limit for axial loading can range from 0.75 to 0.9 of the bending fatigue limits for smaller diameter specimen [5,8]. In bending tests for a given nominal stress, the stress gradient depends on the specimen’s diameter or thickness. The larger the thickness or diameter, the smaller the bending stress gradient (as it is illustrated in Figure 2.11) and hence the larger the average stress in a local region on the surface. For axially loaded unnotched specimen, a nominal stress gradient does not exist due to which the average and the maximum nominal stresses have the same magnitude resulting in less size effects than in bending.

![Figure 2.11: Stress gradient in smaller and larger diameter specimen [5]](image-url)
c. **Surface Finish:** The type of the surface will be of an important aspect influencing the fatigue behavior for the reason that most fatigue failures originate at the surface. The surface effects are the results of difference in surface roughness, microstructure, chemical composition and residual stresses. This effect will be more enlarged at long lives where a greater number of cycles is involved with the crack nucleation.

### 2.2.2 Strain based fatigue approach

The stress based approach to the fatigue analysis of components works well for situations in which mostly elastic stresses and strains are present. However components have nominally cyclic elastic stresses but notches, welds or other stress concentration zones present in the component may result in local cyclic plastic deformation. Under these conditions, the other approach that uses the local strains as the governing fatigue parameter (the local strain-life method) was developed in the late 1950s and has been proved to be more effective in predicting the fatigue life of a component. The local strain-life method is based on the assumption that the life spent on crack nucleation and small crack growth of a notched component can be approximated by a smooth laboratory specimen under the same cyclic deformation at the crack initiation site as in the Figure 2.12.

![Figure 2.12: A schematic of the strain based fatigue testing](image)

*Figure 2.12: A schematic of the strain based fatigue testing [1]*
It is possible to determine the fatigue life at a point in a cyclically loaded component if the relationship between the localized strain in the specimen and fatigue life is known. The strain-life relationship is typically represented as a curve of strain amplitude ($\varepsilon_a$) versus fatigue life ($2N_f$) and is generated by conducting strain-controlled axial fatigue tests on smooth, polished specimens of the material. Strain controlled axial fatigue testing is recommended because this resembles the material behavior at stress concentrations and notches in a component even when the bulk of the component behaves elastically during cyclic loading.

The local strain life method can be used proactively for a component during early design stages. Fatigue life estimation may be made for various potential design geometries and manufacturing processes prior to the existence of any actual components provided the material properties are available. This approach is preferred if the load history is irregular or random and where the mean stress and the load sequence effects are thought to be of importance. This method also provides a rational approach to differentiate the high-cycle fatigue and the low-cycle fatigue regimes and to include the local notch plasticity and mean stress effect on fatigue life.

2.2.2.1 Constant strain amplitude fatigue behavior

The strain based approach to fatigue problems is widely used at present for the reason that the strain can be measured and has been shown to be correlating with low-cycle fatigue. For example, gas turbines operate at fairly steady stresses but when they are started or stopped, they are subjected to a very high stress range. The local strains can be well above the yield strain and the stresses cannot be measured but only calculated or estimated. The most common application of the strain based fatigue approach is the fatigue of notched members. In a notched component subjected to cyclic loads the behavior of the material at the root of the notch is best considered in terms of strain. Since fatigue damage is assessed directly in terms of local strain, this approach is called the ‘local strain approach’.
In the strain based approach, tests are performed under constant amplitude, fully reversed cycles of strain as shown in Figure 2.3(a). Steady state hysteresis loops can predominate throughout most of the fatigue life and the total strains can be reduced to elastic and plastic strain ranges or amplitudes. Cycles to failure can range from about 10 to $10^6$ cycles. The strain-life curves are often called ‘low cycle fatigue data’ for the reason that much of the fatigue data is obtained at fewer than about $10^5$ cycles.

Strain-life fatigue curves plotted in log-log scales are shown in Figure 2.13 where $2N_f$ is the number of reversals to failure. At a given life $2N_f$, the total strain is the sum of the elastic and plastic strains. Both the elastic and plastic curves can be approximated as straight lines in a log-log plot. At large strains or short lives the plastic strain component is predominant whereas at small strains or longer lives, the elastic strain component is predominant. The intercepts of the two straight lines at $2N_f = 1$ are $\sigma'_f / E$ for the elastic component and $\varepsilon'_f$ for the plastic component. The slope of the elastic and the plastic lines are ‘$b$’ and ‘$c$’, respectively. This gives the equation for strain-life data as proposed by Morrow i.e., the relation of the total strain amplitude ($\varepsilon_a$) and the fatigue life in terms of reversals to failure ($2N_f$) can be expressed in the following form:

$$\varepsilon_a = \varepsilon'_a + \varepsilon''_a = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c$$

(2.30)

where, $\sigma'_f$ is the fatigue strength coefficient, ‘$b$’ is fatigue strength exponent (-0.04 to -0.15 for metals), $\varepsilon'_f$ is fatigue ductility coefficient, ‘$c$’ is fatigue ductility exponent (-0.3 to -1.0 for metals). The equation 2.30 is called the strain-life equation and is considered as the foundation for the strain based approach to fatigue. This equation is the summation of two separate curves for elastic strain amplitude – life ($\varepsilon'_a - 2N_f$) and for plastic strain amplitude – life ($\varepsilon''_a - 2N_f$).
2.2.2.2 Mean strain / stress effects

Strain controlled deformation and fatigue behavior presented in the previous sections were for completely reversed straining i.e., \( R_\varepsilon = \varepsilon_{\text{min}} / \varepsilon_{\text{max}} = -1 \) (mean stress \( \approx 0 \)). However in many cases a mean strain can be present. Strain controlled cycling with a mean strain usually results in a mean stress, which may relax fully or partially with continued cycling as shown in Figure 2.14. This relaxation is due to the presence of plastic deformation and so the rate or amount of relaxation depends on the magnitude of the plastic strain amplitude. As a result, there is more mean stress relaxation at larger strain amplitudes [10]. Stress relaxation is different from cyclic softening and can occur in a cyclically stable material. In conjunction with the local strain life approach, many models have been proposed to quantify the effect of mean stresses on fatigue behavior. The commonly used models in the ground vehicle industry are those proposed by Morrow and by Smith, Watson and Topper.
Morrow’s mean stress correction method

Morrow has proposed the following relationship when a mean stress is present:

$$\varepsilon_a = \frac{\sigma' - \sigma_m}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c$$

(2.31)

According to this equation, the mean normal stress can be taken into account by modifying the elastic part of the strain-life curve by the mean stress ($\sigma_m$). The model indicates that a tensile mean stress would reduce the fatigue strength coefficient $\sigma'_f$ whereas a compressive mean stress would increase the fatigue strength coefficient as depicted in Figure 2.15.

Figure 2.15: Morrow’s mean stress correction model [1]
Smith-Watson-Topper (SWT) Parameter

Smith, Watson and Topper proposed a method that assumes that the amount of fatigue damage in a cycle is determined by $\sigma_{max} \varepsilon_a$, where $\sigma_{max}$ is the maximum tensile stress and $\varepsilon_a$ is the strain amplitude. The SWT parameter states that “$\sigma_a \varepsilon_a$ for a fully reversed test is equal to $\sigma_{max} \varepsilon_a$ for a mean stress test”. This thus can be represented in the following mathematical form [1]:

$$\sigma_{max} \varepsilon_a = \sigma_{ar,rev} \varepsilon_{ar,rev} \quad \text{for } \sigma_{max} > 0 \text{ and } 2N_f = \text{constant} \quad (2.32)$$

where $\sigma_{ar,rev}$ and $\varepsilon_{ar,rev}$ are the fully reversed stress and strain amplitudes respectively. The SWT parameter predicts no fatigue damage if the maximum tensile stress becomes zero and negative. The equation proposed by SWT model is [1]:

$$\sigma_{max} \varepsilon_a = \left(\sigma'_f\right)^2 E (2N_f)^2 + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \quad \sigma_{max} > 0 \quad (2.33)$$

2.2.2.3 Effect of surface finish and other factors on strain-life behavior

Similar to S-N approach, in addition to mean stress, many other factors such as stress concentrations, residual stresses, multiaxial stress states, environment, size and surface finish influence the strain-life fatigue behavior of a material. Residual stress effects on fatigue life are similar to mean stress effects. Hence there is very little influence at shorter lives due to stress relaxation resulting from plastic deformation and more influence at long lives, mainly in the high cycle fatigue region.

Surface finish effects are also similar to those for the S-N approach. Since fatigue cracks often nucleate early in the low-cycle regime due to large plastic strains there is little influence of surface finish at short lives. Conversely, there is more influence in the high-cycle fatigue regime where elastic strain is dominant. Therefore only the elastic portion of the strain-life curve is modified to account for the surface finish effect.
2.2.3 Critical plane approach

Critical plane approach refers to the analysis of stresses and strains as they are experienced by a particular plane in a material, as well as the identification of which plane is likely to experience the most damage. This approach is used to account for the effects to cyclic, multiaxial load histories on the fatigue life of materials and structures. In this approach, the stresses and strains during cyclic loading are determined for various orientations (planes) in the material and the stresses and strains acting on the most severely damaging plane are used to predict fatigue failure. Many notched engineering components are subjected to biaxial or multiaxial loadings such as combination of bending and torsion or tension and torsion. These consists of in-phase and out of phase loading [11,12].

The initial work on the development of critical plane model for multiaxial loading was done by Brown and Miller [11,13]. They reviewed much of the available multiaxial low-cycle fatigue literature with particular emphasis on the formation and early growth of cracks. Analogous to the shear and normal stress proposed by Findley for high-cycle fatigue, Brown and Miller proposed that both the cyclic shear and normal strain on the plane of maximum shear must be considered. Cyclic shear strains will help to nucleate cracks and the normal strain will assist in their growth. According to their theory, the cracks developed were categorized into Case A and Case B cracks. Figure 2.16(a) illustrates Case A cracks for torsion loading wherein the shear stress acts in a direction parallel to the surface or to the length of the crack. No shear stress is acting perpendicular to the free surface along the crack depth as a result of which these cracks will be shallow and have a small aspect ratio. Figure 2.16(b) shows the Case B cracks for biaxial tension. In this case the shear stress acts to cause the cracks to grow into the depth and will result in the cracks intersecting surface at an angle of 45°. The damage model formulated by Brown and Miller is given by [11]:

\[
\Delta \gamma_{max} + S \Delta \varepsilon_n = \left(1.3 + 0.7k\right) \frac{\sigma'_f}{E} (2N_f)^b + \left(1.5 + 0.55k\right) \varepsilon'_f (2N_f)^c \tag{2.34}
\]

where \(\Delta \gamma_{max}\) is the maximum shear strain range, \(\Delta \varepsilon_n\) is the normal strain range on the
plane experiencing the shear strain range \( \Delta \gamma_{max} \), \( 'k' \) is a material dependent parameter that represents the influence of the normal strain on material crack growth. Mean stress effects could also be included using Morrow’s mean stress approach by subtracting the mean stress from the fatigue strength coefficients with the fact that the mean stress on the maximum shear strain amplitude plane, \( \sigma_{n,\text{mean}} \) is one-half the axial mean stress which yields [11]:

\[
\frac{\Delta \gamma_{max}}{2} + k \Delta \varepsilon_n = \left[ (1.3 + 0.7k) \left( \frac{\sigma'_f - 2\sigma_{n,\text{mean}}}{E} \right) (2N_f)^{b} \right] + \left[ (1.5 + 0.5k) \varepsilon'_f (2N_f)^{c} \right]
\]

(2.35)

Figure 2.16: Schematic showing Case A and Case B cracks [11]

The work done by Brown and Miller was further developed by Fatemi and Socie [11,14,15] who replaced the normal strain term by the normal stress. During shear loading, the irregularly shaped crack surface results in frictional forces that will reduce crack tip stresses which inhibits the crack growth and increasing the fatigue life. Tensile stresses and strains will separate the crack surfaces and reduce frictional forces as shown in Figure 2.17.
The Fatemi and Socie model can be interpreted as the cyclic shear strain modified by the normal stress to include the crack closure effects. The governing equation of the Fatemi and Socie model is given by [11]:

\[
\gamma_{ac} \left( 1 + \alpha \frac{\sigma_{n,\text{max}}}{\sigma_y} \right) = \frac{\tau'_f}{G} (2N_f)^b + \gamma'_f (2N_f)^c
\]  

(2.36)

Where, \(\gamma_{ac}\) is the largest amplitude of shear strain for any plane, \(\sigma_{n,\text{max}}\) is the peak tensile stress normal to the plane of \(\gamma_{ac}\), occurring at any time during the \(\gamma_{ac}\) cycle, \(\alpha\) is an empirical constant with values ranging from 0.6 to 1.0 depending on the material, \(\sigma'_y\) is the yield strength for the cyclic stress-strain curve.

The above discussed models for critical plane approach were developed primarily using materials for which the dominant failure mechanism is shear crack nucleation and growth. For the materials that fail essentially by crack growth on the planes of maximum tensile strain or stress, SWT parameter may be employed [11,16]. In such materials, the cracks nucleate in shear but the early life is controlled by crack growth on planes normal to the maximum principle stress and strain as shown in Figure 2.18.
Smith et al. proposed a suitable relationship that includes both the cyclic strain range and the maximum stress, commonly referred to as SWT parameter. This parameter is used as a correction for mean stresses in uniaxial loading situation in the case of both proportionally and non-proportionally loaded components made of materials that fail predominantly due to tensile cracking. The SWT parameter for multiaxial loading is based on the principle strain range, $\Delta \varepsilon_1$ and maximum stress on the principle strain range plane, $\sigma_{n,max}$ and given by [11]:

$$
\left( \frac{\sigma_{n,max}}{2} \right) \Delta \varepsilon_1 = \left[ \left( \frac{\sigma'_f}{E} \right)^2 (2N_f)^{2b} \right] + \left[ \sigma'_f \varepsilon'_f (2N_f)^{b+c} \right] 
$$

(2.37)

### 2.2.4 Variable amplitude loading

Most of the prevenient fatigue tests were performed using the constant amplitude loading. But in service the components/structures in actual operation can undergo fatigue loading of varying amplitudes, also termed as service loading. The variations in the service loading pattern may be regular or a random pattern. Based on this the random loads are categorized into two types. They are ‘Narrow band’ random loading and ‘Broad band’ random loading. The random loading pattern is called a narrow band if the individual load cycles can be distinguished while the case in which the individual load cycles cannot be distinguished is called the broad band random loading. The investigation of metal fatigue...
under variable amplitude loading is called as the study of cumulative damage. A variable amplitude load history is also referred to as ‘Load Spectrum’. Palmgren and Miner suggested that fatigue damage at a given stress level could be considered to accumulate linearly with the number of stress cycles. This principle is known as the “Palmgren-Miner law”. This is often also referred to as ‘Linear Damage Rule”. According to this rule, if a specimen stressed at $S_1$ has a life of $N_{f1}$ cycles, then the damage after $N_1$ cycles will be the ratio $N_1/N_{f1}$. Similarly at a stress level of $S_2$, the damage after $N_2$ cycles will be $N_2/N_{f2}$ where $N_{f2}$ is the life at the stress level $S_2$ (Figure 2.19). According to the linear damage rule, for ‘n’ number of stress levels :

$$\sum_{i=1}^{n} \frac{N_i}{N_{fi}} = 1$$  \hspace{1cm} (2.38)

Figure 2.19: A schematic showing two stress points in S-N curve

For the case of broad band random loading where there are irregular variations in the stress levels, it is difficult to discretize each stress level in order to apply the Palmgren-Miner rule. Cycle counting technique is used to reduce a complex variable amplitude stress history into a number of discrete simple constant amplitude stress events associated with the fatigue damage. Rainflow cycle counting technique is the most widely used method.
This technique was initially proposed by Matsuiski and Endo in 1968. The rainflow method is based on the analogy of rain drops falling on a pagoda roof and running down the edges of the roof. Different variations of this method are three-point cycle counting, Range-pair proposed by Rice in 1997 and Four point counting rule proposed by Amzallag in 1994. The most commonly used method is the “three-point cycle counting” technique. This method uses three consecutive points in a stress-time history to determine whether a cycle is formed. The criteria for determining whether a cycle is formed or not is shown in Figure 2.20.

![Figure 2.20: A schematic of the rules for three point cycle counting](image)

The three stress points $S_1$, $S_2$ and $S_3$ define the two consecutive ranges:

- $\Delta S_{12} = |S_1 - S_2|$
- $\Delta S_{23} = |S_2 - S_3|$

If $\Delta S_{12} \leq \Delta S_{23}$, one cycle from $S_1$ to $S_2$ is extracted and if $\Delta S_{12} \geq \Delta S_{23}$, no cycle is counted. This method requires that the stress history be re-arranged so that it starts with either the highest peak or the lowest valley, whichever is greater in absolute magnitude. Then the cycle identification rule is applied to check for every three consecutive stress points from the beginning until a closed loop is defined. The points forming the cycle (1-2-1') are extracted out and the remaining points are connected to each other.
This procedure is repeated from the beginning until the remaining data is exhausted. Figure 2.21 and Table 2.1 show a schematic of such cycle extraction process using three-point Rainflow cycle counting technique.

Figure 2.21: A schematic of Rainflow cycle extraction [4]
Table 2.1: Extracted cycles using Rainflow cycle counting method [4]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Cycle</th>
<th>Mean Stress</th>
<th>Max. Stress</th>
<th>Min. Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>E-F</td>
<td>1</td>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>A-B</td>
<td>-0.5</td>
<td>1</td>
<td>-2</td>
</tr>
<tr>
<td>3</td>
<td>H-C</td>
<td>0.5</td>
<td>4</td>
<td>-3</td>
</tr>
<tr>
<td>4</td>
<td>D-G</td>
<td>0.5</td>
<td>5</td>
<td>-4</td>
</tr>
</tbody>
</table>

### 2.3 Fatigue Sensors - Literature Review

The practice of designing structures to take into account fatigue is highly abstruse since the actual loading history of the structure is not known and cannot be accurately predicted. Therefore there is a need for a device which would monitor fatigue damage and provide a reliable estimate of remaining fatigue life of a particular structure in order to provide a warning of impending fatigue failure. Hence, to determine the state of the fatigue damage and to predict the remaining service life in the structures, test engineers rely on fatigue detectors, fuses and gages. These are to be attached to the structure being monitored so that the test elements are aligned with the direction of the maximum principal stress / strain applied to the structure being tested. As such, these fatigue measuring and monitoring devices were capable of monitoring fatigue damage in only one fixed direction.

Further these fatigue gages typically contained only one test element which necessitated multiple tests on the structure being tested or alternatively the attachment of multiple gages to obtain the desired values of fatigue damage or service life remaining. Some of these are either expensive or follow tedious measurement procedures. Some kinds of fatigue monitoring devices, which were meant for multi-directional fatigue monitoring are limited in their operation to only measure or monitor structures with different lengths of artificial cracks or structures having welded joint. Other gages containing multiple test elements were limited in that they were designed to measure compressive stress only.
In an endeavor to address the exigency of early stage fatigue measurement in the structures during the span of their functional service period, a variety of methods were solicited for facilitating in the timely actions needed to be taken to avoid any ghastly consequences. Some of the other types of fatigue monitoring devices developed recently are:

- Fatigue fuses
- Piezo-electric based sensors
- Electro-chemical sensors
- Eddy current based sensors
- Ultrasonic based sensors
- Magnetic flux leakage sensors

Important features of some of these fatigue monitoring sensors, their operation characteristics along with their advantages and drawbacks are further discussed in the sections to follow.

2.3.1 Fatigue fuses

Fatigue fuses can also be categorized as crack gage type devices. The fatigue fuses in general, are made from a sheet of metal same as that of the structure under study. The fatigue fuse comprises of a thin ribbon or strand of wires and are adhered to the structure generally near the site of the crack initiation. Some of the fatigue fuse gages developed recently [17–23] are discussed further.

Remote and powerless miniature fatigue monitoring device: The fatigue fuse consists of a small coupon fabricated from aluminum or other material that is known to form well defined striations [17]. It is designed to contain a pre-crack that assist in providing a location for the striation formation. The coupon is fabricated from a material with a face-centered cubic crystal structure for the reason that these metals form a well-defined striations on slip planes parallel to <110> slip directions. Some of the materials that could be used are aluminum, nickel and copper.
Figure 2.22 shows a schematic of the side view and top view of the fatigue fuse (A). This is attached to the structure whose fatigue is to be monitored with (D) as the bonding faces. The face (C) is not in contact with the structure. The coupon is pre-cracked (B) at the center and the operation of this device is based on this pre-crack which advances the fracture surface in incremental distances proportional to the applied cyclic stress. The loading being experienced by the structure will be transferred to the coupon through the adhesive bonding.

As the cyclic loads are applied on the structure the crack increases and well defined striations are produced. The device is removed from the structure and split apart along the pre-rack location to observe the striations that were developed as a result of the cyclic loading. Whenever a stress cycle is experienced in the structure, a striation is formed in the fatigue monitor device.

Figure 2.22: The side view and plan view of the remote and powerless miniature fatigue monitoring device [17]

UNCLASSIFIED: Distribution Statement A. Approved for public release
The number of the striations thus recorded is independent of the geometry and composition of the structural member. To evaluate the striations, for the peaks and valleys the coupon surface is contrast-enhanced by adding carbon to the surface. Its surface is scanned using a laser source to illuminate the spacing between the dark stripes and the reflected energy is captured by a detector which produces a voltage pulse train over different time intervals. The voltage pulses are related to the striation spacing which in turn is related to the stress intensity ranges.

According to the author, this device measures the stress intensity ranges as a result of the loading experienced by the sensor coupon which are then related to the fatigue life. There are however some drawbacks of the sensor. The process of assessment of the fatigue life is not continuous as the sensor has to be removed from the structure and then analyzed based on the striations formed which includes a number of steps. Moreover, the sensor needs to be pre-cracked prior to mounting on the structure. Another aspect is the limitation of the material that is used for the sensor needs to be a face centered cubic crystal structure.

Fatigue indicator with slots: The fatigue indicating device is an invention of Nelson et al [18], consists of an electrically conductive foil coupon having crack initiating slots of different sizes oriented at different angles. The coupon is securely adhered at the selected portion to the structure by means of an adhesive. The stresses and strains experienced by the structural member during the operation are transmitted to the coupon (C) via the adhesive layer. The adhesive comprises of an epoxy, polyester or cyanocrylate. In response to the loading, the coupon starts to crack at the crack initiating sites in the coupon. The Figure 2.23 shows a schematic of the fatigue sensing gage with slots.

Figure 2.24 shows the top view and side view of the fatigue monitoring sensor with slots. The crack initiating zones (A) are typically slots or notches oriented at different angles. They are responsive to different ranges of the accumulated fatigue depending on the relative geometry with respect to the other. The holes (B) on either ends of the coupon act as crack terminators.
The provision of crack terminators is to avoid the rupture between the predetermined 
locations that may result in the separation of one portion of the coupon from another. In 
order to avoid any risk of initiation of cracks at regions where they are intended only to 
terminate, the adhesive (D) is not applied over the complete area of the coupon but it is 
confined only to the center regions where crack initiating slots (A) are present. Thus the 
strains on structural members are not transmitted to regions containing the crack termin-
nating holes. The crack initiating slots zones are made responsive to different amounts

UNCLASSIFIED: Distribution Statement A. Approved for public release
of fatigue damage by varying their size, shape etc., thereby the coupon can progressively sample the strains in the selected region (region where the coupon is attached on to the structure) of the structural member to which it is attached.

The coupon is typically electrically insulated from the structural member due to the non-conductive adhesive being used. The coupon is electrically conductive for the purpose that a voltage source and a milli-ammeter (M) or other current responsive device can be connected to the coupon to measure any small changes in the electrical resistance as a result of the rupture of the coupon at the crack initiating zones and relate it to stress generated. Hence this helps in analyzing the accumulated fatigue by means of S-N curves.

**Longitudinal rib load counter with notches:** Füssinger et al [19] have proposed the fatigue sensor which is a longitudinal rib load counter with notches. The device consists of a longitudinal rib (E) attached or integrated to the surface of the structure (H) whose fatigue behavior is to be monitored. The device (rib) has a number of transverse notches (F) of different heights. Each of the notches have a rounded end adjacent to the surface of the structure and a pointed end extending away from the structure. The load counter attached onto the structure is shown in Figure 2.25.

![Figure 2.25: The longitudinal rib load counter with notches attached on to the structure](image)

The loading conditions experienced by the structure are transferred to the rib. After certain amount of loading, there is certain quantity of deterioration in the structure. As a result of this, cracks (G) will occur in the failure region, which lies between the sharp
The other side of the notch i.e., towards the base of the notch is designed in a way as no cracks can occur during the complete life of the structure. This is due to the provision of large rounding radius of the notches at their base and the root of the notch being situated directly at the base of the rib. As a result, the cross-section at the root of the notch increases considerably and the increase of tension by the linking of the test piece remains at low and uncritical. The fatigue life of the structure can be estimated based on the visual inspection of the rib during the operation. This load counter can be used in case of all ductile notch sensitive materials. Some of the important features of this sensor is that it can detect the environmental influences (corrosion) affecting the structure. The usage of this sensor is limited by its location on the structure as the rib is disposed normal to the surface of the structure and there is no analyzing apparatus employed. As a result, the fatigue damage accumulated can be estimated by just the visual inspection and not have a means of continuous and remote monitoring.

**Fatigue monitoring coupon with notches:** This sensor consists of one or more flat and elongated coupons fabricated of the same material as that of the structural member whose fatigue behavior is to be monitored. The coupons are placed on the structure to experience the same kind of loading history as that of the structure onto which they are secured. The Figures 2.26 and 2.27 shows the schematic of the different kinds of coupons designed by Brull et al [20]. Each of the coupons has different stress concentration zones that differ in intensity with the notch pattern on the coupons from very mild stress concentration to very severe stress concentration. Due to this the stress developed in the coupons vary from one to the other even for the same loading conditions. This results in the coupons to have a different fatigue life and so they all fail at different times prior to the structure which would give a warning of the structure’s impending failure.
The austerity of the stress developed at the notches is controlled by the geometry of the notches in a coupon i.e., circular or elliptical notches produce mild stress concentrations whereas sharp notches as in Figure 2.27 produce severe stresses. The coupons are designed in a way that each coupon has different notch geometries on its longitudinal side with the notch pair in each coupon being geometrically similar.

By having several coupons in the fuse, each with a different stress concentrations, it is possible to estimate the residual life of the structure at several stages in life. In order
to develop a strain concentration at the notch, the fuse containing the coupons is bonded over a small strip at either ends. Due to this, the gage encounters only a spatial average of the strain experienced by the underlying structure. The gluing region of the fuse is shown by the shaded region in Figure 2.28.

![Figure 2.28: The fuse containing coupons with notches [20]](image)

One of the main disadvantages of this design is due to the localized nature of attachment. This is obvious in circumstances where the fuse is to be applied to a curved surface and in particular on a concave surface (inside of hole). Under such circumstances, the gage could presumably experience out-of-plane displacements which bear no relation to the strain experienced by the structure.

**Fatigue damage indicator with slit:** The fatigue sensing device discussed in this section has a thin rectangular metal base (U) of uniform thickness and a very narrow crack-like slit (T) cut in one side and a Teflon parting strip (V) attached to the base below the slit as shown in Figure 2.29. The gage is attached to the structure with an adhesive (S). As the structure (R) is subjected to fatigue loading during its regular operation, a fatigue crack begins at the inner end of the slit and as a result of the continued loading in the structure, the length of the crack increases [21]. The device is installed onto the structure in a way that the longer ends should lie perpendicular to the direction of principal stress in the structure. The Figure 2.29 shows the schematic of the sensor.
The principle of working of this device as proposed by Smith is the accumulation of damage in the device is indicated by the progressive crack growth. This is used to infer information about the fatigue state of the structure. The sensor is attached to the structure by means of an adhesive covering the entire surface of the base except for the rectangular area covered by the teflon strip that acts as a parting material which is attached to the surface under base of the sensor parallel to the direction of the slit. The purpose of this parting layer is to provide a region of uniform width centered on the slit where the indicator is not attached to the structure and to provide a region wherein the crack can propagate freely from one end to the other in the longitudinal direction under displacement controlled condition.

When the load is applied to the structure, a stress concentration is formed near the tip of the slit and hence a fatigue crack is initiated at that location which will start to propagate to the other end of the device as the loading is repeated. In order to monitor the accumulative fatigue damage experienced by the structure during its operation in the real time, a fatigue damage indicator is first attached onto the structure in a way as to enable the sensor to be exposed to the principal loads in the structure. In the next stage, an identical gage is located in a similar manner on an identical piece of structure for

---

**Figure 2.29: A schematic of the fatigue damage indicator with a slit [21]**
laboratory testing, which is then exposed to repeated loading which might be different from the actual loading pattern as that in actual service. As the laboratory specimen fails, the crack growth at that point is documented. This is followed by a periodic documentation of the crack growth in the structure in actual operation. When the crack in the structure in actual operation reaches a point, it can be said that a fraction of the fatigue life expended is equal to the ratio of crack growth in the indicator in actual service to the crack growth at the time of failure of the laboratory specimen.

The proposed gage however would not be possible for certain applications like aircraft fatigue – damage tracking. This is because of unacceptable variability in experimental results under spectrum type fatigue loading. In order for the existence of a good correlation between the fatigue behavior of the gage and that of the structure, there needs to be a certain degree of similarity between the stress-state conditions at the crack tip in the sensor and the conditions in the structure at the location to be monitored. Under variable amplitude loading conditions, the influences of crack tip blunting and overload-induced residual stresses at the crack tip would make that similarity hard to obtain. Furthermore, it is also suspected that such effects would be difficult to eliminate using the calibration methods.

**Fatigue sensor with variable slots:** The fatigue sensor discussed here is proposed by Creager [22]. This fatigue fuse has cut out portions (Y) that define the fuse elements (X) and variable unbounded areas are formed about the fuse elements to result in the fatigue failure at different times much before the failure of the structural member onto which it is mounted. The structure and the sensor are subjected to similar loading during the actual operation. The shapes of the fuse elements vary by the depths in the slots (X1, X2, X3) and when combined with variable unbounded lengths that are configure to fail at different timings in a sequence. Figure 2.30 shows a schematic of the front and side view of the sensor.
The sensitivity of the fuse can be increased by focusing the stress and strain in the notch area. This is achieved by the variation of length of the unbounded region (AD) of each fuse element and thinning the fuse leg (AA, AB, AC) along the central portion of the unbounded region. In addition to this, the sensitivity can be improved also by simultaneously thickening the fuse leg external to the central portion of the unbounded region or by attaching a stiffer material to the fuse leg in the region external to the unbounded region. The fatigue life at which each of the fuse legs fails is controlled by the unbounded areas that vary in length. The unbounded areas can also be formed symmetrically and asymmetrically about the cut out portions. The fuse elements (X) are expected to fail at different intervals in a particular sequence as a result of the fatigue loading. The fatigue accumulation in the fuse legs can be remotely monitored by electrical means.
**Fatigue sensor with slots and ligaments:** The fatigue sensor discussed in this section is a metallic coupon designed to have breakable ligaments with two layouts. In the first layout (Figure 2.31a), the ligaments are of variable lengths wherein the sensor can be used to measure the fatigue strength or fatigue damage of metallic or polymeric materials. In the second layout (Figure 2.31b), the ligaments are of equal lengths but made of different materials with different elastic modulus wherein the sensor can be used to measure the fatigue strength and fatigue damage of certain composite materials.

![Figure 2.31: Fatigue sensor with ligaments and slots](image)

The sensor coupon shown in Figure 2.31(a) has ligaments with varying lengths and varying surface areas. The sensor coupon is attached on to the structure to be tested and when the structure is subjected to fatigue loading, the loads experienced by the structure are transferred on to the sensor coupon. As a result each of the ligament fails in the order starting from the weaker ligament to the stronger ligament. Thus by monitoring the number of ligaments failed, fatigue damage can be estimated based on the S-N curves of the coupon material.

All the above mentioned fatigue sensors are passive which provide the fatigue life by determining the extent of damage seen with the sensor. Another interesting class of fatigue sensors are active type, which can provide a signal to indicate the fatigue. Some of such active type of fatigue sensors are discussed in the following sections.
2.3.2 Piezo-electric based fatigue sensors

The piezoelectric fatigue sensors are based on the principle that they develop a potential in proportion to an applied mechanical stress. It can exhibit dimensional change as it is subjected to the external electrical field. This special characteristic is due to the motion of the dipoles which result in the change of the dipole moment inside the material [24]. The electro-mechanical characteristics of the piezoelectric material make it suitable to be used as actuators or sensors. In many cases, one piezoelectric material is used as the source to produce ultrasonic signal and another piezoelectric material can be used as a source to receive the signal. In this case any change in the signal due to the defect indicate the presence of a crack and would reduce the amplitude of the received signal.

In one of these applications, a piezoelectric element is used in conjunction with an impedance analyzer to detect the crack on the surface of a structure. This method showed that electro-mechanical impedance of the piezoelectric element located close to the crack can be affected by the presence of the crack. Besides, a self-diagnosis technique to determine the status of the bond between the piezoelectric material and the structure can also be introduced with the use of the electro-mechanical impedance. Whilst there is profuse amount of work reported in the open literature [25–28] on the use of piezoelectric material for structural integrity assessment and damage detection, in most of these works reported, the piezoelectric material is not subjected to operating environment.

A built-in piezoelectric sensor / actuator network: The piezoelectric gage proposed by Ihn et al. [25] employs sensor signals generated from piezoelectric actuators in its vicinity that are built into the structures in which the crack growth needs to be detected. The crack gage consists of three components i.e., diagnostic signal generation, signal processing and damage diagnostics.

A piezoelectric actuator can generate diagnostic waves that can propagate along the structure for the damage interrogation. The changes in the received signals as the structure undergoes the fatigue loading during its actual operation can be analyzed to reveal
structural flaws. Figure 2.32 shows a schematic of the arrangement of the piezoelectric sensor and actuator arrangement on a structure.

The measurements are performed from a network of built-in piezoelectric actuators and sensors installed on the structure and the first measurements are considered as a baseline that represents the initial condition of the structure. When an elastic wave propagated through a region where there is a change in the material properties, scattering occurs in all the directions.

![Figure 2.32: The built-in piezo-electric sensor/actuator network [25]](image)

The signals transmitted from the sensor are modified to forward scattering waves and the scattered energy provides a very good information about a crack propagating across
the actuator and the sensor path. The scattered wave in the time domain can be obtained by subtracting the baseline data recorded for the structure with the initial damage size from the sensor data for the structure with the extended damage. This scattered wave can be used as a means of the crack detection. It carries information on both amplitude changes and phase changes from the crack propagation. The sensor measurements at certain intervals of time are subtracted from the baseline and the damage index is evaluated. This procedure will be repeated for continued structural health monitoring.

**Piezoelectric strain sensor array:** Another interesting variation of piezoelectric fatigue gage as proposed by Henderson et al. [26]. The schematic of such sensor is shown in Figure 2.33. A piezoelectric polymer film (AH) is coated with a thin continuous layer of conductive material (AG) on one side with the other side of the sheet coated with a non-continuous pattern (AI) with a thin layer of conductive material. The continuous metallic layer on one side is used as a ground electrode while the non-continuous pattern constitutes individual electrodes. Sensor leads (AF) are then connected to each individual electrode and then to a signal processor which has an in-built software for determining the strain amplitudes of the surface of the structure from the signals processed. The resulting output can be used to record the strain-time data that can later be analyzed to study the time dependent behavior of the structure.

The major advantage of this sensor configuration is that it provides dynamic response with respect to strain experienced by the structure. The polymer film generally used in this case is the polyvinylidene fluoride (PVDF). The PVDF has the advantage of being lightweight, durable, easily shaped and stacked, possess high sensitivity to strain and can be isotropic in plane. The PVDF sheet has an adhesive backing layer (AG) on the first electrode by the virtue of which the polymer film is secured onto the structure. When the structure undergoes loading, strains are induced in the piezoelectric sensor and a voltage is generated. The output voltage from the piezoelectric polymer film sensor is captured by a signal processor included in the setup from which the time-dependent strain data can be recorded and hence the fatigue life is of the structure is determined. The strain
sensor is made of PVDF film which has some inherent advantages such as light weight, durable and has high sensitivity to strain. The author claims that such an array of strain sensor can replace prior art sensors as a single strain sensor can be made from a single polymer film and involves less cost and effort for the installation.

![Figure 2.33: The piezo-electric strain sensor array [26]](image)

**Structural Impedance Sensors:** Park et al. [27] proposed a methodology to detect and locate structural damage by employing two different damage detection techniques. The schemes employed for the damage detection utilizes the electro-mechanical coupling property of piezo-electric materials and tracking the changes in the frequency response function data. This is based on the principle that any physical changes in the structure can cause changes in the mechanical impedance. Mechanical impedance is a measure of a structure's resistance to motion when subjected to a given force. The mechanical impedance of a point on a structure is the ratio of the force applied at that point to the resulting velocity at the same point. It thus relates forces with velocities acting on a mechanical system. Mechanical impedance can also be stated as the inverse of mechanical admittance. Due to the electro-mechanical coupling property of the piezo-
electric materials, the change in the mechanical impedance of the structure will result in a change in the electrical impedance of the piezo-electric sensor, the sensor being in contact with the structure. Thus, the occurrence of the structural damage can be qualitatively detected by monitoring the change in the electrical impedance of the piezo-electric sensor.

![Coupled electro-mechanical admittance Y=Re(Y)+j Im(Y)](image)

Figure 2.34: A schematic of the PZT-driven dynamic structural sensor [27]

The working schematic of the PZT sensor is shown in Figure 2.34. The PZT is surface bonded such that it undergoes axial vibration when being subjected to an externally applied voltage. As seen in Figure 2.34, one end of the PZT is fixed and the other end is connected to the host structure. The wave equation for the PZT bar connected to the structure is represented by

\[
Y(\omega) = i\omega a \left[ \varepsilon_{33}^{T} (1 - i\delta) - \frac{z_{S}(\omega)}{z_{S}(\omega) + z_{a}(\omega)} d_{3x}^{2} \hat{Y}_{xx} \right]
\]

(2.39)

where, ‘\(Y\)’ is the electrical admittance (inverse of impedance), \(z_{a}\) and \(z_{S}\) are the mechanical impedance of the PZT and the structure, \(d_{3x}^{2}\) is the piezo-electric coupling constant in the arbitrary ‘\(x\)’ direction at zero stress, \(\varepsilon_{33}^{T}\) is the dielectric constant at zero stress, \(\delta\) is the dielectric loss tangent of the PZT. The equation 2.39 gives shows that the electrical impedance (inverse of ‘\(Y\)’) of the PZT bonded on to a structure is directly related to the mechanical impedance (\(z_{S}\)) of the structure. If the structure is subjected to damage, the
parameters such as the mass, damping, stiffness etc. would be changed which will result in the change in the mechanical impedance. The change thus induced will result in the change in the electric impedance in the PZT sensor.

**Piezoelectric paint sensor:** The piezoelectric paint sensor [28] discussed here is utilized for detection of surface fatigue cracks. The working principle of the piezoelectric paint sensor is based on the electromechanical coupling properties of the sensor. The sensor when directly deposited on to the structure under study, undergoes mechanical strain being transferred from the structure under loading. Thus resulting mechanical strain in the sensor results in voltage signals being generated from it. This sensor is made of polymer based piezoelectric paints, which can be deposited on the structure. The advantage of this sensor over the ceramic based sensors such as lead-zirconate-titanate (PZT) is that it is not brittle and there shall be no cracking of the sensor in case of large deformations. The piezoelectric paint consists of tiny piezoelectric particles mixed with a polymer matrix. The blend of the polymer matrix and the ferroelectric ceramics (type of piezoelectric material) to form piezoelectric composites would result in the combination of the high electro-active properties of the latter and the mechanical flexibility and formability of the former. The working of these sensors are based on direct piezoelectric effect i.e., when a stress / strain is applied to the piezoelectric paint sensor in a direction perpendicular to the polarization direction (Figure 2.35), a voltage is generated which tries to return the piece of piezoelectric paint to its original dimensions.

This change in the dimensions result in a voltage generated by the piezoelectric material which is given by the equation:

\[
V_c \propto Y_c \epsilon_1 \tag{2.40}
\]

where, \(Y_c\) is the Young’s modulus of the piezoelectric paint and \(\epsilon_1\) is the average strain over the area of the paint sensor electrode.
The above equation shows that the electric voltage generated by the piezoelectric sensor is proportional to the mechanical strain in the film paint. The crack detection scheme using this technique is done by employing a piezoelectric paint sensor with multiple electrodes for measuring the signal. Figure 2.36 shows a schematic when a paint sensor is used with two electrode pairs.

The two electrodes are to be connected with different input channels to a device that reads the signal (such as oscilloscope). When the structure with the sensor attached is subjected to excitation loads, voltage signal (given by equation 2.40) is generated by the piezoelectric material. In case of a crack generated in the structure in the vicinity of the sensor (i.e., the crack has to pass through the electrode), the measured signals from the two electrodes is different. This would indicate the occurrence of the crack in the sensor region. On the other hand, the signals from the two electrodes would be identical if there is no crack generated in the vicinity of the sensor.

Figure 2.35: Schematic of the piezo-electric paint sensor [28]
The two electrodes are to be connected with different input channels to a device that reads the signal (such as oscilloscope). When the structure with the sensor attached is subjected to excitation loads, voltage signal (given by equation 2.40) is generated by the piezoelectric material. In case of a crack generated in the structure in the vicinity of the sensor (i.e., the crack has to pass through the electrode), the measure signals from the two electrodes is different. This would indicate the occurrence of the crack in the sensor region. On the other hand, the signals from the two electrodes would be identical if there is no crack generated in the vicinity of the sensor.

### 2.3.3 Electro-chemical fatigue sensor

The electrochemical fatigue sensor (EFS) [29] falls under the category of non-destructive fatigue crack testing methods. During the application, an EFS sensor is applied to each location of interest and crack will be detected in the areas that are near or in the immediate vicinity of the sensor. The EFS system works on fundamental electrochemical principles. The inspection area is anodically polarized to create a passive film on the area.
of interest. The polarizing voltage produces a DC base current in the electrochemical cell. When the structure being tested undergoes a cyclic stress, the current flowing within the cell varies in response to the applied mechanical stress. As a result, an AC current is superimposed on the base DC current. Depending on the structural material, the loading conditions, as well as the state of the fatigue damage in the structure, the transient current within the cell provides information on any fatigue crack activity. Figure 2.37 shows the configuration of the electrochemical sensor.

![Figure 2.37: A schematic of the electrochemical fatigue sensor [29]](image)

The main components of the EFS system are the EFS sensor, electrolyte and a potentiostat. Each of the EFS sensor has an adhesive layer on one side which is attached to the structure under study. The open area (AM) in the middle of the sensor is used to hold the electrolyte which is filled through the lower filler tube (AL) while air escapes out of the upper bleeder tube (AK). The sensor electrode (AJ) is a stainless steel mesh which is sandwiched between the upper (AP) and lower (AN) sections of the sensor and is completely covered, when the electrolyte is filled in the sensor. The electrolyte is basically a water-based solution that is amiable to most of the metals. The electrolyte is chemically inert and environmentally safe. The potentiostat is a power supply that provides the
voltage difference between the working electrode and a reference electrode, through the electrolyte.

During the study of the fatigue behavior in the structure, both the electrodes are comprehended in the electrochemical cell. During the operation of the sensor, the structure will be the working electrode and the sensor is the reference electrode which is sandwiched within the EFS electrode.

The electrochemical conditions imposed during the test are designed to induce a stable, passive oxide film on the surface of the material. During cyclic loading, the fatigue process causes micro-plasticity and strain localization on a very fine scale. The interaction of the cyclic slip and the passivation process causes temporary and repeated alterations to the passive film. These alterations including both dissolution and re-passivation processes, give rise to transient currents. Transient currents result from cyclic changes in the electrical double layer at the interface of the metal and the electrolyte. These currents generally possess the same frequency as that of the mechanical stress and have a complex phase relationship. In addition, the disruption of the surface oxide film by the cyclic slip causes an additional component of the transient current which has twice the frequency of the elastic current. This may be attributed to the plasticity effects occur during both the tensile and compressive portions of the loading cycle. As fatigue damage occurs, the crack induced plasticity introduces higher harmonic components into the transient current.

2.3.4 Eddy current sensors

The Meandering Winding Magnetometer (MWM) eddy current arrays was proposed by Zilberstein et al. [30–35] which permit fatigue damage monitoring at various critical locations in a structure. These MWM sensor arrays are made from thin metal windings embedded between layers of durable substrate materials. The MWM sensor is an inductive sensor that utilizes a meandering primary winding with a number of fully parallel secondary windings which would be the sensing elements. Some of the typical MWM sensor arrays are shown in Figure 2.38.
The windings of the sensor are adhered to a substrate. The square wave design of the drive winding induces periodic magnetic field in the material of the structure under study. A software is used to convert the sensor impedance magnitude and phase response to material properties like conductivity. As a result of fatigue damage, there will be an increase in dislocation density and formation of persistence slip bands which will result in change of electrical conductivity of the material and in case of ferromagnetic materials, it will result in change of magnetic permeability. This is the working principle of the MWM array sensors. In an MWM array, a drive winding is excited with a current at a prescribed frequency (typically from under 1 kHz up to 1 MHz). This current will provide a spatially distributed time varying magnetic field which in turn induces eddy current in conducting test materials. The secondary windings (sensing elements) sense the variations in the magnetic field due to the presence of local defects that alter the flow of induced eddy currents.
2.3.5 Ultrasonic based sensors

The ultrasonic based structural health monitoring sensors have been developed by Bao et al. [30,36] for real time monitoring of cracks in components made of ductile materials. The component under study is monitored using an angle beam, through transmission technique using two transducers strategically placed on either sides of the critical location where the cracks are expected to initiate like holes. Figure 2.39 shows a schematic of such sensors mounted on a specimen with a hole that acts as a stress raiser / crack initiation point. As the applied stress is increased, the received signal shifts with respect to time due to the effects of changes in the geometry and change in ultrasonic velocity arising from the acousto-elastic effect. If a crack is present, the received signal also decreases in amplitude as the crack opens under stress. If such applied stress is predominantly large so as to open the crack, then the ratio of the received ultrasonic energy to that with no stress is a reliable indicator of the presence of the crack and the growth of such cracks can be continuously monitored by tracking this energy ratio during the fatigue loading.

Figure 2.39: A schematic of transducers set-up on a plate with center hole [36]
2.3.6 Magnetic flux leakage sensors

Masatoshi et al. [37] have developed magnetic based sensors to detect plastic deformation and fatigue damage. The magnetic sensor is made of semi-conductor GaAs Hall element and the apparatus also uses X-ray diffraction to measure the residual stress distribution in components under fatigue loading. Statistical processing of the data obtained from the leakage magnetic flux sensor and the residual stress measured by the X-ray diffraction method is used to calculate the plastic deformation and the fatigue damage. Figure 2.40 shows a schematic of the apparatus for leakage magnetic flux measurement with a simple (dog bone) tensile testing specimen.

![Figure 2.40: Schematic of apparatus for leakage magnetic flux measurement [37]](image)

The specimen under study is placed on the apparatus with the axial direction of the specimen parallel to the x-axis as in Figure 2.40. Prior to the magnetic measurement, a polarization in a uniform field is performed along the axial direction of the specimen after demagnetization treatment. Leakage magnetic flux, $B_z$ normal to the specimen surface was observed by using Hall sensor. It has been reported that stress is a significant factor affecting the magnetization of the ferromagnetic materials [4, 8, 9]. The change in the residual stress affects both internal stress and micro-structure in the component. The change in the internal stress influences the magnetic properties of the ferromagnetic material because of an inverse magneto-restrictive effect which results in a change in the
magnetic permeability of the material. In general, in-homogenous deformation occurs during tensile and fatigue loading and as a result the distribution of the residual stress and the plastic strain is produced in the component. As a result the degree of plastic deformation and fatigue damage is possible to be estimated based on the distribution states of $B_z$ on the component.

2.4 Summary

As discussed in this chapter so far, a variety of techniques can be used for determining fatigue life of the structural components. The medley of the fatigue measuring or sensing devices can be categorized based on their respective modus operandi and the principle of operation as can be seen in the case of fatigue fuses, piezoelectric based sensors, magnetic flux based sensors, electro-chemical sensors, Impedance based sensors, eddy current sensors etc. Each of the sensors or the monitoring devices has its own ascendancies and bottlenecks. Table 2.2 shows an outline of all the sensors discussed in this chapter.

For example, the remote and powerless miniature fatigue monitoring device [17] has a requirement of coupon material to be a face-centered cubic crystal structure as the metals with such crystal structure exhibit the ability to form striations on slip plane. From the above discussion it is very obvious that the process of sensing and analyzing the fatigue behavior of the structural member using this kind of fatigue fuse type of device involves number of steps in determining the fatigue life. The fatigue monitoring sensor with longitudinal rib load counter with notches [19] is attached or integrated into the structure in a way that the plane of the sensor is perpendicular to the structure. In this case there should be a provision of the availability of sufficient room on the surface of the structure. The reason for this is the fatigue behavior of the structure is studied by just the visual inspection of the cracks developed at the ends of the notches in the coupon.
Table 2.2: A summary of some of the fatigue sensors developed in the past

<table>
<thead>
<tr>
<th>S. No</th>
<th>Sensor Name</th>
<th>Principle of operation</th>
<th>Comments (Cons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remote and powerless miniature fatigue monitoring device [17]</td>
<td></td>
<td>1. In some cases, the testing elements have to be subjected to pre-cracking.</td>
</tr>
<tr>
<td>2</td>
<td>Fatigue indicator with slots [18]</td>
<td></td>
<td>2. The testing elements have to be subjected to artificial weakening.</td>
</tr>
<tr>
<td>3</td>
<td>Longitudinal rib load counter with notches [19]</td>
<td></td>
<td>3. They can measure the fatigue damage or stress in a particular direction.</td>
</tr>
<tr>
<td>4</td>
<td>Fatigue monitoring coupon with notches [20]</td>
<td>Fatigue fuses</td>
<td>4. Complex fabrications have to be employed.</td>
</tr>
<tr>
<td>6</td>
<td>Fatigue sensor with variable slots [22]</td>
<td></td>
<td>6. They would not account/mimic for the ambient conditions.</td>
</tr>
<tr>
<td>7</td>
<td>Fatigue sensor with slots and ligaments [23]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>A built-in piezoelectric sensor/actuator network [25]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Piezoelectric strain sensor array [26]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Structural Impedance sensors [27]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Piezoelectric paint sensor [28]</td>
<td>Active Sensors</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Electro-chemical Fatigue Sensor [29]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Eddy current sensors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Ultrasonic based sensors [36]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Magnetic Flux Leakage sensors [37]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the case of the fatigue damage indicator with a slit [21] the sensor configuration is complicated as in the case of the adhesive layer and the teflon tape. Moreover, the fatigue life is determined by comparing the crack length at the notch tip of the sensor in actual service, with the crack length on a similar specimen on which a similar kind of loading is applied in the laboratory and this may hinder the purpose of monitoring the fatigue behavior of the structural member on a continuous basis. The piezoelectric paint sensor [28] has some limitations in its functionality. Even though these sensors are used
for dynamic strain sensing applications, they cannot differentiate in the two plane strain
directions. Thus they can be used only for uni-directional strain monitoring which is in
the plane of the paint film.

All the fatigue sensors currently available have limitations or disadvantages with re-
spect their operation. Some of the devices are just limited to the measurement of the
crack length on the structure, others work in such a way that the fatigue measurement
may not be a direct method but it involves a multi-step procedure while some devices give
the fatigue life of the structural members through comparing with a series of laboratory
experiments. The aim of the current research is to design a versatile fatigue monitoring
gage that can be employed on any kind of structures and minimizing the complexities of
the gages mentioned so far. The next chapter presents the design concept of the fatigue
sensor. The design consists of analytical modeling as well as elastic and elasto-plastic
finite element simulations.
Chapter 3

Design of the Sensor

Previous chapter provided an overview of the existing fatigue monitoring devices highlighting their merits and drawbacks. The fatigue sensors described were broadly classified into active and passive devices. The fatigue fuses fall into the passive sensor category while the piezoelectric based sensors and the electrochemical fatigue sensors fall into passive type of devices. Keeping the disadvantages of the existing sensors in view, a novel fatigue monitoring device is conceived. Some of the important features of this sensor is its simplicity in design, ease of installation and the fact that the sensor need not be located at a critical location. The sensor can be placed in the vicinity of stress concentration zones like holes, notched etc. and can mimic the stresses and strains at the critical locations in the structure.

3.1 Concept of the Design

The fatigue monitoring sensor consists of alternate slots and strips having different strain magnification factors with respect to nominal (reference) strain. The sensor is designed in such a way that the strips experience the strains which closely resemble the actual strain distribution in the critical area of the component. The sensor can be placed outside the notch but still would experience the same fatigue damage as the notch tip. The sensor is attached to the surface of structural member whose fatigue behavior is to
be monitored by means of a suitable adhesive. The strips henceforth termed as ligaments, will fail in a sequential manner from the ligament experiencing the highest strain magnification to the lowest. Each ligament failure corresponds to the particular fatigue damage accumulated by the structure being diagnosed. This information allows for predicting remaining component life. A schematic of the fatigue sensor and its arrangement in a structure is shown in Figure 3.1.

![Fatigue Sensor](image)

**Figure 3.1:** Fatigue gage and its mounting configuration

The inset in Fig. 3.1 shows a schematic representation of an initial design of a fatigue sensing gage. The gage mainly comprises of a metallic coupon with alternate strips and slots. The strips in the sensor are called ligaments. As seen from the figure, each ligament is divided into two parts with different areas of cross-section and the size of smallest area of cross-section (the active ligaments) are decreasing from one end to the other. The ligaments on either ends of the gage with uniform area of cross-section are called reference ligaments. The strain in the reference ligament is related to the strain in the component where the gage is placed. The strain ratio of each of the active ligament is a magnification of the strain in the reference ligament thereby relating to the strain in the critical location on the structure. When fixed in an appropriate position, the test gage should experience the same strain and ambience as that experienced by the test structure.

*UNCLASSIFIED: Distribution Statement A. Approved for public release*
As the gage is subjected to cyclic stress of known magnitude, each of the ligaments will experience elongation or contraction similar to that experienced by the structure. Active ligaments will experience different amounts of induced strains ($\varepsilon$) and stress ($\sigma$) from the same total elongation, as these active ligaments vary in length and cross-sectional area. Thus the amount of induced strains and stresses of each active ligament vary as a function of its length and cross-sectional area, which facilitates the design of the required strain magnification for any given application. As a result each ligament will thus start to fail in the order from highest to lowest induced strain. Thus induced strains and stress can be related to the service life of the structure and in this way the remaining service life or the expended service life of the structure can be determined.

The sensor material can be same as that of the structure or different. As different ligaments give different strain magnifications during the actual testing of the laboratory specimen, it can potentially reduce the number of experimental tests required for the calibration and thereby graph the S-N curve for the sensor material. The sensor can be used on a new structure or can even be employed on the structures that are already in service and moreover the sensor does not call for any kind of artificial weakening of the ligaments. It can also be used to measure the expended fatigue life of the structural member and henceforth reduce the service depot or the downtime of the component under testing. The fatigue sensor coupon can be fabricated from a number of engineering materials like Al, Ti, Cu, Ni etc., and other metals and their alloys for which the mechanical and fatigue properties are known.

### 3.2 Analytical (Elastic) Modeling

This section presents the various stages in the process of the design of the fatigue monitoring sensor. Figure 3.2 shows a two ligament section of the fatigue gage comprising of a reference and active ligaments. In this design, there is a symmetry in the active ligaments (C). The elastic strain in the middle portion of the active ligament is compared with respect to the reference ligament ‘R’.
Figure 3.2: Design of the coupon with symmetry in the active ligaments

The dimensions of the actual active ligament are fixed relative to this reference where ‘A’ and ‘L’ refer to cross-section area and length respectively. The reference and active ligaments along with the basic nomenclature of the parameters used in analytical modeling is represented in Figure 3.2. It may be noted that the practical gage employed for the fatigue life measurement will have a reference ligament ‘R’ and a series of active ligaments with the actual number of these decided based on the specific design parameters. The active ligaments will have different lengths and areas of cross-section in the middle depending on the application. This basic configuration is considered for developing an analytical analysis. Figure 3.3 shows a fatigue sensor layout with one reference ligament and 9 active ligaments numbered 1 through 9. The arrows in Figure 3.3 refer to the direction in which displacement is applied for the analytical and initial elastic finite element simulations.

The strain analysis of our fatigue gage design is based on three important assumptions, as described in the previous section. The following is a derivation for the calculation of the ratio of strain in the active ligament to the strain in the reference ligament (see Fig. 3.2).
The total length of the ligament is [38]:

\[ L = L_{\text{out}} + L_{\text{mid}} + L_{\text{out}} = L_R \]  \hspace{1cm} (3.1)

\[ \Delta L = \Delta L_R = \Delta L_{\text{out}} + \Delta L_{\text{mid}} + \Delta L_{\text{out}} \]  \hspace{1cm} (3.2)

The strain in the reference ligament is calculated as

\[ \varepsilon_R = \frac{\Delta L_R}{L_R} = \frac{\Delta L_{\text{out}} + \Delta L_{\text{mid}} + \Delta L_{\text{out}}}{L} \]  \hspace{1cm} (3.3)

The strain in the middle portion of the active ligament ‘C’ is

\[ \varepsilon_{\text{mid}} = \frac{\Delta L_{\text{mid}}}{L_{\text{mid}}} \]  \hspace{1cm} (3.4)

From the equations 3.3 and 3.4 we have,

\[ \frac{\varepsilon_{\text{mid}}}{\varepsilon_R} = \left( \frac{\Delta L_{\text{mid}}}{\Delta L_{\text{out}} + \Delta L_{\text{mid}} + \Delta L_{\text{out}}} \right) \times \left( \frac{L}{L_{\text{mid}}} \right) \]  \hspace{1cm} (3.5)

Using Hooke’s law, we have \( \Delta L = (PL/AE) \). Substituting for \( \Delta L \) in equation 3.5 and modifying it, the expression for the ratio of the strain in the outer and middle part of
each ligament to the strain in the reference ligament is obtained as:

\[
\frac{\varepsilon_{i,\text{out}}}{\varepsilon_R} = \left( \frac{L}{L_{i,\text{out}}} \right) \left( \frac{\alpha_{i,\text{out}}}{\alpha_{i,\text{out}} + \alpha_{i,\text{mid}} + \alpha_{i,\text{out}}} \right) \tag{3.6}
\]

\[
\frac{\varepsilon_{i,\text{mid}}}{\varepsilon_R} = \left( \frac{L}{L_{i,\text{mid}}} \right) \left( \frac{\alpha_{i,\text{mid}}}{\alpha_{i,\text{out}} + \alpha_{i,\text{mid}} + \alpha_{i,\text{out}}} \right) \tag{3.7}
\]

Where, \( \varepsilon \) is the induced strain, \( \alpha \) is a shape factor i.e., ratio of length to the cross-sectional area of the ligament \((L/A)\), \( i \) is the ligament number (here \( i = 1 \) to 9), \( L \) is the total length of the ligament and \( A \) is the cross-sectional area of the ligament.

The equations 3.6 and 3.7 are used to calculate the strain ratio of the outer and inner parts of each of the active ligaments to the strain in the reference ligament. The data in the Table 3.1 shows the length of each part of all the nine active ligaments considered and the corresponding strain ratio of the middle portion and the outer portions of the active ligaments. The dimensions in the Table 3.1 are in millimeters. The area of cross-section of the middle portion of all the nine active ligaments is 100 sq. mm and that of the outer portions of all the active ligaments is twice the value of the middle portion [38].

The Matlab code for calculating the strain ratios is mentioned in Appendix A. The dimensions of the ligaments can be calculated based on the ratio of strain in the middle portion of the active ligaments to the strain in the reference ligament which in turn is related to the actual strain in the component. In other words, the dimensions of each of

---

**Table 3.1: The length of the ligaments as input and the resulting strain ratios**

<table>
<thead>
<tr>
<th>Ligament #</th>
<th>Outer</th>
<th>Middle</th>
<th>Outer</th>
<th>Outer</th>
<th>Middle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligament 1</td>
<td>5</td>
<td>90</td>
<td>5</td>
<td>0.52632</td>
<td>1.05263</td>
</tr>
<tr>
<td>Ligament 2</td>
<td>10</td>
<td>80</td>
<td>10</td>
<td>0.55556</td>
<td>1.11111</td>
</tr>
<tr>
<td>Ligament 3</td>
<td>15</td>
<td>70</td>
<td>15</td>
<td>0.58824</td>
<td>1.17647</td>
</tr>
<tr>
<td>Ligament 4</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>0.65200</td>
<td>1.25000</td>
</tr>
<tr>
<td>Ligament 5</td>
<td>25</td>
<td>50</td>
<td>25</td>
<td>0.66667</td>
<td>1.33333</td>
</tr>
<tr>
<td>Ligament 6</td>
<td>30</td>
<td>40</td>
<td>30</td>
<td>0.71429</td>
<td>1.42857</td>
</tr>
<tr>
<td>Ligament 7</td>
<td>35</td>
<td>30</td>
<td>35</td>
<td>0.76923</td>
<td>1.53846</td>
</tr>
<tr>
<td>Ligament 8</td>
<td>40</td>
<td>20</td>
<td>40</td>
<td>0.83333</td>
<td>1.66667</td>
</tr>
<tr>
<td>Ligament 9</td>
<td>45</td>
<td>10</td>
<td>45</td>
<td>0.90909</td>
<td>1.81818</td>
</tr>
</tbody>
</table>
the active ligaments can be designed in such a way that they would fail after a certain percentage of the fatigue life expended. Thus, knowing the desired strain magnification, it is possible to determine the dimensions of each of the active ligaments. Following this simple analysis, we derived an expression for calculating the length of the middle portion of the active ligaments based on the strain ratios. The derivation of the length of the middle portion of each ligament depending on the corresponding strain ratio is presented further.

**Assumptions:**

\[ A_{C2} = A_R \]
\[ A_{C1} = 2 \times A_{C2} = 2 \times A_R \]
\[ \frac{\varepsilon_{C2}}{\varepsilon_R} = X \text{ (Given)} \]

The ratio of strain in the middle portion of the ligament to the strain in reference ligament is given by:

\[ \frac{\varepsilon_{C2}}{\varepsilon_R} = \frac{L}{L_{C2}} \times \frac{\alpha_{C2}}{\alpha_{C1} + \alpha_{C2} + \alpha_{C3}} \]  

(3.8)

where,

\[ \alpha = \frac{L}{A} ; \quad \alpha_{C1} = \frac{L_{C1}}{A_{C1}} ; \quad \alpha_{C2} = \frac{L_{C2}}{A_{C2}} ; \quad \alpha_{C3} = \frac{L_{C3}}{A_{C3}} \]

Substituting in the equation 3.8, we have:

\[ \frac{\varepsilon_{C2}}{\varepsilon_R} = \frac{L_R}{L_{C2}} \times \left( \frac{\left( \frac{L_{C2}}{A_{C2}} \right)}{\frac{L_{C1}}{A_{C1}} + \frac{L_{C2}}{A_{C2}} + \frac{L_{C3}}{A_{C3}}} \right) \]  

(3.9)

But from the given data, we have

\[ A_{C2} = A_R \]
\[ A_{C1} = 2 \times A_{C2} = (2 \times A_R) \]
\[ \frac{\varepsilon_{C2}}{\varepsilon_R} = X \text{ and } L_{C3} = L_{C1} ; \quad A_{C3} = A_{C1} \]
Substituting for these values in the equation 3.9

\[ X = \frac{L_R}{L_{C2}} \times \frac{(\frac{L_{C2}}{A_R})}{\left(\frac{L_{C1}}{2A_R} + \frac{L_{C2}}{A_R} + \frac{L_{C3}}{2A_R}\right)} \quad (3.10) \]

\[ X = \frac{L_R}{\left(\frac{L_{C1}}{2A_R} + \frac{L_{C2}}{A_R} + \frac{L_{C1}}{2A_R}\right) \times A_R} \]

\[ X = \frac{L_R}{\left(\frac{L_{C1}}{2} + L_{C2}\right)} \]

\[ X = \frac{L_R}{L_{C1} + L_{C2}} \quad (3.11) \]

From the Figure 3.2, \( L_{C1} = \frac{(L_R - L_{C2})}{2} \), substituting in equation 3.11, we have

\[ X = \frac{L_R}{\left(\frac{L_{C1}}{2} - L_{C2}\right) + L_{C2}} = \frac{L_R}{\left(\frac{L_{C1}}{2} + L_{C2}\right) / 2} = \frac{(2 \times L_R)}{L_R + L_{C2}} \quad (3.12) \]

On simplifying the equation 3.12, we have the equation for \( L_{C2} \):

\[ L_{C2} = \left[\left(\frac{2L_R}{X}\right) - L_R\right] \quad (3.13) \]

where \( L_R \) and \( X \) are known values.

From the above relation of \( L_{C2} \) as in equation 3.13, the value of \( L_{C1} \) can be obtained as

\[ L_{C1} = L_R - \frac{L_R}{X} \quad (3.14) \]

A Matlab program is developed wherein the input will be the length and cross-section area of the reference ligament and the pre-defined ratio of strains in the middle portion of each of the active ligament to the strain in the reference ligament are provided as inputs [38].

**Inputs:**

The length of the reference ligament: 20 mm

The cross-section of reference ligament: 5 sq.mm

The number of active ligaments: 5
The strain ratios of each of the ligament with respect to the reference ligament in the order of increasing magnitude are given as 1.2, 1.3, 1.5, 1.6, 1.7 for the 5 active ligaments i.e., the order of the strain ratios are such that, as the size of the middle portion of the active ligaments increases, the strain ratio decreases. In other words, the higher strain ratio corresponds to the middle portion of the active ligament with smaller size. The output corresponding above given inputs are listed in Table 3.2. From Table 3.2, it can be seen that as the strain ratio increases, the length of the middle portion decreases. This means the ligament with the shorter length will have larger strain and hence will fail first, assuming all ligaments have the same area of cross-section. From the table 3.3, it is obvious that as the length of the middle portion of the ligament decreases, the length of outer portion increases in the same proportion. This explanation can be strengthened with the table 3.4.

Table 3.2: The length of the middle portion of the active ligaments as output

<table>
<thead>
<tr>
<th>Ligament C_1</th>
<th>Ligament C_2</th>
<th>Ligament C_3</th>
<th>Ligament C_4</th>
<th>Ligament C_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.33</td>
<td>10.77</td>
<td>6.67</td>
<td>5</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Table 3.3: The length of the outer portion of the active ligaments as output

<table>
<thead>
<tr>
<th>Ligament C_1</th>
<th>Ligament C_2</th>
<th>Ligament C_3</th>
<th>Ligament C_4</th>
<th>Ligament C_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.33</td>
<td>4.61</td>
<td>6.67</td>
<td>7.5</td>
<td>8.23</td>
</tr>
</tbody>
</table>

Table 3.4: The total length of the active ligaments calculated

<table>
<thead>
<tr>
<th>Ligament C_1</th>
<th>Ligament C_2</th>
<th>Ligament C_3</th>
<th>Ligament C_4</th>
<th>Ligament C_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

As mentioned before, the length of the outer portion of each ligament increase in the same proportion in which the length of the middle portion decreases resulting in constant value for the total length of the ligament which tallies with the input value of the length of the reference ligament (L_R) which is same as the total length of each of the ligaments. Hence we can conclude that the derivation and the computer program to be flawless.

UNCLASSIFIED: Distribution Statement A. Approved for public release
Further investigation has been done in order for finalizing the layout design of the fatigue sensor. Elastic finite element simulations have been performed to study the strain / stress behavior across the width of each of the ligaments on the design with symmetry in the active ligaments. After some insight analysis and by making some changes to the layout of the sensor coupon, a final design is proposed. The final design has two reference ligaments on one end of the coupon and a series of active ligaments with varying middle region. The active ligaments are symmetrical about their middle region. The coupon as a whole is symmetrical with the line of symmetry being the center (vertically) of the smallest ligament. A more detailed discussion on the elastic finite element simulations of the final design are presented in the following sections.

3.3 Numerical Simulations

Analytical modeling of the sensor described in the previous section, provided the basis for design calculations required for determining the validity of the sensing principle. However, it needs further simulations and more comprehensive design analysis to understand its practical applicability as well as limitations. Hence, this section describes the efforts in the numerical simulation of the operational characteristics of the designed sensor.

3.3.1 Elastic finite element simulations

The elastic finite element simulations of the fatigue gage response was performed using commercially available FEA software COMSOL 3.5a [38,39]. The “Structural Mechanics module” in Comsol was used as it deals with the analysis of stresses and strains in mechanical structures subjected to different kinds of loads. The main objective of this analysis is to determine and identify the important design parameters and understand their effect on the strain experienced by different active ligaments. This also helps in optimizing different dimensional parameters of the designed gage. In these simulations, the coupon when subjected to displacements, in such a way that the deformation is confined to the elastic region only.

UNCLASSIFIED: Distribution Statement A. Approved for public release
The boundary conditions adopted for in the finite element analysis simulation of the fatigue sensor can be seen in Figure 3.3. The simulations done at this stage are just the two dimensional model and as seen from the Figure 3.3, the bottom end of the coupon is constrained in all directions and a displacement is applied on the upper edge of the coupon which results in deformation of the ligaments. In actual working environment when the sensor is attached onto the structure, it experiences the same displacements as that in the structure at the point where the sensor is placed. In order to simulate this effect on the sensor, a displacement is applied on the upper edge of the coupon.

In the elastic finite element simulations, the mechanical properties of the sensor material such as the elastic modulus, poisons ratio and density are used as input parameters (shown in Table 3.5). In this case, the material for the sensor considered is aluminum 1100 alloy. After the properties of the material are provided, the boundary conditions are specified and then the model is meshed. The default setting of triangular meshing was performed with the maximum element size as 9.38 mm and maintaining the minimum element size as 0.0042 mm. The mesh in the region of interest i.e., the middle region of the ligaments is further refined and care was taken such that the size of the mesh had no effect on the results obtained. The displacement applied on the top edge of the sensor is equal to 1% of the length of the reference ligament in equal increment of 2 mm. The output that is analyzed is the strain distribution across the width of each of the ligaments at the middle portion which is represented by the dotted line in Figure 3.3.

Table 3.5: Elastic material properties of Al 1100 alloy

<table>
<thead>
<tr>
<th>Material property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Modulus, $E$</td>
<td>$69 \text{ GPa}$</td>
</tr>
<tr>
<td>Poisson’s ratio, $\mu$</td>
<td>$0.33$</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>$2710 \text{ Kg/m}^3$</td>
</tr>
</tbody>
</table>
The important parameters identified in the designed gage configuration are:
1. Ligament geometry of the gage
2. Symmetry of the gage

The effect of these parameters on the strain distribution across different ligaments is analyzed using the FEA simulation and these results are discussed further.

3.3.1.1 Ligament geometry of the gage

The ligament layout of the gage configuration plays a significant role obtaining proper strain distribution in the reference ligament. Figure 3.4 shows the strain distribution in the middle portion of the reference ligament (R) from Figure 3.3. The vertical axis of the plot in Figure 3.4 shows the normal strain in Y-direction (i.e., the direction of the applied displacement) and the horizontal axis shows the width of the middle portion of the reference ligament. Different lines in the plot represent displacements applied in the equal incremental steps of 2 mm. As observed from the graph, the strain distribution in the middle portion of the reference ligament is not uniform throughout the width. The maximum strain concentration is at the outer ends of the ligament and decreasing towards the inner end of the reference ligament at higher displacements which is not as desirable.

Figure 3.4: Strain distribution in reference ligament ‘R’
However, it may be observed that the range of strain variation across the width is decreasing as the applied displacement is decreased. To reduce the strain variation in the middle portion of the reference ligament, another reference ligament is added adjacent to the existing one. Figure 3.5 shows the coupon with the second reference ligament ‘R2’ in addition to the reference ligament ‘R1’.

![Figure 3.5: The coupon with two reference ligaments](image)

Figure 3.5: The coupon with two reference ligaments

![Figure 3.6: Strain distribution in the reference ligaments ‘R 1’ and ‘R 2’](image)

Figure 3.6: Strain distribution in the reference ligaments ‘R 1’ and ‘R 2’
In Figure 3.6, the left half of the plot shows the strain distribution in the outermost reference ligament (R 1), while the right half of the plot depicts strain distribution in the middle portion of the second ligament (R 2). It may be seen from the Figure 3.6 that the strain distribution in the middle portion of the second reference ligament is more uniform compared to the first reference ligament. Hence, it was found the necessity to have second reference ligament for the calculations and analysis of strain ratios. From Figures 3.4 and 3.6, it is clear that the end geometry (one or two reference ligaments) of the gage play a very important role in obtaining a more uniform strain distribution in the reference ligaments.

3.3.1.2 Symmetry of the gage

The plot in Figure 3.7 shows the strain distribution across the width of ligament 9 in Figure 3.3. It is obvious from the Figure 3.7 that the strain distribution across the width of the ligament is not uniform at higher displacements. For example, at the highest displacement applied (0.01 m), a maximum strain of around 0.015 is observed at the left edge of the ligament which decreases to a minimum value of around 0.011 in the middle region and then an increase of strain upto a value of 0.013 on the right edge of the ligament is observed. This can lead to the ligament damage in extreme case especially having a strain difference of ±0.004 at a given displacement. Moreover, the strain the middle region of the active ligament is related to the strain in the critical region of the component by a strain magnification factor. This is defined by the ratio of the strain in the active ligament to the strain in the reference ligament. In order to achieve this strain magnification, the strain distribution across the width of the active ligaments should be uniform. Hence this necessitated further improvement in design, which is carried out through using double symmetry.
Figure 3.7: The strain distribution in the smallest ligament of the coupon without symmetry.

Figure 3.8 shows an improved configuration of the gage with a double symmetrical arrangement. The gage in Figure 3.8 has two reference ligaments and five active ligaments (i.e., L1, L2, L3, L4 and L5) in the left half of the gage and the other half is its mirror image, which constitutes symmetry about the ligament 5.

Figure 3.8: Fatigue sensor with a double symmetry design

UNCLASSIFIED: Distribution Statement A. Approved for public release
Figure 3.9: Strain distribution in the ligament # 4 of the coupon with double symmetry.

Figure 3.9 shows the strain distribution in the middle portion of the ligament 5 in the gage with double symmetry. When the double symmetrical design is considered, it can be observed from Figure 3.9, that the strain in the active ligament is uniform at lower displacement applied and as the displacement is increased, the strain distribution becomes slightly non-uniform but symmetrical with respect to the middle region of the ligament. The strain difference is less than ±0.001 which is acceptable.

Another parameter that has found to have significant influence on the strain distribution in the active ligaments within the gage is the fillet radius. Larger the fillet radius resulted in more uniform stress / strain distribution across the width of the active ligament in the middle region. The fillet radius was chosen such a way as to have uniform strain distribution across the width of the active ligaments and clearly distinguish the outer and middle regions of the same.

The elastic finite element simulations were performed on the sensor coupon to define a better layout of the design of the fatigue sensor which would have the required functional
abilities. Finally, the design with the double symmetry i.e., the coupon with symmetry about the active ligament with smallest middle region is chosen. Also to note that each of the active ligaments are symmetrical (vertically) about their middle region. In the following stage, the sensor characteristics with respect to cyclic loading conditions need to be evaluated. This necessitates the elasto-plastic simulations, which involves the evaluation of the strain behavior from the elastic region of the standard stress-strain curve to the plastic region.

3.3.2 Elastic-plastic FEA simulations

The elastic-plastic simulations were performed commercially available FEA software ANSYS 10 was used to perform these simulations. Although COMSOL has been used in the initial conceptual design, ANSYS is found to be more efficient for the later stage cyclic loading condition simulations. These simulations were performed in two different modes i.e., bilinear and Multilinear with kinematic hardening model for the reason that this works well in cases of cyclic loadings. The geometry created is 2D with plane stress condition as the loads / displacements applied act in the plane parallel to the sensor.

In the previous section, the effect of monotonic elastic loading in which the sensor material is loaded by applying a tensile load is studied. As the applied loads exceed the yield strength of the material permanent plastic stresses induced in the sensor. To take these elastic and plastic stresses into account and model the sensor, Ramberg-Osgood relation (equation 2.6) is used as mentioned in Section 2.1. A theoretical stress - strain curve shown in Figure 3.10 is plotted to depict the bilinear and multilinear characteristics, as these two modes are considered for the simulation over the entire range of strains.

The Ramberg-Osgood relation depicts a non-linear stress-strain material behavior as shown by the red curve in Figure 3.10. In this case, there is no specific point that defines the end of the elastic zone and the onset of progression into the plastic zone. In this case, the yield strength of the material is taken as the strain corresponding to 0.2% offset strain (shown by green dotted line). The bilinear stress-strain material behavior, shown
by dotted blue line in Figure 3.10 is the result of a slight modification of the multilinear curve. In this case, the elastic region of the stress vs. strain curve remains a straight line until the yield point which in this case is a specified point and then the onset of the plastic region of the curve is another straight line from the yield point but with a lesser slope than that of its elastic counterpart (shown as black lines in Figure 3.10). The ordinate of the point of intersection of the two straight lines is the yield point of the elasto-plastic bilinear curve. In the following sections, the results of the finite element simulations of the 2-dimensional geometry of the sensor coupon are discussed.

The finite element simulations are performed for a two dimensional model of the fatigue sensor using a bilinear material model. Aluminum and stainless steel are used as sensor materials for this simulation. The boundary conditions on the gage are that the bottom end is fixed and cyclic displacements applied on the upper end of the coupon, as depicted in Figure 3.11. The displacements applied are tensile followed by compressive which count to about 1 cycle. The reason for applying 1 cycle of loading is because the material properties considered are stabilized cyclic properties.
The displacement applied on the specimen is calculated based on the following equation:

$$\Delta L = \frac{\sigma_0}{E} \times L$$  \hspace{1cm} (3.15)

where, $\Delta L$ is the displacement applied on the upper end of the coupon, $\sigma_0$ and $E$ are the yield strength and Young’s modulus of the sensor material and $L$ is the length (vertical) of the reference ligament. This equation derived from the Hooke’s law and the stress value is chosen to be equal to the yield strength of the material in order to have the deformation of the material into the plastic zone which is past the yield strength of the material comprising the coupon. Figure 3.12 shows the nodes created in fatigue gage layout after the meshing in ANSYS. The element type used was PLANE 82 which is a higher order version of the regular 4-node 2D element. This element type provides more accurate results for quadrilateral automatic mesh and can be used for irregular shapes [40]. The default triangular meshing was used with the mesh size around 2% to 5% the length of the respective edge in order to obtain a fine mesh. As a compromise between having a finer mesh and the time and memory consumed for the computation of the model, care was taken with respect to the mesh size so as to not affect the results.
Figure 3.12: Nodes created after meshing the 2D model in Ansys

Figure 3.13 shows the stress vs. total strain plot (using bilinear behavior) for the reference ligament and the active ligaments 1 to 4 when monotonic loading is applied on the sensor. In this case, the displacement applied on the sensor is such that only elastic stresses / strains are generated in the reference ligament. Even when the reference ligament is confined to elastic limit of the stress-strain behavior, it can be seen from the Figure 3.13, that all active ligaments experience some amount of permanent plastic strain in the middle portion of these ligaments. The magnitude of the strain induced in the smallest ligament (i.e., Ligament 4) is the highest among all other active ligaments. The strains induced in the other active ligaments decrease as the size of the middle portion (in the order from Ligament 3 to Ligament 1) increases.

The effect of cyclic loading of the sensor is simulated to understand its stress-strain behavior over the complete range of strains. Alternating tensile and compressive displacements were applied on the upper edge of the coupon with the bottom edge being fixed. It may be noted that the loading pattern in this case is time independent.
Figure 3.13: Plot of stress vs. total strain

Figure 3.14: Multilinear hysteresis curve from the fatigue sensor simulation for aluminum

The Figure 3.14 shows the stress vs. strain for aluminum for the multilinear (non-linear) material behavior. It can be observed from the plots that the strain induced in the active ligaments are greater than the strain in the reference ligaments. The strain in the active ligaments increase in the order from the ligament with larger length \( L_{\text{mid}} \) in the active ligament to the smaller \( L_{\text{mid}} \) (i.e. Ligament 1 to Ligament 4). This behavior
depicts one of the unique features of the sensor. The sensor can be placed at a certain
distance away from the critical location (stress concentration or damage initiation zone)
in the structure but would still be able to mimic the conditions at the damage initiation
zone. Even if the sensor is placed at a location on the structure where the stresses /
strains are in the elastic region of the material behavior, the active ligaments would
undergo higher plastic strains, which would represent the damage initiation zones in the
structure.

3.4 Effect of Ligament Dimensions on Strain Ratio

The effect of the ligament dimensions on the strain ratio were done by performing
simple elastic FEA simulations using the “Structural Mechanics module” in Comsol 3.5a.
The FEA was done on various active ligaments by varying the dimensions like width of
the middle region of the active ligaments (w), width of the outer region of the active
ligaments (W), length of the testing region of the active ligaments (LA).

Figure 3.15: Dimensional nomenclature of 2D model for sensitivity of strain ratio analysis
The 2D geometry consists of an active ligament and a pair of reference ligaments on either sides of the active ligament as shown in Figure 3.15 which depicts a schematic of the nomenclature of the dimensional parameter used in the FEA simulations. This helps in the design of the fatigue sensor based on the dimensional limitation for a particular application and the required strain ratio for each of the active ligaments.

![Figure 3.16](image-url)

Figure 3.16: Plot of strain ratios of active ligaments for different 'L' ratio; (a) Length ratio of 2 (b) Length ratio of 2.5 (c) Length ratio of 4 (d) Length ratio of 5

In the current analysis, the length of the reference ligament ($L_R$) has been kept constant at 2.5 mm. The width of the outer region of the active ligaments ($W$) considered are 0.4mm, 0.5mm and 0.6mm. Different values for the width of the middle portion of the active ligaments ($w$) were chosen such that the width ratio i.e., the ratio “$W/w$” varies from 1 to 10. Similarly, the length of the testing region of the active ligaments were chosen such that the length ratio i.e., $L_R/L_A$ obtained are 2, 2.5, 4 and 5. The

UNCLASSIFIED: Distribution Statement A. Approved for public release
FEA model was subjected to monotonic tensile displacement such that the ligaments are subjected to displacements that correspond to the elastic region of the material behavior. In this case, the displacements applied are 1% of the length of the reference ligament, which is 25 microns.

Figure 3.16 (a), (b), (c) and (d) represent the plots for different ‘L’ ratios 2, 2.5, 4 and 5 respectively. Figure 3.16 (a) shows that the strain ratio increases exponentially as the width ratio increases. This can be easily explained based on the difference in widths between the center of the ligaments to the outer region. When this difference is negligible, it is expected to have a strain ratio of 1 which is the case of reference ligament. However, as the ligament width reduces (as it happens in active ligaments) the strain ratio increases along with the width ratio for a given length ratio. This behavior is similar for all the three ligament widths 0.4, 0.54 and 0.6 plotted in Figure 3.16(a), with the overall change in the strain ratio being only ±0.03. When the length ratio is increased to 2.5 (as shown in Figure 3.16(b)), this variation in strain ratio is changed marginally for all the three widths. However the variation in strain ratio at higher width ratios, in this case being ±0.08. Comparing these with L-ratio curves 4 and 5 in Figure 3.16 (c) and (d) respectively, the observed variation in the strain ratio at higher width ratios for all the three curves (for different widths) is ±0.15.

Figure 3.17 is a re-plot of the data presented in Figure 3.16, by taking different length ratios in the same plot. In this case, Figure 3.17 (a and b) represent plots of strain ratios for widths 0.4 and 0.6 respectively. From Figure 3.17, it can be seen that the change in the length ratio has significant change in the strain ratio. For a particular value of the outer width of the active ligament, the change in the length ratio would significantly change the strain ratio of the ligament. From Figure 3.17 (a), for a width ratio (W/w) of 5 and length ratio of 5, the strain ratio obtained is 2.5. For this configuration, the value of w is 0.08 mm. For the same value of was 0.085 mm, from Figure 3.17 (b), the width ratio (W/w) obtained is 7.5. In this case, for the same length ratio of 5, the strain ratio obtained is 2.7.

UNCLASSIFIED: Distribution Statement A. Approved for public release
Figure 3.17: Plot of strain ratios with varying 'L' ratio and widths of the outer region of the active ligament (a) $W = 0.4$ mm (b) $W = 0.6$ mm

In order to achieve a significant difference in strain ratios of active ligaments, it is optimal to choose the lengths of the active ligaments with larger length ratios with respect to the reference ligament, thereby the failure of the ligaments can be achieved at wider life.
intervals. Thus, depending on the requirement of the particular application of the fatigue sensor, the dimensions of the same can be determined from the above plots. However in the present study we chose the length of the reference ligament \( (L_R) \) to be 2.5 mm and length of the smallest active ligament \( (L_A) \) to be 0.5 mm while the width of the outer region of the active ligament \( (W) \) to be 0.4 mm and the width of the middle region of the active ligament \( (w) \) to be 0.2 mm. This would give a strain ratio of 1.72, which will be equivalent to the stress concentration factor observed for a V notch test specimen that we would like to use for testing the fatigue sensor.

### 3.5 Summary

So far in this chapter, the analytical modeling and numerical simulations consisting of elastic and elastic-plastic finite element analysis on the fatigue sensor ligament have been discussed. The sensor coupon with symmetry in the active ligaments was chosen based on the analytical modeling. From the elastic simulations, it has been observed that the strain distribution in the middle portions of the reference and the active ligaments was not uniform. In order to obtain a uniform strain distribution across the width of the ligaments, several modifications were done to the initial design and included two reference ligaments with double symmetry about the smallest active ligament was chosen. Elastic-plastic finite element simulations were performed on this design to study the behavior of the sensor coupon when subjected to cyclic loading where the ligament material undergoes plastic deformation. The effect of the strain ratios on the dimensions of the ligaments were discussed by means of FEA simulations. From the curves obtained, based on the strain ratio required, the dimensions of the active ligaments can be decided to suit to the application. In the next chapter, the two methods employed for the fabrication of the prototype sensor i.e., Micro Wire - Electro Discharge Machining (\( \mu \)-Wire-EDM) and the optical lithography process conventionally used for the fabrication MEMS devices will be presented.
Chapter 4

Fabrication of the Sensor

In the previous chapter, the sensor design and simulation of its characteristics under repetitive cyclic loadings were discussed. These lead to the optimization of the design and resulted in the development of a potentially practical sensor concept. The manufacturing details of this sensor are mainly discussed in this chapter. The prototype fatigue sensors were fabricated using micro Wire-Electro-Discharge-Machining (µW-EDM) and Photolithography. Wire EDM (wire-cut EDM or wire cutting) uses a single strand metallic wire (usually brass) which is fed through the work piece, and thereby cutting the work piece at the point of contact with the metal wire. Photolithography is a fabrication process used in fabrication of parts with a dimensional scale of few microns to nanometers.

4.1 Fabrication using Micro Wire-EDM

Wire EDM (Electrical Discharge Machining) is an electro-thermal production process in which a thin single stand metal wire is fed through the thin sheets to be machined [41]. The wire is constantly fed from a spool, which is held between diamond guides on either side of the work piece. Usually the work piece is held horizontally and the wire is fed through it vertically and held between the diamond guides on the upper and lower side of the work piece. The guides are CNC controlled and move in a horizontal plane. In much advanced machines, the upper guide can move independently allowing to cut tapered...
edges in the work piece. Electro discharge machines work by eroding material in the path of electrical discharges that form an arc between an electrode tool (thin metal wire) and the work piece. As the spark jumps across the gap between the electrode and the work piece, the material is removed from both the work piece and the electrode (very minimal as compared to the material removal from the work piece). The region in the vicinity of the wire and the workpiece is exposed to the continuous flow of a dielectric fluid that would prevent possible shorting between the wire and the workpiece. Figure 4.1 shows a schematic of the EDM process.

![Figure 4.1: A schematic depicting the wire EDM process](image)

The EDM process has certain advantages compared to other conventional fabrication processes. Complex shapes can be cut using EDM that would otherwise be difficult using conventional cutting tools. This process can be used to machine components that should have low residual stresses, as it uses very low cutting forces. Extremely hard materials can also be machined while obtaining a very good surface finish.

The prototype fatigue sensors were fabricated using AGIE Excellence Micro-Wire-EDM machine (shown in Figure 4.2). The Micro-wire-EDM differs from the regular
EDM with respect to the dimensions of the electrode wire, which is typically of the order of few micrometers with machinable feature sizes also in the µm scale. The wire diameter used in this case is 0.1mm. The output quality target roughness obtained on the sensor was around 0.7 µm while maintaining the machining tolerance at 8 µm in aluminum and stainless steel. This process was used to fabricate the single ligaments of the sensor as well as the complete fatigue sensor. Figure 4.3 shows the complete sensor in aluminum, while Figure 4.4 shows the single ligament in aluminum with all the dimensional details.

Figure 4.2: A schematic depicting the wire EDM process

Figure 4.3: Prototype full sensor fabricated using Wire EDM process
4.2 Fabrication using Photo-Lithography

Photolithography is an optical method of transferring the image of geometric patterns from a photo mask on to a light sensitive photoresist on a substrate. It is essentially the same process that is used in lithographic printing. A series of chemical treatments then either engraves the exposure pattern into, or enables deposition of a new material in the desired pattern on the material underneath the photoresist. This process is widely used for the mass fabrication of the MEMS components, ICs etc.

These fatigue sensor structures were fabricated with nickel on silicon substrates using photolithography and electro-plating. The lithography process is performed in a class 100 clean room facility in the Parkview campus of Western Michigan University. The
photolithography process in general has the following steps which will further be discussed in detail.

1. Cleaning and preparation of the substrate
2. Sputtering of thin film adhesive and conductive layers
3. Spin coating of photo-resist
4. Pre-Bake (Soft Bake)
5. Mask fabrication
6. Exposure
7. Development
8. Electroplating
9. Removing the resist
10. Sensor release

4.2.1 Surface preparation of the substrate

Fabrication of micro fatigue sensors is started with cleaning of one side polished 300 µm thick, 2” diameter <100> single crystal Si wafers. The cleaning of the silicon wafers is done following a standard “RCA Cleaning” [42,43]. This process involves handling of some dangerous chemicals and so the procedure has to be done in fume hood following the required safety measures. The list of chemicals and equipment required for this process are Hydrofluoric acid (HF), Hydrochloric acid (HCl), Hydrogen Peroxide (H₂O₂) and Ammonium Hydroxide (NH₄OH), hot plate with magnetic stirrer, wafer holder, tweezers for handling the silicon wafers, timer device, thermometer for measuring the temperature of the solutions. The RCA cleaning of wafers involves three important steps, as described below.

1. Cleaning in organic solution: This step required preparation of an organic solution. Hydrogen Peroxide (H₂O₂) and Ammonium Hydroxide (NH₄OH) are taken in the ratio 1:1 and diluted in DI water (5 times in volume). The silicon wafers are immersed in this solution maintained at 80°C for 15 minutes, while
continuously stirring. This process removes any organic contaminants like dust particles, grease etc. present on the wafer surface. The wafers are then removed from the solution and rinsed with DI water and air dried using dry nitrogen gas.

2. Cleaning in HF solution: The (33 concentrated) hydrofluoric acid (HF) is diluted in DI water (1:20). The RCA I cleaned wafers are immersed into the HF solution for about 45 - 60 minutes. This solution removes surface oxide layer on the Si wafers. The wafers are taken out and rinsed with DI water and air dried in dry nitrogen gas.

3. Ionic Cleaning: The ionic solution contains HCl, H2O2 and DI water in the ratios of 1:1:6 respectively. This solution is maintained at 80°C. Already cleaned wafers from the previous steps, are immersed in the ionic solution for about 20 - 30 minutes while stirring the solution continuously. This process removes any ionic or heavy metallic contaminants from the silicon wafers. Once the immersion process is done, the wafers are rinsed finally and air dried in nitrogen.

These cleaned wafers are used for sensor fabrication using sputtering, lithography and electroplating.

### 4.2.2 Sputtering of thin film adhesive and conductive layers

Since the final sensor structures are built on the silicon substrate by means of electroplating, there is a need to have a conducting layer on the substrate. Copper is one of the most widely used conducting seed layers for electroplating. This requires an adhesive layer between the silicon substrate and conducting later, in order to promote strong adhesion between the conducting layer and substrate, as these will be subjected to different processing conditions during the lithography and electroplating. Titanium is commonly used as the adhesive promoting layer on Si. Therefore, thin films of titanium followed by copper are sputter deposited on to the silicon substrate.

The deposition of these thin films are done by “Physical Vapor Deposition (PVD)”, in particular, “Magnetron sputtering”. Physical Vapor Deposition is a vacuum deposition
process in which the material to be deposited is converted into vapor / atomic state and condensed on to the substrate. This involves purely physical processes such as high temperature evaporation in vacuum or plasma based sputtering technique. Sputtering is removal of atoms from a target (material to be deposited) as a result of energy transfer from energetic ions bombarding the surface. The ejected atoms condense on the surface of the substrate placed opposite to the target. When power is supplied to a magnetron by applying negative voltage (around -300 volts.) in an inert gas atmosphere (e.g. Argon) to the target, it attracts the positive ions from the inert gas to the target surface. When the positive ion collides with atoms at the surface of the target, they transfer energy to the surface atoms. Whenever the energy transferred is greater than the surface binding energy, the target atoms are ejected out, which form a layer on the substrate surface. Figure 4.5 shows the schematic of magnetron sputtering process.

Figure 4.5: A schematic of the PVD process
The silicon wafers after the RCA cleaning, are transferred to the magnetic sputtering system (PVD 75, Kurt J. Lesker Inc., U.S.A.) to perform the thin film coating of the adhesive layer (Titanium) followed by a conductive layer (Copper). As this is a dual magnetron system, titanium and copper sputtering targets (3” in diameter and ¼” thick circular discs) are pre-loaded along with the cleaned substrates on the substrate holder. This facilitates the deposition of both layers without releasing vacuum in the system. Initially the system is evacuated to a base pressure of $5 \times 10^{-5}$ Torr before introducing ultra high purity Argon at the operating pressure ($5 \times 10^{-2}$ Torr). Sputtering of the titanium was performed operating the power supply in constant current mode at 300 mA. depositing the Ti layer for 5 minutes yielded a thickness around 15-20 nm. After the Ti sputtering, Cu layer was deposited at a current of 300 mA for about 20 minutes which yielded a thickness of around 100-200 nm.

After sputtering, the silicon wafers are subjected to dehydration bake. The dehydration bake is performed in a convective oven at a temperature of $100 - 120^\circ C$ for 30 minutes. The purpose of the dehydration bake is to remove any trapped moisture in the thin films. Figure 4.6 shows a cross-sectional layout of the silicon substrate after the two layers deposited. Figure 4.7 shows a picture of the PVD 75 magnetron sputtering system used for the deposition of the seed layers with the inset showing the interior of the vacuum chamber of the PVD 75 sputtering machine.

![Figure 4.6: Cross-sectional layout of the silicon substrate with Ti and Cu layers](image)

UNCLASSIFIED: Distribution Statement A. Approved for public release
4.2.3 Lithography process

4.2.3.1 Spinning of photo-resist

Photo resist is an organic liquid that is used in lithography to transfer the image of a pattern from a mask. This is used to form a mold on the silicon substrate to be used in electroplating to form the required structures. A negative, epoxy-type, near UV photo-resist based on EPON SU-8 (MicroChem Inc., U.S.A.) epoxy resin that has been originally developed by IBM is used in this fabrication process. It is a very viscous polymer that can be spun or spread over a thickness ranging from 1 µm to couple of millimeters. It can be used to pattern high aspect ratio structures. Some of the features of the SU-8 are high contrast, high aspect ratio imaging, almost vertical sidewalls and fast photo speeds.
for high volume manufacture. In the current lithography process, since electroplating needs to be performed at the end, a layer of hexa(dimethyl)silazane (HDMS) should be spun prior to spinning the photo-resist. The spinning of the HDMS is performed at a spin speed of 3000 rpm for about 30 seconds. The spinning of the HMDS is immediately followed by the spinning of the photo-resist (SU-8). The spinning of the resist is done in two stages. In the first stage the resist is spun at a speed of 500 rpm for about 15 seconds followed by the second stage spinning at a speed of 2500 rpm for 30 seconds. A few drops of SU-8 resist is initially put in the center of the silicon wafer. During the first stage spinning, the resist is made to spread evenly over the entire surface of the silicon wafer. In the second stage spinning, the required thickness of the resist is attained. This particular combination of the spinning parameters would result in a thickness of 50 µm of the resist layer as prescribed by the manufacturer. Figures 4.8 (a) and (b) shows the schematic of the spinning process and the cross-sectional view of the silicon wafer with the resist respectively.

Figure 4.8: Photo-resist spinning [44]; (a) A schematic of the photo-resist spinning process; (b) Cross-sectional layout of the silicon substrate with photoresist
4.2.3.2 Soft Bake

The photo-resist layer is subjected to soft bake to remove the solvent in the photo-resist to prevent it from sticking to the contact mask in the next step. The parameters for the soft bake procedure should be carefully chosen. If the resist is under baked, it would result in improper profile of the resist and on the other hand if the resist over baked, it would destroy the photo-active compound in the resist and thereby reducing its sensitivity. These are generally supplied by the photo-resist manufacturer. The soft bake is done using a hot plate in two stages. In the first stage, the wafer is placed on the hot plate maintained at 65°C for 5 minutes and the temperature is increased to 95°C and then maintained at this temperature for 20 minutes. Figure 4.9, shows the process of the soft bake.

![Figure 4.9: A schematic of the soft bake process [44]](image)

4.2.3.3 Mask Fabrication

The fabrication of the mask is a mini lithography process in itself. The mask used in the lithography contains the pattern of the structure that has to be transferred on to the silicon wafer. There are two basic types of masks used in the lithography. They are positive and negative masks. The positive and negative masks differ in the type of the
image pattern on it. The type of the mask to be used generally depends on the type of photo resist being used for the lithography process. In this case, a negative mask is used, to facilitate the use of negative resist (SU-8). Generally, the photo masks for optical lithography are made of either soda lime glass or quartz and coated with a layer of sputtered chromium (Cr) with the thickness of the layer around 100 nm. A layer of resist (PMMA, a positive resist) is spun on the Cr layer on the glass plate. The blank mask plates can be obtained commercially and they come ready with the Cr layer and the resist layer.

In the first step of the mask fabrication, the pattern is created using AutoCAD drawing tool. The pattern created in this step should be an antipode of the actual pattern required on the mask. Thus created pattern is printed on a transparent sheet which would be used as a masking device to transfer the pattern on to the Cr coated glass plate in the further steps. It may be noted that this kind of process is useful as long as the minimum feature size is around 50 – 100 µm. The Figure 4.10 shows the layout of the pattern created on the transparency (primary mask).

Figure 4.10: Pattern layout on the primary mask (transparency)
The image on the primary mask is transferred on to the resist spun blank Cr coated glass plate by exposing it using either optical or electron beam lithography tool. The exposure process is done by MA/BA 6 mask aligner (SÜSS MicroTec AG) in the Lurie Nanofabrication Facility at University of Michigan, Ann Arbor. Since, the resist on the glass plate is PMMA (positive resist), the regions of the resist that are exposed to the light of desired wavelength, breaks the bonds in the molecular chain, which results in its removal in the development step. After exposure, the resist is developed by immersing the glass plate in a positive resist developer solution, which removes the exposed regions of the resist. This will leave parts of the mask plate with the resist and the rest of the plate with the Cr layer exposed. The mask plate is immersed in a chromium etchant solution. This would etch (remove) any of the exposed chromium on the mask plate leaving behind untouched, the chromium masked by the unexposed regions of the resist. The remaining photo-resist is then removed by immersing the mask plate in PMMA resist removal solution which removes the photo-resist from the mask plate leaving behind the required pattern of the Cr on the mask plate. The resulting mask plate is shown in Figure 4.11 (a). This layout consists of 4 regions as depicted in the figure. Each region corresponds to the fatigue sensor for different thicknesses. Figure 4.11 (b) shows the high magnification of the region 1 from Figure 4.11 (a).

The final mask was obtained on a 5" × 5" soda lime glass plate. The mask layout has four regions (numbered 1 through 4 as shown in Figure 4.10. Each of the four regions are for different thicknesses (25 µm, 50 µm, 75 µm and 120 µm respectively) of the final fatigue sensor. This particular layout has been made in order to make provision to fabricate the prototype fatigue sensors of different thicknesses using the same mask. Each of the four regions on the mask plate are encompassed in a circular ring of outer diameter of 2 inches which serves as contact ring during the electroplating process.
Figure 4.11: Mask fabrication; (a) The layout of the final mask plate; (b) High magnification picture of region 1 in the final mask

4.2.3.4 Exposure and Development

The Si wafer substrate with resist layer of required thickness is exposed to UV light in a mask aligner (MA/BA 6 mask aligner: SÜSS MicroTec AG) in order to transfer the pattern on the mask on to the resist. Since, 2 inches diameter silicon wafers are used.
for fabricating the fatigue sensors, the pattern from one of the four regions on the mask is first exposed. Figure 4.12 shows the picture of the MA 6 mask aligner used for the exposure.

![Image of the MA 6 mask aligner](image1.png)

**Figure 4.12: A picture of the MA 6 mask aligner**

The required thickness of the fatigue sensors is 50 µm for which, the silicon wafer must be aligned such that the outer edge of the silicon wafer should coincide precisely with the outer circle of the region 2 on the mask plate. This is done in the mask aligner with the aid of proper in-built optics. Once they are aligned, the silicon wafer and the mask are brought into contact and vacuum is created between the two faces in order to have a perfect contact. The silicon wafer with the resist is exposed to UV radiation through the mask plate. The exposure dosage for this particular photoresist (SU-8 2050) should be around $150 - 210 \text{ mJ/cm}^2$ and the time required for the exposure is about 15 seconds as per the manufacturer’s specifications. Since the mask layout has some transparent regions and opaque regions, there will be different areas on the resist that are exposed. As SU-8 is a negative resist, the areas exposed to the UV light strengthens the bonds in the polymeric chain compared to the unexposed regions.

*UNCLASSIFIED: Distribution Statement A. Approved for public release*
Immediately after the exposure silicon wafer is subjected to a two step Post-exposure bake (PEB) by placing it on a hot plate. Initially the wafer is heated at $65^\circ C$ for 2 minutes followed by the second stage of heating at a temperature of $95^\circ C$ for 10 minutes. The post exposure bake is needed to selectively cross link the exposed portions of the resist (SU 8). The two step process helps in minimizing the residual stresses during the cross-linking. Exposure time and temperature were optimized to achieve optimum cross-link conditions. Post exposure bake also helps in minimizing the unwanted reactions and effects during electroplating where the resist mold is exposed to aggressive acidic environment. The schematic of the PEB procedure is shown in Figure 4.13.

![Schematic of PEB procedure](image)

Figure 4.13: A schematic of the PEB procedure [44]

After the PEB, the wafer with resist is immersed in SU-8 developer solution (1-Methoxy 2-Propyl acetate). The developing of the resist means the removal of the weakly bonded regions of the photoresist from the unexposed regions. In order to have a properly developed resist, the silicon wafer should be subjected to strong agitation while immersed in the developer solution. The silicon wafer can be removed from the solution and ob-
served under optical microscope in timely intervals to observe if the resist is properly developed. Figures 4.14 (a) and (b) shows schematics of the 2D cross-sectional view of the exposure process and development processes, and 3D schematic view of the developed resist.

Figure 4.14: Exposure and development process [44]. (a) A schematic of the exposure and the development process; (b) A schematic of the 3D view of the developed resist

4.2.4 Electroplating

Electroplating is a process generally used for producing thick metallic micro-structures on a given substrates. The set-up used to perform the electroplating is referred to as an “electrolytic cell”. An electrolytic cell consists of a cathode (object to be coated), an anode
(made of the metal to be coated) and a bath of electrolyte solution into which both the cathode and the anode are immersed (see Figure 4.15). Both the anode (connected to +ve terminal of power supply) and the cathode (connected to the -ve terminal of the power supply) are connected to an external power supply which supplies a direct current to the anode and there by oxidizing the metal that comprise it and allowing them to be dissolved in the electrolyte solution. The dissolved metal ions in the electrolyte solution are reduced at the interface between the solution and the cathode, resulting in the deposition of the metal ions on the cathode. In an electroplating process, the rate at which the anode is dissolved is equal to the rate at which the cathode is plated which is based on the current flowing through the circuit. A voltmeter is connected in parallel to the power supply and an ammeter in series to measure the voltage and current flowing through the circuit respectively. Figure 4.15 shows a schematic of the electrolytic cell.

![Figure 4.15: A schematic of electrolytic cell setup](image)

The silicon wafer with metallic seed layers (Ti & Cu) and photo-resist mold is used in the electroplating step. The plating is done in the regions where the Cu conducting layer is exposed within the photo-resist mold. This is used as the cathode since the
material has to be plated on to it. The prototype fatigue sensors are made of nickel and hence a small square metallic piece of nickel \((2'' \times 2'' \times 1/24'')\) is used as anode. The electrolyte used in this case is Nickel Sulfamate \((Ni(SO_3NH_2)_2)\) also called as Nickel bis (sulphamidate) and Sulfamic acid nickel(2+) with a pH in the range of 4.4 - 4.7. This plating solution has certain advantages compared to the other nickel plating solutions. It is capable of producing stress free deposits than other nickel plating baths and also produce ductile fine grained hard deposit. It also has high deposition rate and can be operated at high current densities. Figure 4.16 (a) shows the electroplating setup and Figure 4.16 (b) shows the anode and the cathode used in the electroplating process. The cathode consists of the silicon wafer secured inside a custom built jig. The jig has a metallic ring inside, placed such a way that it touches the circular contact ring on the outer periphery of the Si wafer. A conducting wire connects this contact ring to the power supply through the hollow stem which is a part of the jig.

There are certain precautions to be taken for the electroplating process. The electrolyte should be maintained at a temperature of \(48^0C\) during the entire plating time and subjected to continuous stirring by placing a magnetic stirrer in the bath. This ensures uniform composition in the entire volume of the bath and the temperature is also uniform over the volume. The \(pH\) of the plating solution is continuously monitored and always maintained around 4.5. The current to the cathode is calculated based on the current density and the total plating area on the cathode, which determines the number of sensor structures to be plated. The following parameters were employed for the electroplating process:

- Area of one sensor = 25.2 \(mm^2\)
- Total number of sensors = 24
- Total plating area = 7.8576 \(cm^2\)
- Current density (according to manufacturer’s specs.) = 10 \(mA/cm^2\)
- Current to be supplied to the anode = 78.58 mA
- Deposition rate = (8-10) \(\mu m/hour\)
- Total duration of the plating \(\approx 6\) hours

UNCLASSIFIED: Distribution Statement A. Approved for public release
Figure 4.16: Electroplating setup. (a) Electroplating set-up with the power supply; (b) A picture of the anode and cathode used in the electroplating.

The electroplating of nickel is done in a carefully controlled clean room environment and monitoring the above parameters. Figure 4.17 (a & b) shows a schematic of the 2D cross-sectional view of the Ni plated on the silicon wafer along with a 3D view respectively.
4.2.5 Resist removal and release of sensors

After completing the electroplating process, the silicon wafer is removed from the electrolyte, rinsed with DI water to remove any residue of the acidic solution and then air dried with dry nitrogen. The removal of the resist is done either by spraying or immersing the silicon wafer with the plated structures, in a solution called “Remover PG” which is commercially available at MicroChem Corp. Care is taken at all times such that the bath temperature is maintained at less than \(80^\circ C\) since, the flash point of the Remover PG is \(88^\circ C\) [44]. The silicon wafer while immersed in the Remover PG solution, should be subjected to mechanical or ultrasonic agitation which will enhance the physical transport of swollen / dissolved resist away from the wafer [44]. After the complete removal of the resist, the wafer with structures is rinsed in Iso-propyl alcohol (IPA) and DI water to remove all residues. The silicon wafer is blow dried in dry nitrogen. Figure 4.18 (a & b) shows a schematic of 2D and 3D views of the silicon wafer with the plated material after the resist is removed.
Figure 4.18: A schematic of the 2D and 3D views of the silicon wafer after resist removal step

The sacrificial removal of the conducting seed layer (PVD sputtered Cu) constitutes the final step in releasing the Ni fatigue sensor structures. The etchant used for the removal of copper is 30% Ammonium per sulfate (APS). The silicon wafer is immersed in the etchant which is subjected to continuous stirring. At first an etchant solution of 10% APS, which was found to have a small etch rate, that we count not observe significant etching even after 25 hours. The concentration of the etchant solution was increased to 30% in 5 hour time steps. The copper conducting seed layer was completely etched after 16 hours and the Ni structures started to float in the etchant solution one after the other. Once the etching is completely done, the released Ni structures were rinsed in IPA and then in DI water to remove any traces of the etchant. The structures were then subjected to blow drying in dry nitrogen. Figure 4.19 shows the picture of one such released Ni structures. The released Ni structures were observed under optical microscope to check the dimensional accuracy of the features and the dimensions of the features obtained were very close to the designed values to within ±2%. Figure 4.20 shows the optical microscope images of the one of the released Ni structures.
Figure 4.19: Picture of one of the released Ni structures

Figure 4.20: Optical microscope image of the released sensor
4.3 Summary

So far in this chapter, the fabrication methods employed to fabricate the fatigue sensors were discussed. The fabrication processes used are Micro Wire-EDM and UV-lithography. The former was used to fabricate single ligaments and full sensor in Al 1100 and SS 304. The fatigue sensors fabricated using UV-lithography are electroplated Ni. The overall footprint area of the full fatigue sensors obtained are around 5.6 mm in width and 8 mm in length. The UV-lithography was performed in Class 100 clean room. The fabricated prototype samples were also observed in optical microscope and SEM to check the dimensional accuracy of the features. In the next chapter, various aspects pertaining to the experimental testing of the fatigue sensors are discussed. In the first part, various methods employed to determine the gluing region (the solid region on the top and bottom part of the ligaments) of the fatigue sensor are presented. Experimental testing of the single ligaments and full sensors will be presented. The results from the experimental testing will be supported by validation using FEA simulations.
5.1 Design Requirements

The design and fabrication of the fatigue sensors is followed by the work that led to installation and testing. Having performed the finite element simulations and the fabrication of the prototype sensors, its installation on a specimen for testing required the selection of the suitable adhesive for attaching it on to the test specimen. As the structure would be subjected to variable loading conditions and exposed to discrete ambient conditions, the adhesive should not only be able to withstand these test conditions, at the same time transmitting the loading variations to the sensor, without any constraints. The sensor material is typically a metal like aluminum, stainless steel, nickel, permalloy etc. This chapter describes the methodology followed in the selection of a suitable adhesive, optimization of the gluing procedure, testing methods employed and the results of preliminary testing of the single ligament sensor and final testing of the complete fatigue sensor.

5.1.1 Adhesive selection

The selection of a suitable adhesive is important because the sensor coupons after attaching onto the test structure, should remain adhered for a very long time while un-
dergoing the real time loading conditions. The adhesive de-bonding due to cyclic loading patterns can render the sensor useless, if a suitable adhesive is not chosen. Selection of an appropriate adhesive with maximum possible gluing area of the sensor could help in withstanding larger stresses and longer cycling periods, to ensure the failure of sensor before the possible de-bonding of the adhesive. For this reason, area of the gluing region and thereby the overall sensor foot-print area is decided after the selection of the most appropriate adhesive. Hence, we have selected 3 varieties of commercially available general purpose glues and 3 others that are tailor designed for bonding of strain gages. In order to identify the most suitable adhesive among these, a procedure has been designed to test the glue properties as explained in the following section.

Figure 5.1: A schematic showing the specimen for adhesive testing

The specimen for the glue testing consists of two metal plates brought in contact with one another by overlapping certain amount of the region as shown in the Figure 5.1. The side view in Figure 5.1 shows the overlapping region. The adhesive is formed as thin layer in the overlapping region on both metal plates and clamped together for a fixed time for good bonding.
The initially selected glues are “Epoxy Cement”, “Liquid Fusion” and “Super Glue” that are commercial glues. The epoxy cement comes in a two separate constituents where in one is the actual glue and the other being the catalyst or the curing agent. They are to be premixed in equal quantities just before the application. The mixture is a thick paste like substance. The next is the liquid fusion which is also commercially available and is very viscous. The third adhesive selected is super glue whose viscosity is intermediate to the previous two. The curing time of this glue is about 5 to 10 seconds along with some clamping pressure applied while curing.

The other three custom prepared glues are “M Bond 200”, “M Bond 450” and “M Bond 610” [45–47]. M Bond 200 is an adhesive that is extensively used for attaching the strain gages. The curing time for this glue is about 1 to 2 minutes under clamping pressure (thumb pressure). M bond 450 is a high performance two-component (resin and curing agent) solvent thinned epoxy system that is specially formulated for strain gage applications. It is capable of forming very strong, thin, repeatable bonds. It is formulated especially for high accuracy and elevated temperature installations. The operating temperatures is around $-452^\circ F$ to $750^\circ F$. M Bond 610 is also a two component (resin + curing agent), solvent thinned, epoxy-phenolic adhesive intended for high performance applications. It also has a wider temperature range about $-452^\circ F$ to $750^\circ F$ and has a low viscosity and capable of achieving glue films with thickness less than 0.005 mm. The only difference between the M Bond 450 and M bond 610 is that the former is well suited for environments with high humidity. A specific procedure is developed for the application of adhesive in all the cases which is described further:

1. **Surface preparation:** The purpose of surface preparation is to develop a chemically clean surface, a surface alkalinity corresponding to a pH of 7 and visible gage layout lines for locating and orienting the sensor coupon (while placing the coupon). The surface preparation involves wet abrading, conditioning and neutralizing. In preparation of the surface for gluing, the surface is abraded to remove any loosely bonded adherents (scale, rust, paint, galvanized coatings, oxides, etc.), and to de-
velop a surface texture suitable for bonding. The wet abrading is performed using 220 grit, 400 grit, 600 grit and 1200 grit sand papers in the order mentioned, in the presence of an alkali based solution (M-Prep Conditioner A, which is 6% Phosphoric Acid by volume in distilled water). After the wet abrading, a neutralizer (M-Prep Neutralizer, which is a mixture of 0.02% Ammonium Hydroxide, 0.05% Trisodium Phosphate and 0.01% Sodium Tetraborate Pentahydrate by volume in distilled water) is used to completely clean the conditioner on the surface.

2. **Cleaning:** After the surface preparation, the samples are cleaned in an ultra-sonic bath with isopropyl alcohol for about 45 - 60 minutes, followed separately again in acetone.

3. **Glue application:** After cleaning the surface and determining the exact glue regions, the chosen glue is applied as a thin layer on the sides of the samples to be attached and clamped together for curing. When using M Bond 610 or M Bond 450, the curing agent and the resin are mixed prior to the surface preparation step to allow enough time for proper mixing. Also it maybe noted that M Bond 610 and M Bond 450 needs high temperature curing.

A tensile load is applied on either ends of the specimen as depicted in Figure 5.1. The tensile load is ramped up continuously till the adhesion fails and the metal plates come apart. The load ($P$) at which the metal plates separate due to the de-bonding of adhesive is identified as the shear strength and the normal stress is calculated based on the following equations:

$$\tau_{test} = \frac{P}{h \times w}$$  \hspace{1cm} (5.1)

$$\sigma_{test} = \frac{P}{t \times w}$$  \hspace{1cm} (5.2)

The Figure 5.2 shows the results of the glue testing performed for the above mentioned six types of glues. The vertical axis represents the adhesion strength (shear strength) of the glue and the horizontal axis shows the specimen number. We have used four sets of specimen for each glue.

*UNCLASSIFIED: Distribution Statement A. Approved for public release*
Figure 5.2: Plot showing the adhesion strength of the adhesives

The plot in Figure 5.2 clearly shows that M Bond 610 has the highest adhesion strength followed by Super Glue next. Hence, M Bond 610 is used as an adhesive for testing the sensors on the designed specimen. It is also interesting to note that M Bond 610 is less viscous compared to Super Glue and other adhesives that facilitate thin adhesive layer thicknesses even of the order of 5 μm or less, which ideally suits for this application.

5.1.2 Gluing area determination

The adhesive selection is followed by investigations to determine the gluing area of the sensor based on its thickness. The load supposed to be acting in the gluing region is calculated by

\[ P = A_{\text{glue}} \times \tau_{\text{test}} \]  \hspace{1cm} (5.3)

where, \( A_{\text{glue}} \) is the area of the gluing region in the sensor coupon and \( \tau_{\text{test}} \) is the shear strength obtained from the glue testing results. The stress in the mid region of the smallest active ligament is obtained by

\[ \sigma_{\text{mid}} = \frac{P}{A_{\text{mid}}} \]  \hspace{1cm} (5.4)
where, $\sigma_{\text{mid}}$ is the stress in the mid portion of the smallest active ligament and $A_{\text{mid}}$ is the area of cross-section of the active ligament.

The stress corresponding to 1% strain in the mid portion of the smallest active ligament is being considered here in place of $\sigma_{\text{mid}}$ in the equation 5.4. This value is obtained from the finite element calculations using ANSYS and the stress corresponding to 1% strain is used as this value is close to the ultimate tensile strength of the material. This stress in the mid portion of the smallest active ligament is related to the shear strength at the gluing region by substituting the value of ‘$P$’ in equation 5.4 from equation 5.3, which results in,

$$\sigma_{1\%} = \frac{A_g \tau_{\text{test}}}{A_{\text{mid}}} \quad \text{(5.5)}$$

where

$$A_g = (L_g \times W_g) \quad \text{and}$$

$$A_{\text{mid}} = (t \times w_g)$$

By re-arranging the terms in the equation 5.5, we have:

$$\frac{L_g}{t} = \frac{(\sigma_{1\%} \times w_{\text{mid}})}{(\tau_{\text{test}} \times w_g)} \quad \text{(5.6)}$$

Figure 5.3 depicts the variables used in the above equation. The equation 5.7, gives the relation between the length of the gluing region and the thickness of the sensor for a particular material. The reason for the dependence of the length of the glue region on the material in terms of stress corresponding to 1% strain in the ligament is obtained from the 2D FEA simulations. From the length of the gluing region, the area of the gluing can be calculated using the product of the length of the gluing region and the total width of the sensor coupon. The area of the gluing region is calculated for each of the design mentioned in the previous chapter i.e., for the thickness of 0.001”, 0.005” and 0.02” for aluminum and stainless steel. The resulting values of the length of the gluing region and hence the total length (vertical length) are listed in table 5.1 for all the six designs. It can be seen from the table that the sensor made of Aluminum has lesser gluing
region compared to the Stainless Steel for the same thickness. This is due to the stress corresponding to 1% strain in aluminum being less than that in Stainless steel. It may be noted that, the length of the gluing region changes in proportion to the thickness of the sensor.

![Diagram of sensor design](image)

Figure 5.3: Sensor depicting the variables used in sensor design

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>(L_g)</th>
<th>(H = [2.5 + (2*\text{L}_g)])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inch</td>
<td>mm</td>
<td>Inch</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.001</td>
<td>0.0254</td>
<td>0.0197</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.005</td>
<td>0.1270</td>
<td>0.1180</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.02</td>
<td>0.508</td>
<td>0.3937</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.001</td>
<td>0.0254</td>
<td>0.0393</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.005</td>
<td>0.1270</td>
<td>0.1575</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.02</td>
<td>0.508</td>
<td>0.63</td>
</tr>
</tbody>
</table>

### 5.2 Experimental Testing

The experimental testing of the sensors is divided into two main categories. The first part is the single ligament testing, where one active ligament is tested to understand its behavior under fatigue loading. The single ligaments tested were fabricated using micro Wire-EDM. In the second stage, the full sensors are tested. The fatigue sensors were fabricated using micro Wire-EDM and using UV-lithography. The fatigue sensors
fabricated using micro Wire-EDM are made of Al 1100 alloy, while Nickel is used for those fabricated using UV-lithography. The experimental testing of the prototype was performed using MTS 810 Material Test System (Figure 5.4). The single ligament and the full sensors are mounted on to the backing specimen as described in the subsequent sections. The specimen was subjected to cyclic loading with respect to a maximum load, which is determined based on its yield strength. The applied maximum load should always be less than the load corresponding to the yield strength of the material. The stress ratio and the frequency of the cyclic loading in each case was (-) 0.5 and 1 Hz respectively. The potential drop method was employed for testing the single ligaments which provided the corresponding crack length data as the crack propagates with increasing number of cycles [48,49]. The specimen has also been observed with a high magnification tele-microscope for the crack initiation in the backing specimen and the breaking of the ligament. Figure 5.5 shows the set-up of the tele-microscope used for the testing.

![Figure 5.4: The MTS machine used for the testing of the prototype sensor](image-url)
5.2.1 Single ligament testing

Figure 5.6 shows the dimensions of the single ligament with the actual dimensions and the dimensions of the gluing region and the total height of the ligament are listed in table 5.1.

Figure 5.6: A schematic showing the actual dimensions of the single ligament
FEA simulations were performed on the single active ligaments to obtain the ratio of strains of each of the active ligament to the strain in the reference ligament. These simulations have been performed using ANSYS under cyclic displacement loading. As described in section 3.1, the loads on the structure will be transferred through the glued region of the sensor since it is the only portion that is in contact with the structure. As a result, all the ligaments experience similar displacements. In order to simulate this effect in the FEA simulations, displacements (cyclic displacements) were applied on the top edge of the sensor while keeping the bottom edge of the sensor fixed. The values of the displacements applied on the ligaments were 1% of the length of the reference ligaments, which corresponds to the strains in the elastic region of the material. The geometry of the single ligaments considered in the FEA simulations are shown in Figure 5.7.

![Figure 5.7: Layout of the model for single ligament FEA simulations](image)

The model layout consists of the respective active ligament in the center and a reference ligament on either side. Each of the four ligaments were considered separately. The values of the stresses and strains are taken at the middle node of the ligaments shown by black dots in Figure 5.7. The results of these simulations are shown in Figure 5.8 which provides the ratio of strains in the active ligament to the strain in the reference ligament. The strain ratios obtained were similar for both aluminum and stainless steel. Typically, the strain ratios are to be matched with respect to the testing component/system design.
The next step in the testing is the design of the backing specimen onto which the prototype sensor is to be attached. This backing specimen would simulate the real time structure. Cyclic loadings would be applied onto this specimen and thus the loads experienced by the specimen will be transmitted to the sensor. In the real time scenario, the structures will have some stress concentration zones. To have this effect, a notch is cut on each specimen. The strain ratios thus obtained were used as a basis for determining the dimensions of the notch to be cut on the backing specimen on to which the single ligament would be attached to and tested. It is designed in such a way that the stress concentration factor of the notches \( (k_t) \) will be equal to the strain ratio of the ligament obtained above. The single ligament testing was performed on the ligament \# 4 i.e., the smallest ligament on the sensor (the ligament corresponding to design \# FD 3 in Table 5.1).
The strain ratios obtained correspond to that of material within the elastic limit during the loading process. The single ligaments are attached on to a backing specimen with a notch that acts as a stress raiser. During the course of loading, the area around the notch would have plastic zone. Hence, proper location has to be chosen on the specimen where there would be no plastic stresses generated during the loading. In order for this, a finite element simulation was performed on the specimen from which the stress distribution in the specimen was observed. FEA simulations with monotonic loading was performed on the specimen with the notch using COMSOL. The Figure 5.9 (dimensions shown are in ‘mm’) shows the specimen used. From the FEA simulations on the backing specimen, the stress distributions across the width of the specimen were observed. The stress distributions were observed at the notch plane and at different locations (going vertically from the notch plane). Figure 5.10 shows the stress distribution across the width of the specimen at the notch plane (black plot) and at a location 5 mm above the notch plane (green plot). It can be seen that at a distance of 5 mm (vertically) from...
the notch plane, the stress distribution across the width of the specimen is uniform and this region of the specimen is in elastic region. Figure 5.11 shows the specimen after the single ligaments (encircled in yellow) were attached at the prescribed locations.

![Stress Distribution Diagram](image)

Figure 5.10: Stress distribution across the width of the backing specimen for single ligament testing

![Specimen with Ligaments](image)

Figure 5.11: The specimen with single ligaments attached on to the specimen
Prior to performing the cyclic loading on the ligament, it is necessary to determine the yield strength of the specimen material used. Hence, a blank specimen was subjected to tensile testing and plotted the stress-strain curve. The yield strength of the material is found to be around 5500 N. Based on this value obtained, the cyclic loading parameters were determined. A set of 5 specimen were prepared with 0.005” thick aluminum single ligaments attached at the pre-determined locations on each of them. The five specimens were subjected to cyclic loading using a tensile testing machine. These were subjected to 5 different maximum loads, i.e., 5000 N, 4500 N, 4000 N, 3500 N and 3000 N respectively. Figure 5.12 shows the Load vs. number of cycles plot with load on the specimen on the vertical axis and number of cycles on horizontal axis.

![Figure 5.12: Results from the single ligament testing](image)

For each specimen (i.e., for each load applied), number of cycles of the cyclic loading has been plotted for the crack initiation in the specimen at the notch tip, ligament breaking and the complete specimen failure. It is evident from the plot that for higher...
loads, there is not much fatigue life between the crack initiation and complete failure. The ligament breaks at cycles closer to specimen failure. On the other hand, as the applied loads decreased, the number of cycles at which the ligament breaks is closer to the crack initiation and the time between the ligament breaking and the specimen failure increases. This indicates that there is still enough time for repairing or replacing the component well ahead of the complete failure. The pictures of the broken ligaments after testing are shown in Figure 5.13.

![Figure 5.13: The pictures of broken single ligaments from testing for applied maximum loads of (a) 5500 N; (b) 4500 N; (c) 4000 N; (d) 3500 N](image)

5.2.2 Full sensor testing

As mentioned above, the prototype full sensors tested were fabricated using micro Wire-EDM process and UV-lithography. The sensors fabricated using micro Wire-EDM are made of Al 1100 alloy while the sensors fabricated using UV-lithography are electroplated nickel. The backing specimen and the placement of the sensor on the specimen were the same as the ones used for the single ligament testing. The following experimental testing were performed for the full sensor:
- Test #1: µWire-EDM fabricated Al 1100 alloy fatigue sensor on Al 1100 alloy specimen
- Test #2: Micro-fabricated Ni fatigue sensor on Al 1100 alloy specimen
- Test #3: Micro-fabricated Ni fatigue sensor on Al 6061 alloy specimen
- Test #4: Micro-fabricated Ni fatigue sensor on SS 304 alloy specimen

For the testing of full sensor made of Al 1100 alloy, a set of 6 specimens were prepared with 0.005” thick aluminum prototype sensors attached at the pre-determined locations on each of them. The six specimens were subjected to cyclic loading using a tensile testing machine. These were subjected to 6 different loads, i.e., 5500 N, 5000 N, 4500 N, 4000 N, 3500 N and 3000 N respectively. Figure 5.14 shows the Load vs. number of cycles plot with load on the specimen on the vertical axis and number of cycles on horizontal axis.

Figure 5.14: Results from the testing of EDM fabricated Al 1100 full sensor on Al 1100 alloy specimen

UNCLASSIFIED: Distribution Statement A. Approved for public release
For each specimen (i.e., for each load applied), number of cycles of the cyclic loading has been plotted for the crack initiation in the specimen at the notch tip, each of the four active ligaments breaking and the complete specimen failure. It is observed from the plot that for higher loads, the smallest ligament start to break at cycles closer to crack initiation. On the other hand, at lower maximum loads applied, the number of cycles at which the ligament breaks is closer to the crack. The results also indicates that the ligaments were failing in a particular order i.e., smallest active ligament (Ligament 4) to the larger active ligament (Ligament 1). For the smallest load (3000 N), there was no fracture in the specimen even for 35000 cycles and so the test was stopped. This indicates that there is still enough time for repairing or replacing the component well ahead of the complete failure. If the number of cycles at which the specimen failed is considered to be 100% life of the same, the number of cycles at which each ligament failed will correspond to certain life expended by the specimen. This is measured by the percentage fraction of the number of cycles at which each ligament failed to the expected life of the specimen.

For the testing of micro-fabricated nickel fatigue sensor on Al 1100 alloy specimen and Al 6061 specimen, a set of 3 specimen made of 0.005” thick of respective material was chosen in each case. The specimen with the fatigue sensors mounted were subjected to a maximum loads of 5500 N, 4000 N and 3000 N. The values of the maximum loads are chosen such that we have one set in high loads, one set in low load range and one set in mid-range when compared to the testing of the Al 1100 fatigue sensor on Al 1100 specimen. For testing of the micro-fabricated Ni fatigue sensor on SS 304 specimen, a set of two specimen were made from stainless steel. The maximum loads applied in this case is 5500 N and 4000 N. The testing of these fatigue sensors were performed similar to the single ligament testing as regards to the testing parameters such as load ratio and frequency of cyclic loading and the testing equipment. Figures 5.15 through 5.17 shows the results from the testing of these sensors.
Figure 5.15: Results from the testing of micro-fabricated Ni full sensor on Al 1100 alloy specimen

Figure 5.16: Results from the testing of micro-fabricated Ni full sensor on Al 6061 alloy specimen

UNCLASSIFIED: Distribution Statement A. Approved for public release
Figure 5.17: Results from the testing of micro-fabricated Ni full sensor on SS 304 alloy specimen

Table 5.2: Table showing the elastic modulus and yield strength of materials used in testing

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>(\sigma_0) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 1100</td>
<td>69</td>
<td>120</td>
</tr>
<tr>
<td>Al 6061</td>
<td>68.9</td>
<td>131</td>
</tr>
<tr>
<td>Electroplated Ni</td>
<td>115</td>
<td>490</td>
</tr>
<tr>
<td>SS 304</td>
<td>193</td>
<td>215</td>
</tr>
</tbody>
</table>

Table 5.2 lists the elastic modulus and yield strength which define the ductility of the materials used for the sensor and specimen in the testing. The micro-fabricated Ni fatigue sensors were tested by attaching on specimen made of materials with different strengths. The Al 1100 with low elastic modulus and low yield strength is a low strength material which is very ductile compared to the SS 304 with high elastic modulus and yield strength making it less ductile. The specimen made of Al 6061 can be considered as material with intermediate strength compared to specimen made of the other two materials. When the micro-fabricated Ni sensors placed on Al 1100 i.e., sensor made of
strong material on a comparatively more ductile specimen (Figure 5.15), the failure of the ligaments were observed to be closer to the failure point of the specimen. On the other hand, when the micro-fabricated Ni sensor is tested by placing on specimen made of SS 304 which is stronger and less ductile material than the sensor (Figure 5.17), the failure of the ligaments in the sensor are closer to the crack initiation in the specimen. In the case when the Ni sensor is placed on Al 6061 (Figure 5.16), the failure of the ligaments are spread almost equally between crack initiation and final failure of the specimen as compared to the other two cases. It is also interesting to note that when the sensor made of stronger material placed on specimen of comparatively more ductile specimen (Figure 5.15), the time gap between the failure of the ligaments is very small compared to the case wherein the ductility of the sensor material is more than the specimen material (Figure 5.17), the gap between the breaking of the ligaments is much widely spaced.

In all the cases it is found that the ligaments start to fail after the crack initiation in the specimen and before the final fracture. There is a shift in the breaking of the ligaments with respect to number of loading cycles as the strength of the material increases (i.e., as the ductility of the material decreases). For instance at the load point of 5500 N, the ligament # 4 on Al 1100 specimen broke around 100 cycles while the life is higher in the case of Al 6061 and SS 304 specimen. This can be explained based on the plastic zone or the damaged area on the specimen as a result of the cyclic loading. Figure 5.18 shows the location of the fatigue sensor on the specimen (shown by the orange square) along with the damage area induced in the specimen. In the case of the Al 1100 specimen, the damage area / plastic zone is much widespread across the specimen and the fatigue sensor is in the path of the damage area. On the other hand the damage zone in the Al 6061 specimen is mostly concentrated in a very small region around the notch tip. It may be noted that these damage areas are for the same magnitude of cyclic loads applied on both the specimen. In the case of the fatigue sensor on Al 1100 specimen, the sensor is in very close proximity to the damage and hence the ligaments fail at lesser number of cycles. In the second case, the fatigue sensor on the Al 6061 (lesser ductile than Al 1100)
is far from the damage area (concentrated only at the notch tip) and hence the ligaments fail after going through large number of cycles. The results from the experimental testing are further validated using finite element analysis and are discussed in detail in the next section.

![Figure 5.18: Illustration plastic zone around the notch tip corresponding to a maximum load of 5500 N in the two Al alloy specimen](image)

### 5.3 Analysis of Test Results

The results of the experimental testing on different specimen and sensor combinations were analyzed using finite element analysis. The main objective of this analysis is to determine the stress / strain distribution within the different ligaments of the sensor. Since the displacement applied on the sensor during the experimental testing are not known, FEA simulations were performed on the specimen to obtain the strains on the specimen at the location where the sensor is attached. The FEA simulations were performed using COMSOL. The results from the FEA simulation were used in conjunction with the Smith Watson Topper (SWT) fatigue life equation described in Section ??.

The SWT parameter is used to predict the fatigue damage in components subjected to cyclic loading. The equation proposed by SWT model is given by:

\[
\sigma_{max} \varepsilon_a = \frac{(\sigma_f')^2}{E} (2N_f)^{2b} + \sigma_f' \varepsilon_f (2N_f)^{b+c} \quad \sigma_{max} > 0 \quad (5.7)
\]

UNCLASSIFIED: Distribution Statement A. Approved for public release
where, $\sigma_{\text{max}}$ is the maximum stress, $\varepsilon_a$ is the strain amplitude, $E$ is the elastic modulus of the material, $\sigma'_f$ is the fatigue strength coefficient, $b$ is the fatigue strength exponent, $N_f$ is the number of cycles to failure, $\varepsilon'_f$ is the fatigue ductility coefficient and $c$ is the fatigue ductility exponent.

Figure 5.19: 2D models for FEA with cracks in Al 1100 specimen at 4000 N
A 2D model of the specimen with the notch is simulated at the particular instance of a ligament break. As described before, the experimental testing was carried out using potential drop method wherein the crack length generated at certain intervals of the loading cycles in the specimen is recorded throughout the testing period. From this recorded data, by knowing the number of cycles at which each ligament failed, the corresponding crack length generated in the specimen is considered. Based on this, for a particular material and the load point in the testing (i.e., 3000 N, 4000 N and 5500 N) a 2D model of the specimen was created by simulating a crack opening (additional crack) from the notch tip. Figure 5.19 shows one set of such 2D models with the additional cracks extending from the notch tip that correspond to Al 1100 specimen subjected to the cyclic loading with the maximum load of 4000 N. Such 2D models were created for each load points (5500 N, 4000 N and 3000 N), each of the two specimen material (Al 1100, Al 6061) and for each ligament failure. The number of cycles to failure ($N_f$) shown in the figure correspond to the life at which each of the respective ligaments on the sensor failed during the testing. The crack lengths generated in the specimen at that respective cycle count is also listed in the figure. The crack length corresponding to the failure of ligament # 4 is the smallest as this ligament failed first followed by the other active ligaments.

Figure 5.20 shows the meshed elements on the notched specimen. The mesh size obtained on a particular edge is about 0.5% its length. The meshing is refined at the location of interest which in this case is the region where the sensor is located on the specimen as shown in the inset of Figure 5.20 and this resulted in a total number about 50,000 mesh elements and overall mesh quality as 0.75 which is measured from a scale of 0 to 1 wherein higher the quality the better the mesh. The meshing could not be refined over the entire geometry because of the restrictions of memory consumption while solving the problem.
The following steps were carried out for the FEA analysis:

1. The specimen was subjected to a monotonic displacement of about 0.4 mm which is about 2% of the gage length of the specimen (shown in Figure 5.9). The specimen when tested in the MTS 810 tensile testing machine, it is held in the pneumatic grips. As the machine applies a certain load on the specimen, a uniform displacement is applied on the specimen when it is held by the grips. So the FEA simulations require the displacement applied corresponding to applied load as an input. Figure 5.21 shows the layout of the specimen with applied boundary conditions for the finite element analysis. The displacement is applied in steps of 0.01 mm on the top edge of the specimen while keeping the bottom edge fixed. The side edges of the specimen (shown in red) are constrained against any displacement in the horizontal direction.
Figure 5.21: Boundary conditions applied on the specimen for the FEA simulations

2. The stress distribution was obtained across the width of the specimen at the edge where the displacement is applied. The stress distribution was obtained for each displacement step applied on the specimen in separate simulations. Figure 5.22 shows the stress distribution from one of the simulations wherein each curve represents the stress distribution for one load step. The vertical axis represents the stress (in MPa) and the horizontal axis represents the width of the specimen (in mm). It can be seen from the figure that the stress distribution across the width of the specimen where applied displacements were non-linear. At a particular load step, it can be seen that the stresses at the leading edge (left side) are lesser compared to that at the trailing edge (right side). This may be attributed to the presence of the notch on left side of the specimen. Further, this may also be the reason to have more displacement in the leading edge of the specimen compared to the other side.
Figure 5.22: The stress distributions on specimen for each displacement step from the FEA simulations

3. A Matlab program was written to perform the “Force” calculations from the obtained stress distributions. Each curve of the stress distribution is integrated over the width of the specimen to get the area under each curve corresponding to the particular applied displacement step. The area under the each curve is divided by the width of the specimen to get the average value of stress across the width. This stress value is multiplied with the cross-section area of the specimen at the edge where the load is applied in order to get the average value of the “Force” on the edge of the specimen. This way, the force acting on the edge for each applied displacement step is evaluated.

4. The force values obtained from the above step is plotted on a graph against corresponding displacement steps on the horizontal axis. An illustration of this plot is shown in Figure 5.23.
5. The force vs. displacement plot obtained from the above step is used and for each of the load points used in the testing (i.e., 3000 N, 4000 N and 5500 N), the corresponding values of the displacements were obtained by interpolation.

6. The displacement values pertaining to the specific material of the specimen, particular load points of testing and corresponding to each ligament failure are obtained in the above step which are then applied on the specimen (Figure 5.21).

7. From the resulting FEA simulations in step # 6, strain values are calculated in the region where the sensor is attached on the specimen (shown by the green line in Figure 5.21).

8. The strain values obtained are multiplied by the length of the reference ligament of the sensor to obtain the displacement values that will be applied on the sensor ligaments. Figure 5.24 shows the active ligaments taken separately for each simulation. Figure 5.25 shows the meshed elements in the 2D model of one of the single active ligaments. The default setting of triangular mesh type was used with a maximum element size being 0.01 mm and minimum element size as 0.001 mm. The overall quality of the meshing is 0.825 with total number of elements generated are around 25000.

Figure 5.23: Illustration of Force vs. displacement plot
Figure 5.24: The fatigue sensor showing the individual active ligaments considered for the FEA simulations

Figure 5.25: Meshed 2D model of single active ligament

9. The displacements obtained from step # 8 are applied on the respective active ligaments. Figure 5.26 shows the loading pattern and the boundary conditions applied on the ligaments. The force vs. displacement graphs obtained from step # 5 are found to be linear until the force value of 5500 N. Hence, if we consider the value of displacement to be applied on the ligament to be ‘x’, which would be the maximum value of the displacement applied on the ligament, the minimum value of the displacement applied during compression is (-0.5*x). This value corresponds to the load ratio (-0.5) considered during the testing since the force vs. displacement...
is linear in the load range considered (i.e., 3000N, 4000 N and 5500 N). Alternating
tensile and compressive displacements are applied on the top edge of the ligament
while keeping the bottom edge fixed as shown in Figure 5.26.

10. The values of $\sigma_{max}$ (maximum stress), $\varepsilon_{max}$ (maximum strain) and $\varepsilon_{min}$ (minimum
strain) are obtained from the FEA simulation of the ligaments. These values are
taken at the center node of the ligament (shown by red dot in Figure 5.26). From
these values the strain amplitude is calculated as:

$$\varepsilon_a = \varepsilon_{max} - \varepsilon_{min}$$

(5.8)

Figure 5.26: The schematic depicting boundary conditions on the ligament

The values of the maximum stress and the strain amplitude are obtained from each of the
simulations for the combinations of the specimen material (Al 1100 and Al 6061), load
points from the testing (3000 N, 4000 n and 5500 N) and each of the active ligaments
(Ligament 1 through Ligament 4). Table 5.3 shows the values obtained from such sim-
ulations on the fatigue sensor made from Al 1100 attached on to Al 1100 specimen. In
this case, the material of the specimen and the sensor material used is Al 1100 which is
very ductile. The strains generated in sensor shows plasticity in the middle region of the
ligament which is evident from the maximum strain values wherein a value of 0.002 in
strain denotes the onset of plasticity. The stresses and strains generated in the ligaments

UNCLASSIFIED: Distribution Statement A. Approved for public release
is highest for the smallest ligament (ligament # 4) and it decreases as the length of the middle region of the active ligament increases.

These values are plotted along with the curve from SWT equation for respective material of the fatigue sensor. The simulations were done for the sensor materials made from Al 1100 and micro-fabricated Ni. The electroplated Ni fatigue sensors fabricated by UV-lithography were analyzed for the elastic modulus. For this, the CSM \( NHT^2 \) nano-indentation tester with a Berkovich indenter was used. A series of indentations were performed on the Ni fatigue sensors. The average of the values of elastic modulus is obtained as 200 GPa which is similar to the bulk Ni (207 GPa) material. This similarity based on the plating parameters and the plating solution was also reported in the literature [50–52]. The material properties employed in the SWT equation for Al 1100 and electroplated Ni [51,53–64] are listed in the Table B.1 in Appendix B.

![Figure 5.27: The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 3000 N](image)

Figure 5.27: The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 3000 N
Table 5.3: The results from FEA simulation of electroplated Al 1100 on Al 1100 specimen

<table>
<thead>
<tr>
<th>Load:5500 N</th>
<th>Disp. Applied on specimen</th>
<th>Strain on Specimen : sensor plane</th>
<th>Disp. Applied on sensor</th>
<th>Fatigue Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>(\varepsilon_{\text{max}})</td>
<td>mm</td>
<td>(\varepsilon_{\text{max}})</td>
</tr>
<tr>
<td>Ligament 1</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Ligament 2</td>
<td>0.1287</td>
<td>0.0014</td>
<td>0.0035</td>
<td>4.00E-03</td>
</tr>
<tr>
<td>Ligament 3</td>
<td>0.1228</td>
<td>0.0012</td>
<td>0.003</td>
<td>1.22E-03</td>
</tr>
<tr>
<td>Ligament 4</td>
<td>0.116</td>
<td>0.0011</td>
<td>0.00275</td>
<td>1.22E-03</td>
</tr>
</tbody>
</table>

| Load:4000 N | Ligament 1 | 0.0899 | 8.57E-04 | 0.00214 | 1.59E-03 | -8.00E-04 | 0.0012 | 110 |
|             | Ligament 2 | 0.0862 | 8.18E-04 | 0.00205 | 1.68E-03 | -8.50E-04 | 0.00127 | 116  |
|             | Ligament 3 | 0.0819 | 7.80E-04 | 0.00195 | 1.78E-03 | -9.00E-04 | 0.00134 | 120  |
|             | Ligament 4 | 0.0803 | 7.57E-04 | 0.00189 | 2.65E-03 | -2.80E-04 | 0.00147 | 121  |

| Load:3000 N | Ligament 1 | 0.0616 | 5.88E-04 | 0.00147 | 1.10E-03 | -5.50E-04 | 0.00082 | 76   |
|             | Ligament 2 | 0.0607 | 5.76E-04 | 0.00144 | 1.18E-03 | -6.00E-04 | 0.00089 | 83   |
|             | Ligament 3 | 0.0598 | 5.67E-04 | 0.00142 | 1.30E-03 | -6.50E-04 | 0.00098 | 90   |
|             | Ligament 4 | 0.0594 | 5.60E-04 | 0.0014  | 1.45E-03 | -7.30E-04 | 0.00109 | 100  |
Figure 5.28: The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 4000 N

Figure 5.29: The results from the FEA simulations of Al 1100 fatigue sensor on Al 1100 specimen at max. Load of 5500 N
Figure 5.27 through 5.29 shows the results from the FEA simulations of fatigue sensors made of Al 1100 alloy attached on the specimen of the same material. The solid curve in the graphs are from the SWT parameter ($\sigma_{\text{max}}\epsilon_a$) defined by the equation 5.7. The data points in the graphs are the points at which each ligament failed during the tests. The graphs are plotted for each test point (each level of maximum load point) of the experimental testing. It can be seen that the ligaments failed at lives that coincide with the material behavior as prescribed by the SWT fatigue life equation. For the higher load points of 5500 N and 4000 N (Figure 5.29 and 5.28 respectively) the data points coincide with the theoretical SWT curve and for the lower load point of 3000 N (Figure 5.29) there is a very slight offset from the SWT curve which is at longer lives of the fatigue sensor (i.e., during the failure of Ligament 1 and 2). The reason for choosing the SWT parameter material behavior is because it was proved to be applicable to a wide variety of materials compared to other fatigue models like Goodman, Morrow and Gerber. Similar FEA simulations were performed for the cases of the fatigue sensors made of electroplated Ni (UV-lithography) attached on to specimen made of Al 1100 and Al 6061. The results of these simulations are shown in Appendix B. It was observed that when the sensor and specimen material used are same, the experimental results showed good correlation with respect to the theoretical material behavior as defined by SWT parameter (from Figures 5.27 through 5.29). In the case when the sensor material used is different from the specimen material the experimental results showed a conservative behavior with respect to the SWT material behavior of the sensor material as indicated by Figures B.1 through B.6 i.e., the ligaments failed earlier than predicted by the SWT curve. From the Figures B.1 through B.3 wherein the sensor material used is electroplated Ni on Al 1100 specimen. The sensor material is less ductile than the specimen material and the failure of the ligaments is closer with respect to each other while on the other hand when the same sensor material is used on a stronger material (Al 6061) compared to the previous case, the failure of the ligaments occurred at wider intervals.
5.4 Summary

In this chapter, various methods of validations were presented. Experimental testing were performed to determine the adhesion strength of some of the commercially available adhesives and a couple of special purpose glues. Analytical equations based on the strength of the adhesives and thickness of the sensor coupon were derived in order to determine the length of the gluing region of the fatigue sensors. Finite element simulations were performed to determine the location of the fatigue sensor on the specimen so that the latter is placed away from the high stressed regions (notch) in the specimen. The single ligaments and the full fatigue sensors attached on the specimen were subjected to cyclic loadings to observe the break in each ligament. The specimen material used are Al 1100, Al 6061 and SS 304 while the fatigue sensors made of Al 1100 and electroplated Ni were used. In the case of the single ligaments, it was observed that the ligaments failed after the crack initiation at the notch tip in the specimen and before the complete failure of the specimen. In case of the full sensors, a similar trend is observed wherein all the ligaments failed after the crack initiation and before the failure of the specimen. The results from the experimental testing in terms of a number of cycles to failures were validated by performing FEA simulations on the respective sensor and specimen combinations. The simulations were performed for the combinations of Al 1100 sensor on Al 1100 specimen as well as micro-fabricated Ni sensors on Al 1100 and Al 6061 specimen. The failure of the ligaments were compared with the estimates based on the SWT parameter and it was observed that the failure points of the ligaments were in tune with the expected behavior as represented by the SWT fatigue life curves.
Chapter 6

Testing and Data Acquisition

In the previous chapter, the aspects regarding the laboratory testing of the fatigue sensor and its correlation to fatigue life were discussed. The full sensors fabricated from micro-Wire-EDM as well as micro-fabrication techniques were tested. The micro-fabricated full sensors were tested on different backing specimen and the validation of the results were discussed. Developing a sensor alone is not sufficient, if this has to be utilized in practical applications. Hence an effort has been made to design and develop appropriate data acquisition system. In fact, in this particular case this sensor has been tested using wireless networking in collaboration with another group. In this chapter, the details of the circuit design for the wireless data acquisition of the fatigue sensors and its testing will be discussed.

6.1 Circuit Design

This section discusses the data acquisition signal conditioning circuit that was developed at the College of Engineering and Applied Sciences, Western Michigan University. Initially, a simple circuit designed for crack sensors [65] is used. However, considering the uncertainties in measurement of small resistances of the fatigue sensor, a better constant current source [66] is utilized in this work. This circuit was initially designed and tested in the Wireless Network Laboratory at Western Michigan University, before finally eval-
uated with the fatigue sensor. Considering the difficulties faced with the measurement of very small changes in voltage, especially during the breakage of the ligaments, which results in quite small changes in resistance, a new signal conditioning circuit was built. The proposed design is based on a differential operational amplifier circuit which can measure very small changes in resistance and reduce the noise significantly. Figure 6.1 shows the developed signal conditioning circuit that performs the function of a constant current source for the fatigue sensor.

\[
I_{\text{Load}} = \left( \frac{R2}{R1} \right) \frac{V2}{R5}
\]

For \( R1 = R3 \) and \( R2 = R4 + R5 \)

![Figure 6.1: Constant current DAQ circuit [66]](image)

### 6.2 Testing of the DAQ System

In this section, the application of the DAQ system to the fatigue sensor will be discussed. The fatigue sensors used for testing the DAQ system are 0.005" (0.127 mm) thick stainless steel (type SS 304) and were fabricated using μWire-EDM (shown in Figure 6.2). As part of the data acquisition of the fatigue sensor, two sets of testing were performed. In both the cases, thin metallic wires (22 gage i.e., 0.6 mm diameter steel wire) were
connected to the either ends of the fatigue sensor (schematic is shown in Figure 6.2). The thin wires were connected on to the sensor using spot welding. The spot welding of the wires was done using “Miyachi Unitek” 250 Watt dual pulse spot welding unit (Figure 6.3). Many trials were performed to come up with the correct power required to spot weld the thin wires on to the 0.005” thick fatigue sensor coupon which resulted in using 5% of the full power i.e., (5 of 250 Watts = 12.5 Watts) for the current combination of the 22 gage steel wire and the fatigue sensor.

Figure 6.2: Fatigue sensor used for DAQ and the schematic of the spot welded wire terminals

Figure 6.3: The spot welding machine used for welding the wire terminals on the fatigue sensor

*UNCLASSIFIED: Distribution Statement A. Approved for public release*
Table 6.1: The results from the manual cutting of the ligaments

<table>
<thead>
<tr>
<th>Ligament # cut</th>
<th>Resistance (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ligament cut</td>
<td>0.569</td>
</tr>
<tr>
<td>1</td>
<td>1.043</td>
</tr>
<tr>
<td>2</td>
<td>1.64</td>
</tr>
<tr>
<td>3</td>
<td>1.964</td>
</tr>
<tr>
<td>4</td>
<td>2.356</td>
</tr>
<tr>
<td>5</td>
<td>2.496</td>
</tr>
<tr>
<td>6</td>
<td>2.732</td>
</tr>
<tr>
<td>7</td>
<td>2.932</td>
</tr>
<tr>
<td>8</td>
<td>3.216</td>
</tr>
<tr>
<td>9</td>
<td>3.463</td>
</tr>
</tbody>
</table>

The first of the two sets of the DAQ tests consisted of connecting the terminals from the fatigue sensor to an “Agilent” 8½ digit digital multimeter. Here, each of the ligaments was manually cut by observing under a stereo microscope from the center of the sensor towards the ends. The resistance across the terminals of the fatigue sensor was observed when each of the ligaments is cut. The resistance change per each ligament cut is shown in Table 6.1. The ligament numbering is shown in Figure 6.4.

![Figure 6.4: The schematic showing the numbering of the ligaments](image-url)
The second test was performed to evaluate the wireless transmission of data from the fatigue sensor. The terminals from the fatigue sensor were connected to the wireless transmitter. On the other end, the base station (computer) is connected to the receiver. The schematic of the data flow is shown in the Figure C.1. The computer is equipped with the special software for the processing and displaying the resistance and the voltage data from the fatigue sensor. The screenshot of the software interface is shown in Figure 6.5.

![Screenshot showing the software interface](image)

**Figure 6.5:** Screenshot showing the software interface

The output from the interface shows the voltage change per each of the ligament cut. The current used in the circuit used was 10 mA. The Table 6.2 shows the results from the wireless transmission data i.e., the voltage change per each of the ligament cut.
Table 6.2: The results of the voltage change per each ligament cut obtained using wireless

<table>
<thead>
<tr>
<th>Ligament # cut</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ligament cut</td>
<td>0.005692</td>
</tr>
<tr>
<td>1</td>
<td>0.010433</td>
</tr>
<tr>
<td>2</td>
<td>0.016411</td>
</tr>
<tr>
<td>3</td>
<td>0.019642</td>
</tr>
<tr>
<td>4</td>
<td>0.023558</td>
</tr>
<tr>
<td>5</td>
<td>0.024962</td>
</tr>
<tr>
<td>6</td>
<td>0.027321</td>
</tr>
<tr>
<td>7</td>
<td>0.029323</td>
</tr>
<tr>
<td>8</td>
<td>0.032161</td>
</tr>
<tr>
<td>9</td>
<td>0.034634</td>
</tr>
</tbody>
</table>

Figure 6.6: The results from the fatigue sensor DAQ testing
Figure 6.6 shows the plot of the measured resistance and voltage from the DAQ testing of fatigue sensor. From the Figure 6.6 and Tables 6.1 & 6.2, it can be observed that as the number of ligaments cut (from center to outwards) increased the resistance change in the material of the sensor and thus the corresponding voltage is increasing. The full circuit voltage (when no ligaments are cut) is around 5.7 mV as opposed to the maximum voltage (when all the ligaments are cut) is around 35 mV. The results from both the tests i.e., resistance measurement from the manual cutting of the ligaments and the voltage measurement from the wireless transmitted data yielded same results as shown in the plot in Figure 6.6. A portable data acquisition module has been built as shown in Figure 6.7. The DAQ module consists of a power supply unit that can run on a battery and it also houses the wireless data transmitter. The components of the module are encased in a transparent polycarbonate housing for better aesthetics. The overall footprint dimensions of the module is around 6” x 6”.
Chapter 7

Conclusions and Future
Recommendations

7.1 Conclusions

The goal of the research was to design and develop a fatigue sensor for prognosis and monitoring the fatigue damage in structural components. This comprises the design of the sensor which includes analytical and numerical modeling, fabrication and experimental testing of the prototype sensor. The fatigue monitoring sensor consists of alternate slots and strips (ligaments) having different strain magnification factors with respect to the nominal (reference) strain. The sensor has to be attached to the surface of structural member whose fatigue behavior is being monitored. The ligaments fail in a sequential manner from the ligament experiencing the highest strain magnification to the lowest. Each ligament failure corresponds to the fatigue damage accumulated by the structure being diagnosed.

Sensors with different ‘ligament’ configurations were designed and analyzed. Ligament design involved the two parts with different areas of cross-section with the size of smallest area of cross-section (the active ligaments) decreasing from one end to the other. The ligaments on either ends of the gage with uniform width are called reference liga-
ments. **The final design of the fatigue sensor consists of a double symmetry, i.e., symmetry about the active ligament with smallest middle region and each of the active ligaments are symmetrical (vertically) about their middle region.** The double symmetry design provided more uniform stress/strain distribution across the width of the ligament. The strain in the reference ligament is related to the strain in the component where the gage is placed. The strain ratio of each of the active ligament is a magnification of the strain in the reference ligament thereby relating to the strain in the critical location on the structure. When fixed in an appropriate position, the test gage should experience the same strain history and ambience as that experienced by the test structure. The overall dimensions of the designed fatigue monitoring sensor is 5 mm x 3 mm with a minimum feature size of 0.1 mm. Initial design considered aluminum and stainless steel as possible materials for fabrication.

At the outset the sensor structure is designed using simple geometrical and analytical modeling methods. This was further refined through numerical modeling methods. As the sensor and structure is subjected to cyclic stress of known magnitude, each of the ligaments will experience elongation or contraction equal to or larger than that experienced by the structure. The response of alternating cyclic loading and the stress vs. strain hysteresis was obtained for two dimensional models using bilinear and multilinear material model. From the results of the initial analytical modeling it was observed that the active ligament with the smallest middle region experiences highest stress/strain and the values decrease as the middle region of the active ligaments increase. Based on the FEA results the design of the sensor was finalized. Numerical modeling is divided into two parts. First part of this modeling is related to the static-elastic simulations that were carried out using COMSOL finite element software. Second part of the numerical analysis is mainly related to simulation of the elastic-plastic behavior of the sensor structure, in response to applied cyclic displacements. **An interesting observation was made when the sensor is strained up to a point wherein the reference ligament remains in the elastic region of the stress-strain behavior, all active**
ligaments experience plastic strain in the middle portion of these ligaments. Even if the sensor is placed at a location on the structure where the stresses / strains are in the elastic region of the material behavior, the active ligaments would undergo higher plastic strains, which would represent the actual strains at the critical damage zone in the structure.

The fabrication of the fatigue sensor was done in two stages. In the first stage, single ligaments were machined using micro Wire-Electro-Discharge-Machining (µW-EDM). These single ligaments were fabricated from two different materials i.e., Al 1100 and SS 304 materials. In the second stage, full sensor coupons were fabricated using µW-EDM as well as micro-fabrication methods. The full sensor coupons fabricated by µW-EDM were made from 0.001”, 0.005” and 0.02” thick Al 1100 alloy and SS 304. The micro-fabrication technique used is UV-microlithography, which is a clean room procedure. The micro-fabricated fatigue sensors were made from electroplated Ni. The overall footprint area of the single ligaments are 3.5mm x 0.6mm and that of the full sensor coupon is 5 mm x 8 mm. Though, the structures fabricated using the wire EDM have very fine edge finish and stress free, these are to be fabricated in a serial mode, which is time consuming and expensive for routine manufacturing. On the other hand the sensors fabricated using UV-lithography and electroplating can be batch fabricated as one can have a number of structures on a single substrate.

In terms of experimental analysis, major outcomes are related to the selection of adhesive for attaching the sensor to a test structure and the determination of the gluing region with respect to the overall sensor area as well as testing of the prototype sensors. Selection of suitable adhesive is done by a series of experiments on single overlap specimen. This work is successful in developing a procedure for the selection and testing of an adhesive for passive fatigue sensors designed in this work and others that are similar in principle. Further, this work established a method to understand the relation between the area of gluing region w.r.t.
**the thickness of the sensor.** The special purpose adhesive M Bond 610 from Vishay Precision Group Inc. is observed to be the most suitable for this purpose.

The experimental testing was done on single ligaments followed by the full sensor fabricated by both methods. A dog-bone shaped tensile testing specimen with a sharp V-notch is used. The location of the sensor on the specimen is determined to be away from the stress concentration zone (notch) on the specimen. Determination of the location of the sensor on the specimen has been carried out by extensive FEA simulations which is about 1.5 mm away from the notch tip horizontally and 1 mm vertically away from the notch plane.

The specimen with single ligaments is subjected to cyclic loads at different levels of max. loads of 5000 N, 4500 N, 4000 N, 3500 N and 3000 N in separate experiments. The maximum value of the load level of 5000 N was chosen such that it is below the load corresponding to the yield strength of the specimen material. The cyclic loads were applied at a frequency of 1 Hz. and a load ratio of \( R = P_{\text{min}}/P_{\text{max}} = -0.5 \). The number of cycles was recorded for the start of damage in the specimen (crack initiation at the notch tip), ligament breaking and complete failure of the specimen. **The sensor testing has clearly demonstrated beyond any doubt that the ligaments of the designed sensor fail at regular intervals after crack initiation and before the final failure of the sensor. Hence, this fatigue sensor can be used with any application when remaining life of a structure is to be maintained continuously and routine operating conditions.** The full sensor fabricated from Al 1100 alloy using wire EDM were tested by attaching on to specimen made of the same material at max. load levels of 5500 N, 5000 N, 4500 N, 4000 N, 3500 N and 3000 N. **The crack initiation in the specimen was recorded by Potential Drop (PD) method, in tandem with visual observation under a tele-microscope. The breaking of the ligaments was observed using another tele-microscope. It is observed that each of the ligaments failed after the crack initiation in the specimen and before the final failure of the specimen. The ligaments failed**
in the order of the active ligament with smaller middle region failing first to the ligaments with larger middle region following later. Similar testing of the full sensor coupons made of electroplated Ni were performed by attaching them on to Al 1100 alloy, Al 6061 alloy and SS 304 specimens which have varying ductility. This is to simulate the behavior of the fatigue sensor on different materials with differing strengths. The max. load levels used for these tests are 5500 N, 4000 N and 3000 N. A similar trend is observed in the testing of the Ni sensors on the specimen of different materials. When the material of the sensor is stronger than the specimen material, the failure of the ligaments were closer to the final fracture of the specimen and the gap between the failure of each ligaments in the sensor are closer to each other. On the other hand, when the sensor material is more ductile than the specimen material, the failure of the ligaments occurred closer to the crack initiation in the specimen and the time gap between the failure of each ligament is widely spaced.

The results from the experimental testing of the full sensor were validated by a series of finite element simulations. The PD method used during the testing enables in recording of crack lengths at any point during the testing. Based on this recorded data, 2D models were created with simulated crack lengths at which each ligament failed. Finite element simulations were performed on these 2D models by subjecting them to respective cyclic displacements. The displacements applied on the specimen were calculated based on the load vs. displacement behavior of the specimen of respective material. The SWT parameter was evaluated in each of these cases at the sensor location on the specimen. Thus evaluated SWT parameter was plotted against the theoretical SWT curve of the respective sensor material. It is observed that the results from the FEA simulations are in close correlation to the material fatigue behavior as described by the theoretical SWT curve. From the comparison of the experimental results, it was observed that when the sensor material and specimen material are same, the experimental results showed correlation with respect to the theoretical material behavior.
defined by the SWT parameter. When the specimen material is different from the sensor material, the experimental results showed a conservative behavior when compared to the theoretical curve defined by the SWT parameter. One of the limiting factors of this sensor is found to be in the case when the sensor material and structure material are different and the ambient temperatures are rigorously changing. More study has to be performed in this regards to take into account the relative thermal expansion between the sensor and structure material.

Finally, the details of data acquisition system designed for the fatigue sensors were presented. The DAQ system for the fatigue sensor consists of circuit design, software and hardware development. A constant current circuit was developed which can measure very small changes in the resistance resulting from the breaking of the ligaments. The hardware module of the DAQ system consists of a power source and a means of wireless transmission of the data from the fatigue (change in resistance / voltage) from the fatigue sensor to a base station (generally a PC or laptop). The wireless DAQ system was tested by measuring the resistance when each of the ligament is manually cut and correlating the data thus obtained by subjecting the fatigue sensor to cyclic loads on the machine and obtaining the corresponding voltage values when each ligament fails which arewirelessly transmitted by the DAQ system. A module for the data acquisition system was designed wherein all the required components such as the battery operated power source and the wireless transmitter are enclosed in a transparent polycarbonate casing. The development of the data acquisition system enables the use of this sensor in automatic continuous monitoring applications, without requiring external human intervention. This will enhance the usability of the sensor for structural health monitoring of automotive and aeronautical structural components and others.
7.2 Future Recommendations

Three main areas have been identified for future works. The first one is to design the fatigue sensor for use in case of multi-axial loading. One such case would be a combination of axial and torsional loading as the current sensor is compatible with uniaxial (tension-compression cyclic) loading. One probable way to achieve that is by designing the sensor in the form of a rosette consisting of single ligaments to measure the fatigue damage in other directions. The other possible way to monitor the fatigue due to mutli-axial loading is that, the fatigue sensor could be fabricated as a multi-layer (stacked) structure such that each layer can monitor the fatigue in a particular direction of interest. The other aspect is to design the sensor and draw the analysis so as to account for variable amplitude cyclic loading conditions which is the case in most of the real-life situations.
References


*UNCLASSIFIED: Distribution Statement A. Approved for public release*


UNCLASSIFIED: Distribution Statement A. Approved for public release


UNCLASSIFIED: Distribution Statement A. Approved for public release


Appendices
Appendix A

Matlab Codes

This Appendix contains the codes for the MATLAB program discussed in section 3.2.

A.1 Matlab code for calculating strain ratios

The program takes the lengths and cross-sectional areas of each part of the ligaments as input and calculates the strain ratios as the output based on the relation in equation 3.7.

```matlab
clear
clc

%% INPUTS

La = input (' Enter the length of the Ligament A : ');
Aa = input (' Enter the Cross-sectional area of the Ligament A : ');
Epa = input (' Enter the ratio of strain at the part to the strain at the sensor : ');

N = input (' Enter the total number of active Ligaments on the coupon : ');

for i=1:N
    Enter_the_values_for_the_Ligament =i
```

UNCLASSIFIED: Distribution Statement A. Approved for public release
n(i)=input ('Enter the number of parts in the Ligament : ');

for j=1:n(i)

D='Enter the values of the length and C/s area of each part of the ligament in the order of decreasing C/s area ';

disp(D);

L(i,j)=input ('Enter the length of the part : ');

A(i,j)=input ('Enter the Cross-sectional area of the part : ');

end

SSF(i)=0;

for j=1:n(i)

SF(i,j)=L(i,j)/A(i,j);

SSF(i)=SSF(i)+SF(i,j);

end

SigmaSF(i)=SSF(i);

for j=1:n(i)

E(i,j)=(L(i,j)*SF(i,j))/(L(i,j)*SigmaSF(i));

end
A.2 Matlab code for calculating length of the ligaments

This section contains the code for the MATLAB program for generating the lengths of the middle and outer portions of the active ligaments of the design in section 3.2. The program takes the dimensions of the reference ligament and the strain ratios to give the dimensions of the active ligaments based on the respective strain ratios with respect to the reference ligaments. The calculations of the dimensions of the length of the active ligaments are based on the equations 3.13 and 3.14.

```matlab
1 clear;
2 clc;
3 Lr=input('Enter the length of reference ligament : ');
4 Ar=input('Enter the Cross-section of reference ligament : ');
5 N=input('Enter the number of active ligaments : ');
6 for i=1:N
7     XmidC(i)=input('Strain ratio w.r.t. reference ligament "R" : ');
8     AmidC(i)=Ar;
9     AoutC(i)=(2*Ar);
10    LmidC(i)=(((2*Lr)/XmidC(i))-Lr);
11    LoutC(i)=(Lr-(Lr/XmidC(i)));
12    LtotalC(i)=(LmidC(i)+(2*LoutC(i)));
6 end
```
A.3 Matlab code for calculating average force from the stress distributions on the top edge of the specimen where the displacements were applied.

```matlab
1 close all;
2 clear all;
3 Width = 0.055;
4 W = 0.035;
5 Thk = 0.003175;
6 Acs = Width * Thk;
7 DS6 = load ('Disp_Steps6.dat');
8 DSteps6(:,1) = DS6(1:1:41,2) * 1000;
9 S216Data = load ('S216_LS2_41.dat');
10 S215Data = load ('S215_LS2_41.dat');
11 S214Data = load ('S214_LS2_41.dat');
12 S213Data = load ('S213_LS2_41.dat');
13 S212Data = load ('S212_LS2_41.dat');
14 S226Data = load ('S226_LS2_41.dat');
15 S225Data = load ('S225_LS2_41.dat');
16 S224Data = load ('S224_LS2_41.dat');
17 S223Data = load ('S223_LS2_41.dat');
18 S222Data = load ('S222_LS2_41.dat');
19 S236Data = load ('S236_LS2_41.dat');
20 S235Data = load ('S235_LS2_41.dat');
21 S234Data = load ('S234_LS2_41.dat');
22 S233Data = load ('S233_LS2_41.dat');
23 S232Data = load ('S232_LS2_41.dat');
24 S216XWidth(:,1) = S216Data(1:1:138,1);
25 S215XWidth(:,1) = S215Data(1:1:138,1);
```
26 S214XWidth(:,1)=S214Data(1:1:138,1);
27 S213XWidth(:,1)=S213Data(1:1:138,1);
28 S212XWidth(:,1)=S212Data(1:1:104,1);
29 S226XWidth(:,1)=S226Data(1:1:104,1);
30 S225XWidth(:,1)=S225Data(1:1:104,1);
31 S224XWidth(:,1)=S224Data(1:1:104,1);
32 S223XWidth(:,1)=S223Data(1:1:138,1);
33 S222XWidth(:,1)=S222Data(1:1:138,1);
34 S236XWidth(:,1)=S236Data(1:1:52,1);
35 S235XWidth(:,1)=S235Data(1:1:52,1);
36 S234XWidth(:,1)=S234Data(1:1:52,1);
37 S233XWidth(:,1)=S233Data(1:1:31,1);
38 S232XWidth(:,1)=S232Data(1:1:52,1);
39 for j=0:39
40 S21xSyStress(1:1:138,j+1)=S21xData(138*j+1:138*j+138,2);
41 j=j+1;
42 end
43 S21xLP2(:,1)=S21xXWidth(:,1);
44 S21xLP2(:,2)=S21xSyStress(:,1);
45 S21xLP3(:,1)=S21xXWidth(:,1);
46 S21xLP3(:,2)=S21xSyStress(:,2);
47 S21xLP4(:,1)=S21xXWidth(:,1);
48 S21xLP4(:,2)=S21xSyStress(:,3);
49 S21xLP5(:,1)=S21xXWidth(:,1);
50 S21xLP5(:,2)=S21xSyStress(:,4);
51 S21xLP6(:,1)=S21xXWidth(:,1);
52 S21xLP6(:,2)=S21xSyStress(:,5);
53 S21xLP7(:,1)=S21xXWidth(:,1);
54 S21xLP7(:,2)=S21xSyStress(:,6);
55 S21xLP8(:,1)=S21xXWidth(:,1);
S21xLP8(:,2)=S21xSyStress(:,7);
S21xLP9(:,1)=S21xXWidth(:,1);
S21xLP9(:,2)=S21xSyStress(:,8);
S21xLP10(:,1)=S21xXWidth(:,1);
S21xLP10(:,2)=S21xSyStress(:,9);
S21xLP11(:,1)=S21xXWidth(:,1);
S21xLP11(:,2)=S21xSyStress(:,10);
S21xLP12(:,1)=S21xXWidth(:,1);
S21xLP12(:,2)=S21xSyStress(:,11);
S21xLP13(:,1)=S21xXWidth(:,1);
S21xLP13(:,2)=S21xSyStress(:,12);
S21xLP14(:,1)=S21xXWidth(:,1);
S21xLP14(:,2)=S21xSyStress(:,13);
S21xLP15(:,1)=S21xXWidth(:,1);
S21xLP15(:,2)=S21xSyStress(:,14);
S21xLP16(:,1)=S21xXWidth(:,1);
S21xLP16(:,2)=S21xSyStress(:,15);
S21xLP17(:,1)=S21xXWidth(:,1);
S21xLP17(:,2)=S21xSyStress(:,16);
S21xLP18(:,1)=S21xXWidth(:,1);
S21xLP18(:,2)=S21xSyStress(:,17);
S21xLP19(:,1)=S21xXWidth(:,1);
S21xLP19(:,2)=S21xSyStress(:,18);
S21xLP20(:,1)=S21xXWidth(:,1);
S21xLP20(:,2)=S21xSyStress(:,19);
S21xLP21(:,1)=S21xXWidth(:,1);
S21xLP21(:,2)=S21xSyStress(:,20);
S21xLP22(:,1)=S21xXWidth(:,1);
S21xLP22(:,2)=S21xSyStress(:,21);
S21xLP23(:,1)=S21xXWidth(:,1);

UNCLASSIFIED: Distribution Statement A. Approved for public release
S21xLP23(:,2)=S21xSyStress(:,22);
S21xLP24(:,1)=S21xXWidth(:,1);
S21xLP24(:,2)=S21xSyStress(:,23);
S21xLP25(:,1)=S21xXWidth(:,1);
S21xLP25(:,2)=S21xSyStress(:,24);
S21xLP26(:,1)=S21xXWidth(:,1);
S21xLP26(:,2)=S21xSyStress(:,25);
S21xLP27(:,1)=S21xXWidth(:,1);
S21xLP27(:,2)=S21xSyStress(:,26);
S21xLP28(:,1)=S21xXWidth(:,1);
S21xLP28(:,2)=S21xSyStress(:,27);
S21xLP29(:,1)=S21xXWidth(:,1);
S21xLP29(:,2)=S21xSyStress(:,28);
S21xLP30(:,1)=S21xXWidth(:,1);
S21xLP30(:,2)=S21xSyStress(:,29);
S21xLP31(:,1)=S21xXWidth(:,1);
S21xLP31(:,2)=S21xSyStress(:,30);
S21xLP32(:,1)=S21xXWidth(:,1);
S21xLP32(:,2)=S21xSyStress(:,31);
S21xLP33(:,1)=S21xXWidth(:,1);
S21xLP33(:,2)=S21xSyStress(:,32);
S21xLP34(:,1)=S21xXWidth(:,1);
S21xLP34(:,2)=S21xSyStress(:,33);
S21xLP35(:,1)=S21xXWidth(:,1);
S21xLP35(:,2)=S21xSyStress(:,34);
S21xLP36(:,1)=S21xXWidth(:,1);
S21xLP36(:,2)=S21xSyStress(:,35);
S21xLP37(:,1)=S21xXWidth(:,1);
S21xLP37(:,2)=S21xSyStress(:,36);
S21xLP38(:,1)=S21xXWidth(:,1);
116 \texttt{S21xLP38(:,2)=S21xSyStress(:,37);}
117 \texttt{S21xLP39(:,1)=S21xXWidth(:,1);}
118 \texttt{S21xLP39(:,2)=S21xSyStress(:,38);}
119 \texttt{S21xLP40(:,1)=S21xXWidth(:,1);}
120 \texttt{S21xLP40(:,2)=S21xSyStress(:,39);}
121 \texttt{S21xLP41(:,1)=S21xXWidth(:,1);}
122 \texttt{S21xLP41(:,2)=S21xSyStress(:,40);}
123 \texttt{pS21xLP2=polyfit(S21xLP2(:,1),S21xLP2(:,2),5);}
124 \texttt{funS21xLP2=@(x) (pS21xLP2(1)*(x.^5))+(pS21xLP2(2)*(x.^4))+(pS21xLP2(3)*(x.^3))+(pS21xLP2(4)*(x.^2))+(pS21xLP2(5)*x)+pS21xLP2(6);}
125 \texttt{AreaS21xLP2=integral(funS21xLP2,0,Width);}
126 \texttt{StressS21xLP2=AreaS21xLP2/Width;}
127 \texttt{ForceS21xLP2=StressS21xLP2*Acs*1e6;}
128 \texttt{pS21xLP3=polyfit(S21xLP3(:,1),S21xLP3(:,2),5);}
129 \texttt{funS21xLP3=@(x) (pS21xLP3(1)*(x.^5))+(pS21xLP3(2)*(x.^4))+(pS21xLP3(3)*(x.^3))+(pS21xLP3(4)*(x.^2))+(pS21xLP3(5)*x)+pS21xLP3(6);}
130 \texttt{AreaS21xLP3=integral(funS21xLP3,0,Width);}
131 \texttt{StressS21xLP3=AreaS21xLP3/Width;}
132 \texttt{ForceS21xLP3=StressS21xLP3*Acs*1e6;}
133 \texttt{pS21xLP4=polyfit(S21xLP4(:,1),S21xLP4(:,2),5);}
134 \texttt{funS21xLP4=@(x) (pS21xLP4(1)*(x.^5))+(pS21xLP4(2)*(x.^4))+(pS21xLP4(3)*(x.^3))+(pS21xLP4(4)*(x.^2))+(pS21xLP4(5)*x)+pS21xLP4(6);}
135 \texttt{AreaS21xLP4=integral(funS21xLP4,0,Width);}
136 \texttt{StressS21xLP4=AreaS21xLP4/Width;}
137 \texttt{ForceS21xLP4=StressS21xLP4*Acs*1e6;}
138 \texttt{pS21xLP5=polyfit(S21xLP5(:,1),S21xLP5(:,2),5);}
139 \texttt{funS21xLP5=@(x) (pS21xLP5(1)*(x.^5))+(pS21xLP5(2)*(x.^4))+(pS21xLP5(3)*(x.^3))+(pS21xLP5(4)*(x.^2))+(pS21xLP5(5)*x)+pS21xLP5(6);}
140 \texttt{AreaS21xLP5=integral(funS21xLP5,0,Width);}
141 \texttt{StressS21xLP5=AreaS21xLP5/Width;}

UNCLASSIFIED: Distribution Statement A. Approved for public release
142 ForceS21xLP5=StressS21xLP5*Acs*1e6;
143 pS21xLP6= polyfit (S21xLP6(:,1),S21xLP6(:,2),5);
144 funS21xLP6=@(x) (pS21xLP6(1)*(x.^5))+(pS21xLP6(2)*(x.^4))+(pS21xLP6
(3)*(x.^3))+(pS21xLP6(4)*(x.^2))+(pS21xLP6(5)*x)+pS21xLP6(6);
145 StressS21xLP6=integral(funS21xLP6,0,Width);
146 ForceS21xLP6=StressS21xLP6/Width;
147 pS21xLP7= polyfit (S21xLP7(:,1),S21xLP7(:,2),5);
148 funS21xLP7=@(x) (pS21xLP7(1)*(x.^5))+(pS21xLP7(2)*(x.^4))+(pS21xLP7
(3)*(x.^3))+(pS21xLP7(4)*(x.^2))+(pS21xLP7(5)*x)+pS21xLP7(6);
149 StressS21xLP7=AreaS21xLP7/Width;
150 ForceS21xLP7=AreaS21xLP7/Width;
151 pS21xLP8= polyfit (S21xLP8(:,1),S21xLP8(:,2),5);
152 funS21xLP8=@(x) (pS21xLP8(1)*(x.^5))+(pS21xLP8(2)*(x.^4))+(pS21xLP8
(3)*(x.^3))+(pS21xLP8(4)*(x.^2))+(pS21xLP8(5)*x)+pS21xLP8(6);
153 StressS21xLP8=AreaS21xLP8/Width;
154 ForceS21xLP8=AreaS21xLP8/Width;
155 pS21xLP9= polyfit (S21xLP9(:,1),S21xLP9(:,2),5);
156 funS21xLP9=@(x) (pS21xLP9(1)*(x.^5))+(pS21xLP9(2)*(x.^4))+(pS21xLP9
(3)*(x.^3))+(pS21xLP9(4)*(x.^2))+(pS21xLP9(5)*x)+pS21xLP9(6);
157 StressS21xLP9=AreaS21xLP9/Width;
158 ForceS21xLP9=AreaS21xLP9/Width;
159 pS21xLP10= polyfit (S21xLP10(:,1),S21xLP10(:,2),5);
160 funS21xLP10=@(x) (pS21xLP10(1)*(x.^5))+(pS21xLP10(2)*(x.^4))+(pS21xLP10
(3)*(x.^3))+(pS21xLP10(4)*(x.^2))+(pS21xLP10(5)*x)+pS21xLP10(6);
161 StressS21xLP10=AreaS21xLP10/Width;
162 ForceS21xLP10=AreaS21xLP10/Width;

UNCLASSIFIED: Distribution Statement A. Approved for public release
StressS21xLP10 = \text{AreaS21xLP10}/\text{Width};
ForceS21xLP10 = \text{StressS21xLP10}\,*\text{Acs}\,*\,1\,\text{e6};
\text{pS21xLP11} = \text{polyfit}\,(\text{S21xLP11}\,(::,1),\text{S21xLP11}\,(::,2),5);
\text{funS21xLP11} = @(x) \left( \text{pS21xLP11}\,(1)\,*\,(x\,*\,5)\right) + \left( \text{pS21xLP11}\,(2)\,*\,(x\,*\,4)\right) + \left( \text{pS21xLP11}\,(3)\,*\,(x\,*\,3)\right) + \left( \text{pS21xLP11}\,(4)\,*\,(x\,*\,2)\right) + \left( \text{pS21xLP11}\,(5)\,*\,x\right) + \text{pS21xLP11}\,(6);
\text{AreaS21xLP11} = \text{integral}\,(\text{funS21xLP11},0,\text{Width});
\text{StressS21xLP11} = \text{AreaS21xLP11}/\text{Width};
\text{ForceS21xLP11} = \text{StressS21xLP11}\,*\text{Acs}\,*\,1\,\text{e6};
\text{pS21xLP12} = \text{polyfit}\,(\text{S21xLP12}\,(::,1),\text{S21xLP12}\,(::,2),5);
\text{funS21xLP12} = @(x) \left( \text{pS21xLP12}\,(1)\,*\,(x\,*\,5)\right) + \left( \text{pS21xLP12}\,(2)\,*\,(x\,*\,4)\right) + \left( \text{pS21xLP12}\,(3)\,*\,(x\,*\,3)\right) + \left( \text{pS21xLP12}\,(4)\,*\,(x\,*\,2)\right) + \left( \text{pS21xLP12}\,(5)\,*\,x\right) + \text{pS21xLP12}\,(6);
\text{AreaS21xLP12} = \text{integral}\,(\text{funS21xLP12},0,\text{Width});
\text{StressS21xLP12} = \text{AreaS21xLP12}/\text{Width};
\text{ForceS21xLP12} = \text{StressS21xLP12}\,*\text{Acs}\,*\,1\,\text{e6};
\text{pS21xLP13} = \text{polyfit}\,(\text{S21xLP13}\,(::,1),\text{S21xLP13}\,(::,2),5);
\text{funS21xLP13} = @(x) \left( \text{pS21xLP13}\,(1)\,*\,(x\,*\,5)\right) + \left( \text{pS21xLP13}\,(2)\,*\,(x\,*\,4)\right) + \left( \text{pS21xLP13}\,(3)\,*\,(x\,*\,3)\right) + \left( \text{pS21xLP13}\,(4)\,*\,(x\,*\,2)\right) + \left( \text{pS21xLP13}\,(5)\,*\,x\right) + \text{pS21xLP13}\,(6);
\text{AreaS21xLP13} = \text{integral}\,(\text{funS21xLP13},0,\text{Width});
\text{StressS21xLP13} = \text{AreaS21xLP13}/\text{Width};
\text{ForceS21xLP13} = \text{StressS21xLP13}\,*\text{Acs}\,*\,1\,\text{e6};
\text{pS21xLP14} = \text{polyfit}\,(\text{S21xLP14}\,(::,1),\text{S21xLP14}\,(::,2),5);
\text{funS21xLP14} = @(x) \left( \text{pS21xLP14}\,(1)\,*\,(x\,*\,5)\right) + \left( \text{pS21xLP14}\,(2)\,*\,(x\,*\,4)\right) + \left( \text{pS21xLP14}\,(3)\,*\,(x\,*\,3)\right) + \left( \text{pS21xLP14}\,(4)\,*\,(x\,*\,2)\right) + \left( \text{pS21xLP14}\,(5)\,*\,x\right) + \text{pS21xLP14}\,(6);
\text{AreaS21xLP14} = \text{integral}\,(\text{funS21xLP14},0,\text{Width});
\text{StressS21xLP14} = \text{AreaS21xLP14}/\text{Width};
\text{ForceS21xLP14} = \text{StressS21xLP14}\,*\text{Acs}\,*\,1\,\text{e6};
pS21xLP15 = polyfit(S21xLP15(:,1), S21xLP15(:,2), 5);

funS21xLP15 = @(x) (pS21xLP15(1)*(x.^5))+(pS21xLP15(2)*(x.^4))+(pS21xLP15(3)*(x.^3))+(pS21xLP15(4)*(x.^2))+(pS21xLP15(5)*x)+pS21xLP15(6);

AreaS21xLP15 = integral(funS21xLP15, 0, Width);

StressS21xLP15 = AreaS21xLP15/Width;

ForceS21xLP15 = StressS21xLP15*Acs*1e6;

pS21xLP16 = polyfit(S21xLP16(:,1), S21xLP16(:,2), 5);

funS21xLP16 = @(x) (pS21xLP16(1)*(x.^5))+(pS21xLP16(2)*(x.^4))+(pS21xLP16(3)*(x.^3))+(pS21xLP16(4)*(x.^2))+(pS21xLP16(5)*x)+pS21xLP16(6);

AreaS21xLP16 = integral(funS21xLP16, 0, Width);

StressS21xLP16 = AreaS21xLP16/Width;

ForceS21xLP16 = StressS21xLP16*Acs*1e6;

pS21xLP17 = polyfit(S21xLP17(:,1), S21xLP17(:,2), 5);

funS21xLP17 = @(x) (pS21xLP17(1)*(x.^5))+(pS21xLP17(2)*(x.^4))+(pS21xLP17(3)*(x.^3))+(pS21xLP17(4)*(x.^2))+(pS21xLP17(5)*x)+pS21xLP17(6);

AreaS21xLP17 = integral(funS21xLP17, 0, Width);

StressS21xLP17 = AreaS21xLP17/Width;

ForceS21xLP17 = StressS21xLP17*Acs*1e6;

pS21xLP18 = polyfit(S21xLP18(:,1), S21xLP18(:,2), 5);

funS21xLP18 = @(x) (pS21xLP18(1)*(x.^5))+(pS21xLP18(2)*(x.^4))+(pS21xLP18(3)*(x.^3))+(pS21xLP18(4)*(x.^2))+(pS21xLP18(5)*x)+pS21xLP18(6);

AreaS21xLP18 = integral(funS21xLP18, 0, Width);

StressS21xLP18 = AreaS21xLP18/Width;

ForceS21xLP18 = StressS21xLP18*Acs*1e6;

pS21xLP19 = polyfit(S21xLP19(:,1), S21xLP19(:,2), 5);
funS21xLP19=@(x) (pS21xLP19(1)*(x.~5))+(pS21xLP19(2)*(x.~4))+
               (pS21xLP19(3)*(x.~3))+(pS21xLP19(4)*(x.~2))+(pS21xLP19(5)*x)+
               pS21xLP19(6);

AreaS21xLP19=integral (funS21xLP19,0,Width);

StressS21xLP19=AreaS21xLP19/Width;

ForceS21xLP19=StressS21xLP19*Acs*1e6;

pS21xLP20=polyfit (S21xLP20(:,1),S21xLP20(:,2),5);

funS21xLP20=@(x) (pS21xLP20(1)*(x.~5))+(pS21xLP20(2)*(x.~4))+
               (pS21xLP20(3)*(x.~3))+(pS21xLP20(4)*(x.~2))+(pS21xLP20(5)*x)+
               pS21xLP20(6);

AreaS21xLP20=integral (funS21xLP20,0,Width);

StressS21xLP20=AreaS21xLP20/Width;

ForceS21xLP20=StressS21xLP20*Acs*1e6;

pS21xLP21=polyfit (S21xLP21(:,1),S21xLP21(:,2),5);

funS21xLP21=@(x) (pS21xLP21(1)*(x.~5))+(pS21xLP21(2)*(x.~4))+
               (pS21xLP21(3)*(x.~3))+(pS21xLP21(4)*(x.~2))+(pS21xLP21(5)*x)+
               pS21xLP21(6);

AreaS21xLP21=integral (funS21xLP21,0,Width);

StressS21xLP21=AreaS21xLP21/Width;

ForceS21xLP21=StressS21xLP21*Acs*1e6;

pS21xLP22=polyfit (S21xLP22(:,1),S21xLP22(:,2),5);

funS21xLP22=@(x) (pS21xLP22(1)*(x.~5))+(pS21xLP22(2)*(x.~4))+
               (pS21xLP22(3)*(x.~3))+(pS21xLP22(4)*(x.~2))+(pS21xLP22(5)*x)+
               pS21xLP22(6);

AreaS21xLP22=integral (funS21xLP22,0,Width);

StressS21xLP22=AreaS21xLP22/Width;

ForceS21xLP22=StressS21xLP22*Acs*1e6;

pS21xLP23=polyfit (S21xLP23(:,1),S21xLP23(:,2),5);

funS21xLP23=@(x) (pS21xLP23(1)*(x.~5))+(pS21xLP23(2)*(x.~4))+
               (pS21xLP23(3)*(x.~3))+(pS21xLP23(4)*(x.~2))+(pS21xLP23(5)*x)+
pS21xLP23(6);
230 AreaS21xLP23=integral(funS21xLP23,0,Width);
231 StressS21xLP23=AreaS21xLP23/Width;
232 ForceS21xLP23=StressS21xLP23*Acs*1e6;
233 pS21xLP24=polyfit(S21xLP24(:,1),S21xLP24(:,2),5);
234 funS21xLP24=@(x) (pS21xLP24(1)*(x.^5)+(pS21xLP24(2)*(x.^4))+(pS21xLP24(3)*(x.^3))+(pS21xLP24(4)*(x.^2))+(pS21xLP24(5)*x)+pS21xLP24(6);
235 AreaS21xLP24=integral(funS21xLP24,0,Width);
236 StressS21xLP24=AreaS21xLP24/Width;
237 ForceS21xLP24=StressS21xLP24*Acs*1e6;
238 pS21xLP25=polyfit(S21xLP25(:,1),S21xLP25(:,2),5);
239 funS21xLP25=@(x) (pS21xLP25(1)*(x.^5)+(pS21xLP25(2)*(x.^4))+(pS21xLP25(3)*(x.^3))+(pS21xLP25(4)*(x.^2))+(pS21xLP25(5)*x)+pS21xLP25(6);
240 AreaS21xLP25=integral(funS21xLP25,0,Width);
241 StressS21xLP25=AreaS21xLP25/Width;
242 ForceS21xLP25=StressS21xLP25*Acs*1e6;
243 pS21xLP26=polyfit(S21xLP26(:,1),S21xLP26(:,2),5);
244 funS21xLP26=@(x) (pS21xLP26(1)*(x.^5)+(pS21xLP26(2)*(x.^4))+(pS21xLP26(3)*(x.^3))+(pS21xLP26(4)*(x.^2))+(pS21xLP26(5)*x)+pS21xLP26(6);
245 AreaS21xLP26=integral(funS21xLP26,0,Width);
246 StressS21xLP26=AreaS21xLP26/Width;
247 ForceS21xLP26=StressS21xLP26*Acs*1e6;
248 pS21xLP27=polyfit(S21xLP27(:,1),S21xLP27(:,2),5);
249 funS21xLP27=@(x) (pS21xLP27(1)*(x.^5)+(pS21xLP27(2)*(x.^4))+(pS21xLP27(3)*(x.^3))+(pS21xLP27(4)*(x.^2))+(pS21xLP27(5)*x)+pS21xLP27(6);
250 AreaS21xLP27=integral(funS21xLP27,0,Width);
Stress = \frac{\text{Area}}{\text{Width}}; \\
\text{Force} = \text{Stress} \times \text{Acs} \times 1 \times 10^6; \\
p = \text{polyfit}(S21, : 1, S21, : 2, 5); \\
\text{fun} = @(x) (p(1) \times (x-5)) + (p(2) \times (x-4)) + (p(3) \times (x-3)) + (p(4) \times (x-2)) + (p(5) \times x) + p(6); \\
\text{Area} = \int(\text{fun}, 0, \text{Width}); \\
\text{Stress} = \frac{\text{Area}}{\text{Width}}; \\
\text{Force} = \text{Stress} \times \text{Acs} \times 1 \times 10^6; \\
p = \text{polyfit}(S21, : 1, S21, : 2, 5); \\
\text{fun} = @(x) (p(1) \times (x-5)) + (p(2) \times (x-4)) + (p(3) \times (x-3)) + (p(4) \times (x-2)) + (p(5) \times x) + p(6); \\
\text{Area} = \int(\text{fun}, 0, \text{Width}); \\
\text{Stress} = \frac{\text{Area}}{\text{Width}}; \\
\text{Force} = \text{Stress} \times \text{Acs} \times 1 \times 10^6; \\
p = \text{polyfit}(S21, : 1, S21, : 2, 5); \\
\text{fun} = @(x) (p(1) \times (x-5)) + (p(2) \times (x-4)) + (p(3) \times (x-3)) + (p(4) \times (x-2)) + (p(5) \times x) + p(6); \\
\text{Area} = \int(\text{fun}, 0, \text{Width}); \\
\text{Stress} = \frac{\text{Area}}{\text{Width}}; \\
\text{Force} = \text{Stress} \times \text{Acs} \times 1 \times 10^6;
273 \texttt{pS21xLP32=polyfit}\,(S21xLP32(:,1),S21xLP32(:,2),5);
274 \texttt{funS21xLP32= @(x) \((pS21xLP32(1)*(x.^5))+(pS21xLP32(2)*(x.^4))+}
275 \hspace{1cm} \texttt{pS21xLP32(3)*(x.^3))+(pS21xLP32(4)*(x.^2))+(pS21xLP32(5)*x)+}
276 \hspace{1cm} \texttt{pS21xLP32(6));}
277 \texttt{AreaS21xLP32=integral\,(funS21xLP32,0,Width);}
278 \texttt{StressS21xLP32=AreaS21xLP32/Width;}
279 \texttt{ForceS21xLP32=StressS21xLP32*Acs*1e6;}
280 \texttt{pS21xLP33=polyfit}\,(S21xLP33(:,1),S21xLP33(:,2),5);
281 \texttt{funS21xLP33= @(x) \((pS21xLP33(1)*(x.^5))+(pS21xLP33(2)*(x.^4))+}
282 \hspace{1cm} \texttt{pS21xLP33(3)*(x.^3))+(pS21xLP33(4)*(x.^2))+(pS21xLP33(5)*x)+}
283 \hspace{1cm} \texttt{pS21xLP33(6));}
284 \texttt{AreaS21xLP33=integral\,(funS21xLP33,0,Width);}
285 \texttt{StressS21xLP33=AreaS21xLP33/Width;}
286 \texttt{ForceS21xLP33=StressS21xLP33*Acs*1e6;}
287 \texttt{pS21xLP34=polyfit}\,(S21xLP34(:,1),S21xLP34(:,2),5);
288 \texttt{funS21xLP34= @(x) \((pS21xLP34(1)*(x.^5))+(pS21xLP34(2)*(x.^4))+}
289 \hspace{1cm} \texttt{pS21xLP34(3)*(x.^3))+(pS21xLP34(4)*(x.^2))+(pS21xLP34(5)*x)+}
290 \hspace{1cm} \texttt{pS21xLP34(6));}
291 \texttt{AreaS21xLP34=integral\,(funS21xLP34,0,Width);}
292 \texttt{StressS21xLP34=AreaS21xLP34/Width;}
293 \texttt{ForceS21xLP34=StressS21xLP34*Acs*1e6;}
294 \texttt{pS21xLP35=polyfit}\,(S21xLP35(:,1),S21xLP35(:,2),5);
295 \texttt{funS21xLP35= @(x) \((pS21xLP35(1)*(x.^5))+(pS21xLP35(2)*(x.^4))+}
296 \hspace{1cm} \texttt{pS21xLP35(3)*(x.^3))+(pS21xLP35(4)*(x.^2))+(pS21xLP35(5)*x)+}
297 \hspace{1cm} \texttt{pS21xLP35(6));}
298 \texttt{AreaS21xLP35=integral\,(funS21xLP35,0,Width);}
299 \texttt{StressS21xLP35=AreaS21xLP35/Width;}
300 \texttt{ForceS21xLP35=StressS21xLP35*Acs*1e6;}
301 \texttt{pS21xLP36=polyfit}\,(S21xLP36(:,1),S21xLP36(:,2),5);

\textit{UNCLASSIFIED: Distribution Statement A. Approved for public release}
funS21xLP36=@(x) (pS21xLP36(1)*(x.^5))+(pS21xLP36(2)*(x.^4))+
(pS21xLP36(3)*(x.^3))+(pS21xLP36(4)*(x.^2))+(pS21xLP36(5)*x)+
pS21xLP36(6);

AreaS21xLP36=integral(funS21xLP36,0,Width);

StressS21xLP36=AreaS21xLP36/Width;

ForceS21xLP36=StressS21xLP36*Acs*1e6;

pS21xLP37=polyfit(S21xLP37(:,1),S21xLP37(:,2),5);

funS21xLP37=@(x) (pS21xLP37(1)*(x.^5))+(pS21xLP37(2)*(x.^4))+
(pS21xLP37(3)*(x.^3))+(pS21xLP37(4)*(x.^2))+(pS21xLP37(5)*x)+
pS21xLP37(6);

AreaS21xLP37=integral(funS21xLP37,0,Width);

StressS21xLP37=AreaS21xLP37/Width;

ForceS21xLP37=StressS21xLP37*Acs*1e6;

pS21xLP38=polyfit(S21xLP38(:,1),S21xLP38(:,2),5);

funS21xLP38=@(x) (pS21xLP38(1)*(x.^5))+(pS21xLP38(2)*(x.^4))+
(pS21xLP38(3)*(x.^3))+(pS21xLP38(4)*(x.^2))+(pS21xLP38(5)*x)+
pS21xLP38(6);

AreaS21xLP38=integral(funS21xLP38,0,Width);

StressS21xLP38=AreaS21xLP38/Width;

ForceS21xLP38=StressS21xLP38*Acs*1e6;

pS21xLP39=polyfit(S21xLP39(:,1),S21xLP39(:,2),5);

funS21xLP39=@(x) (pS21xLP39(1)*(x.^5))+(pS21xLP39(2)*(x.^4))+
(pS21xLP39(3)*(x.^3))+(pS21xLP39(4)*(x.^2))+(pS21xLP39(5)*x)+
pS21xLP39(6);

AreaS21xLP39=integral(funS21xLP39,0,Width);

StressS21xLP39=AreaS21xLP39/Width;

ForceS21xLP39=StressS21xLP39*Acs*1e6;

pS21xLP40=polyfit(S21xLP40(:,1),S21xLP40(:,2),5);

funS21xLP40=@(x) (pS21xLP40(1)*(x.^5))+(pS21xLP40(2)*(x.^4))+
(pS21xLP40(3)*(x.^3))+(pS21xLP40(4)*(x.^2))+(pS21xLP40(5)*x)+

UNCLASSIFIED: Distribution Statement A. Approved for public release
\[ p_{S21xLP40}(6); \]
\[ \text{Area}_{S21xLP40} = \int (f\text{un}_{S21xLP40}, 0, \text{Width}); \]
\[ \text{Stress}_{S21xLP40} = \text{Area}_{S21xLP40}/\text{Width}; \]
\[ \text{Force}_{S21xLP40} = \text{Stress}_{S21xLP40} \times \text{Acs} \times 1e6; \]
\[ p_{S21xLP41} = \text{polyfit} (S21xLP41(:,1), S21xLP41(:,2), 5); \]
\[ \text{fun}_{S21xLP41} = @(x) (p_{S21xLP41}(1) \times (x.^5)) + (p_{S21xLP41}(2) \times (x.^4)) + (p_{S21xLP41}(3) \times (x.^3)) + (p_{S21xLP41}(4) \times (x.^2)) + (p_{S21xLP41}(5) \times x) + p_{S21xLP41}(6); \]
\[ \text{Area}_{S21xLP41} = \int (\text{fun}_{S21xLP41}, 0, \text{Width}); \]
\[ \text{Stress}_{S21xLP41} = \text{Area}_{S21xLP41}/\text{Width}; \]
\[ \text{Force}_{S21xLP41} = \text{Stress}_{S21xLP41} \times \text{Acs} \times 1e6; \]
\[ \text{Force}_{S21x}(2,1) = \text{Force}_{S21xLP2}; \]
\[ \text{Force}_{S21x}(3,1) = \text{Force}_{S21xLP3}; \]
\[ \text{Force}_{S21x}(4,1) = \text{Force}_{S21xLP4}; \]
\[ \text{Force}_{S21x}(5,1) = \text{Force}_{S21xLP5}; \]
\[ \text{Force}_{S21x}(6,1) = \text{Force}_{S21xLP6}; \]
\[ \text{Force}_{S21x}(7,1) = \text{Force}_{S21xLP7}; \]
\[ \text{Force}_{S21x}(8,1) = \text{Force}_{S21xLP8}; \]
\[ \text{Force}_{S21x}(9,1) = \text{Force}_{S21xLP9}; \]
\[ \text{Force}_{S21x}(10,1) = \text{Force}_{S21xLP10}; \]
\[ \text{Force}_{S21x}(11,1) = \text{Force}_{S21xLP11}; \]
\[ \text{Force}_{S21x}(12,1) = \text{Force}_{S21xLP12}; \]
\[ \text{Force}_{S21x}(13,1) = \text{Force}_{S21xLP13}; \]
\[ \text{Force}_{S21x}(14,1) = \text{Force}_{S21xLP14}; \]
\[ \text{Force}_{S21x}(15,1) = \text{Force}_{S21xLP15}; \]
\[ \text{Force}_{S21x}(16,1) = \text{Force}_{S21xLP16}; \]
\[ \text{Force}_{S21x}(17,1) = \text{Force}_{S21xLP17}; \]
\[ \text{Force}_{S21x}(18,1) = \text{Force}_{S21xLP18}; \]
\[ \text{Force}_{S21x}(19,1) = \text{Force}_{S21xLP19}; \]
\[ \text{Force}_{S21x}(20,1) = \text{Force}_{S21xLP20}; \]
342 ForceS21x (21,1)=ForceS21xLP21;
343 ForceS21x (22,1)=ForceS21xLP22;
344 ForceS21x (23,1)=ForceS21xLP23;
345 ForceS21x (24,1)=ForceS21xLP24;
346 ForceS21x (25,1)=ForceS21xLP25;
347 ForceS21x (26,1)=ForceS21xLP26;
348 ForceS21x (27,1)=ForceS21xLP27;
349 ForceS21x (28,1)=ForceS21xLP28;
350 ForceS21x (29,1)=ForceS21xLP29;
351 ForceS21x (30,1)=ForceS21xLP30;
352 ForceS21x (31,1)=ForceS21xLP31;
353 ForceS21x (32,1)=ForceS21xLP32;
354 ForceS21x (33,1)=ForceS21xLP33;
355 ForceS21x (34,1)=ForceS21xLP34;
356 ForceS21x (35,1)=ForceS21xLP35;
357 ForceS21x (36,1)=ForceS21xLP36;
358 ForceS21x (37,1)=ForceS21xLP37;
359 ForceS21x (38,1)=ForceS21xLP38;
360 ForceS21x (39,1)=ForceS21xLP39;
361 ForceS21x (40,1)=ForceS21xLP40;
362 ForceS21x (41,1)=ForceS21xLP41;
363 DispS21x (1,1)=DispS212;
364 DispS21x (2,1)=DispS213;
365 DispS21x (3,1)=DispS214;
366 DispS21x (4,1)=DispS215;
367 DispS21x (5,1)=DispS216;
Appendix B

Results from FEA Simulations

This appendix contains the results from the FEA simulation of the sensor and specimen discussed in Section 5.3.

Table B.1: The strain life properties of Al 1100 and electroplated Ni

<table>
<thead>
<tr>
<th></th>
<th>Al 1100 alloy</th>
<th>Electroplated Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$</td>
<td>69 GPa</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Fatigue strength coefficient, $\sigma'_f$</td>
<td>166 MPa</td>
<td>919 MPa</td>
</tr>
<tr>
<td>Fatigue strength exponent, $b$</td>
<td>-0.0961</td>
<td>-0.07</td>
</tr>
<tr>
<td>Fatigue ductility coefficient, $\epsilon'_f$</td>
<td>1.6433</td>
<td>1.66</td>
</tr>
<tr>
<td>Fatigue ductility exponent, $c$</td>
<td>-0.6433</td>
<td>-0.9</td>
</tr>
</tbody>
</table>
Table B.2: The results from FEA simulation of electroplated Ni sensor on Al 1100 specimen

<table>
<thead>
<tr>
<th>Load: 5500 N</th>
<th>Disp. Applied on specimen</th>
<th>Strain on Specimen: sensor plane</th>
<th>Disp. Applied on sensor</th>
<th>Fatigue Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>ε_{max}</td>
<td>mm</td>
<td>ε_{max}</td>
</tr>
<tr>
<td>Ligament 1</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Ligament 2</td>
<td>0.1287</td>
<td>0.0014</td>
<td>0.0035</td>
<td>5.13E-03</td>
</tr>
<tr>
<td>Ligament 3</td>
<td>0.1228</td>
<td>0.0012</td>
<td>0.003</td>
<td>4.94E-03</td>
</tr>
<tr>
<td>Ligament 4</td>
<td>0.116</td>
<td>0.0011</td>
<td>0.00275</td>
<td>9.93E-03</td>
</tr>
</tbody>
</table>

| Load: 4000 N | Ligament 1 | 0.0899 | 8.57E-04 | 0.00214 | 3.97E-03 | -2.00E-04 | 0.00298 | 459 |
| Ligament 2 | 0.0862 | 8.18E-04 | 0.00205 | 3.82E-03 | -1.92E-04 | 0.00287 | 442 |
| Ligament 3 | 0.0819 | 7.80E-04 | 0.00195 | 4.64E-03 | -2.05E-04 | 0.00334 | 494 |
| Ligament 4 | 0.0803 | 7.57E-04 | 0.00189 | 6.69E-03 | -6.20E-04 | 0.00365 | 499 |

| Load: 3000 N | Ligament 1 | 0.0616 | 5.88E-04 | 0.00147 | 2.74E-03 | -1.37E-04 | 0.00205 | 316 |
| Ligament 2 | 0.0607 | 5.76E-04 | 0.00144 | 2.96E-03 | -1.48E-04 | 0.00222 | 342 |
| Ligament 3 | 0.0598 | 5.67E-04 | 0.00142 | 3.42E-03 | -1.71E-04 | 0.00256 | 395 |
| Ligament 4 | 0.0594 | 5.60E-04 | 0.0014   | 4.00E-03 | -2.03E-04 | 0.00302 | 463 |
Table B.3: The results from FEA simulation of electroplated Ni sensor on Al 6061 specimen

<table>
<thead>
<tr>
<th>Ligament</th>
<th>Disp. Applied on sensor</th>
<th>Strain on Specimen: sensor plane</th>
<th>Fatigue Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>$\varepsilon_{\text{max}}$</td>
<td>$S_{\text{max}}$ (MPa)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\varepsilon_{\text{min}}$</td>
<td></td>
</tr>
<tr>
<td>Load:5500 N</td>
<td>Ligament 1</td>
<td>0.126</td>
<td>0.00297</td>
</tr>
<tr>
<td></td>
<td>Ligament 2</td>
<td>0.113</td>
<td>0.00268</td>
</tr>
<tr>
<td></td>
<td>Ligament 3</td>
<td>0.11</td>
<td>0.00259</td>
</tr>
<tr>
<td></td>
<td>Ligament 4</td>
<td>0.108</td>
<td>0.00255</td>
</tr>
<tr>
<td>Load:4000 N</td>
<td>Ligament 1</td>
<td>0.098</td>
<td>0.00268</td>
</tr>
<tr>
<td></td>
<td>Ligament 2</td>
<td>0.081</td>
<td>0.00238</td>
</tr>
<tr>
<td></td>
<td>Ligament 3</td>
<td>0.078</td>
<td>0.00234</td>
</tr>
<tr>
<td></td>
<td>Ligament 4</td>
<td>0.077</td>
<td>0.0023</td>
</tr>
<tr>
<td>Load:3000 N</td>
<td>Ligament 1</td>
<td>0.06</td>
<td>0.00201</td>
</tr>
<tr>
<td></td>
<td>Ligament 2</td>
<td>0.059</td>
<td>0.00194</td>
</tr>
<tr>
<td></td>
<td>Ligament 3</td>
<td>0.058</td>
<td>0.00192</td>
</tr>
<tr>
<td></td>
<td>Ligament 4</td>
<td>0.057</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

UNCLASSIFIED: Distribution Statement A. Approved for public release
Figure B.1: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 1100 specimen at max. load of 3000 N
Figure B.2: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 1100 specimen at max. load of 4000 N
Figure B.3: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 1100 specimen at max. load of 5500 N.
Figure B.4: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 6061 specimen at max. load of 3000 N
Figure B.5: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 6061 specimen at max. load of 4000 N
Figure B.6: The results from the FEA simulations of Electroplated Ni fatigue sensor on Al 6061 specimen at max. load of 5500 N
Appendix C

DAQ Wireless Network

In this appendix, the details of the wireless network modules developed for data acquisition of the fatigue sensors are presented.

A cost-effective and self-sufficient wireless sensor network (WSN) was developed to monitor the fatigue of a structure. The WSN consists of wireless sensing nodes or ‘motes’ and a base station to interface a device such as a PC or a laptop with the network. The motes and base station consists of MICAz wireless mote hardware running TinyOS, an operating system specially built for this purpose. The base station acts as a bridge for messages between the serial connection. The data transfer takes place using a universal asynchronous receiver/transmitter (UART) in conjunction with an RS 232 cable. The motes can specifically manage the sensor hardware and leave the high-level control to the PC side of the application such as activating and de-activating the motes or setting the frequency at which the motes report data to the base station.
Figure C.1: A schematic representation of the fatigue sensor DAQ work flow.